Indoor Thermal Comfort in Naturally Ventilated and Mixed-mode Ventilated Buildings

Xiang Deng

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Indoor Thermal Comfort in Naturally Ventilated and Mixed-mode Ventilated Buildings

Xiang Deng

This thesis is presented as part of the requirements for the conferral of the degree of Doctor of Philosophy

Sustainable Buildings Research Centre
Faculty of Engineering and Information Sciences
The University of Wollongong

March 2018
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This research has been conducted with the support of an Australian Government Research Training Program Scholarship.
DECLARATION

I, Xiang Deng, declare that this thesis is submitted in partial fulfilment of the requirements for the conferral of the degree of Doctor of Philosophy, from the University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

__________________________________________

Xiang Deng

29 October 2017
ABSTRACT

The recent development of many environmentally high-performance buildings with low or net-zero energy consumption, together with the aim of providing comfortable and healthy indoor thermal environments, has led to a renewed interest in the implementation of natural ventilation systems as an alternative to the more commonplace mechanically ventilated and air conditioned solution of past decades.

However, the uptake of natural ventilation in modern buildings, particularly in the non-residential sectors, has been somewhat limited due to the unsteady and unpredictable nature of the forces that drive natural ventilation, such as wind speed and direction, and indoor-to-outdoor temperature differences. Although a great deal of research has been carried out previously to address this issue, there are still some research gaps on the optimisation of natural ventilation from building design through to building operations that remain to be filled. For example, the occupant perceptions of indoor thermal comfort in high performance buildings with advanced natural ventilation still need to be further studied. As building opening is the key factor influencing the natural ventilation effect, it is necessary to systematically analyse the overall influence of all the window parameters; how to develop an automatic window control strategy that could respond to the dynamic change of weather conditions to fully tap the natural wind potential.

The intention in the present work was to carry out an investigation into the indoor thermal comfort of high performance buildings using natural/mixed-mode ventilation and to also develop strategies for the window design and operation optimisation in order to realise a low-carbon and liveable built environment.

An investigation into the thermal comfort of a high performance building was carried out by collecting field data to assess building thermal performance and by carrying out a post-occupancy evaluation (POE) of occupant thermal perceptions. The results indicated that occupants in high performance buildings might have a greater tolerance to non-ideal indoor comfort conditions throughout the year. A comparison between a static thermal comfort model, i.e. Fanger’s PMV model (Fanger 1970) and a dynamic thermal comfort model, i.e. the adaptive thermal comfort model (ASHRAE 55 2013), revealed that the static thermal comfort model matched the field study results of the case study building in winter, while the dynamic thermal comfort model worked better in summer conditions.
The characteristics of the external openings in a building envelope (windows, doors, etc.) is a key set of factors that influence the effectiveness of natural ventilation. In the present study, a range of Computational Fluid Dynamics (CFD) simulations were carried out to examine how the characteristics of top-hung windows fundamentally affect indoor airflow patterns and thermal comfort in a cross-ventilated space. The Taguchi method was used to design the simulation scenarios and the analysis of variance (ANOVA) method was used to determine the most significant factors influencing indoor thermal comfort. The results for a wide range of parameters considered for the case study building indicated that outdoor air temperature, window height and window opening angle influenced indoor thermal comfort most significantly.

Since the optimisation of natural ventilation control systems also has the potential to significantly improve indoor thermal comfort in a given building (in addition to window design optimisation), a variety of CFD simulations of the local thermal comfort conditions in a shared, open-plan and mixed ventilated office were carried out. The simulated scenarios covered most natural ventilation situations under the natural ventilation strategy used in the case study building at the time of writing. Three indices (i.e. thermal stratification, the extended predicted mean vote, and draught rate) and the corresponding criteria specified in ISO 7730 (2005) were selected and then used to assess local thermal comfort. The results indicated that draught was the main issue in the case study building. The simulations indicated that modulation of the window opening areas based on the current natural ventilation strategy of the case study building were not sufficient to maintain indoor thermal comfort. The simulation revealed that the minimum outdoor air temperature should be more than 25°C if using natural ventilation to ensure indoor thermal comfort.

Many strategies for controlling natural ventilation in high performance buildings have been previously developed using rule based approaches. However, such approaches may not modulate windows in a sufficiently sophisticated way to offset the negative influence that dynamic changes in the weather have on indoor thermal comfort (Tomažič et al. 2013). Thus, an optimal natural ventilation control strategy combining heuristic decision making and feedback control was developed. This control strategy consisted of an outdoor air temperature forecast algorithm, a decision tree to determine the optimal ventilation mode, and an iterative learning controller (ILC) to determine the window opening percentage under natural ventilation. A multi-zone thermal model of a net-zero
energy Solar Decathlon house was coupled with an air flow network model (developed using the TRNSYS simulation platform) and then used to test control strategies. The optimal control strategy was demonstrated (through simulations) to be more capable of providing the case study building with an acceptable indoor operative temperature for most of the natural ventilation periods when compared to a rule based control strategy. Moreover, the optimal natural ventilation strategy reduced the likelihood of overcooling, while maintaining a relatively stable indoor operative temperature.

The findings obtained from this thesis provided a better understanding of the thermal comfort conditions in high performance buildings using advanced natural/mixed-mode ventilation systems, and could also facilitate the optimal design and control optimisation of natural/mixed-mode ventilation systems to improve indoor thermal comfort.
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CHAPTER 1 INTRODUCTION

1.1 Background and motivation

Indoor thermal performance influences on the wellbeing and health of occupants as they generally spend more than 90% of their time in buildings (Lee and Chang 2000). Thermal discomfort may cause subclinical symptoms such as restless, distracted, headache and fatigue (Roelofsen 2002) and therefore, influence occupant productivity. A study showed that the learning ability of students was greatly influenced by the indoor thermal conditions of the classroom (Mendell and Heath 2006). In residential buildings, aged people tended to be dysthymia under thermal discomfort conditions (Taylor et al. 1995).

Natural ventilation acts a critical role in maintaining acceptable indoor thermal comfort conditions. The benefits of natural ventilation include but not limited to, increased energy efficiency, improved indoor air quality (IAQ), reduced greenhouse gas (GHG) emissions, reduction in occupant illness associated with indoor environmental quality and increased work productivity. Australian sustainable building movement gained momentum during and after the Sydney Olympics in 2000 (Mellon 2012). With the rise of the sustainable building movement, the application of natural ventilation is popularising. Many studies (Aynsley 1999, Miller et al. 2012, Deuble and de Dear 2012, Kima et al. 2016, Ezzeldin and Rees 2013, Drake et al. 2010) investigated the possibility to maintain indoor thermal comfort using natural wind in the populous districts in Australia. It was found that the popularity of natural ventilation was climate dependent. When compared to those in cold climatic zones, residents in subtropical or temperate climatic zones are more likely to utilise natural ventilation to maintain indoor thermal comfort. However, there are still some drawbacks that should be further investigated when natural ventilation is considered for indoor thermal comfort control. For buildings with large spaces or multiple rooms, indoor thermal comfort conditions are not consistent across the whole interior areas due to the complex interior layout and the uncontrollability of natural wind (Santamouris and Allard 1998, Daish et al. 2016). As a matter of fact, many studies (Wong et al. 2002, Buratti et al. 2013, Luo et al. 2015) have investigated the overall thermal performance of naturally ventilated buildings. However, the results from CFD simulation and field measurements indicated that an uneven distributed indoor air temperature and air speed could lead to the difference in the thermal perception of occupants (Zhou et al. 2013, Li et al. 2014). Although several studies identified and emphasised the difference in the
thermal perception of occupants in naturally ventilated buildings (Tan and Glicksman 2005, Tan and Glicksman 2010, Horikiri et al. 2015), few have analysed the influences of large interior space, complex layout or multiple rooms on the difference in the thermal perception of occupants. In addition, the indoor thermal comfort of the areas of interest such as meeting rooms, individual offices and shared desk areas in office buildings or bedrooms and living rooms in residential buildings should also be considered rather than focusing on the overall thermal performance of the whole building.

Occupant perceptions of indoor thermal comfort in high performance buildings with natural ventilation or mixed-mode ventilation are distinctive from those in traditional buildings (Baird 2015). High performance buildings are generally equipped with low energy technologies including natural ventilation and therefore, have low energy consumption. A previous study (Leaman and Bordass 2007) indicated that these buildings were more fragile in overall IEQ and thermal comfort performance although occupants were more tolerant to the indoor environment. Occupants in these buildings tend to perceive their working environment as warm in the subtropical area (Paul and Taylor 2008). The results from thermal comfort assessment are easily conflicting in these buildings as the thermal state varied in time and space (Gou et al. 2013). Therefore, it is inappropriate to evaluate the thermal comfort in high performance buildings using general guidelines developed for traditional buildings (Deuble and de Dear 2012) and the applicability of the classical thermal comfort models to high performance buildings remains to be answered.

Last but not the least, the instability of wind could also influence indoor thermal comfort (Khan et al. 2008). Indoor temperature and airflow rate might experience fluctuations and the thermal neutrality could be hard to achieve when using natural ventilation. Building design optimisation has, therefore, been considered to overcome barriers related to the use of natural ventilation (Kleiven 2003). The main idea of building design optimisation for natural ventilation is to ensure that the indoor temperature and airflow rate are well controlled under the desired ranges to achieve indoor thermal comfort (Santamouris and Allard 1998). Building design optimisation for natural ventilation involves many aspects such as building location, building orientation, building form, indoor partition, opening and urban layout (Heating et al. 2006). Among them, building opening is one of the key governing factors influencing natural ventilation as it is the only direct approach for external wind entering naturally ventilated buildings (Visagavel and Srinivasan 2009).
Many studies (Ayad 1999, Dascalaki et al. 1999, Gan 2000, Etheridge 2001, Eftekhari et al. 2003, Visagavel and Srinivasan 2009, Ravikumar and Prakash 2009) have investigated the influence of a single window parameter such as opening size, opening height above the ground, the amount of openings and the relative position of openings on the indoor thermal comfort. However, the majority of studies investigated the building opening parameters independently and the synergy of each parameter was often neglected.

With the advent of building management systems (BMSs), the automatic window opening control is becoming possible and has been implemented in many buildings. Automatic window control aims to represent human control of windows and allow a more accurate regulation of human thermal comfort conditions and building performance (Rijal et al. 2008). Properly designed automatic window control algorithms can reduce the limitation of natural ventilation resulted from improper building design or extreme outdoor weather conditions (Lenoir 2013). However, most automatic controlled natural ventilation systems cannot fully satisfy indoor thermal comfort and IAQ requirements as their window modulation algorithms only took limited factors that influence indoor thermal comfort (e.g. indoor temperature, outdoor temperature, wind speed) into account (Eftekhari et al. 2003, May-Ostendorp et al. 2013, Wang and Greenberg 2015). As a matter of fact, the indoor thermal comfort condition is influenced by a combined effect of diverse environmental and human factors. The window modulation decision should be made based on a comprehensive consideration of all the essential factors. Furthermore, many existing studies employed rule based control strategies for window modulation (Yun et al. 2009, May-Ostendorp et al. 2013, Wang and Greenberg 2015, Ezzeldin and Rees 2013, Zhao et al. 2016). Considering the dynamic change of working conditions, the rule based control sometimes cannot modulate window timely to offset the negative influence of the changes of indoor thermal comfort (Tomažič et al. 2013). As a consequence, these control strategies could only achieve sub-optimal control for indoor thermal comfort.

Based on the research background and motivation introduced above, the challenges for naturally ventilated and mixed-mode buildings to improve indoor thermal comfort include three aspects, i.e. occupant perception evaluation, the building design optimisation and the building opening operation optimisation. Thermal comfort zone should be carefully assessed as the occupant perception of indoor thermal comfort in buildings with natural ventilation or mixed-mode ventilation is different from those in
traditional buildings. As the most important factor influencing natural ventilation was window opening, window design optimisation is therefore a key focus in this dissertation to identify optimal window design to optimise airflow organisation and improve indoor thermal performance. For building operation optimisation, the research topic is that how to develop optimal natural ventilation control strategies that can respond to the dynamic change of weather conditions to reduce thermal discomfort time due to the drawbacks of natural ventilation.

1.2 Aim and objectives

The aim of this dissertation is to examine the thermal comfort of high performance buildings and optimise window design and control to maximise the satisfaction and comfort of occupants. The aim of this dissertation is achieved through the following objectives:

1. Exploration of the thermal performance of high performance buildings with mixed-mode ventilation systems;
2. Investigation of the effects of window parameters on the performance of natural ventilation and indoor thermal comfort and identification of the optimal window design through Taguchi method;
3. Investigation of the local thermal discomfort of open plan office buildings through computational fluid dynamics (CFD) simulation; and
4. Development of a control strategy to optimise the window modulation and facilitate natural ventilation to reduce the thermal discomfort hours and building energy consumption.

1.3 Research methodology

The overall research methodology employed in this study is illustrated in Fig. 1.1.

The objective 1 was achieved through post-occupancy evaluation (POE) surveys and in situ measurement. The building use studies (BUS) surveys were used to perceive the indoor thermal comfort of the case study building. Both long-term indoor thermal performance data recorded through the building management system (BMS) and spot measurements using mobile indoor environmental test equipment were used to achieve this objective.

The objective 2 was achieved through computational fluid dynamics (CFD) simulation.
The CFD models of a series of cross-ventilated models were developed in order to analyse the influence of the configurations of top-hung windows such as window width and window height on the indoor thermal comfort and airflow pattern. Taguchi method was employed to design the simulation scenarios.

The objective 3 was realised through CFD simulations. The CFD models were employed to analyse the local thermal comfort including the extended predicted mean vote (PMVe), draught rate and thermal stratification when using cross ventilation in the case study building.

An optimal window control strategy was developed in the objective 4 to facilitate natural ventilation in buildings. The control strategy combined heuristic decision making and feedback control to determine optimal window opening for indoor thermal comfort control. The performance of the control strategy was tested using a multi-zone building model developed using the TRNSYS simulation platform.
Chapter 1 Introduction

**Indoor thermal comfort investigation and building optimisation for indoor thermal comfort improvement in naturally ventilated/mixed-mode buildings**

**Field investigation and simulations**
- Post-occupancy evaluation of indoor thermal comfort perceptions
- *In situ* measurement of indoor thermal performances
- Modelling of cross-ventilated spaces with top-hung windows
- Modelling of a high performance office building
- Modelling of a high performance residential building

**Research tools**
- BUS survey
- BMS system and portable IEQ test equipment
- ANSYS Fluent software
- ANSYS Fluent software and portable IEQ test equipment
- TRNSYS software and portable IEQ test equipment

**Research objectives**
- **Building thermal environment investigation:** examination of thermal performance and occupant thermal perceptions in high performance mixed-mode ventilated buildings
- **Window design optimisation:** investigation of the influence of window parameters on the indoor airflow pattern and thermal comfort
- **Optimisation of an existing window control strategy:** investigation of local thermal discomfort of open plan office buildings
- **Development of a new window control strategy:** formulation of an optimal window control strategy to improve indoor thermal comfort

Fig. 1.1 Schematic diagram of the research methodology used in this dissertation.
1.4 Thesis outline

This dissertation has been divided into seven chapters as follows:

This chapter has provided the background and motivation of this dissertation. The aim and objectives of this dissertation and the primary research methodologies have also been presented.

Chapter 2 provides a review of the studies related to indoor thermal comfort in naturally ventilated and mixed-mode buildings with a key focus on the building design optimisation and natural ventilation control optimisation to improve indoor thermal comfort.

Chapter 3 investigates the thermal environment in a high performance building. Field measurement and post-occupancy evaluation (POE) survey were carried out to understand the occupant perception discrepancy. A comparison was made between a static model and a dynamic model to give an insight into the most suitable thermal comfort model for such type of buildings.

Chapter 4 presents a top-hung window design optimisation to understand the influences of window configuration and outdoor weather condition on indoor thermal comfort and airflow rate using CFD simulations. The Taguchi method was used to design the simulation scenarios. Analysis of variance (ANOVA) was used for the percentage contribution analysis. Signal-to-Noise (S/N) ratio method was used to identify the near-optimal window attribute combination.

Chapter 5 presents an evaluation of the indoor local thermal comfort in a high performance office building and an optimisation of window control to improve indoor local thermal comfort using CFD simulations. The airflow pattern and local thermal comfort performance both before and after the implementation of natural ventilation control optimisation were analysed.

Chapter 6 presents the development and evaluation of an optimal window control strategy to facilitate natural ventilation. A thermal and airflow network coupled multi-zone model of a residential house was developed using TRNSYS and then used to test the performance of this strategy. A comparison was also made between the use of this control strategy and a rule based control strategy for indoor thermal comfort control.
Chapter 7 summarises the key findings obtained from this dissertation and provides some recommendations for future work in this direction.

1.5 Publications

Part of contents in Chapters 3, 4 and 6 of this dissertation was based on three publications listed below. The author of this dissertation was the primary contributor (the first author or correspondence author) to the technical content and academic insight of the papers, whereas the contributions from the other authors were mainly on reviewing content, presentation and formatting, and proofreading.


CHAPTER 2 LITERATURE REVIEW

This chapter focuses mainly on naturally ventilated building design and natural ventilation control optimisation to improve indoor thermal comfort. Previous literature has been reviewed to give insights into the approaches used to assess thermal comfort in naturally ventilated buildings, the measurement and modelling of naturally ventilated buildings, optimisation of the design of naturally ventilated buildings, and strategies for natural ventilation control.

This chapter is organised as follows. Section 2.1 describes the fundamentals of thermal comfort. Section 2.2 summarises the methods used in the field to investigate indoor thermal comfort in naturally ventilated buildings. Section 2.3 presents the experimental design and modelling of naturally ventilated buildings. Design optimisation and natural ventilation control of buildings are reviewed in Sections 2.4 and 2.5 respectively, and Section 2.6 provides a brief summary of this chapter.

2.1 Thermal comfort fundamentals

The indoor environment of buildings is a key concern for the health and well-being of occupants. Many factors influence the indoor environment, but they can generally be assessed via the thermal comfort, the indoor air quality (IAQ), visual comfort, and acoustic quality (Guideline 2005).

Frontczak and Wargocki (2011) reported that whilst not universally consistent across all studies, thermal comfort was slightly more important than the other indoor environmental factors, as shown in Fig. 2.1.
Thermal comfort is defined as ‘a condition of mind that expresses satisfaction with the thermal environment and is assessed mainly by subjective evaluation’ (ISO 7730 2005). It is generally believed that there are six primary factors which directly affect thermal comfort, i.e. metabolic rate, clothing insulation, air temperature, radiant temperature, humidity, and air speed (Hindmarsh and Macpherson 1962).

2.1.1 Thermal comfort models

Based on the state of an ambient environment, thermal comfort models can be categorised as either static or dynamic (Djongyang et al. 2010). The most common models for each group are the predicted mean vote (PMV) model and the adaptive thermal comfort model (Yang et al. 2014).

2.1.1.1 Predicted mean vote (PMV) model

The predicted mean vote (PMV) model proposed by Fanger (1970) is based on the principle of heat balance and data from thousands of subjects exposed to controlled environments. The PMV assumes that thermal comfort is achieved when heat loss through radiation, conduction, convection, and evaporation equals the production of heat by a human body where the core body temperature is maintained at 37°C. The PMV index
has a seven point scale (Table 2.1) for participants to express thermal sensations under given thermal environments.

<table>
<thead>
<tr>
<th></th>
<th>Cold</th>
<th>Cool</th>
<th>Slightly cool</th>
<th>Neutral</th>
<th>Slightly warm</th>
<th>Warm</th>
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<tr>
<td></td>
<td>-3</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>2</td>
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The relationship of the PMV index to the imbalance between actual heat from the body and the heat required for thermal comfort at a specified activity in a given thermal environment can be described by the following equation.

\[
PMV = (0.303e^{-0.036M} + 0.028)L
\]  

(2.1)

where \( M \) is the metabolic rate and \( L \) is the thermal load defined as the difference between the internal production of heat and heat loss to the actual environment.

However, there are discrepancies between the PMV prediction and the actual mean vote (AMV) of occupants in buildings (Kim et al. 2015). For example, the PMV model overestimates the warmth of people in heavier clothing and underestimates the cooling effect of an increased movement of air (Humphreys and Nicol 2002). To overcome these limitations, an adaptive predicted mean vote (aPMV) model, as shown in Eq. (2.2), was proposed by Yao et al. (2009) to introduce an adaptive coefficient into the PMV model based on the black box theory:

\[
aPMV = \frac{PMV}{1 + \lambda \times PMV}
\]  

(2.2)

where \( \lambda \) is an adaptive coefficient which considers culture, climate, social, psychological and behavioural adaptations.

Since the metabolic rate is difficult to measure or estimate, it is normally assumed to be constant for some specified activities in the PMV model, but Gilani et al. (2016) found a correlation between the mean blood pressure and the activity level in air conditioned environments.
buildings, as shown in Eq. (2.3). Based on this correlation, the activity level can be modified to improve the accuracy of the PMV model.

\[ M = 0.1092 \times \exp(MPA \times 0.0296) \]  
(2.3)

where \( MPA \) is the mean arterial blood pressure.

Humphreys and Nicol (2002) found that PMV could lead to wrong results when used to predict the mean comfort votes of a group of people in everyday conditions in buildings, so they improved the PMV model with the following equation.

\[ PMV_{\text{new}} = 0.8 \times (PMV - D_{PMV}) \]  
(2.4)

where \( D_{PMV} \) is the deviation correction function associated with indoor and outdoor climates and 0.8 is the regression coefficient.

Brager and de Dear (1998) found that the PMV model predicted a warmer thermal sensation than the occupants actually felt in naturally ventilated buildings in warm climates. Fanger and Toftum (2002) speculated that occupant expectation was the main reason for overestimation. This influence was expressed by an expectancy factor that multiplies PMV to adjust the mean thermal sensation vote of the occupants in non-air conditioned buildings in warm climates, as shown in Eq. (2.5).

\[ PMV_e = e \times PMV \]  
(2.5)

where \( e \) is the expectancy factor. In regions with few air conditioned buildings, the recommended expectancy factor could be 0.7–0.8, but in regions with many air conditioned buildings, the recommended expectancy factor could be 0.8–0.9. In regions where most buildings are air conditioned, the recommended expectancy factor could be 0.9–1.
2.1.1.2 Predicted percentage of dissatisfied (PPD)

Fanger (1970) realised that PMV was only the mean value to be expected from a group of people, and hence extended the PMV by proposing an index of predicted percentage of dissatisfied (PPD), as shown in Eq. (2.6), to provide a quantitative prediction of the number of people dissatisfied with certain ambient conditions. This distribution of PPD is based on observations from climate chamber experiments rather than field measurements.

\[
PPD = 100 - 95 \times \exp(-0.03353PMV^4 + 0.2179PMV^2)
\]  

(2.6)

To provide a more intuitive impression of the relationship between PMV and PPD, PPD as a function of PMV is also presented in Fig. 2.2. Note here that 5% of people are still dissatisfied with the thermal comfort even when the people were in thermal neutrality (i.e. PMV=0).

Fig. 2.2 Relation between PMV and PPD (García 2010).
2.1.1.3 *Adaptive thermal comfort model*

The PMV model only proved to be valid for a person in a steady state environment (de Dear 2004) because people generally do not just passively perceive the ambient environment. They continually adapt to the ambient environment in order to approach thermal comfort by physiological adaptation, psychological adaptation, and behavioural adjustment (Roaf et al. 2010).

In order to consider the thermal comfort adaptation process, de Dear and Brager (1998) developed an acceptable operative temperature range for naturally conditioned spaces, as shown in Fig. 2.3. It consisted of a regressed equation with 80% and 90% acceptable indoor operative temperature bands based on 21,000 sets of raw data around the world. This adaptive thermal comfort model is being widely used for buildings with dynamic environments such as naturally ventilated buildings.

![Fig. 2.3 Acceptable operative temperature ranges for naturally conditioned spaces (de Dear and Brager 1998).](image)

2.1.1.4 *Local thermal discomfort*

The PMV model and the adaptive thermal comfort model can assess the overall indoor thermal comfort conditions rather than local thermal discomfort. Local thermal discomfort is usually caused by thermal stratification, asymmetric radiant, draught, and
cold or warm floors (Olesen 1985). The requirements to avoid local thermal discomfort can be found in ISO 7730 (2005) and ASHRAE 55 (2013) standards.

2.1.2 Natural ventilation for thermal comfort

2.1.2.1 Natural ventilation principle

Natural ventilation uses natural forces rather than mechanical systems to drive airflow through a space to improve indoor air quality and thermal comfort for occupants and reduce energy consumption (Willmert 2001).

There are two fundamental driving forces for natural ventilation, i.e. thermal buoyancy and wind pressure (Santamouris and Allard 1998); these two driving forces usually occur concurrently but wind pressure is the dominating driving force in cross ventilated buildings, whereas thermal buoyancy dominates in single-sided ventilated buildings (Kleiven 2003).

Based on the form and layout of buildings, natural ventilation can be categorised as single zone ventilation and multi-zone ventilation (Feustel 1999). Single zone ventilation assumes the whole building as a single, well-mixed zone without internal partitions (Axley 2007), whereas multi-zone ventilation considers the airflow patterns in the building to be non-uniform and hence separates the building into several zones (Feustel 1999).

With regard to the opening configuration in buildings, natural ventilation can be divided into single-sided ventilation, cross-ventilation and courtyard ventilation (Awbi 1996). Single-sided ventilation allows one or more opening to exist on the single side of an enclosed building (Gan 1999), while cross-ventilation occurs when there are openings on two or more sides of a building (Mohamed et al. 2011). Courtyard ventilation draws fresh and cool air from openings at the bottom of a building and then prompts an outflow through openings at the top (Al-Hemiddi and Al-Saud 2001).

2.1.2.2 Advantages and disadvantages of natural ventilation for thermal comfort

Rather than using active ventilation to provide comfortable indoor conditions, naturally ventilated buildings depend on passive ventilation. There are some limitations with natural ventilation in securing indoor thermal comfort, and they are presented in the following three aspects (Emmerich et al. 2001).
Chapter 2 Literature review

- **Dependency**: The availability of natural ventilation is largely influenced by outdoor environmental factors (e.g. air temperature, wind speed, wind direction, humidity, solar radiation and rain) and building configuration parameters (e.g. building orientation, window position and internal layout) (Santamouris and Allard 1998).

- **Unpredictability**: Since the indoor thermal conditions are highly dependent on outdoor weather conditions, any variations of outdoor weather make maintaining indoor thermal comfort relatively unpredictable (Aynsley 1999).

- **Uncontrollability**: Because of transient weather change and the control hysteresis of natural ventilation, a complete elimination of fluctuating indoor thermal conditions is impossible, and even within a building with outstanding natural ventilation design and control, the thermal comfort still cannot be maintained under some extreme outdoor weather conditions (Emmerich et al. 2001).

Despite this, the benefits of using natural ventilation cannot be ignored. Previous studies have shown that occupants in naturally ventilated or mixed-mode ventilated buildings are at least as comfortable as those in air conditioned buildings (Paul and Taylor 2008) because they have a wider range of thermal comfort zones (Brager and de Dear 1998). The power spectral analysis revealed that human sensation is sensitive to the wind frequency and the spectral characteristics of natural wind and mechanical wind were obviously different (Ouyang et al. 2006). Natural wind stimulates the wind signals transferred from skin to brain and the heat exchange of skin due to natural wind is larger than that of mechanical wind due to the long term evolution (Zhu 2000). Therefore, comfortable air temperature desired in naturally ventilated buildings is normally higher than that in air conditioned buildings and occupants can accept a broader speed range of natural wind than mechanical wind (Busch 1992). Moreover, occupants can make a thermal adaptation in naturally ventilated buildings to restore thermal comfort (Brager and de Dear 1998). They have more opportunities to determine the most comfortable thermal conditions through individual access to the operable windows and curtain blinds.

This review showed that occupants in naturally ventilated buildings perceive their thermal comfort as being quite different from those in air conditioned buildings. The PMV model is only accurate in buildings with air conditioning systems, so modified PMV models were developed to overcome the limitations of the PMV model. The adaptive thermal comfort model links the indoor climatic condition with the outdoor climatic context of the building and also takes care of past thermal experiences and the current thermal
expectations of the occupants (Singh et al. 2010). However, the adaptive thermal comfort model cannot accurately assess the clothing and activity levels of the occupants, so the evaluation is not as precise as the modified PMV models (Singh et al. 2011). The model used to evaluate indoor thermal comfort evaluation should be carefully selected.

2.2 Field investigation of thermal comfort in naturally ventilated buildings

The investigation of thermal comfort in naturally ventilated buildings can be divided into objective and subjective measurements. Objective measurements investigate the thermal perception of the occupants while subjective measurements generally analyse the thermal performance of the building. Objective measurements are usually achieved through post-occupancy evaluation (POE) whilst subjective measurement means an in situ measurement of environmental factors.

2.2.1 Post-occupancy evaluation (POE)

POE is a tool to systematically study building performance to improve the current conditions by commissioning and guiding future building designs (Preiser 2013). Fig. 2.4 presents the basic process of POE (Blyth et al. 2006).

![POE process proposed by Blyth et al. (2006).](image)

POE differs from other methods in that the occupants are the main stakeholders (Council 2002), the criteria are based on the designed intents rather than industrial standards (Council 2002), and the target performance is occupant perception rather than actual building performance metrics (Nicol and Roaf 2005). Besides, POE tends to utilise qualitative analysis (Dunlap et al. 2000, Candido et al. 2016).

Qualitative methods such as interviews and questionnaires are used to help understand the interrelationships between the thermal performance of a building and occupant perceptions. The interviews and questionnaires enable the subjective perception of indoor parameters to be quantified by rating temperature, ventilation, overall satisfaction, etc. (Meir et al. 2009).
The literature review from Al Horr et al. (2016) showed that POE was mainly used to evaluate building performance and occupant productivity, and thermal comfort is one of the most significant factors affecting occupant productivity. Nicol and Roaf (2005) compared the POE results with the results from a field study of 15 academic buildings. It was shown that the occupants evaluated the indoor thermal environment depending on the context, and the results varied with time. Abbaszadeh et al. (2006) conducted a POE survey to compare green and non-green office buildings in terms of the indoor environmental quality and found that on average, the occupants in green buildings were more satisfied with the indoor thermal comfort and air quality than those in non-green buildings. Holmes and Hacker (2007) investigated the performance of a mixed-mode building in the UK through POE and found that mixed-mode buildings were in a good way to reduce energy consumption and provide comfortable indoor thermal conditions. Brager and Baker (2009) conducted a web-based survey of 12 mixed-mode buildings and compared the results with a benchmark database of 370 buildings, and found that the mixed-mode buildings performed very well in terms of thermal comfort when compared to the overall building stock.

Goto et al. (2007) conducted a long term POE survey in six office buildings in Japan to identify how the occupants adapt to the indoor climate and found that the adjustment of clothing was the major behavioural difference between naturally ventilated and air conditioned buildings. Choi et al. (2010) analysed the influence of age on the preferred air temperature and thermal satisfaction through a POE survey and found that people over 40 years old had higher levels of satisfaction than those under 40 in the cooling season.

Deuble and de Dear (2012) investigated two academic office buildings (i.e. one was a naturally ventilated building and the other was a mixed-mode building) through POE survey and found that occupants with higher levels of environmental concern were more tolerant of building thermal performance.

Kim and de Dear (2012) made use of a POE database to investigate the indoor environmental factors and overall satisfaction. The statistical analysis revealed that there was a nonlinear relationship between the indoor environmental factors and overall satisfaction, and the indoor thermal condition had a negative impact on the overall satisfaction of occupants if the building is underperformed.
Kim et al. (2013) investigated the influence that gender difference had on occupant perceptions of indoor environmental quality based on a POE database from CBE (Centre for the Built Environment) at the University of California, Berkeley. A logistic regression analysis identified a significant relationship between female gender and dissatisfaction with the thermal environment. Berge and Mathisen (2016) performed a POE survey to investigate the performance of residential buildings and found that the temperature requirements differed from room to room.

These studies showed that POE tends to utilise qualitative analysis to help understand the interrelationships between the thermal performance of naturally ventilated or mixed-mode buildings and the occupant perception by rating temperature, ventilation, and overall satisfaction (Zagreus et al. 2004, Leaman et al. 2007, Meir et al. 2009). However, the POE results only reflect subjective perception and cannot provide quantitative indicators to control the indoor environment (Hadjri and Crozier 2009).

2.2.2 *In situ* measurement

The sense of thermal comfort depends on the air temperature, the radiant temperature, the air humidity and the air movement, all of which can be measured over a long term or at a point in time (Carlucci and Pagliano 2012). Long term measurements are used to evaluate the number of hours that the thermal conditions of a building are outside the recommended range (Olesen and De Carli 2002), the effect of shading on thermal comfort over the whole year (Lin et al. 2010) and the thermal adaptation of occupants to indoor climate in naturally ventilated buildings (Goto et al. 2007), over a long period. A point in time measurement concentrates on indoor thermal comfort in specific conditions such as the percentage of thermal dissatisfaction at high relative humidity conditions (Fountain et al. 1999), thermal comfort when using night ventilation (Blondeau et al. 1997), and the effect of warm air supplied facially on occupant comfort (Kaczmarczyk et al. 2010).

These *in situ* measurements collect ventilation related data within existing buildings which are mainly used to evaluate the ventilation performance, develop empirical equations or mathematical models, and validate the performance of numerical models. *In situ* measurements can be taken in a real building or in an environmental chamber, usually with an anemometer, thermometer, particle image velocimetry and tracer gas (Sherman 1990, Sandberg 2007, Han et al. 2009, Indraganti 2010).
To date, a number of studies have carried out in situ measurements to investigate natural ventilation and indoor thermal comfort. For example, Dascalaki et al. (1995) measured the air velocities at the window opening height in four single-sided environmental chambers using hot wire sensors, and the average indoor airflow rate using a tracer gas detector. A coefficient defined as the ratio of mean indoor air velocity and the actual outdoor air velocity was calculated to represent the relative rate of indoor airflow. Feriadi and Wong (2004) tested some residential buildings in Indonesia using dry bulb temperature, relative humidity and mean radiant temperature sensors placed in an aluminium mounting platform. At the same time, POE questionnaires were completed by the occupants to understand their preferred thermal conditions. It was found that in hot and humid tropical climates, the favourite temperature was 26°C, which was 3°C lower than the local neutral temperature. Santamouris et al. (2008) analysed the concentrations of carbon dioxide collected by carbon dioxide sensors from 287 classrooms of 182 naturally ventilated schools and found that with the airflow around 8 l/p/s, a carbon dioxide concentration of 1000 ppm, which was the upper limit in most cases, could be anticipated. Han et al. (2009) used the Swema 3000 test system to measure the air velocity, temperature and relative humidity in naturally ventilated residential buildings for urban and rural areas in Hunan, China, during a cold winter. A POE survey was also conducted at the same time. The results showed that the neutral temperature was 14°C for urban residences and only 11.5°C for rural residences.

These studies used in situ measurements to collect real data for quantitative analysis of the ventilation of the objective buildings. A combined utilisation of in situ measurements and POE surveys was frequently used to better understand the correlations between real indoor thermal conditions and occupant perceptions. However, in situ measurements are not easy because there are many unexpected and uncontrollable disturbances such as the thermos-fluid boundary conditions (Melikov et al. 2007, Chen 2009), which means the results obtained from a building may not be applicable to other similar buildings (Chen 2009).

As a summary, two fundamental methods are used to investigate indoor thermal comfort, i.e. POE survey and in situ measurements. A POE survey uses interviews or questionnaires to qualitatively evaluate indoor thermal performance and occupant thermal perception, while in situ measurements collect thermal comfort-related data within buildings to quantitatively analyse the thermal comfort of naturally ventilated buildings.
2.3 Experimental design and numerical modelling of naturally ventilated buildings

2.3.1 Experimental design

An experimental design uses measuring techniques to predict or evaluate the natural ventilation within realistic physical building models. It is normally based on either full scale experimental models or small scale experimental models (Chen 2009).

2.3.1.1 Full scale experimental models

Full scale experimental models use environmental chambers to simulate rooms or buildings (Chen 2009), but they should be placed inside a wind tunnel to emulate outdoor wind conditions. In an environmental chamber, the thermo-fluid boundary conditions can generally be controlled, unlike in situ measurements (Zhang et al. 2009). Fig. 2.5 shows some applications of full scale experimental models used to analyse natural ventilation.

Fig. 2.5 Examples of full scale experimental models (Richards et al. 2001, Arce et al. 2008, Wang et al. 2015).

Full scale experimental models are widely used to investigate natural ventilation. For example, using experimental data collected from a full scale wind tunnel experimental facility, Nishizawa et al. (2007) found that the main flow, the rebounding and changing flow direction, deflected flow, surface flow, and circulating flow were the main characteristics of cross-ventilation. Larsen and Heiselberg (2008) constructed a full scale building model inside a wind tunnel to analyse the effect that wind incidence angles have on the airflow patterns in the windows, and then proposed an equation to calculate the airflow under single-sided ventilation. Richards et al. (2001) constructed a 6m cube in an
open countryside to analyse the distribution of wind pressure on the building façade and found that the roof and leeward walls were the areas where the airflow pattern could be changed easily by variations in the velocity profile, turbulence, and Reynolds number. Arce et al. (2008) used a full scale model to investigate the thermal performance of a solar chimney for natural ventilation under Mediterranean daylight and night time conditions, and found that the average airflow improved significantly due to the solar chimney.

Full scale experimental models can provide a realistic prediction of natural ventilation in buildings but they are generally expensive and time consuming. Full scale experimental models are generally used to obtain the data required to validate numerical models such as CFD models that are used to predict the natural ventilation or facilitate the design of natural ventilation systems (Chen 2009).

2.3.1.2 Small scale experimental models

Small scale experimental models can predict or evaluate ventilation within reduced scale building models (Chen 2009), but unlike full scale experimental models, they are more economical. Small scale experimental models are based on similarity theory (Durst 2008) to mimic the real airflow characteristics of natural wind inside and around buildings. Fig. 2.6 shows some applications of small scale experimental models used to analyse natural ventilation.

Fig. 2.6 Examples of small scale experimental models (Ding et al. 2005, Karava et al. 2011, Walker et al. 2011).

To maintain similarity between a small scale model and a real building, important flow parameters such as the Reynolds number, the Grashof number, and the Prandtl number of
small scale model must be the same as a real building (Chen 2009). However, it is almost impossible to satisfy the requirements of similarity if heat transfer is included in the small scale models (Etheridge 2015).

Small scale models are very effective when studying ventilation for indoor thermal comfort and analysing the indoor airflow pattern. For example, Kang and Lee (2008) used a small scale model to investigate natural ventilation in a large factory building with a louvred ventilator. Lee et al. (2007) developed a 1/20 scale model of a naturally ventilated broiler house to analyse the distribution of air through a particle image velocimetry (PIV) test. Boulard et al. (1999) utilised a half scale test cell to simulate the temperature and airflow pattern on the floor surface of a single span greenhouse by considering the absorption of solar radiation. A small scale model can also be used to validate the results from CFD simulations (Durst 2008, Chen 2009).

2.3.2 Numerical models

Numerical models based on physical idealisations of building systems are also used to design and analyse natural ventilation. Numerical models are classified as either macroscopic models or microscopic models (Emmerich et al. 2001).

2.3.2.1 Macroscopic models

Macroscopic models normally refer to multi-zone building models based on physical idealisations of building systems as a collection of control volumes (Feustel 1999). Multi-zone building models describe a building as a set of zones interconnected by airflow paths based on energy and mass balance equations. These zones are presumed to be well mixed and the air state in a zone remains constant if there are no external or internal disturbances (Weber et al. 2002). Unlike single zone models, a multi-zone building model can provide more details because they separate the building into a set of zones. Multi-zone building models can also be used for single zone analysis.

Several multi-zone modelling software tools are now available for indoor airflow analysis, such as CONTAM, COMIS and BREEZE (Orme 1999). These tools can perform steady state and transient analyses, but they cannot analyse the indoor thermal environment because indoor heat transfer actually interacts with the movement of indoor air (Axley et al. 2002). However, building energy simulation software such as EnergyPlus, eQUEST, DOE-2, ESP-r, and TRNSYS could solve heat transfer problems
(Fernández-Membrive et al. 2015), which is why the software for indoor airflow simulation and building energy simulation are normally combined for multi-zone building analysis.

There are three basic thermal and airflow coupling methods: sequential coupling, ‘Ping-pong’ and ‘Onions’ (Hensen 1995, Breesch and Janssens 2002), as shown in Fig. 2.7.

Fig. 2.7 Three different airflow-thermal coupling methods (Hensen 1995, Breesch and Janssens 2002).

Note that sequential coupling transfers the airflow results into the thermal model without interaction, whereas ‘ping-pong’ introduces the thermal simulation results from the last time step into the airflow model to acquire the airflow results which are then returned to the thermal model. Only the ‘Onion’ method realises the coupling at each time step. One successful application of the ‘Onion’ method is COMIS, which has been integrated with the thermal analysis tool TNRSYS (Weber et al. 2002).

2.3.2.2 Microscopic models

Microscopic models have a system of partial differential equations where the physical domain is subdivided into a larger number of grids (Emmerich et al. 2001). The most commonly used microscopic model for designing and analysing natural ventilation is the
computational fluid dynamics (CFD) model developed on the Navier-Stokes equations (Hirsch 2007).

Computation fluid dynamics (CFD) models can mimic the airflow based on theoretical fluid equations and yield a database of the simulated airflow and visual airflow charts (Anderson and Wendt 1995). The main advantages of CFD modelling include (Sharma 2016):

- A reduction in time and cost compared to the experimental models;
- An alternative to difficult or dangerous experiments; and
- It can provide detailed information about the airflow pattern.

The results of CFD simulations depend on the building model mesh, the boundary, the solver, and the number of iterations (Hajdukiewicz et al. 2013). This means that accuracy may not be realised if these settings are not reasonable.

The application of CFD models for natural ventilation analysis are summarised as follows:

- Multi-zone airflow pattern: Tan and Glicksman (2005) integrated a multi-zone model with CFD modelling to investigate how the atrium affected the airflow pattern. Tan and Glicksman (2005) also investigated a large atrium by CFD simulation and found that dividing it into at least two smaller zones by virtual walls could better mimic the real airflow pattern and improve the accuracy of the simulation results. Wang and Chen (2007) analysed the pressure drops at the openings of a multi-zone office building using CONTAM, which were then used as the CFD boundary conditions to simulate the air distribution in each room. The CFD simulation became more accurate when the CFD model was combined with the CONTAM model. Wang and Chen (2008) concluded through CFD simulations that an assumption of a uniform air temperature in a zone was acceptable in multi-zone airflow network models when the dimensionless temperature gradient is smaller than 0.03. Han et al. (2015) built a multi-zone airflow model using CFD to calculate the infiltration rate in an office building and found that energy consumption due to air infiltration could take approximately 12% of the total amount of annual energy consumed.

- Indoor air quality (IAQ): Gan (1999) used CFD to investigate the effective depth of fresh air in rooms with single-sided natural ventilation and found that the
effective depth was affected by the outdoor temperature and the width and height of window openings. Lee and Awbi (2004) investigated the effect that internal partitioning had on indoor air quality in a CFD model room with mixed ventilation and found that a contaminated source had almost no influence on the air quality under the given height of the partition and the gap underneath. Lee and Awbi (2004) tried different sizes of internal partitions in a small room model to investigate their effects on the indoor air quality. Chiang et al. (2005) compared different louvres to identify the rates at which the air changed, while Van Hooff and Blocken (2013) studied the decay of CO₂ in a large naturally ventilated semi-enclosed stadium and found it was impossible to use a single value to represent the concentration of CO₂ for the whole stadium due to a weak mixing of indoor air. Shaaban et al. (2014) investigated the influence of the ventilation rate and density of gaseous contaminant on indoor air quality in a chemical laboratory. Wang and Chow (2015) analysed the impact of human movement on the distribution of infectious airborne particles in a hospital by simulating different walking speeds. Ma et al. (2015) simulated the distribution of PM2.5 in indoor spaces when using natural ventilation and found that the concentration of PM2.5 was much higher near the inlet, the outlet and the walls, and the air velocity had a slight influence on its internal distribution. Jin et al. (2016) simulated a wind induced hospital building in the suburb of Guangzhou and found that the rate of air change could reach 30-160 ACH for rooms with cross-ventilation but only 0.5-7 ACH for rooms with single sided ventilation.

- Thermal comfort: Elmualim (2006) used CFD to determine how dampers and heat sources influence indoor thermal conditions in a building with a wind catcher and found that the wind catcher could reduce the internal air temperature by 6°C when the temperature difference between the external and internal temperatures was approximately 8°C. Stavrakakis et al. (2008) evaluated the influence that rough terrain had on the indoor thermal environment in cross-ventilated buildings using CFD and found that the roughness of terrain in flat rural areas had no significant influence on the indoor thermal comfort conditions, i.e. the PMV values. Mochida and Lun (2008) predicted the wind environment and thermal comfort at the pedestrian level in an urban area by CFD simulations. Lin et al. (2008) conducted a series of numerical simulations to study the effect of different vegetation
patterns on the outdoor thermal comfort of pedestrians. Hussain and Oosthuizen (2013) analysed a three-storey building with an atrium with buoyancy-driven natural ventilation using CFD simulations and found that the variation in internal thermal loads had a limited influence on the thermal environment of the building (i.e. the indoor temperature fluctuation was less than 1°C). Hajdukiewicz et al. (2013) used a CFD model to investigate the indoor environmental conditions in a highly glazed naturally ventilated meeting room and found that the indoor air temperature was influenced mainly by the outdoor air temperature, the air speed and direction in the window and solar radiation through the window. Prakash and Ravikumar (2015) studied the thermal comfort of a CFD building model with adjacent window openings and different window opening percentages were examined to increase the indoor thermal comfort. Yang et al. (2015) investigated the transient development of the buoyancy driven ventilation using a CFD building model and found that the thermal stratification could be raised if there was a large indoor heat source. Hosseini et al. (2016) investigated the indoor airflow and thermal comfort under six differently designed wind catchers using CFD simulations and found that increasing their width led to significant variations in the thermal comfort associated to the PMV value. The highest level of thermal comfort was obtained with a 2.5 m wide wind catcher. Shafiei Fini and Moosavi (2016) built up a couple of CFD models for two naturally ventilated multi-storey buildings to analyse the factors influencing the indoor airflow pattern and thermal performance and found that solar radiation due to the sunshine could change the pattern of indoor temperature and the velocity contours.

These experimental models can generally be used for analysing building performance and validating numerical models. The numerical models are good alternatives to some difficult experiments and can provide detailed information, but the accuracy of the numerical models should be a guaranteed prerequisite.

## 2.4 Design optimisation of naturally ventilated buildings

### 2.4.1 Design optimisation problem of naturally ventilated buildings

Natural ventilation parameters such as wind speed, wind direction and turbulence intensity are relatively unstable and uncontrollable when compared to mechanical ventilation. The design optimisation of naturally ventilated buildings aims to fully tap the
natural ventilation potential for indoor thermal comfort control through counterbalancing various antagonistic building parameters. Improper building design leads to an improper airflow pattern and temperature distribution within a building, thus subjecting it to stuffy air, local draught, overcooling, etc. (Field 2007, Omrani et al. 2017), all of which cause thermal discomfort and undermine the applicability of natural ventilation.

2.4.1.1 Optimisation parameters

Optimisation parameters for natural ventilation refer to the factors related to the building configuration that influence natural ventilation and indoor thermal comfort. There are several governing factors for naturally ventilated buildings such as location and orientation, building form, indoor partitions or obstacles, and openings and urban layouts (Heating et al. 2006). Table 2.2 provides a summary of the parameters considered in existing studies.

Building opening is one of the key factors which influence natural ventilation because it is the only way wind can enter naturally ventilated buildings (Visagavel and Srinivasan 2009). Building opening configurations greatly affect indoor airflow pattern, indoor air quality, and thermal comfort, so on the basis of this ventilation mechanism. Building openings can be classified as window and door, chimney and atrium, and crack and aperture (Santamouris and Allard 1998). Table 2.3 summarises the key characteristics of these building openings.
Table 2.2 Summary of the optimisation parameters for natural ventilation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Comment</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate parameters (outdoor temperature, humidity, wind, solar radiation, etc.)</td>
<td>Climate parameters determine the occupant dressing, thermal perceptions and expectations; They influence building design, heat gains and the potential for natural ventilation.</td>
<td>Brager and de Dear 2001, Haase and Amato 2009</td>
</tr>
<tr>
<td>Building orientation</td>
<td>Building orientations determine the amount of radiation received by a building, natural ventilation air flow rates and the indoor airflow pattern.</td>
<td>Wang and Hien 2007, Thomas and Garnham 2007, Gao and Lee 2011</td>
</tr>
<tr>
<td>Building form (roof pitch, shading, building dimension, and the number of floor levels)</td>
<td>Building forms influence the surface pressure of the building and change the airflow pattern in the opening. When the external resistance of air flow is smaller than the internal resistance, the diminished effect of the internal partition or obstacle on the indoor airflow pattern cannot be ignored.</td>
<td>Cóstola et al. 2009, Aflaki et al. 2015</td>
</tr>
<tr>
<td>Indoor partition or obstacle</td>
<td></td>
<td>Chang et al. 2006, Chu and Chiang 2013</td>
</tr>
<tr>
<td>Opening (window, door, chimney, and crack)</td>
<td>Openings influence the indoor airflow pattern. The key characteristics of building openings are summarised in Table 2.3.</td>
<td>Jiang et al. 2003, Gao and Lee 2011, Xu and Liu 2013, Afonso 2015</td>
</tr>
<tr>
<td>Urban layout (green rate, urban orientation, urban block height and floor-area ratio)</td>
<td>A well designed urban layout can facilitate a good urban microclimate and improve the indoor environment.</td>
<td>Gulyás et al. 2006, Taleghani et al. 2013</td>
</tr>
</tbody>
</table>

Table 2.3 Key characteristics of building openings (Jiang et al. 2003, Gao and Lee 2011, Xu and Liu 2013, Afonso 2015, Daish et al. 2016, O’Sullivan and Kolokotroni 2016).

<table>
<thead>
<tr>
<th>Opening type</th>
<th>Ventilation pattern</th>
<th>Key factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window and door</td>
<td>Single-sided ventilation and cross-ventilation</td>
<td>Window type, height, width, height above the ground and fly screen, and door height and width</td>
</tr>
<tr>
<td>Chimney and atrium</td>
<td>Stack ventilation</td>
<td>Cross-section area, height, inclination and solar duct</td>
</tr>
<tr>
<td>Crack, aperture</td>
<td>Infiltration</td>
<td>Bore diameter</td>
</tr>
</tbody>
</table>
2.4.1.2 Optimisation objectives

For design optimisation of naturally ventilated buildings, the objectives to be optimised are normally related to indoor air quality, indoor thermal comfort, and building energy conservation. The optimisation objectives related to indoor air quality include air change rate, the mean age of air, pressure difference/pressure coefficient, CO₂ concentration, etc. The objectives for improving indoor thermal comfort are normally assessed by the thermal comfort indices presented in Section 2.1. When more than one optimisation objective is to be considered, multi-objective optimisation based on the Pareto front or weighted sum method is often used. For example, Magnier and Haghighat (2010) searched for a Pareto front for thermal comfort and energy consumption. Stavrakakis et al. (2011) weighted four different thermal comfort indices and then optimised thermal comfort by searching the optimal window configuration in naturally ventilated buildings.

2.4.1.3 Design optimisation platform

Nowadays, there are many simulation models available for evaluating building performance to identify the optimal building configurations that will maximise natural ventilation potential. Building performance can be evaluated using simplified analytical models, detailed building models, and building performance surrogate models/meta-models (Machairas et al. 2014). The advantages and disadvantages of these models are summarised in Table 2.4.

<table>
<thead>
<tr>
<th>Building model type</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplified analytical model</td>
<td>Easy to find out the optimal results by searching the entire solution space</td>
<td>Difficult to describe the problem mathematically</td>
</tr>
<tr>
<td>Detailed building models</td>
<td>Available to simulate almost all physical phenomena</td>
<td>Require a lot of input data such as climatic data, building geometry and material property.</td>
</tr>
<tr>
<td>Building performance surrogate models/meta-models</td>
<td>Can provide a good approximation of nonlinear building performance for subsequent optimisation</td>
<td>Computationally expensive</td>
</tr>
</tbody>
</table>

Table 2.4 Characteristics of three types of building models (Ong et al. 2003, Machairas et al. 2014).
2.4.2 Overview of the design optimisation of naturally ventilated buildings

Studies on the design optimisation of naturally ventilated buildings could be classified as either single objective optimisation or multi-objective optimisation.

2.4.2.1 Single objective optimisation

Single objective optimisation can be described as optimising a problem using a single objective function. As mentioned above, the optimisation objectives for naturally ventilated buildings normally consist of indoor air quality, indoor thermal comfort, and building energy conservation. Single objective optimisation only focuses on one of these objectives.

Natural ventilation can remove indoor air pollutants and odours by introducing fresh air into the interior spaces, so through the building layout and urban design optimisation, indoor air quality is improved significantly when natural ventilation is used. For example, Zhou et al. (2014) optimised the wind path by adjusting the orientation and space of the buildings in a community and found that when the distance between the buildings increased from 28m to 34m and their orientation was northwest, the indoor air could be reduced to 6 minutes in 90% of the rooms. Liu et al. (2014) tried to maximise the building pressure and unit pressure difference in a residential community in Chongqing, China, using CFD simulations and field investigations and found that the building pressure and unit pressure difference was increased by 10–30% by optimising the spacing and orientation of the building.

Moreover, the internal layout of a building affects the indoor airflow pattern and influences the indoor air quality. Chu et al. (2010) aimed to improve the internal discharge coefficient in partitioned buildings with wind driven cross-ventilation through wind tunnel experiments and found that the internal discharge coefficient was dependent on the internal porosity but independent of external porosity.

Chu and Chiang (2013) analysed the ventilation rate in a low rise building with cross-ventilation. Their numerical and experimental results showed that when the porosity of the walls was less than 3%, the resistance caused by external openings dominated the rate of ventilation, but the diminishing effect of obstacles could not be ignored when the internal resistance was more than the external resistance.
Due to the conjunction between indoor and outdoor environments, a building opening also influences the rate of natural ventilation. Tantasavasdi et al. (2001) improved the air exchange rate of the natural ventilation of a building model in Bangkok to cater for the prevailing wind by optimising the sizes of the inlet and outlet. It was found that to capture enough natural wind into the building, the area of inlet and outlet apertures should be at least 40% of the total floor area. Gao and Lee (2011) tried to improve the rate of natural ventilation by investigating various opening parameters of a hypothetical residential unit and found that locating two groups of windows in opposite directions or perpendicular to each other had the best effect.

Natural ventilation can increase indoor thermal comfort by increasing natural air movement as a passive cooling strategy. Wang et al. (2007) decreased the indoor air temperature in a residential building in summer by optimising the window-to-wall ratio based on a combination of CFD (i.e. ANSYS Fluent) and ESP-r building simulation. The results suggest that a window-to-wall ratio of 0.24 and a 600 mm horizontal shading could improve indoor thermal comfort most. Stephan et al. (2011) tried to increase the available natural ventilation time in a residential building to maintain indoor thermal comfort by using GenOpt to optimise the size of building opening and found that for the case study building, a 1.5×0.3 m$^2$ window could satisfy indoor thermal comfort requirements for 92% of the natural ventilation time. Stavrakakis et al. (2012) identified the most suitable indoor thermal comfort conditions in a naturally ventilated building. The results from an artificial neural network (ANN) meta-model based on CFD simulation were created to identify the optimal window design for the indoor thermal comfort. Mochida et al. (2006) maximised the passive cooling effects by using TRNSYS to investigate relative factors such as cross-ventilation and solar shading by trees and found that trees planted around a building made a huge difference to passively cool the indoor space.

In order to minimise energy consumption, Gong et al. (2013) used an orthogonal array (i.e. the Taguchi method) to investigate the influence of building configuration parameters such as the thickness, roof insulation, external wall insulation, orientation of windows, window-wall ratio, type of glazing, and sunroom depth/overhang depth on the energy consumption of naturally ventilated buildings in 25 cities across China. They found that the thickness of external wall insulation and the depth of sunroom (enclosed balcony) were the two most important parameters on the annual thermal load of the building, with a contribution of approximately 70% and 10%, respectively. He et al.
(2017) investigated the energy savings in naturally ventilated buildings in hot and humid summer climates and found that the enthalpy of the outdoor air and the airflow rate were among the essential factors that influence the energy saving potential.

Since the main purposes of natural ventilation are to improve indoor air quality and the thermal comfort, existing studies which focus on building energy conservation for naturally ventilated buildings are relatively limited.

2.4.2.2 Multi-objective optimisation

For multi-objective optimisation, a decision should be made based on the trade offs between different optimisation objectives. A multi-objective optimisation problem can generally be stated in a mathematical form as shown below (Wang et al. 2005):

\[
\begin{align*}
\text{Min or max } & \quad F(x_1, x_2, \cdots, x_n) \\
\text{Subject to: } & \quad G(x_1, x_2, \cdots, x_n) \geq 0 \quad x_i \in S_i
\end{align*}
\]  

(2.7) (2.8)

where \( F \) and \( G \) are the vectors of the objective functions and constraints, respectively, and \( S_i \) is the constraint that each variable \( x_i \) should be subjected to.

Nie et al. (2015) analysed the energy consumption and natural ventilation rate of different building orientations in a typical residential building in Changsha, China, using DesignBuilder. They found that the most appropriate building orientation was west for maximum natural ventilation and south for minimum energy consumption, but in order to make a trade-off between natural ventilation and energy consumption, the best orientations were south and north. Guo et al. (2015) tried to find a trade-off between the architectural design and indoor thermal comfort by optimising natural ventilation through CFD simulations in terms of three architectural aspects, i.e. site planning, building shape, and building envelope. The results gave insights into the mismatch and poor synergy between the architectural design and building thermal comfort maintenance. Bre et al. (2016) optimised a typical single family house with mixed-mode ventilation by selecting a weighted sum of indoor thermal and energy performance as the objective. The results showed that in order to maximise the available natural ventilation time, the external walls should have a low thermal transmittance, high thermal capacity and high thermal delay, while the internal walls should have a high thermal transmittance and thermal capacity,
and low thermal delay. Chang et al. (2006) investigated the mean indoor air speed and turbulence intensity by simulating the indoor airflow pattern in a naturally ventilated multi-zone building and found a 12% reduction in the mean indoor air speed and a 30-50% reduction in the turbulence intensity due to indoor partitions.

Horikiri et al. (2015) analysed by CFD the indoor thermal comfort in a 3D model of a furnished and occupied room with different layouts of the sofa indoors. They selected two indices (i.e. the percentage of dissatisfied and operative temperature) as the optimisation objectives and found the room layout with one sofa placed against either the south wall or east wall would improve the indoor thermal comfort by changing the patterns of indoor airflow, but the operative temperature was almost not affected by the room layouts. Norton et al. (2009) improved the indoor environmental heterogeneity (i.e. the heterogeneity of indoor air temperature and air age) using naturally ventilated livestock building models; they found that the highest level of environmental heterogeneity was reached when the incidence of outdoor wind was between 10 and 40°. Taleghani et al. (2013) studied the annual energy demand and hours of discomfort during the free running time in Dutch dwellings and found that reducing the external building surface exposed to the climatic environment could lead to a higher energy efficiency and improved the thermal comfort in summer. Ramponi et al. (2014) analysed the available night ventilation time and energy consumption in an office building in the centre of urban areas and found that increasing the density of buildings in urban areas would greatly reduce the night time ventilation potential and increase energy consumption for cooling.

It is common to use numerical building models as platforms to optimise single objective and multi-objective building design because they can overcome the drawbacks of trial and error using simulation alone (Wang 2005).

In order to find the optimal or near optimal solutions with less computational time, some meta-modelling techniques (e.g. genetic algorithm, response surface methodology and orthogonal array) have also been used in some studies to approximate a relationship between the simulation results (i.e. indoor temperature, air change rate and energy conservation) and the input variables (i.e. building configuration parameters).
2.5 Natural ventilation control

Besides proper design, natural ventilation control is also essential to achieve the desired intent. There are two types of controls related to naturally ventilated buildings, i.e. occupant control and automatic control (Aggerholm 2002).

2.5.1 Occupant control

In naturally ventilated buildings, occupant control refers to manually adjusting the windows, doors, blinds and curtains to regulate indoor airflow to make occupants thermally comfortable (Kumar et al. 2016). Occupant control is one of the essential factors in adaptive thermal comfort adjustment (de Dear and Brager 1998). Roetzel et al. (2010) reviewed factors influencing occupant behaviour and identified the driving forces for the natural ventilation actions taken by occupants.

Karava et al. (2007) found that there was a strong correlation between the window opening behaviour and season; windows were not open as much in winter as in summer and the other seasons. The frequency of window switching is highest in the transition seasons. Haldi and Robinson (2008) discovered that room temperature was the key driver of window switching behaviour, similar to the outdoor temperature (Nicol 2001). Raja et al. (2001) revealed that windows were opened mostly when the indoor temperature was between 20 and 27°C and the outdoor temperature was above 25°C in naturally ventilated buildings.

A comprehensive longitudinal field survey of the thermal adaptive actions of occupants in several non air-conditioned office buildings during the warm summer in Switzerland was investigated by Haldi and Robinson (2008) and it was found there was a relationship between the percentage of window opening and indoor and outdoor temperatures by following the information showed in Fig. 2.8. In cold climate area such as the UK, occupants tend to open their windows due to high indoor temperatures in winter because of the application of the heating system. A strong relationship between heating setpoint and window opening behaviours in winter was identified through a logistic regression model analysis (Jones et al. 2017).
Roetzel et al. (2010) observed that window control mostly occurred when occupants arrived in office buildings because of their exposure to outdoor fresh air on their way to work.

Note also that occupants tend to change the window openings before they leave a space (Roetzel et al. 2010), but ventilation during the night time might not be as feasible as the daytime because of security issues (Fritsch et al., 1990).

Herkel et al. (2008) proposed a model for occupant behaviour, as shown in Fig. 2.9, for window opening control which revealed the relationship between the main driving forces of window opening and window status.
Fig. 2.9 Scheme of occupants window opening behaviour (Herkel et al. 2008).

2.5.2 Automatic control

Unlike occupant control, automatic control regulates window openings based on control algorithms without continuous and direct human intervention. Brager et al. (2007) pointed out that so far, there was no generic control algorithm available for natural ventilation or mixed-mode ventilation.

Ezzeldin and Rees (2013) introduced a rule based window control strategy for mixed-mode ventilation where the ventilation control algorithm is divided into two parts for the occupied period (Fig. 2.10) and non-occupied period (Fig. 2.11). In this control strategy, natural ventilation had a higher priority than mechanical ventilation if the outdoor conditions were suitable for natural cooling.
Fig. 2.10 The mixed-mode/hybrid cooling control algorithm for occupied periods (Ezzeldin and Rees 2013).
Fig. 2.11 The mixed-mode/hybrid cooling control algorithm for non-occupied periods (Ezzeldin and Rees 2013).

Yun et al. (2009) developed a behavioural algorithm (i.e. Yun algorithm) representing probabilistic occupant behaviour using Markov chain and Monte Carlo methods (Fig. 2.12). This automatic control algorithm was tested in an office building model, and the forecasted results based on the behavioural algorithm were consistent with the occupant window opening behaviour in practice.
Wang and Greenberg (2015) developed a temperature based control strategy to determine the fraction of window opening. The fraction of window opening was modulated based on a linear relationship of the difference between indoor and outdoor temperatures when the zone air temperature was higher than the outdoor air temperature (Fig. 2.13).
Fig. 2.13 Modulation of window opening according to the indoor and outdoor temperature difference ($T_{\text{zone}}$: zone air temperature; OAT: outdoor air temperature) (Wang and Greenberg 2015).

May-Ostendorp et al. (2013) utilised rule extraction techniques to generate a decision tree for window opening control (Fig. 2.14); they found that the proposed rule extraction techniques might allow building automation systems to achieve near optimal control without online model-predictive control (MPC) systems.
Eftekhari et al. (2003) developed a fuzzy controller for naturally ventilated buildings that was implemented in a test room using MATLAB. The fuzzy logic controller adjusted the window openings to achieve thermal comfort inside the naturally ventilated room based on the outside conditions and inside temperature. The design of the open loop fuzzy controller is shown in Fig. 2.15.
Zhao et al. (2016) proposed a predictive control system for mixed-mode ventilation to optimise energy conservation while meeting individual thermal comfort preferences. This window opening control logic is shown in Fig. 2.16. It was developed on the basis of actual BAS settings of a real building and tested in an EnergyPlus building model. The results showed that the predictive control system could save 44% energy during the simulation period compared to a simple rule based control used as a baseline.
Fig. 2.16 Window opening control logic (Zhao et al. 2016).
Note that these control strategies could only achieve sub-optimal results because they do not take the building thermal dynamics into account (Spindler and Norford 2009), and the control delay (i.e. a control decision is made based on the previous indoor and outdoor climate conditions) could also influence the rationality of window opening commands from window control system (Shen et al. 2013).

2.6 Summary

In this chapter, the thermal comfort models, measurement and modelling, and design and control optimisation of naturally ventilated buildings have been reviewed. The literature has revealed that natural ventilation is a good way to improve indoor thermal comfort. Some of the key features obtained through the literature review are as follows:

- The best representative thermal comfort models are the predicted mean vote (PMV) index and the adaptive thermal comfort model. PMV is normally used for air conditioned buildings while the adaptive thermal comfort model is better suited to naturally ventilated buildings.
- Thermal comfort models can be used to evaluate the indoor thermal comfort using objective quantitative indicators. Post-occupancy evaluation (POE) can be used to perceive the influence that psychological factors and objective factors have on the thermal evaluation of occupants.
- Computational fluid dynamics (CFD), scale models and in situ measurements are the primary methods for natural ventilation and thermal comfort research. They are normally used to analyse the impact that building configuration has on natural ventilation and thermal comfort. CFD models have lower time requirements and are more cost effective than experimental models but the accuracy cannot be guaranteed without reasonable settings for the building model mesh, boundary, solver, and the number of iteration steps. Scale models and in situ measurements can provide real data but they can be difficult to put into practice.
- Building design optimisation can fully tap the potential of natural ventilation for indoor thermal comfort.

The literature review also indicated that the following areas in thermal comfort and natural ventilation research are still not fully addressed or explored:
Chapter 2 Literature review

- There is no widely accepted standard or model to evaluate the indoor thermal comfort in mixed-mode ventilated buildings. Inappropriate application of thermal comfort models in mixed-mode ventilated buildings could lead to a mismatch between the estimated and the actual indoor thermal conditions.
- Since occupants in green buildings or net-zero energy buildings tend to perceive that their indoor thermal comfort is better than traditional buildings, the widely used conventional thermal comfort models might not be suitable for evaluating the indoor thermal comfort of these types of buildings.
- In many studies of the design optimisation of naturally ventilated buildings, the building parameters (e.g. building dimensions, orientation and structure, window configuration, internal layout, etc.) were optimised individually, but their interactive impact on indoor thermal comfort was sometimes ignored.
- Most of the mixed-mode ventilated buildings used changeover control strategies for mixed-mode ventilation. Concurrent control strategies where both natural and mechanical ventilation components are controlled at the same time need further study.

Based on the research gaps summarised above, the following key research questions were extracted and would be studied in this dissertation:

1. What is the relationship between the ambient environment in high performance buildings with advanced mixed-mode ventilation systems and the thermal perception of occupants?
2. How do the requirements of indoor thermal comfort influence the building opening design of naturally ventilated buildings?
3. Are there any guiding factors in the design of windows for natural ventilation?
4. How to maximise natural ventilation rate to improve indoor air quality in large open plan office buildings while avoiding local thermal discomfort (e.g. draught) in some critical occupied areas of buildings?
5. How to optimise conventional natural ventilation control strategies or develop new ones to overcome thermal discomfort issues due to the drawbacks of natural ventilation?
CHAPTER 3  THERMAL COMFORT INVESTIGATION OF HIGH PERFORMANCE BUILDINGS WITH ADVANCED MIXED-MODE VENTILATION SYSTEMS

High performance buildings are generally equipped with low energy technologies such as advanced mixed-mode ventilation systems. A previous study indicated that occupant perception of indoor thermal conditions in high performance buildings using advanced mixed-mode ventilation technologies was normally distinct from those in traditional buildings because their thermal states varied in time and space (Leaman and Bordass 2007). Therefore, the relationship between thermal performance and thermal perception in high performance buildings, including the applicability of classical thermal comfort models, needs further study and evaluation.

This chapter will assess the thermal conditions of a high performance building with an automatic window control system and an underflow air distribution system (UFAD) by field measurements and post-occupancy evaluation (POE) surveys. A static thermal comfort model and a dynamic thermal comfort model were also compared to identify which thermal comfort model would better suit buildings with advanced mixed-mode ventilation systems.

This chapter is organised as follows. A case study building is introduced in Section 3.1. The research methodology is described in Section 3.2. Section 3.3 presents the results from field measurements and a post-occupancy survey. Section 3.4 assesses the thermal performance and thermal perception of the case study building and analyses the suitability of two thermal comfort models for this building. The key findings of this chapter are summarised in Section 3.5.

3.1 Introduction to the case study building

The Sustainable Buildings Research Centre (SBRC) building at the University of Wollongong is used as the case study building for this study; it is a net-zero energy office building located at the innovation campus of the University of Wollongong, Australia. It is a two-storey building with research laboratories, an exhibition and lobby area, and office space (Fig. 3.1). This facility was designed to deliver evidence based research and
practice in sustainable building design technologies, particularly in the southern hemisphere.

Fig. 3.1 Illustration of the case study building.
The SBRC building facility consists of two interconnected buildings known as the southern and northern wings. The northern building has a high bay workshop. The southern building has an exhibition area, a lobby area, a training room, three flexible spaces on the ground floor, and an office space on the first floor that includes a general open plan office, meeting rooms, and individual offices; it also has a pitched roof. The north and south facing walls are 3.8 m and 6.5 m high, respectively. There is a row of top-hung windows at the north facing walls and two rows of top-hung windows at the south facing walls. These windows allow for north-south cross ventilation (Fig. 3.1c). There are also casement windows in the individual offices.

3.1.1 Climate

Wollongong is on the east coast of Australia (34S, 151E) and experiences an oceanic climate. Fig. 3.2a shows that the mean summer daily maximum temperature was 25.9°C, the mean winter daily minimum temperature was 8.3°C, and the monthly average relative humidity ranged from 50 to 70%, which means that the air is usually dry and fresh. Since the area is close to the ocean, there is a sea breeze over the whole year and the wind speed is between 1 and 8 m/s for approximately 78% of the time (Fig. 3.2b). Natural ventilation could, therefore, be a preferential alternative in Wollongong due to the moderate climate and gentle sea breeze throughout the whole year.
Chapter 3 Thermal comfort investigation of high performance buildings with advanced mixed-mode ventilation systems

3.1.2 Ventilation control strategy

Due to the moderate climate in Wollongong, the building has a mixed-mode ventilation system consisting of the natural ventilation through a window modulation system and the mechanical ventilation through an underfloor air distribution (UFAD) system. The strategy for the ventilation mode selection is shown in Fig. 3.3.

![Fig. 3.2 Wollongong climatic data.](image)

![Fig. 3.3 Building ventilation control strategy.](image)
Chapter 3 Thermal comfort investigation of high performance buildings with advanced mixed-mode ventilation systems

The natural ventilation mode is utilised when it can maintain the internal temperatures between 20 and 24°C. Failing that the natural ventilation mode is disabled and cooling/heating mode is used (the indoor space temperature set point is 19.5°C for heating and 24.5°C for cooling).

A hysteresis region of 0.5°C is used between the operating modes to ensure there is no frequent oscillation between the ventilation modes. This hysteresis also incorporates a switching delay of 20 minutes.

During natural ventilation, the windows are fully open if the wind velocity is less than 15 km/h (i.e. 4.2 m/s), and the windows are modulated as a linear function of the outdoor wind velocity when the outdoor wind velocity is between 15 and 30 km/h (i.e. 4.2 m/s and 8.3 m/s). The windows are fully closed if the wind velocity is more than 30 km/h (i.e. 8.3 m/s), but if the outside air temperature is less than 16°C or more than 28°C, the windows are closed and the heating or cooling mode is activated. The logic for determining window opening percentage is shown in Fig. 3.4.

![Fig. 3.4 Window opening control strategy.](image)

For mechanical ventilation, supply fans with a variable speed drive are used to maintain a constant static pressure in the supply air system.

An HVAC control system has been integrated into the building management system (BMS) of the case study building. The BMS provides a web-based graphical user
interface (GUI) so that the ventilation mode and indoor environmental conditions can be monitored through the GUI as shown in Fig. 3.5.

3.2 Research Methodology

An exploratory investigation to examine the thermal environment of high performance buildings in order to provide direction for a continued development of meaningful metrics and to assess their indoor thermal comfort is shown in Fig. 3.6.
Chapter 3 Thermal comfort investigation of high performance buildings with advanced mixed-mode ventilation systems

The indoor thermal environment was assessed based on the data collected from the building management system (BMS) and field measurements, as well as the occupant perceptions of thermal comfort via post-occupancy evaluation (POE) surveys. Two classical thermal comfort models were implemented and compared based on the historical data obtained from the BMS to evaluate the thermal performance of the building. These results were compared with the POE survey results to understand which model better represented this type of buildings.

3.2.1 *In situ* measurements

A number of sensors were deployed in the case study building to monitor the indoor thermal environment (Fig. 3.7). Table 3.1 presents the details of the sensors used.

![Fig. 3.7 Sensors used for indoor thermal comfort monitoring: (a) ambient temperature/CO$_2$ sensor; (b) radiant temperature sensor and (c) ambient temperature/humidity/CO$_2$ sensor.](image)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Manufacturer</th>
<th>Measurement range</th>
<th>Accuracy</th>
<th>Response time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Distech controls</td>
<td>0 to 50°C</td>
<td>±0.2°C</td>
<td>&lt; 2 minutes</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>Distech controls</td>
<td>0 to 95%</td>
<td>±2, 3 or 5% RH from 5 to 95% RH</td>
<td>15 seconds</td>
</tr>
<tr>
<td>CO2</td>
<td></td>
<td>0-2000ppm</td>
<td>±30ppm</td>
<td>&lt; 2 minutes</td>
</tr>
<tr>
<td>Radiant temperature</td>
<td>Sontay</td>
<td>0 to 70°C</td>
<td>±0.2°C</td>
<td>Not Given</td>
</tr>
</tbody>
</table>

Table 3.1 Sensor information.
Fig. 3.8 shows the locations of the sensors. The sensors were divided into four groups (S1-S4) at different heights (the details were provided in the section 3.3.1.2) in the open plan space to evaluate whether or not thermal stratification would be a concern. The details and results of the thermal stratification analysis are presented in Section 3.3.

Portable IEQ test equipment (i.e. the Testo 885 infrared thermal camera, see Fig. 3.9) was used to measure the internal surface temperatures.

The outdoor weather conditions were measured by a weather station installed on the roof of the high bay of the case study building (Fig. 3.10). This weather station measures the
air temperature, relative humidity, wind speed, wind direction, global horizontal solar radiation, barometric pressure and rainfall.

![The weather station installed in the case study building.](image)

All the indoor and outdoor climatic data and window opening records, which had been collected every 15 minutes over the whole year of 2015 and the first two months of 2016, were used for this thermal environment investigation.

### 3.2.2 Post-occupancy evaluation (POE) surveys

The building use studies (BUS) questionnaire was selected after reviewing a number of standard surveys available in the public domain (Oseland 1994, Huizenga et al. 2006, Leaman and Bordass 2007, Menezes et al. 2012). BUS is a free tool to evaluate occupant satisfaction; its questionnaire is an established and tested way of benchmarking the levels of occupant satisfaction within buildings against a large database of results for similar buildings. For the research interest of this study, only the results from survey questions related to the indoor thermal comfort were presented. The selected survey questions covered comfort with regard to temperature, air quality, lighting, noise, and overall comfort in summer and winter. The answers are based on a 7-point scale evaluation system which aims to understand occupant subjective thermal perceptions in a quantitative way. A ‘forgiveness factor’ was introduced as a metric of comparison between overall comfort and individual comfort parameters, and it is defined as follows (Leaman and Bordass 2007):
\[
\text{Forgiveness factor} = \frac{\text{Comfort overall}}{\left(\frac{A_s + A_w + T_s + T_w + L + N}{6}\right)} \tag{3.1}
\]

where \text{Comfort overall} is the score of the building’s overall comfort performance, \(A_s\) and \(A_w\) are the average satisfaction scores for indoor airflow in summer and winter respectively, \(T_s\) and \(T_w\) are the average satisfaction scores for the temperature in summer and winter respectively, \(L\) is the average score of satisfaction for lighting, and \(N\) is the average satisfaction score for acoustic.

### 3.3 Results

#### 3.3.1 Indoor thermal environment assessment

##### 3.3.1.1 Natural ventilation control over the whole year

As described above, the case study building equipped with windows that can operate automatically based on the control algorithm presented earlier (Fig. 3.3). Fig. 3.11 presents the average indoor temperature, outdoor temperature and window opening state during the investigated period.

Although the outdoor temperature fluctuated with seasons, the average indoor temperature was mostly kept between 18 and 27°C. The building was frequently naturally ventilated during summer and transitional seasons. Fig. 3.12 presents the control mode, the window state and the corresponding average indoor air temperature under selected winter and summer days.

It can be seen that, the outdoor temperature was always below 16°C in winter. As presented in Fig. 3.3, windows should be closed and the heating mode was activated if the outside air temperature was less than 16°C. Mechanical heating was, therefore, activated during working hours and the average indoor temperature was then maintained at 20±1°C.

For the summer days (Fig. 3.12b), the outdoor temperature could meet the requirements for natural ventilation and natural ventilation was, therefore, implemented over the whole first work day (8:00AM to 22:00PM) and the morning and evening of the second work day (08:00AM to 11:00PM and 19:00PM to 22:00PM). However, the average indoor air temperature kept increasing during the second day as natural ventilation was not sufficient to provide the required cooling to the building. The average indoor air temperature...
exceeded 24°C at 11:00AM which was the upper limit of the indoor thermal comfort zone specified in Section 3.1.2, indicating that natural ventilation could not maintain indoor thermal comfort condition into the specific thermal comfort zone. Mechanical cooling was activated to maintain the indoor temperature below the cooling set point of 24.5°C.
Chapter 3 Thermal comfort investigation of high performance buildings with advanced mixed-mode ventilation systems
Fig. 3.11 Window opening and indoor and outdoor temperatures over the investigated period: (a) Summer (January to February) and Autumn (March); (b) Autumn (April to May) and Winter (June); (c) Winter (July to August) and Spring (September); and (d) Spring (October to November) and Winter (December).
Chapter 3 Thermal comfort investigation of high performance buildings with advanced mixed-mode ventilation systems

Fig. 3.12 Indoor temperature under different operation modes: (a) winter; and (b) summer.

3.3.1.2 Temperature stratification measurements

The difference in vertical temperature between head and ankle could be a concern in buildings and may cause thermal discomfort to the occupants. The case study building had a pitched roof that was 3.8 m high on the north and 6.5 m high on the south, and a UFAD system that could cause thermal stratification.

To measure the vertical temperature difference, sensors were deployed at 0.3 m, 1.3 m (matching the ankle and head levels at a sitting position) and 4.0 m above the floor on the north wall of the building (Fig. 3.13) respectively, and measurements were taken from 15th July 2015 to 15th August 2015 for the winter and from 16th January 2016 to 16th February 2016 for the summer. The results are shown in Fig. 3.14 from a period in winter and summer.

In winter, the heating mode dominated during the working days (Fig. 3.14a). The heat was supplied by the underfloor distributors to improve the indoor temperature at ankle
level and therefore, reduce thermal stratification. The temperature difference between the two heights ranged from -0.3 to 0.5°C. In summer, the temperature difference between head and ankle could reach 2.0°C as a result of cold air accumulating at the lower levels when the building was in the cooling mode. This thermal stratification phenomenon was alleviated when changing from mechanical cooling to natural ventilation.

Fig. 3.13 Location of the temperature sensors.
Fig. 3.14 Temperature difference between the head (1.3m) and ankle (0.3m) under different HVAC modes.

### 3.3.1.3 Interior surface temperature

To understand how a cold wall and ceiling affect the indoor operative temperature, several infrared thermal photographs were taken in the afternoon of a winter day. These infrared thermal photographs of the internal walls and ceiling taken from the west office during the investigative period are shown in Fig. 3.15.
The photographs showed that the temperature of the glass walls was between 16.5 and 17.5°C, the ceiling temperature varied between 18 and 18.5°C, and the ground temperature was between 17.5 and 18.5°C. Since the indoor temperature was maintained at 20±1°C in winter by mechanical heating, the temperature of the internal surface was lower than the indoor air temperature, indicating that the indoor operative temperature, which is defined as the weighted sum values of the radiant temperature and air temperature (ASHRAE 2013), was less than 20°C.

3.3.2 POE survey results

3.3.2.1 Basic information of the participants

Forty-five permanent research staff and students in the case study building were involved in the post occupancy evaluation, of which thirty-nine provided effective replies to the BUS questionnaire in June 2015 for the winter case, while a supplementary BUS survey in February 2016 for the summer case had a response rate of 87%. Participant information is presented in Fig. 3.16.
### Fig. 3.16 Basic information of the participants.

According to Fig. 3.16, more than 50% of the participants were under 30 because the case study building is an open plan office with many young students seated at shared desks.

POE surveys also revealed that the clothing level of the occupants varied a lot with climates. The average clothing level was about 1.75 clo in winter and 0.5 clo in summer according to observation.

#### 3.3.2.2 POE results and analysis

The BUS survey covered every aspect of the indoor environmental conditions of the case study building, but only the thermal comfort section was discussed. Fig. 3.17 shows the POE results for indoor thermal comfort based on the 7-point scale system. The green marker indicated a better performance than the BUS benchmark and the red marker denoted a worse performance. The results showed that the occupants in summer had a
positive evaluation on overall comfort (Fig. 3.17b) whereas in winter their overall satisfaction was neutral.

![Diagram of thermal comfort scale]

Fig. 3.17 A summary of POE satisfaction scores for indoor thermal comfort: (a) Winter; and (b) Summer.

The survey also revealed the issue of cool or cold indoor conditions in winter, which was consistent with the field measurements in Fig. 3.12a where the indoor temperature was lower than the heating set point of 19.5°C at the start of the occupied period. The heating set point was 0.5°C lower than the lower limit of the recommended indoor design temperature in winter (i.e. 20°C for ASHRAE 55 (2013) and ISO 7730 (2005)). This cold interior sufferance temperature resulted in poor indoor thermal conditions.

The value of the ‘forgiveness factor’ from another mixed-mode ventilated office building located in Sydney which used a conventional HVAC system (Deuble and de Dear 2012) was compared with the calculated ‘forgiveness factor’ from the POE survey of the SBRC building. Both buildings were within the same climate zone. The ‘forgiveness factor’ is summarised in Table 3.2. The Australian BUS database for green buildings that use natural ventilation, advanced natural ventilation or mixed-mode ventilation (Leaman et al. 2007) was used as a benchmark.
The “comfort overall” of the case study building was 4.68, which was higher than the building in Sydney and the Australian BUS benchmark. This high “comfort overall” value implied a better overall indoor comfort of the case study building. The ‘forgiveness factor’ matched the average value of the Australian BUS database. A ‘forgiveness factor’ greater than 1 indicated a greater tolerance to the indoor comfort condition. The forgiveness results indicated that the occupants in the case study building were slightly more tolerant, and albeit the differences from the other values in Table 3.2 was quite small.

3.3.2.3 Comparison of thermal comfort models

The predicted mean vote (PMV) model (Fanger 1970) and the adaptive thermal comfort model from ASHRAE 55 (2013) have been widely used and therefore they were also used for the case study building. Fig. 3.18 shows the hourly measurements derived from the BMS data of the case study building during working hours in winter (11th July 2015 – 11th August 2015) and summer (17th December 2015 – 17th January 2016).

Table 3.2 Forgiveness factor.

<table>
<thead>
<tr>
<th>Study variable</th>
<th>Australian BUS database</th>
<th>Case study building</th>
<th>The building in Sydney (Deuble and de Dear 2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comfort overall</td>
<td>4.18</td>
<td>4.68</td>
<td>3.69</td>
</tr>
<tr>
<td>Forgiveness factor</td>
<td>1.02</td>
<td>1.01</td>
<td>0.99</td>
</tr>
</tbody>
</table>
Fig. 3.18 Evaluation of the thermal response of occupants based on different models: (a) the PMV model; (b) the adaptive thermal comfort model.

Fig. 3.18a used the graphic comfort zone method from ASHRAE 55 (2013) to present the results produced by the PMV model. These results indicated a poor indoor thermal environment for both summer and winter because in winter, 40% of the data were distributed outside the thermal comfort zone and towards the cold side area of the psychrometric chart and in summer, 67% of the data were scattered out of both sides of the thermal comfort zone. However, about 90% of the data points in either winter or
summer case (Fig. 3.18b) fell into the acceptable indoor operative temperature ranges, indicating acceptable environments in summer and winter.

The POE survey also provided a thermal sensation vote (TSV) for occupants to assess indoor thermal comfort conditions. The TSV results (Fig. 3.19) could serve as a reference to evaluate the reliability of the two thermal comfort models.

According to the TSV results in Fig. 3.19, 50% of the occupants in the building considered the indoor thermal conditions to be neutral or slightly cool and the rest as cool or cold in winter. In summer, 94% of occupants felt thermally neutral, slightly warm, or slightly cool, indicating good thermal comfort conditions. The result from the PMV model was, therefore, consistent with the TSV results in winter by reporting poor indoor thermal comfort conditions, but these predictions did not match the responses of occupants in summer very well. However, Fig. 3.18b showed an acceptable thermal comfort condition in summer, which agreed with the TSV responses during the summer period.

### 3.4 Discussion

#### 3.4.1 Indoor thermal comfort

Monitoring the window control and average indoor temperature over the whole year indicated that in the mild climate in Wollongong, natural ventilation could provide a
suitable indoor temperature during the most of the time in summer and the transitional seasons. The data from the typical days also revealed that in winter, natural ventilation was not applicable because of the lower outdoor temperatures and therefore mechanical heating was used during the working hours. In summer, mechanical cooling was mostly used in the afternoon if the outdoor temperature exceeded the upper limit of natural ventilation. It is worth noting that there was a large difference in outdoor air temperature between daytime and night time in summer which implied that night ventilation could be used to reduce the hours required for mechanical cooling.

Thermal stratification was a common issue in the buildings with the UFAD system (Kong and Yu 2008, Alajmi and El-Amer 2010). The ASHRAE 55 (2013) recommended that the difference in vertical air temperature should not exceed 3.0°C (i.e. associated with 5% of dissatisfaction). The field measurements indicated that there was thermal stratification in winter and summer in the case study building, but the heat supplied from the UFAD system in winter improved the indoor temperature at the ankle level and then alleviated thermal stratification. Thermal stratification was enhanced by cold air from the underfloor air diffuser in summer but the temperature difference was still under the tolerance specified in ASHRAE 55 (2013).

The temperature of the internal walls in the office was less than 20°C and the indoor temperature was maintained at 20±1°C in winter by using mechanical heating. As a consequence, the operative indoor temperature defined as the weighted sum values of the radiant temperature and air temperature (ASHRAE 55 2013) could be less than the acceptable lower limit of the operative temperature (i.e. 20°C in ASHRAE 55) in winter.

3.4.2 Suitability of thermal comfort models to mixed-mode ventilated buildings

To identify the optimal approach for evaluating the thermal comfort of occupants in the case study building, the thermal sensation results obtained from two existing thermal comfort models were compared to the TSV results. This showed that the PMV model was more suitable in winter whereas the ASHRAE 55 adaptive model was more consistent with the TSV results for summer conditions. This is because mechanical heating was used in winter and the indoor conditions were closer to those environments used to develop steady state comfort models (e.g. the PMV model), however, the frequent use of natural ventilation in summer made the adaptive model more suitable for the case study building.
Such results indicated that the terminal system for the mechanical ventilation did not affect the comfort predictions of the adaptive thermal comfort model.

3.5 Summary

This chapter investigated the indoor thermal comfort conditions of an office building in a subtropical area which used advanced natural ventilation and underfloor air distribution systems. The indoor thermal comfort factors were monitored and analysed and the thermal sensation of occupants was captured through POE surveys. The key findings are summarised as follows:

- Based on the window opening state during the investigated year of 2015, the natural ventilation time was about 1735 hours (mostly happened during the work time in summer and transition seasons) and the indoor temperature was maintained between 18 and 27°C.

- According to the POE surveys and field measurements, the Fanger’s PMV model was more applicable in winter whereas the adaptive thermal comfort model can better predict the overall comfort in summer.

- The case study building with a high ceiling and underfloor air distribution system experienced thermal stratification, but the measurements indicated that the difference in vertical temperature was under the tolerance specified in ASHRAE 55.

- The interior surfaces of the case study building had a cold radiation effect on occupants, which could raise the issue of thermal discomfort.

In conclusion, the POE survey could offer a useful understanding of building indoor thermal comfort because the POE survey showed that the SBRC building is still not commissioned properly to ensure occupant comfort during the surveyed time. The POE survey could be used as a reference to evaluate the applicability of the thermal comfort models.
CHAPTER 4  NUMERICAL ANALYSIS OF THE INFLUENCE OF TOP-HUNG WINDOW CONFIGURATION ON INDOOR THERMAL ENVIRONMENT

The effectiveness of natural ventilation in a building is influenced by many different parameters, but particularly by the configuration of the windows in a given room, e.g. window height, window size, presence of a fly screen, etc. Over recent decades, many efforts have been made to investigate the influence of such window parameters on air flow and indoor environmental quality (see for example Favarolo and Manz 2005, Ravikumar and Prakash 2009, Ravikumar and Prakash 2009, Miguel 1998, Heiselberg et al. 2001). However, the impact of particular window characteristics/parameters in the previous studies was analysed individually and to date, no thorough investigation appears to have been carried out to examine the overall contribution of all window parameters combined with the indoor environment.

This chapter describes an investigation with the aim of determining the effect of the attributes of windows and outdoor air conditions on indoor thermal comfort and air velocity distribution during natural ventilation using CFD simulations applied to a fundamental ventilation geometry.

This chapter is organised as follows: Section 4.1 reports on an investigation of the performance of top-hung window configuration factors; Section 4.2 deals with the particular type of top-hung window used in the Sustainable Buildings Research Centre (SBRC) building to find the key influential factors; and conclusions of this chapter are summarised in Section 4.3.

4.1 Influence of window parameters on thermal comfort in a cross-ventilated room

4.1.1 Methodology for indoor thermal comfort assessment

A schematic diagram outlining the process undertaken in this indoor thermal comfort investigation is presented in Fig. 4.1.
Identify the optimisation objective

Identify the influence factors

Establish cross-ventilated building models

Design the simulation scenarios

Identify the percentage contribution of the influence factors

Identify the optimal combination of parameter levels

The fraction of area that satisfies the PMVe requirements

Window configurations and outdoor weather conditions

CFD models

The Taguchi method

ANOVA analysis

S/N ratio analysis

Set building geometry and boundary conditions

Select the solver

Analyse the grid independence

Solve the model

CFD-post process

Identify the control factors

Select the levels of each factor

Select the orthogonal array

Assign factors into the orthogonal array

Outdoor air temperature, wind velocity and direction, window opening angle, window width, window height, window height above the floor and fly screen were selected as the factors to investigate the fraction of the occupied area of a room that satisfied the extended predicted mean vote (PMVe) requirements. Then cross-ventilated building models were built as the research platform using computational fluid dynamics (CFD) technology. The Taguchi method was used to design the simulation scenarios so as to reduce the number of CFD simulation cases required. Finally, analysis of variance (ANOVA) was used to determine the most significant factors influencing thermal comfort optimisation and the optimal window configurations for the indoor thermal comfort of the case study building were identified using a signal-to-noise (S/N) ratio analysis.

Fig. 4.1 Schematic diagram of the indoor thermal comfort analysis in a case study room with cross-ventilation.

Defined as a horizontal plane of 1.1m in height across the whole rectangular room model.
4.1.1.1 CFD modelling

- Model description

A complex model with many adjustable parameters is more prone to overfitting than a simple model (Czerlinski et al. 1999). Simple models can easily discover their limits, i.e. limits of the boundary conditions, which in turn fosters clarity and progress (Goldstein and Gigerenzer 2011). As a consequence, a hypothetical room with a rectangular floor layout was used to investigate the influence of window parameters on indoor thermal comfort in this chapter. A single top-hung window with fly screen was placed in the upstream façade of a cross-ventilated room model of dimensions 5×5×3 m³ (L×W×H) and implemented in ANSYS Fluent (2013). A plane opening was also placed in the downstream wall of the room with the same size and height above the ground as the window opening in the upstream façade but without a window pane or fly-screen presented. The pilot simulation suggested that jet-flows from the upstream window would upward into the room and the main fraction of the airflow moved forward along the surface of the ceiling due to the top-hung window. The diminished effect of the flow resistance caused by the indoor furniture was not significant. Some studies (Chang et al. 2006, Chu and Chiang, 2013) also suggested the effect of the internal partition or obstacle can be ignored when the external resistance of air flow is larger than the internal resistance. Therefore, indoor furniture was not introduced in order to simplify the room model. For a building model of height H, previous studies (Tominaga et al. 2008, Mochir JV et al. 2002, Blocken et al. 2007) suggested that the computational domain should be at least 5H in height, the lateral boundaries should be at least 5H from the region of interest and the domain downstream of the region of interest should be extended to at least 10H. These guidelines were followed in the present study. The whole computational domain is presented in Fig. 4.2.
Chapter 4 Numerical analysis of the influence of top-hung window configuration on indoor thermal environment

Fig. 4.2 A schematic view of the test room model and the computational domain.

- Solver setting

The Fluent was used to solve the 3D steady model. Large eddy simulation and Reynolds averaged Navier-Stokes (RANS) equations with turbulence model can be used for the indoor and outdoor airflow simulation and there are many turbulence models that could be used with RANS (Allocca et al. 2003). Chen (1995) concluded that the standard k-epsilon model and the re-normalisation group (RNG) k-epsilon model performed the best among eight different turbulence models for natural ventilation simulation. In spite of that the RNG k-epsilon model was slightly better than the standard k-epsilon model, the RNG k-epsilon did not significantly improve the simulation accuracy when compared to the standard k-epsilon model but required more computational cost (Chen 1995). As a consequence, the standard k-epsilon model was used in this study. Convergence was assumed to be obtained when a minimum of 0.1% was reached for the scaled residuals of mass, momentum, turbulent kinetic energy (k) and turbulent dissipation (ε).

- Boundary conditions
The buoyancy effect was also taken into consideration in this study by introducing the heat gains of the internal walls, ceiling and floor. The simulation was a quasi-steady state simulation with the internal surfaces of the room held at a nominal temperature of 24°C as suggested by Gowreesunker and Tassou (2013). As the building model was a hypothetical room with a rectangular floor layout without occupant activity and equipment usage, the other internal heat gains were not considered in this study. Despite the buoyancy effect, the pilot simulations suggested that the influence of buoyancy on natural ventilation was minor as it is a large opening building and hence it is mainly the wind pressure driven natural ventilation. The effect of changes to outdoor air temperature, wind velocity and wind direction relative to normal to the upstream face of the room on internal thermal comfort conditions were investigated.

The boundary conditions of the computational domain were specified as the velocity-inlet and pressure-outlet. The wind speed profile in the velocity-inlet was distributed based on the power law (ASHRAE 2011) as follows:

\[ U = U_w \left( \frac{H}{H_w} \right)^\alpha \]  

where \( U \) is the wind speed at the height of \( H \), m/s, \( \alpha \) is an exponent for the local building terrain and \( U_w \) is the wind speed at the window height of \( H_w \), m/s. The recommended exponent for an open terrain is 0.14 according to the ASHRAE fundamental handbook (ASHRAE 2011), and this value was used in the simulations of this study.

- CFD-post process

A user-defined function (UDF) (Fluent 2013) was used to integrate the PMVe-PPD model into the ANSYS Fluent in order to post-process the CFD simulation results to extract the PMVe-PPD values over the desired region within the test room. More details of the PMVe-PPD code have been listed in Appendix D.

4.1.1.2 Thermal comfort models

A number of studies have indicated that the window configuration is one of the most influential factors [3-5] among the internal and external factors. Window configuration commonly includes window height, window size, fly screen and window type [6]. In this chapter, the following configuration variables for top-hung windows were selected to
evaluate their impacts on the indoor thermal comfort conditions: window width, window height, height of the window bottom above the ground, window opening angle and fly-screen porosity.

The predicted mean vote (PMV) proposed by Fanger (1970) using the principle of heat balance is one of the most well-known models for indoor thermal comfort evaluation.

The predicted mean vote (PMV) model is relevant to indoor thermal comfort analysis in mechanically ventilated/air conditioned buildings, but it has in recent times been deemed as not suitable for naturally ventilated buildings as the PMV model is usually used in an ambient environment with steady airflows (de Dear and Brager 1998). Brager and de Dear (1998) found that the PMV metric predicted a warmer thermal sensation than the occupants actually felt in naturally ventilated buildings in a warm climate. Fanger and Toftum (2002) speculated that the expectations of the occupants were the major factor explaining why the PMV overestimated the thermal sensation of occupants in non-air-conditioned buildings in warm climates. A correction factor, $e$, was multiplied with the PMV index to estimate the thermal sensation vote in naturally ventilated buildings as suggested by Fanger and Toftum (2002). Fanger and Toftum (2002) found that in regions with only brief periods of warm weather during the summer, the expectancy factor for non-air-conditioned buildings might be between 0.9 and 1.0 and the new extension of the PMV model for non-air-conditioned buildings in warm climates matched the practical situation well. In this study, the expectancy factor, $e$, was selected as 0.9 to adapt the PMVe model to the local climate of Sydney. The PMVe model includes the following six variables that influence the thermal sensation of occupants, i.e. occupant activity, clothing, air temperature, mean radiant temperature, air speed and humidity. The values of these six variables were chosen from the literature (de Dear et al. 1991, de Dear and Brager 2002, ASHRAE 2013) for buildings in the subtropical area of Australia using natural ventilation for a typical summer day.

<table>
<thead>
<tr>
<th>Parameter values assumed.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metabolic rate (W/m²)</td>
</tr>
<tr>
<td>70</td>
</tr>
</tbody>
</table>
The predicted percentage dissatisfied (PPD) index was used to estimate the fraction of occupants that would be dissatisfied with the given indoor thermal comfort conditions. The predicted percentage dissatisfied (PPD) is defined as follows (Fanger 1970):

$$PPD = 100 - 95\exp\left(-0.3353PMVe^4 - 0.2179PMVe^2\right)$$ (4.2)

In this study, PMVe values between -0.2 and +0.2, corresponding to PPD values of less than 6%, were considered to meet indoor thermal comfort requirements in line with the Class A in ISO 7730 (2005). The PMVe levels at the heights of 0.1m (ankle), 0.6m (abdomen) and 1.1m (head) are normally recommended as the representative activity area for seated occupants (ASHRAE 2013). In a previous CFD simulation study (Perén et al. 2015), it was shown that air movement mainly occurred at the window height level in a cross-ventilated room. Generally, the bottom of windows in dwellings are relatively close to the head-level height of 1.1m in this research and for this reason, the head-level was selected as the area (A) of interest. The key thermal comfort metric for this study was therefore taken as the area fraction, R, of a horizontal plane of 1.1m in height across the whole room where the local PPD requirement was satisfied as follows:

$$R = \frac{A_{1.1m,PPD\leq 6\%}}{A}$$ (4.3)

where $A_{1.1m,PPD\leq 6\%}$ is the area over which the PPD requirement was satisfied at a height of 1.1m above the floor, and A is the total planform area of the room.

4.1.1.3 Taguchi method and data analysis

- Simulation design

As mentioned before, the following configuration variables for top-hung windows were selected to evaluate their impacts on the indoor thermal comfort conditions: window width, window height, height of the window bottom above the ground, window opening angle and fly-screen porosity. In a number of simulations, the presence of a fly-screen was modelled as a porous-jump boundary in the CFD model. Two types of fly-screen and associated pressure drop parameters were chosen from those described by Miguel (1998)
where screen $R_{w25}$ is a representative of woven mesh screens for windows and $R_{w20}$ is a higher porosity screen. Screen flow properties are shown in Table 4.2.

<table>
<thead>
<tr>
<th>Screen Type</th>
<th>Face permeability $(\text{m}^2)$</th>
<th>Porous medium thickness (m)</th>
<th>Pressure-jump coefficient $(\text{m}^{-1})$</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{w20}$</td>
<td>$3.11 \times 10^{-9}$</td>
<td>$10^{-5}$</td>
<td>$2.334 \times 10^{-3}$</td>
<td>0.90</td>
</tr>
<tr>
<td>$R_{w25}$</td>
<td>$2.71 \times 10^{-10}$</td>
<td>$2.5 \times 10^{-5}$</td>
<td>$119.3 \times 10^{-3}$</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Since the outdoor air temperature, wind direction and speed obviously influence the indoor airflow and temperature fields, the outdoor temperature and wind conditions at the window height were also considered in the simulation analysis. The Taguchi method (Roy 2010) was used to reduce the overall number of simulations required to achieve the objectives of the study. Table 4.3 summarises the three levels chosen for each of the eight parameters. Outdoor air temperatures of 18, 22 and 26°C and external wind speeds range of 2.4, 2.6 and 2.8 m/s were selected in this initial phase of this study as being representative of conditions when occupants are likely to accept a natural ventilation strategy within their buildings (Erhorn 1988). The parameter ranges should be extended in future work. As there were eight factors, each with three levels, a full factorial design for the possible combinations of these parameters levels needs $\left(C_3^1\right)^8$, i.e. 6561 simulations cases. Instead of testing all the possible combinations of parameters, an orthogonal array based on the Taguchi method was selected for only a few of subsets of all the combinations to maximise the simulation coverage while minimising the number of simulation cases. Based on the factor and the level selections in this study, the standard orthogonal array, $L_{27}(3^8)$ was selected to design the simulation scenarios (Table 4.4).
Chapter 4 Numerical analysis of the influence of top-hung window configuration on indoor thermal environment

Table 4.3 Case study building parameters and environmental parameters considered and their values.

<table>
<thead>
<tr>
<th>Level</th>
<th>Outdoor air temperature (°C)</th>
<th>Wind speed (m/s)</th>
<th>Wind direction (°)</th>
<th>Window opening angle (°)</th>
<th>Window width (m)</th>
<th>Window height (m)</th>
<th>Window height above ground (m)</th>
<th>Fly-screen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>2.4</td>
<td>0</td>
<td>10</td>
<td>0.4</td>
<td>0.4</td>
<td>1.2</td>
<td>0 (no screen)</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>2.6</td>
<td>30</td>
<td>25</td>
<td>0.8</td>
<td>0.8</td>
<td>1.4</td>
<td>1 ($R_{w20}$)</td>
</tr>
<tr>
<td>3</td>
<td>26</td>
<td>2.8</td>
<td>60</td>
<td>40</td>
<td>1.2</td>
<td>1.2</td>
<td>1.6</td>
<td>2 ($R_{w25}$)</td>
</tr>
</tbody>
</table>

Table 4.4 Simulation scenario design based on a Taguchi $L_{27}(3^8)$ standard orthogonal array.

<table>
<thead>
<tr>
<th>Simulation case</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
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<td>2</td>
<td>2</td>
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<td>1</td>
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<td>3</td>
<td>2</td>
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<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
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<td>2</td>
<td>3</td>
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<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
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<td>3</td>
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<td>1</td>
<td>1</td>
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<td>3</td>
<td>1</td>
</tr>
<tr>
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<td>1</td>
<td>1</td>
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<td>2</td>
<td>1</td>
</tr>
<tr>
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<td>3</td>
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<td>3</td>
<td>1</td>
<td>3</td>
</tr>
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<td>10</td>
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<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
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<td>3</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
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<td>2</td>
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</tr>
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<td>1</td>
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<td>3</td>
</tr>
<tr>
<td>13</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
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<td>3</td>
</tr>
<tr>
<td>14</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>3</td>
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<td>1</td>
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<td>1</td>
<td>1</td>
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</tr>
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<td>3</td>
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<td>2</td>
<td>1</td>
</tr>
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<td>1</td>
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<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
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<td>3</td>
<td>2</td>
<td>3</td>
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<td>2</td>
</tr>
<tr>
<td>20</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
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<td>1</td>
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<td>3</td>
<td>2</td>
</tr>
<tr>
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<td>2</td>
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<td>2</td>
<td>1</td>
<td>2</td>
</tr>
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<td>23</td>
<td>2</td>
<td>2</td>
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<td>2</td>
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<td>3</td>
<td>3</td>
</tr>
<tr>
<td>24</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>26</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>27</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
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- ANOVA analysis

The analysis of variance (ANOVA) method was used to evaluate the influence of the eight parameters on the value of R (see Eq. 4.7) utilising the sum of squares (SS), and the degrees of freedom (DOF) (Taguchi and Yokoyama 1993). The sum of squares, the degree of freedom and variance can be calculated as follows:

\[
SS_A = \sum_{i=1}^{k_A} \frac{A_i^2}{n_{A_i}} - \frac{(\sum_{i=1}^{k_A} F_i)^2}{k} \quad (4.4)
\]

\[
DOF_A = k_A - 1 \quad (4.5)
\]

\[
V_A = \frac{SS_A}{DOF_A} \quad (4.6)
\]

where \( k_A \) is the number of the levels of factor A, \( n_{A_i} \) is the number of all values at level i of factor A, \( A_i \) is the sum of all values at level i of factor A, \( F_i \) is the value at level i and k is the number of total simulation scenarios, and \( DOF_A \) is the degree of freedom of factor A.

ANOVA can assess the significance of the input parameters on the dependent variable by calculating the percentage contribution which is defined as the portion of a total observed variance for each significant factor (Gopalsamy et al. 2009). The greater the value the more it contributes to the final results. Percentage contribution is calculated according to the following formulae:

\[
P_A = \frac{SS_A - V_e \times DOF_A}{SS_T} \times 100 \quad (4.7)
\]

\[
V_e = \frac{SS_T}{DOF_e} = \frac{SS_A/(DOF_T - DOF_A - DOF_B - DOF_C - DOF_D - DOF_E - DOF_F - DOF_G - DOF_H)} \quad (4.8)
\]

\[
SS_T = \sum_{i=1}^{k} F_i^2 - (\sum_{i=1}^{k} F_i)^2 / k \quad (4.9)
\]

\[
SS_e = SS_T - SS_A - SS_B - SS_C - SS_D - SS_E - SS_F - SS_G - SS_H \quad (4.10)
\]

\[
DOF_T = k - 1 \quad (4.11)
\]

\[
P_e = \frac{SS_e + V_e \times (DOF_T - DOF_e)}{SS_T} \quad (4.12)
\]
where $V_e$ is the variance of error, $SS_T$ is the total sum of squares, and $DOF_T$ is the degree of the freedom of all simulation cases and subscripts A to H refer to the parameters listed in Table 4.3.

- **S/N analysis**

Signal-to-noise (S/N) ratio was used to identify the optimal combination of window parameters. The S/N ratio is a logarithmic transformation of mean square deviation to linearise the influences of different parameter levels:

\[
(S/N)_{A,i} = -10 \log_{10} (MSD)_{A,i}
\]  

(4.13)

The value of $R$ was required to be large, thus, the larger-the-better quality characteristic (Taguchi and Yokoya 1993) was applied. The MSD is therefore defined as:

\[
(MSD)_{A,i} = \left( \frac{\sum_{j=1}^{k} \left( \frac{1}{F_j} \right)^2}{n_{A_i}} \right)
\]  

(4.14)

where $F_j$ is the simulated result for the $j^{th}$ simulation and $k$ is the number of simulations at level $i$ of factor $A$.

#### 4.1.1.4 Grid-sensitivity analysis of the CFD model

In order to minimise any potential inaccuracies related to the CFD mesh density, a grid sensitivity analysis was performed using three types of mesh: a coarse mesh, a medium mesh and a fine mesh. For 3-D models, the mesh refinement ratio ($r_{ji}$) is defined as the ratio of the number of mesh elements in two different meshes ($\Delta_i$, $\Delta_j$, $\Delta_i < \Delta_j$), as shown in Eq. (2). This definition was used for the present grid sensitivity analysis (Hajdukiewicz et al. 2013).

\[
r_{ji} = \left( \frac{\Delta_i}{\Delta_j} \right)^{1/3}
\]  

(4.15)
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The recommended mesh refinement ratio for a non-uniform mesh is considered to be >1.33 for 3-D models (Celik et al. 2008). The number of mesh elements and the refinement ratio for the three types of mesh are shown in Table 4.5.

<table>
<thead>
<tr>
<th>Mesh element</th>
<th>Coarse ((\Delta_1))</th>
<th>Medium ((\Delta_2))</th>
<th>Fine ((\Delta_3))</th>
<th>Mesh refinement ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1,744,137</td>
<td>5,107,106</td>
<td>14,541,827</td>
<td>1.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.42</td>
</tr>
</tbody>
</table>

A series of the vertically distributed test points that passed through the centroid of the case study room model were selected to compare the relative air speeds as a function of elevation, \(h\), when using the three different types of mesh (Fig. 4.3).

![Grid-sensitivity analysis results.](image)

Fig. 4.3 Grid-sensitivity analysis results.
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The results with the medium mesh matched closely with those of the fine mesh. Since simulations with the fine mesh required more computational time than that of the medium mesh, the medium mesh was used for the CFD simulations.

4.1.2 Results and discussions

Cases 15 and 22 were selected to understand the velocity and temperature fields of the case study building. Table 4.6 presents the basic information of boundary settings for Case 15 and 22.

<table>
<thead>
<tr>
<th>Case</th>
<th>Outdoor air temperature (°C)</th>
<th>Wind speed (m/s)</th>
<th>Wind direction (°)</th>
<th>Window opening angle (°)</th>
<th>Window width (m)</th>
<th>Window height (m)</th>
<th>Window height above ground (m)</th>
<th>Fly-screen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>18</td>
<td>2.4</td>
<td>0</td>
<td>40</td>
<td>0.8</td>
<td>0.8</td>
<td>1.6</td>
<td>$R_{w25}$</td>
</tr>
<tr>
<td>22</td>
<td>26</td>
<td>2.6</td>
<td>60</td>
<td>25</td>
<td>0.4</td>
<td>0.8</td>
<td>1.2</td>
<td>$R_{w25}$</td>
</tr>
</tbody>
</table>

Typical results for the velocity and temperature fields of the case study building are shown in Fig. 4.4 and Fig. 4.5.
Chapter 4 Numerical analysis of the influence of top-hung window configuration on indoor thermal environment
Fig. 4.4 Example of CFD simulation results for Case 15: (a) velocity field – elevation view; (b) velocity field – plan view; (c) velocity streamline; and (d) temperatures.
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The CFD results of the velocity field, velocity streamline and temperatures for Case 15 are presented in Fig. 4.4. A jet-flow from the upstream window came into the room as a result of the flow diversion by the top-hung window. The airflow through the window went upward obliquely and after being obstructed by the ceiling of the room, the main fraction of the airflow moved forward along the surface of the ceiling and then went downward to the window on the downstream wall (Fig. 4.4a and Fig. 4.4c). The rest of the airflow moved downward along both of the side walls (Fig. 4.4b and Fig. 4.4c). However, the airflow patterns in these cases with oblique incident winds were different from these with 0° incident winds. A scenario with an incident wind of 60° for Case 22 is presented in Fig. 4.5. As is shown in Fig. 4.5c, a jet-flow from the upstream window came into the room and hit the side wall of the room. The airflow was then separated into two parts: one moved upwards and the other one went downwards.

Besides, Fig. 4.4c and Fig. 4.5c reveals that with the decay of air kinetic energy, the air speed decreased very fast. The air movement at the middle and end of the airflow path was slow when compared to the airflow near the upstream window.
Fig. 4.4d and Fig. 4.5d indicated that the indoor air temperature was influenced by the outdoor air temperature, indoor airflow movement and wall temperature. Indoor air temperatures were close to the outdoor air temperatures in the areas near the upstream window but they were close to the wall temperature in the areas where air movement was not strong.

**4.1.2.1 Influence of window configuration parameters on thermal comfort**

Table 4.7 shows the results of the ratio of the area that satisfies the PPD requirement mentioned above based on the standard simulation design for the $L_{27}(3^8)$ orthogonal array. Using the simulation results shown in Table 4.7, the percentage contributions of the parameters were determined using the ANOVA method. Table 4.8 presents the percentage contributions of these factors in influencing the fraction of the 1.1m plane that satisfied the thermal comfort criterion $R$.

For this particular case study building, the outdoor air temperature had by far the biggest influence on PPD and thermal comfort with a contribution of 82%, followed by window height and window opening angle with 4% and 3% contributions, respectively. It should be noted that due to the nature of the Taguchi method, this initial study used a limited range for some of the variables. It is intended that these ranges should be extended in future work.
### Table 4.7 CFD simulation results for the set of Taguchi $L_{27}^{(3)}$ test cases.

<table>
<thead>
<tr>
<th>Simulation case</th>
<th>Factor A</th>
<th>Factor B</th>
<th>Factor C</th>
<th>Factor D</th>
<th>Factor E</th>
<th>Factor F</th>
<th>Factor G</th>
<th>Factor H</th>
<th>R</th>
<th>$T_{min}$</th>
<th>$T_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22</td>
<td>2.8</td>
<td>30</td>
<td>10</td>
<td>1.2</td>
<td>0.8</td>
<td>1.4</td>
<td>1</td>
<td>0.15</td>
<td>22.5</td>
<td>22.8</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
<td>2.4</td>
<td>30</td>
<td>25</td>
<td>0.8</td>
<td>0.8</td>
<td>1.2</td>
<td>0</td>
<td>0.95</td>
<td>25.0</td>
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</tr>
<tr>
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<td>25</td>
<td>0.4</td>
<td>1.2</td>
<td>1.4</td>
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<td>0</td>
<td>10</td>
<td>0.4</td>
<td>1.2</td>
<td>1.6</td>
<td>0</td>
<td>1</td>
<td>24.1</td>
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<td>10</td>
<td>0.4</td>
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<td>0</td>
<td>0.56</td>
<td>22.9</td>
<td>23.5</td>
</tr>
<tr>
<td>9</td>
<td>22</td>
<td>2.8</td>
<td>30</td>
<td>40</td>
<td>0.4</td>
<td>1.2</td>
<td>1.2</td>
<td>2</td>
<td>0.16</td>
<td>22.4</td>
<td>23.4</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>2.8</td>
<td>60</td>
<td>40</td>
<td>1.2</td>
<td>0.8</td>
<td>1.6</td>
<td>0</td>
<td>0.11</td>
<td>19.3</td>
<td>21.1</td>
</tr>
<tr>
<td>11</td>
<td>18</td>
<td>2.6</td>
<td>30</td>
<td>25</td>
<td>0.8</td>
<td>1.2</td>
<td>1.4</td>
<td>0</td>
<td>0.09</td>
<td>19.4</td>
<td>20.7</td>
</tr>
<tr>
<td>12</td>
<td>22</td>
<td>2.4</td>
<td>60</td>
<td>10</td>
<td>0.8</td>
<td>0.8</td>
<td>1.4</td>
<td>2</td>
<td>0.79</td>
<td>22.8</td>
<td>23.4</td>
</tr>
<tr>
<td>13</td>
<td>26</td>
<td>2.6</td>
<td>60</td>
<td>10</td>
<td>0.8</td>
<td>1.2</td>
<td>1.6</td>
<td>2</td>
<td>1</td>
<td>24.8</td>
<td>25.4</td>
</tr>
<tr>
<td>14</td>
<td>26</td>
<td>2.8</td>
<td>0</td>
<td>25</td>
<td>1.2</td>
<td>0.8</td>
<td>1.2</td>
<td>2</td>
<td>0.99</td>
<td>24.8</td>
<td>25.5</td>
</tr>
<tr>
<td>15</td>
<td>18</td>
<td>2.4</td>
<td>0</td>
<td>40</td>
<td>0.8</td>
<td>0.8</td>
<td>1.6</td>
<td>1</td>
<td>0.12</td>
<td>20.1</td>
<td>21.8</td>
</tr>
<tr>
<td>16</td>
<td>18</td>
<td>2.8</td>
<td>60</td>
<td>10</td>
<td>0.8</td>
<td>0.4</td>
<td>1.2</td>
<td>2</td>
<td>0.2</td>
<td>21.1</td>
<td>22.5</td>
</tr>
<tr>
<td>17</td>
<td>26</td>
<td>2.6</td>
<td>60</td>
<td>40</td>
<td>1.2</td>
<td>0.4</td>
<td>1.4</td>
<td>0</td>
<td>1</td>
<td>24.6</td>
<td>25.3</td>
</tr>
<tr>
<td>18</td>
<td>18</td>
<td>2.4</td>
<td>0</td>
<td>25</td>
<td>1.2</td>
<td>1.2</td>
<td>1.4</td>
<td>2</td>
<td>0.1</td>
<td>19.6</td>
<td>21.5</td>
</tr>
<tr>
<td>19</td>
<td>22</td>
<td>2.6</td>
<td>0</td>
<td>40</td>
<td>0.8</td>
<td>1.2</td>
<td>1.2</td>
<td>1</td>
<td>0.15</td>
<td>22.5</td>
<td>23.2</td>
</tr>
<tr>
<td>20</td>
<td>18</td>
<td>2.4</td>
<td>0</td>
<td>10</td>
<td>0.4</td>
<td>0.4</td>
<td>1.2</td>
<td>0</td>
<td>0.24</td>
<td>21.4</td>
<td>22.8</td>
</tr>
<tr>
<td>21</td>
<td>26</td>
<td>2.4</td>
<td>30</td>
<td>10</td>
<td>1.2</td>
<td>1.2</td>
<td>1.6</td>
<td>1</td>
<td>0.93</td>
<td>25.0</td>
<td>25.5</td>
</tr>
<tr>
<td>22</td>
<td>26</td>
<td>2.6</td>
<td>60</td>
<td>25</td>
<td>0.4</td>
<td>0.8</td>
<td>1.2</td>
<td>1</td>
<td>1</td>
<td>24.5</td>
<td>25.1</td>
</tr>
<tr>
<td>23</td>
<td>22</td>
<td>2.6</td>
<td>0</td>
<td>25</td>
<td>1.2</td>
<td>0.4</td>
<td>1.6</td>
<td>2</td>
<td>0.4</td>
<td>23.0</td>
<td>23.3</td>
</tr>
<tr>
<td>24</td>
<td>22</td>
<td>2.8</td>
<td>30</td>
<td>25</td>
<td>0.8</td>
<td>0.4</td>
<td>1.6</td>
<td>0</td>
<td>0.38</td>
<td>22.9</td>
<td>23.4</td>
</tr>
<tr>
<td>25</td>
<td>22</td>
<td>2.4</td>
<td>60</td>
<td>40</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>0</td>
<td>0.2</td>
<td>22.4</td>
<td>23.0</td>
</tr>
<tr>
<td>26</td>
<td>18</td>
<td>2.6</td>
<td>30</td>
<td>40</td>
<td>0.4</td>
<td>0.8</td>
<td>1.6</td>
<td>2</td>
<td>0.1</td>
<td>20.2</td>
<td>21.4</td>
</tr>
<tr>
<td>27</td>
<td>18</td>
<td>2.6</td>
<td>30</td>
<td>10</td>
<td>1.2</td>
<td>0.4</td>
<td>1.2</td>
<td>1</td>
<td>0.18</td>
<td>21.1</td>
<td>22.3</td>
</tr>
</tbody>
</table>
Table 4.8 ANOVA analysis and percentage contributions to thermal comfort performance metric, $R$.

<table>
<thead>
<tr>
<th>Factor</th>
<th>SS</th>
<th>DOF</th>
<th>Variance</th>
<th>Percentage contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Outdoor air temperature</td>
<td>3.338</td>
<td>2</td>
<td>1.669</td>
<td>82%</td>
</tr>
<tr>
<td>B. Wind speed</td>
<td>0.093</td>
<td>2</td>
<td>0.046</td>
<td>2%</td>
</tr>
<tr>
<td>C. Wind direction</td>
<td>0.136</td>
<td>2</td>
<td>0.068</td>
<td>3%</td>
</tr>
<tr>
<td>D. Window opening angle</td>
<td>0.121</td>
<td>2</td>
<td>0.060</td>
<td>3%</td>
</tr>
<tr>
<td>E. Window width</td>
<td>0.084</td>
<td>2</td>
<td>0.042</td>
<td>2%</td>
</tr>
<tr>
<td>F. Window height</td>
<td>0.157</td>
<td>2</td>
<td>0.078</td>
<td>4%</td>
</tr>
<tr>
<td>G. Window height above ground</td>
<td>0.070</td>
<td>2</td>
<td>0.035</td>
<td>2%</td>
</tr>
<tr>
<td>H. Fly-screen type</td>
<td>0.017</td>
<td>2</td>
<td>0.009</td>
<td>0%</td>
</tr>
<tr>
<td>Error</td>
<td>0.040</td>
<td>10</td>
<td>0.004</td>
<td>3%</td>
</tr>
<tr>
<td>Total</td>
<td>4.056</td>
<td>26</td>
<td>-</td>
<td>100%</td>
</tr>
</tbody>
</table>

4.1.2.2 Optimal window configuration combinations

The signal-to-noise (S/N) ratios for each level of the parameters are summarised in Fig. 4.6. Higher values of the S/N ratio indicated that larger fractions of the room area, $R$, (at an elevation of 1.1m) met the PPD requirement. In this preliminary study, the optimal parameter level combination for $R$ was A3B1C3D1E1F1G1H2. Table 4.9 shows the simulation results as a function of the optimal parameter level combination identified in Fig. 4.6. It is worth noting that the optimal combination result was a near-optimal solution and not necessarily the absolutely optimal solution as discrete values of the parameters were used in the analysis. However, the solution may be used as a reference point for further optimisation. In addition, the optimal combination identified was only valid for the range of parameters chosen in this study. Further simulations are required to build a more comprehensive understanding of the impact of all parameters in a range of practical situations on thermal comfort.
Chapter 4 Numerical analysis of the influence of top-hung window configuration on indoor thermal environment

Fig. 4.6 Signal-to-noise ratio for $R$.

Table 4.9 Simulation results based on the optimal combination.

<table>
<thead>
<tr>
<th>Optimal combination</th>
<th>Outdoor air temperature ($^\circ$C)</th>
<th>Wind speed (m/s)</th>
<th>Wind direction ($^\circ$)</th>
<th>Window opening angle ($^\circ$)</th>
<th>Window width (m)</th>
<th>Window height (m)</th>
<th>Window height above ground (m)</th>
<th>Fly-screen type</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPD</td>
<td>26</td>
<td>2.4</td>
<td>60</td>
<td>10</td>
<td>0.4</td>
<td>0.4</td>
<td>1.2</td>
<td>$R_{w20}$</td>
<td>1</td>
</tr>
</tbody>
</table>

4.2 Airflow rate analysis

Many studies on wind-driven cross-ventilated buildings have been published in the recent years (Karava et al. 2011, Perén et al. 2015, Chu et al. 2015, Shetabivash 2015, Aldawoud 2017), where the influence of the window aspect ratio, size, and position on airflow rate was investigated. However, in many such studies, windows were modelled as simply large openings without taking the effects of the window pane opening angle or other practical factors into consideration (e.g. the presence of fly screens). Hence, this section investigated the influence of window opening angle, fly screen, and outdoor wind speed and direction on the volume airflow rate in wind-driven cross-ventilated buildings.

4.2.1 Methodology for indoor airflow rate assessment

A top-hung window that had the same geometry and attributes with the window in the SBRC building was modelled to investigate the influence of outdoor wind velocity and direction, window opening angle and fly screen on airflow rate in the window. The specific top-hung window was put into a cross-ventilated CFD building model. The Taguchi method was employed to reduce the simulation cases. The contributions of these parameters to airflow rate would be identified through the ANOVA analysis. Lastly, the
functions between the airflow rate and the essential parameters would be regressed for
the forecast of airflow rate in the window.

4.2.1.1 Description of CFD model
The top-hung windows in the SBRC building (see Fig. 4.7) were selected as the research
object. The window was 1.2m in length and 0.6m in height. A CFD building model which
was same with the one in section 4.1 was used as the simulation platform and the window
was placed in the centre of the front façade of the building model. The modelling process
was the same with section 4.1.

Fig. 4.7 Top-hung window in the SBRC building.

4.2.1.2 Simulation design

- Parameter design

The attribute of the fly screen in the window of the SBRC building was identified through
literature (Miguel 1998) and presented in Table 4.10.

<table>
<thead>
<tr>
<th>Screen Type</th>
<th>Face permeability ((m^2))</th>
<th>Porous medium thickness ((m))</th>
<th>Pressure-jump coefficient ((m^1))</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_{w29})</td>
<td>(3.11 \times 10^{-9})</td>
<td>(10^{-5})</td>
<td>(2.334 \times 10^{-3})</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Four parameters at two levels were selected and presented in Table 4.11.
Chapter 4 Numerical analysis of the influence of top-hung window configuration on indoor thermal environment

Table 4.11 Parameters considered and their levels.

<table>
<thead>
<tr>
<th>Level</th>
<th>A Wind direction (°)</th>
<th>B Wind speed (m/s)</th>
<th>C Window opening angle (°)</th>
<th>D Fly-screen type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.8</td>
<td>30</td>
<td>no screen</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>2.2</td>
<td>45</td>
<td>screen (R\textsubscript{w20})</td>
</tr>
</tbody>
</table>

• Orthogonal matrix design

A standard orthogonal array, \( L_8(4^2) \) was chosen to provide parameter level combinations. The orthogonal array is shown in Table 4.12.

Table 4.12 Taguchi \( L_4(4^2) \) standard orthogonal array.

<table>
<thead>
<tr>
<th>Simulation number</th>
<th>Factor A</th>
<th>Factor B</th>
<th>Factor C</th>
<th>Factor D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

4.2.2 Results analysis

4.2.2.1 Influence of window configuration parameters on airflow rate

The simulation results are shown in Table 4.13. Based on the simulation results, the sum of squares (SS), the degrees of freedom, variance and percentage contribution were calculated and presented in Table 4.14.
Chapter 4 Numerical analysis of the influence of top-hung window configuration on indoor thermal environment

Table 4.13 Taguchi $L_4(4^2)$ simulation results.

<table>
<thead>
<tr>
<th>Simulation number</th>
<th>Factor A</th>
<th>Factor B</th>
<th>Factor C</th>
<th>Factor D</th>
<th>Volume airflow rate, $Q$ ($m^3/s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.8</td>
<td>45</td>
<td>No screen</td>
<td>0.63</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>1.8</td>
<td>45</td>
<td>Screen</td>
<td>0.62</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>2.2</td>
<td>45</td>
<td>No screen</td>
<td>0.78</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1.8</td>
<td>30</td>
<td>Screen</td>
<td>0.49</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>2.2</td>
<td>45</td>
<td>Screen</td>
<td>0.76</td>
</tr>
<tr>
<td>6</td>
<td>45</td>
<td>2.2</td>
<td>30</td>
<td>Screen</td>
<td>0.62</td>
</tr>
<tr>
<td>7</td>
<td>45</td>
<td>1.8</td>
<td>30</td>
<td>No screen</td>
<td>0.52</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>2.2</td>
<td>30</td>
<td>No screen</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Table 4.14 ANOVA analysis and percentage contributions to airflow rate.

<table>
<thead>
<tr>
<th>Factor</th>
<th>SS</th>
<th>DOF</th>
<th>Variance</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Wind direction</td>
<td>0.0002</td>
<td>1</td>
<td>0.0002</td>
<td>0%</td>
</tr>
<tr>
<td>B. Wind speed</td>
<td>0.0342</td>
<td>1</td>
<td>0.0342</td>
<td>47%</td>
</tr>
<tr>
<td>C. Window opening angle</td>
<td>0.0375</td>
<td>1</td>
<td>0.0375</td>
<td>51%</td>
</tr>
<tr>
<td>D. Fly-screen type</td>
<td>0.0005</td>
<td>1</td>
<td>0.0005</td>
<td>0%</td>
</tr>
<tr>
<td>Error</td>
<td>0.0005</td>
<td>3</td>
<td>0.0002</td>
<td>1.7%</td>
</tr>
<tr>
<td>Total</td>
<td>0.0728</td>
<td>7</td>
<td>-</td>
<td>100%</td>
</tr>
</tbody>
</table>

According to the analysis results in Table 4.14, wind speed and window opening angle had 47% and 51% contributions to the airflow rate, indicating wind speed and window opening angle were the most significant factors for the airflow rate values.

4.2.2.2 Regression analysis of airflow rate

A qualitative analysis of the influence of window configurations and outdoor weather conditions was presented through ANOVA analysis. The functional relationship between the airflow rate through the window and the two essential parameters, i.e. wind speed and window opening angle remained unknown. As a consequence, a series of the variable range were selected (see Table 4.15) to uncover their relationships.
Table 4.15 Variable range selection.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed</td>
<td>1-3.5m/s</td>
<td>0.5m/s</td>
</tr>
<tr>
<td>Wind direction</td>
<td>0-60°</td>
<td>20°</td>
</tr>
<tr>
<td>Window opening angle</td>
<td>10-50°</td>
<td>10°</td>
</tr>
</tbody>
</table>

The simulation results presented in Fig. 4.8 indicated that both the wind speed and window opening angle had an approximately linear relationship with the airflow rate. The multiple linear regression method could be used to obtain formulae to forecast the airflow rate in the window.

Fig. 4.8 Simulation results of airflow rate in the window influenced by wind direction and window opening angle.

The regression coefficients of formulae were calculated by the least square method (LSM) (Zhu et al. 1986). The results are presented Table 4.16.
Table 4.16 Linear regression coefficient analysis.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Wind speed</th>
<th>Wind opening angle</th>
<th>Constant</th>
<th>R-squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical airflow direction</td>
<td>0.110</td>
<td>0.004</td>
<td>-0.135</td>
<td>0.9</td>
</tr>
</tbody>
</table>

According to results in Table 4.16, the regressed formula had an R-squared value of 0.9, indicating the formulae fit well with the data. This regres formula could be used as a reference for the indoor airflow rate control in the SBRC building.

4.3 Summary

This chapter presented the results of a numerical investigation of indoor thermal comfort and air flow rate in a cross-ventilated space using CFD simulations. The Taguchi method was used to design the simulation cases to identify the near-optimal top-hung window parameters required for the best indoor thermal comfort outcome for a limited range of building and external environmental conditions.

The main conclusions of this study may be summarised as follows:

- Outdoor air temperature, window height and window opening angle were found to be the most important factors influencing the PMVe value in the region of interest (i.e. head level for seated occupants) in the case study building for the range of parameters modelled.

- The optimal parameter level combination to improve the indoor thermal comfort of the focused area of interest was identified through S/N ratio analysis, which could be used as a reference point for future optimisation and development of additional CFD simulations of thermal comfort in naturally ventilated spaces.

- Wind speed and window opening angle were the most important factors influencing airflow rate based on the analysis of a specified top-hung window. A near-linear relationship between the two factors and the airflow rate were discovered.

CFD simulations of the impact of cross-ventilation on internal thermal comfort and airflow rate in a cross-ventilated space have been successfully carried out in this chapter. However, the results concluded were based on the use of a hypothetical room with the rectangular floor layout and hence could only be applied to buildings with similar
Chapter 4 Numerical analysis of the influence of top-hung window configuration on indoor thermal environment

characteristics. Further work was needed to evaluate the influence of the internal layout of buildings on the indoor airflow pattern and thermal comfort.
CHAPTER 5 INDOOR LOCAL THERMAL COMFORT ANALYSIS IN AN OPEN PLAN OFFICE WITH CROSS-VENTILATION

The use of automatically controlled natural and hybrid ventilation in high performance buildings is starting to appear in sectors such as commercial and educational buildings, where the Building Management Systems (BMSs) are programmed to maintain indoor thermal comfort while reducing energy consumption. More generally, many control system types have been developed to maintain the thermal comfort of entire buildings (for example, Mochida et al. 2005, Mahdavi and Pröglhöf 2008, Wang and Greenberg 2015). However, it is not generally necessary to ensure that all the internal volume of a building with large open spaces satisfy thermal comfort requirements. The primary focus should naturally be on occupied areas such as portioned offices, meeting rooms and desks in open-plan offices, where local thermal discomfort caused by temperature and air velocity variations and building interior layout could influence thermal satisfaction of the occupants significantly.

Temperature and airflow were not evenly distributed in open plan office buildings when using natural ventilation and hence more likely to cause local thermal discomfort (Nicol and Humphreys 2002). As a consequence, this chapter aims to further investigate the issues by evaluating and optimising the local thermal comfort in an open-plan/shared office of a mixed-mode/naturally ventilated office building.

The Sustainable Buildings Research Centre (SBRC) in University of Wollongong was selected as the case study building, and thermal stratification, extended predicted mean vote (PMVe) and draught rate (DR²) were employed as the indices of local thermal discomfort assessment. CFD simulations were used to quantify these indices under different outdoor weather conditions.

This chapter is organised as follows. A brief description of the research methodology of this chapter including building modelling and validation, building model boundary setting and the local thermal comfort index description is presented in Section 5.1. Section 5.2

² It is also defined as draught risk in some publications.
analyses the simulation results and provides some suggestions on the natural ventilation control of the case study building for local thermal comfort optimisation. Finally, conclusions are summarised in Section 5.3.

5.1 Methodology

Indoor local thermal comfort in the open-plan, mixed-mode/naturally ventilated office in the Sustainable Buildings Research Centre (SBRC) building was assessed at times when natural ventilation was in operation. The elements of the research methodology used are summarised schematically in Fig. 5.1.

The numerical investigation was supported by in situ measurements to provide data for the CFD modelling, boundary setting and model calibration of the case study building. The simulated data obtained was used for the analysis of indoor local thermal comfort performance when using cross-ventilation. Three indices (i.e. thermal stratification, the extended predicted mean vote and draught rate) and the corresponding criteria were determined to assess the local thermal comfort under different window opening percentages. An improved natural ventilation control strategy was also developed,
following the simulation result analysis, to reduce the local thermal discomfort conditions in the occupied locations of interest\(^3\).

### 5.1.1 Field investigation

#### 5.1.1.1 Description of the cross-ventilated office

The main office area in the case study building was on the first floor. A row of top-hung windows (the bottom of the window was 1.3 m height above the first floor) was located along the full length of the north facing walls, while two rows of top-hung windows (the bottoms of the windows were 4 m and 5.7 m height above the first floor, respectively) were located at the south facing walls, allowing primarily north-south cross-ventilation. The office was separated into two main zones (east and west) by the office kitchen. Field investigation showed about 2/3 of the occupants worked in the east office. The east office, as a consequence, was the research focus of this study. Although thermal comfort performance of the whole office could be obtained through this study, only the eastern zone was selected for the local thermal comfort analysis in order to reduce the research cost. The interior layout of the east office is presented in Fig. 5.2.

---

\(^3\)Six test points presented in Fig. 5.4 were selected as the occupied locations of interest.
Fig. 5.2 Interior layout of the eastern office zone.

Fig. 5.2 shows that a large open-plan area was located in the centre of the east office, while three partitioned individual offices (Room 101A, 101B and 101C) and one quiet room (101D) were built adjacent to the south wall. Besides, the shared desks were separated by partitions (38cm in height).

5.1.1.2 Natural ventilation strategy

The description of the HVAC control strategy in the SBRC building was already documented in Chapter 3 and the reader is referred to this section if details are required.

5.1.1.3 Outdoor measurements

The outdoor weather conditions were measured by the weather station located on the roof of the high-bay of the case study building. Details about the weather station may also be found in Chapter 3. The weather station data was used to provide boundary conditions of the CFD building model in this study.

5.1.1.4 Indoor measurements

For the purpose of validation of the case study building CFD model, indoor local air speed and air temperature were measured using a Testo 480 indoor climate measuring instrument, as shown in Fig. 5.3, and the specifications of the unit are shown in Table 5.1.
Fig. 5.3 Testo 480 indoor climate measuring kits: (a) the comfort probe; and (b) the measuring instrument.

Table 5.1 Testo 480 comfort probe technical information.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air speed</td>
<td>0-5 m/s</td>
<td>±0.03 m/s</td>
</tr>
<tr>
<td>Air temperature</td>
<td>0-50°C</td>
<td>±0.5°C</td>
</tr>
<tr>
<td>Air pressure</td>
<td>700-1100 hPa</td>
<td>±3 hPa</td>
</tr>
</tbody>
</table>

The probe was placed at the head level of a seated occupants \( h = 1.1 \) m in the open-plan area of the eastern office. The measurement locations for the indoor air speed and the indoor air temperature of the case study building is presented in Fig. 5.4. Five test points in the shared area were selected for measurement purposes; three of them (T2, T3 and T4) were selected near the central desk and the left two (T1 and T5) were next to the side desks. Besides, one test point (T6) was placed in an individual office, i.e. Room 101B.

\(^4\)Turbulence intensity is a function of 3-D air velocity (i.e. the ratio of the root-mean-square of the velocity fluctuations to the mean flow velocity). Test 480 calculated the turbulence intensity according to EN13779 by using the comfort probe to measure the 3-D flow velocity.
5.1.2 CFD modelling

The CFD simulation of the case building was performed using the commercial software ANSYS Fluent. The settings of the CFD model replicated the conditions inside the office building during the summer when there were a strong preference and opportunity for using natural ventilation to achieve thermal comfort under the Wollongong climatic conditions.

5.1.2.1 Building geometry

The geometry of the building model was determined based on the architectural drawings and in situ measurements. As a highly detailed CFD model would not greatly improve the accuracy of simulation results but significantly increase simulation time (Hutmacher and Singh 2008), the building model was simplified but with the main building air flow characteristics captured. The numerical/CAD model for the CFD simulation is illustrated in Fig. 5.5.
Chapter 5 Indoor local thermal comfort analysis in an open plan office with cross-ventilation

Fig. 5.5 Geometry of the case study building model: (a) the whole SBRC building; (b) the office section; and (c) the shared desk.

5.1.2.2 Computational domain
These guidelines for the computational domain setting were same with these in Chapter 4 and followed during the present building modelling process. The whole computational
domain is presented in Fig. 5.6. The details of the east office (as presented in Fig. 5.5) were also provided in the building model.

![Fig. 5.6 A schematic view of the computational domain.](image)

5.1.2.3 Choice of boundary conditions

Hourly experimental data was collected during normal office hours (08:00AM-17:00PM) for all the periods during December 2016 when natural ventilation was implemented. The data was used for the setting of the boundary conditions of the CFD model. The following types of data were collected:

- Internal surface temperature

The radiant heat transfer from the enclosure influences the mean radiant temperature and the mean radiant temperature will further affect operative temperature which is an important thermal comfort index (ISO 7730 2005). Therefore, the internal surface temperature of the case study building was collected to set the thermal boundary conditions of the building model for thermal comfort evaluation. Because there was no specified sensor used to measure the internal surface temperature, temperature sensors (Fig. 5.7) placed on the wall and ceiling to measure local air temperature adjacent to the surface were used to approximately present the wall and ceiling temperatures. A comparison of the BMS data and the point-in-time measured data suggested that absolute
difference between the internal surface temperature and the air temperature near the wall and ceiling (or the concrete slab temperature) was within the range of 0 to 2°C. The internal surface temperatures with the corresponding outdoor air temperature from the weather station for the occupied period when using natural ventilation are presented in Fig. 5.8.

Fig. 5.7 Sensors for measuring the temperature of (a) ceiling; (b) wall; and (c) slab.
Fig. 5.8 Estimated internal surface temperatures at (a) ceiling; (b) walls; and (c) slab as a function of outdoor air temperature when using natural ventilation.

From Fig. 5.8, it can be seen that the ceiling temperature was primarily in a range from 22 to 26°C. Because of the very substantial shading from the eaves of the roof, which shaded the external walls from direct solar radiation, and the thermally heavy wall construction (reverse brick-veneer) which retarded the heat transfer and stored thermal energy, the indoor wall surface temperatures were generally relatively stable. The wall temperature was found to occur in a relatively narrow temperature range (22 to 26°C) for 97% of the time during which natural ventilation was in operation. The temperature of the partially exposed office floor slab was generally lower than the other indoor surfaces and the slab temperature measured to be between 22 to 25°C for 96% of the office occupied periods when using natural ventilation (i.e. the outdoor air temperature was mostly between 20 to 24°C and the wind speed was less than 30 km/h).

The median values of the temperature for each interior surface were selected for the purpose of thermal boundary setup. The ceiling temperature was chosen as 24.5°C. Wall temperature was assumed to be 23.5°C and the slab temperature was 23°C.

- Outdoor air speed, direction and temperature

The natural ventilation control logic used in the case study building showed that natural ventilation was used when the outdoor air temperature was between 20 and 24°C (excluding the extreme weather conditions). Outdoor air temperature is clearly one of the most important factors influencing indoor thermal comfort under natural ventilation conditions, since occupants can be exposed to draught/air flows coming directly through
windows, as well as these air flows influencing the overall thermal balance in a building space. As a consequence, both the lower and upper outdoor air temperature bands, i.e. 20 and 24°C were used as the outdoor air temperature in the CFD simulation.

The relative humidity of the outdoor air was obtained from the weather station, and primarily in a range from 55 to 85% for 93% of the office occupied periods when using natural ventilation (see Fig. 5.9). The median value of the relative humidity of the outdoor air temperature, i.e. 70% was selected for the purpose of thermal boundary setup.

![Frequency histograms of the relative humidity](image)

Fig. 5.9 Frequency histograms of the relative humidity.

Velocity inlet and pressure outlet were selected as the boundary conditions in the simulation. The wind velocity profile in the velocity-inlet of the CFD computational domain was set by assuming a power law velocity profile on the atmospheric boundary condition (ASHRAE 2011) which were same with these in Chapter 4.

The external wind speeds of 2.4, 2.6 and 2.8 m/s were selected as the representative conditions in Chapter 4 because occupants are likely to open windows within their buildings when the external wind speed was in the range of 2-3 m/s. However, the window control strategy of the case study building used to modulate windows was developed based on a wide range of wind speed of 0-30 km/h (i.e., 0–8.3 m/s). In order to cover the natural ventilation conditions of the case study building, the outdoor wind speed ranging between 1 to 7 m/s with the interval of 1 m/s was selected as the outdoor wind conditions in this chapter. The SBRC office building was designed to have a narrow floor plate (east-west) and a large number of windows were placed in both north and south walls (see Fig. 108.
5.5) to facilitate good north-to-south cross-ventilation. Azimuth angles of 315, 0, 45, 135, 180 and 225° (i.e. northwest, north, northeast, southeast, south and southwest), hence, were chosen to simulate a north-to-south cross-ventilation in the open plan office. The simulation cases designed were presented in Table 5.2.

Table 5.2 Simulation cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Wind conditions</th>
<th>Window angle (°)</th>
<th>T&lt;sub&gt;out&lt;/sub&gt; (°C)</th>
<th>Case</th>
<th>Wind conditions</th>
<th>Window angle (°)</th>
<th>T&lt;sub&gt;out&lt;/sub&gt; (°C)</th>
</tr>
</thead>
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<td>1 0</td>
<td>36</td>
<td>20</td>
<td>44</td>
<td>1 180</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>1 45</td>
<td>36</td>
<td>20</td>
<td>45</td>
<td>1 225</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
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<td>1 315</td>
<td>36</td>
<td>24</td>
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<td>1 135</td>
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<td>3 225</td>
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<td>58</td>
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<td>61</td>
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<td>20</td>
</tr>
<tr>
<td>20</td>
<td>4 0</td>
<td>36</td>
<td>20</td>
<td>62</td>
<td>4 180</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
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<td>4 45</td>
<td>36</td>
<td>20</td>
<td>63</td>
<td>4 225</td>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td>22</td>
<td>4 315</td>
<td>36</td>
<td>24</td>
<td>64</td>
<td>4 135</td>
<td>36</td>
<td>24</td>
</tr>
<tr>
<td>23</td>
<td>4 0</td>
<td>36</td>
<td>24</td>
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<td>5 0</td>
<td>29</td>
<td>20</td>
<td>68</td>
<td>5 180</td>
<td>29</td>
<td>20</td>
</tr>
<tr>
<td>27</td>
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<td>29</td>
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<td>69</td>
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<td>29</td>
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</tr>
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<td>5 315</td>
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<td>70</td>
<td>5 135</td>
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<td>29</td>
<td>5 0</td>
<td>29</td>
<td>24</td>
<td>71</td>
<td>5 180</td>
<td>29</td>
<td>24</td>
</tr>
</tbody>
</table>
• Fly screens

All the windows in the case study building were equipped with fly screens. In order to understand whether the fly screen would influence the airflow direction through opening windows, a field test was performed using an electric fan (providing an air speed of approximately 4 m/s) as shown in Fig. 5.10 (the fly screen tested was the same as these used in the case study building).

![Field test of airflow pattern: (a) with the fly screen; and (b) without the fly screen.](image)

The test results showed that the screen did not significantly change the direction of the mainstream of the flow. However, the smoke was more diffused during the test with the fly screen when compared to that without the fly screen. As a consequence, the influence of fly screens in all the windows on indoor airflow patterns was also considered for all the simulations in this study. The mesh dimensions of the fly screens in the windows of
the SBRC were very similar to one of the screens tested by Miguel (1998), and the details of the attributes of this particular fly screen are reproduced here in Table 5.3. In the CFD simulations, the fly screens were treated as a layer of porous material, and a pressure-jump boundary condition was set for all the based on attributes shown below.

Table 5.3 Fly screen attributes (Miguel 1998).

<table>
<thead>
<tr>
<th>Screen Type</th>
<th>Face permeability ($m^2$)</th>
<th>Porous medium thickness (m)</th>
<th>Pressure-jump coefficient ($m^{-1}$)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{w20}$</td>
<td>$3.11 \times 10^{-9}$</td>
<td>$10^{-5}$</td>
<td>$2.334 \times 10^{-3}$</td>
<td>0.90</td>
</tr>
</tbody>
</table>

5.1.2.4 **Solver setting**

The Fluent was used to solve the 3D steady model. The standard k-epsilon model was also used in this chapter. Convergence was assumed to be obtained when a minimum of 0.1% was reached for the scaled residuals of mass, momentum, turbulent kinetic energy (k) and turbulent dissipation ($\varepsilon$).

5.1.3 Model accuracy analysis

5.1.3.1 **Grid-sensitivity analysis**

A grid-sensitivity analysis was performed for three grids: a coarse grid, a medium grid and a fine grid. The number of the grid elements and the refinement ratio for these the grids trialled in this study are presented in Table 5.4.

A series of vertically distributed test points located near the occupied area of the case building model were selected to compare the relative air speed (i.e. the air speed at the test point divided by the reference air speed at the inlet of the computational domain) at the height of $h$ based on the three different grids in Fig. 5.11.

Table 5.4. Grid refinement ratio between different grid sizes.

<table>
<thead>
<tr>
<th>Coarse ($\Delta_1$)</th>
<th>Medium ($\Delta_2$)</th>
<th>Fine ($\Delta_3$)</th>
<th>$r_{21}$</th>
<th>$r_{32}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,531,123</td>
<td>6,756,523</td>
<td>16,973,775</td>
<td>1.39</td>
<td>1.36</td>
</tr>
</tbody>
</table>
Fig. 5.11 shows that the coarse mesh works well at the relative height of 0.2 to 0.7, indicating that the coarse mesh in this range of relative height for this model can be employed in future studies. However, there were some significant differences between the simulation results for the coarse grid and fine grid at the relative height of 0 to 0.2 and 0.7 to 1. The simulation results at all the relative heights were not affected a lot when changing the model grid from fine to medium, indicating that the medium grid can provide a good accuracy at a reasonable computational time cost. Therefore, the medium grid was used for the following CFD simulations.

Fig. 5.11. Grid-sensitivity analysis results.

5.1.3.2 Model calibration

The model calibration consisted of a comparison between the measured and simulated data. The calibration criteria were defined as a maximum absolute difference between measured and simulated air speeds of 0.15 m/s and a 1.2°C maximum difference between measured and simulated air temperatures at the specified test points (i.e. T1 to T5). The validation criteria were based on the measurement uncertainty (standard deviation) and sensor accuracy (±0.03 m/s for air speed and ±0.5°C for air temperature in Table 5.1).
(Hajdukiewicz et al. 2013). Table 5.5 shows the absolute differences between measured and simulated indoor air speeds and air temperatures.

Table 5.5 Quantitative comparison of measured and simulated indoor data.

<table>
<thead>
<tr>
<th>Location</th>
<th>Wind speed (m/s)</th>
<th>Wind direction (°)</th>
<th>Air temperature (°C)</th>
<th>Air speed (m/s)</th>
<th>Absolute difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>9.2</td>
<td>22.5</td>
<td>23.4</td>
<td>0.30</td>
<td>0.01</td>
</tr>
<tr>
<td>T2</td>
<td>4.7</td>
<td>45.0</td>
<td>23.4</td>
<td>0.20</td>
<td>0.12</td>
</tr>
<tr>
<td>T3</td>
<td>9.2</td>
<td>22.5</td>
<td>21.8</td>
<td>0.32</td>
<td>0.01</td>
</tr>
<tr>
<td>T4</td>
<td>10.0</td>
<td>45.0</td>
<td>24.4</td>
<td>0.33</td>
<td>0.10</td>
</tr>
<tr>
<td>T5</td>
<td>1.7</td>
<td>0.0</td>
<td>23.1</td>
<td>0.08</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Air temperature (°C)

<table>
<thead>
<tr>
<th>Location</th>
<th>Wind speed (m/s)</th>
<th>Wind direction (°)</th>
<th>Air temperature (°C)</th>
<th>Air speed (m/s)</th>
<th>Absolute difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>9.2</td>
<td>22.5</td>
<td>23.4</td>
<td>24.0</td>
<td>0.3</td>
</tr>
<tr>
<td>T2</td>
<td>4.7</td>
<td>45.0</td>
<td>23.4</td>
<td>24.1</td>
<td>0.5</td>
</tr>
<tr>
<td>T3</td>
<td>9.2</td>
<td>22.5</td>
<td>21.8</td>
<td>22.9</td>
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<tr>
<td>T4</td>
<td>10.0</td>
<td>45.0</td>
<td>24.4</td>
<td>25.6</td>
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<tr>
<td>T5</td>
<td>1.7</td>
<td>0.0</td>
<td>23.1</td>
<td>24.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>

5.1.4 Local thermal comfort index

Thermal comfort indices including thermal stratification, the extended PMV and draught rate were selected for local thermal discomfort analysis.

5.1.4.1 Thermal stratification

Excessive vertical air temperature difference, or thermal gradient, between head and ankles (0.1 m and 1.1 m for seated occupants) leads to local thermal discomfort (ASHRAE 55 2013). The percentage dissatisfied (PD) was used to express the occupant dissatisfaction of the vertical air temperature difference. The percentage dissatisfied as a function of the vertical air temperature difference between head and ankles is defined as (ISO 7730 2005):

\[
PD = \frac{1}{1+\exp(5.76-0.856\Delta t)} \times 100\%
\]  

(5.1)

where \(\Delta t\) is the vertical air temperature difference between head and feet.
5.1.4.2 **Extended PMV (PMVe)**

The extended PMV indicates occupants’ thermal (hot or cold) perceptions for the whole body of the occupant. The details of PMVe were described in Chapter 4.

5.1.4.3 **Draught rate (DR)**

Fanger *et al.* (1988) presented a draught risk model (i.e. Draught rate) predicting the percentage of people dissatisfied as a function of unwanted local cooling of the body caused by air movement. The Draught rate (DR) is defined as:

\[
DR = (34 - t_a)(\bar{V} - 0.05)^{0.62}(0.37\bar{V}Tu + 3.14)
\]  

(5.2)

where \(Tu\) is the turbulence intensity, \(t_a\) is the ambient temperature, and \(\bar{V}\) is the average velocity.

PMVe and DR were post-processed using the user defined function (UDF) in the ANSYS Fluent. The values of PMVe and DR could be obtained at any places within the whole computational domain.

In addition to local indoor thermal comfort, indoor air quality was another issue influencing indoor environmental quality. The long-term monitoring CO\(_2\) concentration data collected from the BMS system during the whole year of 2016 in the case study building suggested that the maximum CO\(_2\) concentration inside the building was less than 700 ppm which was far below the suggested value (i.e. 1000 ppm) in ASHRAE 62.1 (2007). As a consequence, the indoor air quality issue was not considered in this chapter.

5.2 **Results and discussion**

5.2.1 Air velocity distribution analysis

5.2.1.1 **Northerly wind**

Fig. 5.12 shows an elevation (the plane was placed in the middle of the east office) of the airflow distribution around and inside the SBRC office building for Case 20 (see Table 5.2). The wind from the north was 4 m/s at the domain inlet reference height (of 10 m) and the windows were 100% open (associated with a window opening angle of 36°).
In Fig. 5.12, it can be seen that the air stream coming from the north trips at the upper northern vertex of the high bay roof, forming a separated flow zone rotating in an anti-clockwise direction above the office wing of the building, and there was similarly a large vortex formed on the leeward side of the office wing.

There was also a large vortex around the south wall of the office building, leading to a wind coming into the office from the high clerestory windows in the upper south wall. The airflow in the office went along the roof and formulated an airflow cycle in the office. The airflow in the office finally came out from the windows in the north wall and casement windows in the individual offices which had no ceilings, leading to a reverse flow inside the office building that was opposite to the outdoor wind direction.
This overall pattern of the flow aligned with the results of a previous study by Heist et al. (2009) which suggested that if a cross ventilated building was located in the wind shadow of an upstream obstruction, an airflow would go through the building in a direction opposite to that of the wind due to the negative pressure between the block and the building.
A series of vertically aligned test points in the occupied area of the eastern office (Fig. 5.14) were selected to analyse the typical variation of air speed as a function of elevation, $h$, above the floor, normalised with respect to the reference outside wind velocity at the inlet of the computational domain, for external wind speeds of 4 and 7 m/s. Fig. 5.14 shows that the normalised air speed near the ceiling was influenced by outdoor wind speed when compared to that near the occupied area, indicating the airflow pattern near the ceiling varied with different outdoor wind speeds. That was probably because not all the indoor airflow could be characterised by fully developed turbulence (Omrani et al. 2001) and then the indoor flow could not meet the Reynolds similarity criterion (Kandzia and Mueller 2016). As a consequence, the air velocities within these fields did not always scale linearly with the outdoor wind speed.

5.2.1.2 **Southerly wind**

Fig. 5.15 shows an elevation view of the airflow distribution around and inside the SBRC office building for Case 62 (see Table 5.2), which had the same situation as Case 20, but with a southerly wind. The wind was 4 m/s at the weather station height from the south and all the windows were 100% open.

![Fig. 5.15 An elevation view of the airflow distribution around the SBRC building (Case 62).](image_url)
As shown in Fig. 5.15, winds from south resulted in south-to-north cross-ventilation in the case study building. The airflow entered the office through the high-level clerestory windows and the casement windows in the individual offices adjacent to the south wall. The bulk of the air flow then exited the building through windows in the north wall (Fig. 5.16). The airflow pattern in the open-plan office area had similarities with that of Case 20, but with some notable differences, including the following:

- Due to the obstacle of high bay, the office building always had a one-way air flow from south to north inside the building even when the outside wind was reversed.
- The overall indoor air speed in Case 62 with a southerly wind was higher than that in Case 20 with a northerly wind. The indoor airflow in Cased 20 was mainly caused by the static pressure difference while the indoor air movement in Case 62 was the results of the joint effect of dynamic and static pressures.
- Individual office suffered higher air speed in Case 62 in which the casement windows in the individual office worked as air inlets.

Besides, the results suggested that, although the fly screen could make the air flow more diffused based on the field test in Fig. 5.10, strong jet flows for windows still could be observed in Fig. 5.16. Plan views of the air speed distribution at the head level of a seated person (1.1 m above the floor) in the east office are also presented in Fig. 5.17 for Case 20 and 62.
The average air speed inside the east office ranged from 0 to 0.7 m/s in Case 20. Airflow speeds were higher at the walkways close to the north wall, the individual offices and the east wall. With regard to Case 62, because of the wind coming into the office through the casement windows, individual offices exhibited higher air velocities than other places. Airflow from the individual offices went into the open plan offices through both doors and through the open top of the individual offices. It should be noted that there were no ceilings on the top of the individual offices, and the air was freely exchanged with the open-plan areas, as shown in Fig. 5.15. This large air flow cross section between the individual offices and the open plan area meant that local air velocities were not as high as for the jet flow issuing through the door of the quiet room (i.e. the room at the northeast corner of the eastern office zone) since there was a ceiling on the top of the quiet room and the door was the only access for the airflow from the quiet room coming into the open plan office.

Fig. 5.17 also suggested that for both Case 20 and 62, the air speed at the six test points were all within 0.2 to 0.8 m/s, which was below the upper limit of the acceptable velocity, i.e. 1.2 m/s suggested by ASHRAE 55 (2013).
Fig. 5.17 A plan view of the air speed distribution in the east office of the SBRC building: (a) Case 20; and (b) Case 62. (Note that this represents the magnitude of the speed of the air rather than a directional component of velocity).

5.2.1.3 *Local air speed distribution*

In order to better understand the local air speed conditions at the six selected test points under different outdoor wind conditions, a series of 3-D parametric surfaces were plotted as shown in Fig. 5.18 (northerly wind directions, $T_{out}=20^\circ$C) and Fig. 5.19 (southerly wind directions, $T_{out}=20^\circ$C). These plots were generated from the results of the 84 simulation cases (see Table 5.2). The results showed that air speeds at the test points under south-to-north winds were generally higher than those for north-to-south winds. The highest air speed occurred at Test Points 3 and 4 when there were 5-6 m/s winds from southeast. Meanwhile, Test Point 1 seemed to be less influenced by the variation of outdoor wind speed and direction as the air speeds at Test Point 1 was relatively lower.
and less fluctuated than those at the other test points. The conclusion also applied to Test Point 5 only when the building was under south-to-north winds. It should be noted that a risk of high air speed, i.e. higher than 1.2 m/s based on ASHRAE 55 (2013) was observed in Test Point 6 when there was a strong southerly wind (i.e. the wind speed was higher than 1.4 m/s according to Fig. 5.19). That was because the casement windows in the individual office were the air inlets of the building under this situation.
Chapter 5 Indoor local thermal comfort analysis in an open plan office with cross-ventilation

(b) T2

(c) T3
Chapter 5 Indoor local thermal comfort analysis in an open plan office with cross-ventilation

(d) T4

(e) T5
Fig. 5.18 Local indoor air speed as a function of outdoor wind speed and direction at six locations in the SBRC building eastern office zone (wind direction relative to north, $T_{out}=20^\circ C$).
Chapter 5 Indoor local thermal comfort analysis in an open plan office with cross-ventilation

(b) T2

(c) T3
Chapter 5 Indoor local thermal comfort analysis in an open plan office with cross-ventilation

(d) T4

(e) T5
Chapter 5 Indoor local thermal comfort analysis in an open plan office with cross-ventilation

Fig. 5.19 Local indoor air speed as a function of outdoor wind speed and direction at six locations in the SBRC building eastern office zone (wind direction relative to south, $T_{out}=20°C$).

5.2.2 Local thermal comfort analysis

Using the 84 simulation cases for the SBRC building, the local thermal comfort conditions including thermal stratification, thermal perception and draught at the these selected test points in the open plan office were assessed through three indices, i.e. PD, PMVe and DR. ISO 7730 (2005) classified the desired thermal environment for a space into three categories, which are shown in Table 5.6. A previous study (Paul and Taylor 2008) showed that occupants had a border thermal comfort zone in non-air-conditioned buildings. Therefore, Category C was used as the benchmark for indoor local thermal comfort analysis in this study.
Table 5.6. Categories of the thermal environment.

<table>
<thead>
<tr>
<th>Category</th>
<th>PD (%)</th>
<th>PMVe</th>
<th>DR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&lt; 10</td>
<td>±0.2</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>B</td>
<td>&lt; 20</td>
<td>±0.5</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>C</td>
<td>&lt; 30</td>
<td>±0.7</td>
<td>&lt; 30</td>
</tr>
</tbody>
</table>

The PD at each test point was calculated based on the difference in air temperatures at the heights of 0.1 m and 1.1 m (i.e. the ankle and head levels of a seated person, respectively). The PMVe and DR values at the test points were numerical averages of the PMVe and DR values calculated at the heights of 0.1, 0.6 and 1.1 m (i.e. the ankle, waist and head levels of a seated person), respectively.

5.2.2.1 Thermal stratification

Fig. 5.20 shows the frequency distribution of the thermal stratification for all the test points under different outdoor weather conditions.

![Fig. 5.20 Frequency distribution of the thermal stratification.](image)

The results showed that the thermal stratification was less than 0.2°C for 83% of the simulations. The largest thermal stratification was 1-1.2°C for only 0.7% of the conditions. Since the suggested maximum vertical temperature difference was 4°C (i.e. PD<30% for the category C), there was no thermal stratification issue at these test points.

5.2.2.2 Thermal dissatisfaction

This research calculated the PMVe at the selected test points when the outdoor temperature was 20°C and 24°C (see Table 5.2).
Fig. 5.21 shows a plan view of the PMVe distribution at the head level of a seated people (1.1m above the floor) in the east office for Case 1 and Case 4. The northerly wind speed was 1 m/s at the domain inlet reference height and the outdoor air temperature was 20°C. Case 4 used the same wind speed, direction but the outdoor air temperature was 24°C. The windows were 100% open with a window opening angle of 36° in Case 1 and Case 4.

The PMVe inside the east office ranged from -1.4 to -0.3 in Case 7. With regard to Case 4, because of the wind coming into the office was 4°C higher than Case 1, the overall PMVe inside the east office was higher (i.e. -0.4 to 0). All of these indicated that the indoor PMVe distribution was significantly influenced by outdoor air temperature. The PMV values were lower at the walkways close to the north wall, the individual offices and the east wall for both of the two cases due to the relatively higher air speed at these places (based on the analysis in Section 5.2.1.3). However, PMVe at the occupied areas were less influenced by the wind speed.
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Fig. 5.21 A plan view of the PMVe distribution in the east office of the SBRC building: (a) Case 1; and (b) Case 4. (Note that this represents the magnitude of the speed of the air (not a directional component of velocity).

The frequency distributions of PMVe are presented in Fig. 5.22 to understand the thermal comfort performance at the selected test points based on different outdoor air temperatures.
Fig. 5.22 Frequency distributions of PMVe: (a) $T_{\text{out}} = 20^\circ \text{C}$; and (b) $T_{\text{out}} = 24^\circ \text{C}$.

Fig. 5.22a shows that 60% of the conditions did not satisfy the indoor thermal comfort requirements ($\text{PMVe} < -0.7$ for Category C) when the outdoor air temperature was $20^\circ \text{C}$. Due to the influence of low outdoor air temperature, thermal perception at all the test points was considered to be cool/cold ($\text{PMVe} < 0$) based on the statistical results in Fig. 5.22a. However, the indoor thermal comfort conditions were greatly improved when the outdoor air temperature was $24^\circ \text{C}$. The results in Fig. 5.22b revealed that the unmet conditions ($\text{PMVe} < -0.7$) only represented 13.8% of the test cases. In spite of this, the PMVe values were still negative, indicating that the thermal environment in the case study building might typically not be kept to be thermally neutral when the outdoor air temperature was below $24^\circ \text{C}$.

5.2.2.3 Draught rate

Draught rate (DR) is a function of local air temperature, turbulence intensity and air speed. Fig. 5.23 shows the frequency distribution of DR for the outdoor temperatures of $20^\circ \text{C}$ and $24^\circ \text{C}$, respectively, for all the 84 simulations.
The results showed that 54.3% of the simulated test conditions did not meet the draught rate requirement (i.e. DR < 30% for Category C) when the outdoor temperature was 20°C. However, the unmet occasions were reduced by 25.3% when the outdoor temperature was 24°C.

Fig. 5.24 shows the frequency distribution of DR when the outdoor air temperature was 20°C and the outdoor wind speed varied from 1 to 7 m/s. The results showed that more than 50% of the cases exceeded the draught rate threshold (DR > 30%) when the outdoor air speed was above 4 m/s.
Fig. 5.24 Frequency distribution of draught rate as a function of outdoor wind speed ($T_{\text{out}} = 20^\circ\text{C}$).

Since the window opening angle of the case study building would be reduced when the outdoor air speed was higher than 15 km/h (i.e. 4.2 m/s) for the building window control strategy implemented at the time of writing, it could be speculated that the window control strategy did not help to effectively reduce the local draught risk of the case study building.

5.2.3 Natural ventilation control optimisation for local thermal comfort

Section 5.2.2 analysed the local thermal comfort performance at the five test points in the open plan office under natural ventilation, and the results revealed a risk of thermal dissatisfaction and draught in the building when there were low outdoor air temperatures and relatively strong winds.

5.2.3.1 Outdoor air temperature

Thermal dissatisfaction (perception of cold) was mainly caused by the low outdoor air temperature through the analysis of Fig. 5.22. Further simulations were conducted under different outdoor temperatures to investigate the improvement of thermal satisfaction performance at the test points in the open plan office. Table 5.7 shows an example of the PMVe values at the test points when there was a 5 m/s southerly wind. The PMVe values increased with the increase in outdoor temperature and the indoor thermal comfort requirements ($-0.7 < \text{PMVe} < +0.7$ for Category C) could be satisfied when the outdoor temperature was between 25°C to 29°C.
Table 5.7 A comparison of PMVe at the test points under different outdoor temperatures (Southerly wind, $V_{out} = 5$ m/s, fully opened window).

<table>
<thead>
<tr>
<th>Test point</th>
<th>PMVe</th>
<th>20°C</th>
<th>21°C</th>
<th>22°C</th>
<th>23°C</th>
<th>24°C</th>
<th>25°C</th>
<th>26°C</th>
<th>27°C</th>
<th>28°C</th>
<th>29°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1.17</td>
<td>-0.98</td>
<td>-0.80</td>
<td>-0.61</td>
<td>-0.42</td>
<td>-0.23</td>
<td>-0.04</td>
<td>0.15</td>
<td>0.34</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-1.70</td>
<td>-1.47</td>
<td>-1.24</td>
<td>-1.00</td>
<td>-0.76</td>
<td>-0.53</td>
<td>-0.29</td>
<td>-0.05</td>
<td>0.19</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-1.18</td>
<td>-0.99</td>
<td>-0.80</td>
<td>-0.61</td>
<td>-0.41</td>
<td>-0.22</td>
<td>-0.02</td>
<td>0.18</td>
<td>0.38</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-0.91</td>
<td>-0.75</td>
<td>-0.58</td>
<td>-0.41</td>
<td>-0.25</td>
<td>-0.08</td>
<td>0.09</td>
<td>0.26</td>
<td>0.43</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-1.26</td>
<td>-1.07</td>
<td>-0.88</td>
<td>-0.69</td>
<td>-0.50</td>
<td>-0.30</td>
<td>-0.11</td>
<td>0.09</td>
<td>0.29</td>
<td>0.49</td>
<td></td>
</tr>
</tbody>
</table>

Outdoor air temperature was one of the major causes of draught indoors based on the statistical results presented in Fig. 5.23. The draught risk was presumed to be eliminated when the indoor air temperature was above 26°C (ISO 7730 2005). The indoor air temperature was normally higher than the outdoor air temperature during office hours due to the heat gains. There was no need to assess the draught rate indoors when the outdoor air temperature was beyond 26°C. As a consequence, in this study, the draught rate of the case study building was investigated when the outdoor air temperature varied from 20 to 26°C. The results are presented in Table 5.8. The indoor thermal comfort requirements (PPD < 30% for Category C) could be satisfied when the outdoor temperature was higher than 25°C. This result was consistent with the field investigation results from Raja et al. (2001), in which they found most people would open window only when the outdoor temperature was above 25°C in naturally ventilated buildings.

Table 5.8 A comparison of DR at the test points under different outdoor temperatures (Southerly wind, $V_{out} = 5$ m/s, fully opened windows).

<table>
<thead>
<tr>
<th>Test point</th>
<th>DR</th>
<th>20°C</th>
<th>21°C</th>
<th>22°C</th>
<th>23°C</th>
<th>24°C</th>
<th>25°C</th>
<th>26°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>27.3</td>
<td>25.4</td>
<td>23.4</td>
<td>21.5</td>
<td>19.5</td>
<td>17.6</td>
<td>15.6</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>46.4</td>
<td>43.5</td>
<td>40.2</td>
<td>36.8</td>
<td>33.5</td>
<td>30.0</td>
<td>27.2</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>35.7</td>
<td>33.2</td>
<td>30.6</td>
<td>28.1</td>
<td>25.5</td>
<td>23.0</td>
<td>20.4</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>24.7</td>
<td>23.0</td>
<td>21.2</td>
<td>19.4</td>
<td>17.7</td>
<td>15.9</td>
<td>14.1</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>35.1</td>
<td>32.6</td>
<td>30.1</td>
<td>27.6</td>
<td>25.1</td>
<td>22.5</td>
<td>20.0</td>
</tr>
</tbody>
</table>
5.2.3.2 Wind speed

Outdoor wind speed was another major cause of draught in indoors based on the statistical results presented in Fig. 5.24. Although current natural ventilation control strategy of the case study building tried to control indoor air speed by reducing the window opening angle, the statistical results in Fig. 5.24 indicated that the window opening control had little effect on local draught rate control. To increase our understanding of the fundamental reasons for this, a comparison of indoor air distributions is presented in Fig. 5.25.

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![Diagram](image)

**Fig. 5.25** Indoor air velocity distribution with all windows: (a) 100% opened; and (b) 80% opened (Southerly wind, $V_{out}=5 \text{ m/s, } T_{out}=20^\circ \text{C}$).
Fig. 5.25 shows the indoor air distributions with the window opening percentages of 100% and 80% (associated with the window opening angle of 36° and 29°, respectively) when there was a 5 m/s wind from south. The results showed that the airflow patterns near the roof were different under the two given conditions. However, airflow rate near the occupied area was less influenced when reducing the opening angle of the windows.

Table 5.9 shows a comparison of draught rate at the test points under the two given conditions.

<table>
<thead>
<tr>
<th>Test point</th>
<th>DR (%)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fully open (100%)</td>
<td>Partly open (80%)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>26.3</td>
<td>30.6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>64.3</td>
<td>64.6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>33.9</td>
<td>46.8</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>23.3</td>
<td>23.1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>33.2</td>
<td>37.3</td>
<td></td>
</tr>
</tbody>
</table>

The results disclosed that reducing window opening angle using current window control strategy might not alleviate the draught rate when there was a strong wind.

5.2.3.3 Recommendations for natural ventilation control optimisation

Based on the numerical analysis of the case study building, some suggestions for the natural ventilation control system of the case study building are proposed below to further improve indoor thermal comfort when using natural ventilation.

- Improve the threshold of the outdoor air temperature for natural ventilation.

In the case study building, natural ventilation was performed when the outdoor air temperature was between 16 and 28°C, aiming to maintain indoor air temperature between 20°C and 24°C. However, the acceptable temperature zone in naturally/mixed-mode ventilated buildings was higher than mechanical ventilated buildings (Paul and Taylor 2008). According to the analysis in Section 5.2.3.1, the outdoor air temperature was recommended to be between 25°C to 29°C when using natural ventilation to keep the thermal neutral of occupants. Besides, the draught risk could possibly be avoided
when the outdoor temperature was higher than 25°C based on the statistical results presented in Table 5.8.

- Consider wind direction as one of the control variables in the natural ventilation control strategy

Although the case study office building always had a one-way air flow from south to north inside the building due to the obstacle of high bay, an analysis of Case 62 suggested that individual office tended to suffer higher air speed under the southerly wind. ASHRAE 55 (2013) recommended that the maximum indoor air speed was 1.2 m/s. Based on the results presented in Fig. 5.19, the casement windows in the individual office should be closed to meet the ASHRAE 55 requirement when there was a southerly wind over 1.4 m/s.

- Reduce the range of acceptable outdoor air speed for natural ventilation

Statistical results obtained from Fig. 5.24 showed a high risk of draught when the outdoor air speed was above 4 m/s. However, airflow rate near the occupied area was less influenced by adjusting the window opening positions based on current natural ventilation control strategy (see Fig. 5.24 and Table 5.9). It could be speculated that the window control strategy did not help to effectively reduce the local draught risk under these circumstances. Windows, therefore, were suggested to be closed when the outdoor air speed was beyond 4 m/s.

5.3 Summary

This chapter described the investigation of the indoor local thermal comfort of the open-plan area of a cross ventilated office space through a series of simulations using ANSYS Fluent. The CFD simulations were conducted based on the cross-ventilation design and operation of the case study building. The statistical data obtained from the Building Management System were used as the boundary conditions for the CFD simulation. The simulation analysed three key indices, i.e. thermal stratification, PMVe and draught rate, to evaluate the operational performance of the natural ventilation system. The main conclusions of this study are summarised as follows:

- A south-to-north cross-ventilation in the case study building could be observed when the wind was from either north or south due to the obstacle of high bay.
• The individual offices were likely to suffer a risk of high air speed when there was a strong southerly wind.
• The low outdoor air temperature had a negative influence on the PMVe.
• Both of the low outdoor air temperature and high outdoor wind speed led to high draught rate indoors. The minimum outdoor air temperature suggested should be more than 25°C for the sake of using natural ventilation.
• Windows were suggested to be closed during a strong wind outdoors (higher than 4 m/s) instead of reducing the window opening percentage to avoid draught risk.
Natural ventilation control is now an established part of building management systems (BMSs) in modern buildings. Natural ventilation control aims to control the window openings to improve and enhance thermal comfort (Rijal et al. 2008). A number of studies (Mochida et al. 2005, Mahdavi and Pröglhof 2008, Yin et al. 2010, Wang and Greenberg 2015) have reported on the development of natural ventilation strategies for indoor thermal comfort control, but they generally used a rule-based approach which might not always ensure acceptable indoor thermal comfort due to the dynamic changes of outdoor conditions, which means they may only achieve sub-optimal conditions.

This chapter presents an optimal window control strategy to facilitate natural ventilation by combining prediction, heuristic decision making and feedback control\(^5\) to improve indoor thermal comfort and reduce energy consumption. This control strategy was validated by using a multi-zone building model developed on the basis of the TRNSYS simulation platform.

This chapter is organised as follows. Section 6.1 presents the optimal window control strategy. Section 6.2 describes a residential building model used to test the performance of the optimal window control strategy. Section 6.3 presents the indoor thermal comfort performance of the validated case study building model when using the optimal window control strategy and analyses the improvement via a comparison between the optimal window control strategy and a rule-based window control strategy. The conclusions are summarised in Section 6.4.

\(^5\) Feedback control is also defined as iterative learning control (ILC) in some publications.
6.1 Development of the optimal window control strategy

6.1.1 The window control strategy

The window control strategy developed for natural ventilation is shown in Fig. 6.1. This strategy consists of the prediction of outdoor air temperature, the determination of the ventilation mode, and the optimisation of window opening percentage if the natural ventilation mode is selected.

As the outdoor air temperature is one of the most influencing parameters for determining the suitability of using natural ventilation (Raja et al. 2011), it is therefore predicted first using the rolling forecast method (Petropoulos et al. 2017) to avoid the hysteresis of response to changes in the outdoor air temperature. Based on the predicted outdoor air temperature, mechanical ventilation or natural ventilation will be determined by the decision tree generated. If the mechanical ventilation is selected, the indoor air temperature will be maintained at a desired set point (i.e. 26°C in summer in this study).
by air conditioning, but if natural ventilation is selected, a secant method (Garnier et al. 2014) will be used to optimise the window opening percentage to maintain the required indoor thermal comfort. It is worthwhile to note that the effects of weather and security issues were not considered in the development of this control strategy.

Details of outdoor air temperature prediction, ventilation mode selection, and window opening percentage optimisation are presented in Sections 6.1.2, 6.1.3 and 6.1.4, respectively.

6.1.2 Outdoor air temperature prediction

The rolling forecast method was used to predict the outdoor air temperature for the next 30 minutes through a continuous curve-fitting process based on the measurements of outdoor air temperature over the previous 24 hours.

The rolling forecast (or rolling training) method is an add/drop process for statistical prediction over the time period of concern (Petropoulos et al. 2017). To improve the predictive accuracy, the predicted outdoor air temperature for the time step \( k+1 \) was further corrected based on the difference between the real measurement and the predicted temperature for the time step \( k \), as shown in Eq. (6.1).

\[
T_{\text{out,corr}, k+1} = T_{\text{out,pre}, k+1} + (T_{\text{out,real}, k} - T_{\text{out,corr}, k})
\]  

(6.1)

where \( T_{\text{out,corr}, k+1} \) and \( T_{\text{out,corr}, k} \) are the corrected outdoor air temperature at the time steps of \( k+1 \) and \( k \) respectively, °C, \( T_{\text{out,pre}, k+1} \) is the predicted outdoor air temperature at the time step \( k+1 \) without correction, °C, and \( T_{\text{out,real}, k} \) is the measured outdoor air temperature at the time step \( k \), °C.

An example of a four-day outdoor air temperature prediction is shown in Fig. 6.2 where the predicted outdoor air temperature matched the real time data quite well, but the predictive accuracy was further improved through corrections. Maximum deviation between the predicted outdoor air temperature with correction and the real measurement was less than 0.5°C.
Chapter 6 Development and evaluation of an optimal natural ventilation control strategy

Fig. 6.2 Prediction of outdoor air temperature.

6.1.3 Decision tree for ventilation mode selection

A decision tree was used to determine whether the natural ventilation mode can be used under certain conditions. It is an offline pre-generated controller. A decision tree uses a reversed tree-like structure where each internal node represents a test condition on an attribute, each branch is an outcome of the test, and each leaf node presents a class prediction (Han et al. 2011). The decision tree generation process used in this study is shown in Fig. 6.3.
The data used to induct and validate the decision tree were generated based on hourly simulations using a multi-zone building model for the summer weather conditions when the windows operated at different opening percentages (i.e. 25, 50, 75 and 100%). The simulated indoor operative temperature under different window opening percentages and given weather conditions, including the ambient air temperature, relative humidity, solar radiation, wind speed and wind direction, were then prepared as data sets to induct and validate the decision tree.

The data sets were analysed using the adaptive thermal comfort model developed by Deuble and de Dear (2012) to determine whether natural ventilation can be used under given weather conditions and a given window opening percentage. If the indoor operative temperature was within 80% of the acceptable indoor operative temperature range (ASHRAE 55 2013), natural ventilation could be used and the specific data set was labelled as “ON”.

Half the labelled data was randomly selected as the training data for the decision tree induction using the C4.5 algorithm (Pang-Ning et al. 2006). C4.5 inducts the decision tree based on the concept of Shannon entropy to measure the unpredictability or impurity of the information content (Yu et al. 2010). The impurity of the attribute partition decreased with a decreasing Shannon entropy. If a set of training data was allocated to a node S and the probability distribution of the target attributes was \( D = (D_1, D_2 \cdots D_n) \), the Shannon entropy for the training data carried by this distribution is defined as follows (Pang-Ning et al. 2006).

\[
\text{Entropy}(D,S) = - \sum_{i=1}^{n} (D_i \times \log_2(D_i))
\] (6.2)

To induct the decision tree, the induction rules include the Gini index, pre-pruning criteria, and the minimal expected predictive accuracy were defined. The Gini index was used to measure the impurity of a node in order to balance the decision tree scale and splitting accuracy, which is the ratio between the correctly labelled training datasets and the complete training datasets (Rokach and Maimon 2014). The pre-pruning criteria included the minimal gain, the minimal leaf size and minimal size which were used to avoid overfitting the decision tree. The expected predictive accuracy was the ratio expected between the correctly labelled testing data sets and the complete testing data.
sets; the predictive accuracy was related to the quality of the data. A reasonable predictive accuracy (i.e. 93% in this research) should be selected through trial and error tests.

Based on the defined Gini index, pre-pruning criteria, and the expected predictive accuracy, an initial maximum tree depth can be assigned to induct and validate the decision tree. It could begin with a relatively small value in order to control the size of the decision tree, but if the predictive accuracy of the decision tree is larger than the minimum expected value, the decision tree learning process is terminated and the decision tree generated will be used to control ventilation. Failing that, a new tree will be generated by increasing the maximum tree depth in order to improve the predictive accuracy.

6.1.4 Window opening percentage optimisation

Since the decision tree method can only generate discrete values, controlling the indoor operative temperature using the decision tree may not be optimal, so an optimisation strategy was developed to optimise the window opening percentage under a given condition. In this optimisation strategy, the indoor neutral operative temperature, as expressed in Eq. (6.3), was used as the targeted temperature to be controlled (Brager and de Dear 2001).

\[ T_{op} = 0.31 \times \bar{t}_{pma(out)} + 17.8 \]  \hspace{1cm} (6.3)

where \( \bar{t}_{pma(out)} \) is the prevailing mean outdoor air temperature, °C, which is calculated using Eq. (6.4) (ASHRAE 55 2013).

\[ \bar{t}_{pma(out)} = (1 - \alpha) \times t_e(n-1) + \alpha \times t_{rm(n-1)} \]  \hspace{1cm} (6.4)

where \( t_e(n-1) \) is the mean daily outdoor temperature for the day before the day in question, °C, and \( t_{rm(n-1)} \) is the running mean temperature for the day before the day in question, °C, \( \alpha \) is a weight factor to control the speed at which the running mean temperature responds to changes in the outdoor temperature. A lower value of \( \alpha \) could be more appropriate for mid-latitude climates and hence the recommended value of 0.7 (ASHRAE 55 2013) was used in this study.
The secant method was used to optimise the window opening percentage under natural ventilation to minimise the difference between the real-time indoor operative temperature (i.e. mean indoor operative temperature of the whole building) and the indoor neutral operative temperature. The secant method is a numerical root finding method similar to the Newton–Raphson method, but it uses a specific equation to approximate the derivative based on the previous two calculated values, as shown in Eq. (6.5) (Garnier et al. 2014).

\[ x_{n+1} = x_n - f(x_n) \frac{x_n - x_{n-1}}{f(x_n) - f(x_{n-1})} \]  

(6.5)

where \( x_{n-1} \) and \( x_n \) are the window opening percentages at the time steps of \( n-1 \) and \( n \), respectively, \( f(x_{n-1}) \) and \( f(x_n) \) are the differences in air temperature between the derived real time indoor operative temperature and the indoor neutral operative temperature at the time steps of \( n-1 \) and \( n \), respectively.

The iteration will be terminated when the error at the time step \( n+1 \) can satisfy the following equation (Díez 2003).

\[ |\varepsilon_{n+1}| \approx C|\varepsilon_n|^\phi \]  

(6.6)

where \( C \) is a constant dependent on the derivative \( (C = |f''(\alpha)/2f'(\alpha)|^{\phi-1}, \alpha \to f^{-1}(0)) \) and \( \phi \) is the golden ratio.

The results of using the secant method for continuous window opening percentage optimisation are compared with only using the decision tree for window opening control are presented in Section 6.3.

The time step of the simulation was set as 30 minutes to ensure that the window opening mode was not toggled too frequently.
6.2 Development of the simulation platform

6.2.1 Description of the case study building

As natural ventilation is becoming an increasingly attractive method for reducing energy use and improve indoor thermal comfort of residential buildings, a residential house (i.e. the Solar Decathlon house) was used as a case study building to develop the model for evaluating the proposed control strategy (see Fig. 6.4).

Fig. 6.4 Case study building.

The house has a main bedroom, a study/guest bedroom, an open plan living room connected with the dining room and kitchen, and a laundry space and a shower space, and the external envelope and internal enclosure are insulated with glasswool. There are two types of windows, three top-hung clerestories on the south wall of the living room and six side-hung windows in the other walls. All the windows have low-e double argon filled glazing.

CFD model and multi-zone model are two popular tools for indoor airflow pattern analysis. Mora et al. (2002) compared multi-zone and CFD model for indoor airflows and found that zonal model was able to provide a satisfactory estimate of the thermal comfort in small spaces when compared to the CFD model if the details of airflow was not the research interest. Besides, it is time consuming to simulate the indoor thermal comfort
performance of the case study building for a continual year using CFD models. Therefore, a multi-zone model was employed as the research platform to execute the window control strategy.

To translate the physical layout of the house into a building model with a node based network airflow, the following assumptions were made:

- The cracks for closed windows and doors are set at 1mm based on the estimated dimensions of cracks in the house;
- Zones are defined by each room of the house and each zone is assumed to have a uniform distribution of air temperature and pressure;
- The door between the laundry and the living room is assumed to be closed. The laundry and shower spaces are not considered in the airflow network for multi-zone ventilation calculation but they were modelled for thermal simulations; and
- The internal doors that connect the bedroom and the guest room to the living room are assumed to be normally open.

The airflow network of the case study building is shown in Fig. 6.5, with the openable airflow components highlighted in red. Since there are three clerestory windows in the living room, the influence of air buoyancy on their airflow was considered by introducing a virtual horizontal open airflow that is highlighted in green.
6.2.2 The case study building modelling

TRNSYS was combined with COMIS (components Type 56 and Type 157) and used as the simulation platform to account for the indoor airflow and thermal flows in the building model, and to test and validate the natural ventilation control strategy proposed in this study. The control strategy is programmed in MATLAB and integrated within the simulation platform through TRNSYS component Type 22. A schematic of the airflow-thermal model in TRNSYS is shown in Fig. 6.6.
Wind pressure was needed to calculate the wind-induced ventilation in component Type 56. Since the CFD simulation is one of the prime sources (Montazeri and Blocken 2013), it was used to acquire the wind pressure coefficient data around the case study building. Details of the pressure coefficient data are provided in the Appendix E. The Reference meteorological year (RMY) data for the Sydney area was used to evaluate thermal comfort performance of the case building model. The internal heat gains from occupant activities and equipment were scheduled according to literature (Rahman et al. 2010, Hu and Karava 2014) (see Appendix F).

6.3 Results and discussions

6.3.1 Validation of the case study building model

The reliability of the building model was validated using the hourly indoor air temperature data measured over eight consecutive days (27th Jul 2015 - 3rd Aug 2015) during the daytime in winter conditions. When these measurements were taken the windows were fully closed and fully opened for three days and then half opened for two days. Fig. 6.7 shows the simulated and measured indoor air temperatures in the main bedroom.
The deviations of the simulated data points from the bisector (e.g. the test points) were mostly falling within ± 2°C. Only slightly divergences were observed for the fully closed condition. Overall, the proposed numerical approach was capable to predict indoor thermal environment and airflow.

6.3.2 Generation of the decision tree

The decision tree for the selected building was introduced using the open source data mining software RapidMiner (Mierswa 2013). A total of 8,640 hourly simulated data sets (2160 for each of the four window positions, i.e. 25%, 50%, 75% and 100%) were obtained over the whole summer to generate and validate the decision tree. If the predictive accuracy of the decision tree reached the expected value or cannot be improved
further as the depth of the tree increases, the learning process for this decision tree was
terminated and the decision tree generated by this process will be used to control the
ventilation. Fig. 6.8 shows the correlation between the depth of the tree and its predictive
accuracy. Note that the predictive accuracy did not improve very much when the tree was
deeper than 7. Therefore, a maximum tree depth of 7 was used in this study.

![Fig. 6.8 Correlation between the depth and predictive accuracy of the tree.]

The final decision tree model is shown in Fig. 6.9; it had 55 nodes, of which 27 yellow
rectangular nodes represented the categorical parameters, and 12 blue and 16 red ovals at
the bottom were the results of classification. The outdoor air temperature nodes accounted
for 1/3 of the total internal nodes, indicating that the outdoor air temperature was one of
the most critical parameters for natural ventilation. With this decision tree, each data
record could be assigned to a leaf node associated with a specific window state (ON/OFF)
to achieve the window opening prediction. Note there was no internal node (i.e. a node
between the input and output nodes) of the window opening percentage, which implied
that the window opening percentage had less influence than climate on the window
opening mode selected.
Fig. 6.9 The decision tree for ventilation mode selection.
As mentioned above, 50% of the data was used to validate the decision tree. Fig 6.10 shows the results of this validation where the blue bars presented the correctly predicted results and the red bars denoted the incorrectly predicted results; the overall predictive accuracy of the decision tree was 92.7%.

![Validation of the decision tree](image)

**Fig. 6.10 Validation of the decision tree.**

6.3.3 Performance analysis of the window opening control strategy

6.3.3.1 *Outdoor air temperature prediction*

Outdoor air temperature prediction was part of the window opening control strategy and as such will influence the window opening decision making. To identify the impact that the predicted outdoor air temperature had on natural ventilation time, the window control strategies with and without outdoor air temperature predictions were tested through the summer period (1st Dec – 28th Feb) based on the case study building model. The periods during which the indoor operative temperature was outside the 80% acceptable thermal comfort zone (i.e. unmet hours) are presented in Table 6.1.

| Unmet hours of thermal comfort during natural ventilation with and without using the outdoor air temperature prediction. |
|---|---|---|
| Unmet hours (hr) | Guest room | Bedroom | Living room |
| Without prediction | 224.5 | 79.5 | 124 |
| With prediction | 23.5 | 9 | 6.5 |
Implementation of the outdoor air temperature prediction can reduce the response hysteresis of the window opening control, so as shown in Table 6.1, a significant decrease in the unmet hours for each room was achieved by using the outdoor air temperature prediction.

6.3.3.2 Window opening percentage optimisation

The window opening percentage control aimed to improve thermal comfort by approaching the indoor neutral operative temperature when using natural ventilation. To quantify this improvement in indoor thermal comfort, the mean absolute deviation (MAD) defined as the mean absolute bias of the actual indoor operative temperatures from the optimisation objectives (i.e. indoor neutral operative temperatures) was introduced. Table 6.2 summarises the MAD values with and without the window opening percentage optimisation when using natural ventilation through the whole summer.

Table 6.2 Deviations of the mean absolute indoor operative temperature from indoor neutral operative temperatures.

<table>
<thead>
<tr>
<th></th>
<th>MAD (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Guest room</td>
</tr>
<tr>
<td>Without optimisation</td>
<td>2.1</td>
</tr>
<tr>
<td>With optimisation</td>
<td>1.2</td>
</tr>
</tbody>
</table>

As Table 6.2 shows, when using the window opening percentage optimisation, there was a decrease in MAD values (i.e. 0.9°C in the guest room, 0.5°C in the bedroom, and 0.7°C in the living room). Fig. 6.11 shows an example of the indoor operative temperature profiles with and without the window opening percentage optimisation in the bedroom over one typical summer day with a 30-minute simulation interval. The indoor neutral operative temperature (i.e. optimisation objective) and the 80% thermal comfort bands based on ASHRAE 55 (2013) are also shown in Fig. 6.11.
In the window optimisation control scenario, the window opening percentage was
constantly modulated during the day to make the indoor operative temperature approach
the indoor neutral operative temperature. The windows were closed after 23:00PM based
on the decision tree prediction to prevent overcooling.

A statistical analysis of a typical day showed that the MAD value was 0.5°C with window
optimisation and 1.1°C without window optimisation. This indicated that the indoor
operative temperature fluctuated less with window opening percentage control than
without optimisation.
Note that although the outdoor air temperature was the essential factor influencing indoor thermal comfort, the window opening percentage modulation did not strictly follow the variation of outdoor air temperature because the optimal window opening percentage was determined based on the indoor and outdoor conditions. For example, in Fig. 6.11, the opening percentage modulated from 25% to 50% at about 10:00AM (due to the changes of wind direction and speed through weather data analysis) while the outdoor air temperature was 22°C.

6.3.4 Comparison of different window opening strategies

To evaluate the improvement in thermal comfort by using the proposed window control strategy, the proposed strategy was compared with a rule based control strategy using linear window opening control. The rule based control strategy was derived from the changeover mixed-mode ventilation scenario described by Wang and Greenberg (2015). If the indoor air temperature was higher than the outdoor air temperature and the outdoor air temperature was above the setpoint defined as 3°C below the lower limit of the 80% thermal comfort band (i.e. $T_{\text{lower}} - T_{\text{out}} < 3\, ^{\circ}\text{C}$) (Wang and Greenberg 2015), the window opening will be linearly regulated based on the difference in air temperature between indoor and outdoor air (see Fig. 6.12).

Fig. 6.12 Modulation of window opening according to differences in indoor and outdoor temperature ($T_{\text{in}}$: indoor operative temperature; OAT: outdoor air temperature) (Wang and Greenberg 2015).

- Natural ventilation cooling potential
For simplicity, only the bedroom was analysed for thermal comfort. Fig. 6.13 shows the correlations between the indoor operative temperature and the outdoor temperature during the natural ventilation period over the whole summer when two different natural ventilation control strategies were used.

Fig. 6.13 Correlations between indoor operative temperature and outdoor air temperature.

Fig. 6.13 showed a flatter trend from the results of the proposed control, i.e. the predictive and feedback control, indicating that the indoor operative temperature tended to be temperate under relatively extreme outdoor temperatures using natural ventilation. For example, when the outdoor air temperature was higher than 28°C, the proposed control strategy could maintain a relatively lower indoor operative temperature than rule based control. In Fig. 6.13, some data points were more dispersed, indicating that natural ventilation could not always keep the indoor operative temperature in the 80% acceptable thermal comfort bands at all times. Table 6.3 presents the statistical results of the unmet hours during which the indoor operative temperature was outside the 80% acceptable thermal comfort zone under different scenarios.
Table 6.3 Performance of three different natural ventilation scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Unmet hours (hr)</th>
<th>MAD (°C)</th>
<th>Total natural ventilation time (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free running</td>
<td>598.5</td>
<td>2.3</td>
<td>2160</td>
</tr>
<tr>
<td>Rule based control</td>
<td>158.5</td>
<td>1.7</td>
<td>1352</td>
</tr>
<tr>
<td>Predictive and feedback control</td>
<td>9</td>
<td>1.0</td>
<td>1350.5</td>
</tr>
</tbody>
</table>

In the free running case, the thermal comfort requirements were not met for approximately 28% of the time. The rule based control strategy reduced the unmet hours by 74% compared to the free running case (Table 6.3). The scenario with the proposed control strategy was more effective than the rule based control and almost eliminated the discomfort hours, but as a penalty for improving indoor thermal comfort by window control, the total natural ventilation time for both scenarios with window control decreased by approximately 37.5%.

The MAD value in the predictive and feedback control scenario was 0.7°C less than the rule based control scenario because the proposed control strategy considered most of the physical factors that influence indoor thermal comfort by searching for the optimal window opening percentage.

- Indoor operative temperature analysis

Fig. 6.14 shows the half hourly profile of indoor operative temperature and window operation over a typical summer day using different control strategies. The indoor neutral operative temperature (i.e. optimisation objective) and the 80% thermal comfort bands based on ASHRAE 55 (2013) are also given in Fig. 6.14.
Since the outdoor air temperature was the main factor influencing the indoor operative temperature, the line of the indoor operative temperature followed the outdoor air temperature trend in the free running scenario; indoor thermal comfort could be met during the day time in all three cases.
Chapter 6 Development and evaluation of an optimal natural ventilation control strategy

The indoor operative temperature for the two scenarios with control strategies remained within the 80% thermal comfort bands. For the rule based control, window opening would be regulated linearly based on the difference in air temperature between indoor and outdoor when (Wang and Greenberg 2015):

- The indoor air temperature was higher than the outdoor air temperature; and
- The outdoor air temperature was above the setpoint of 3°C below the lower limit of the 80% thermal comfort band (i.e. \(T_{\text{lower}} - 3\degree \text{C}\)).

Therefore, in the rule based scenario, the windows were closed from 07:00AM to 18:00PM (the indoor air temperature was lower than the outdoor air temperature) and from 01:00AM to 07:00AM (the outdoor air temperature was below \(T_{\text{lower}} - 3\degree \text{C}\)). In this proposed strategy, the window opening was modulated to make the indoor operative temperature approach the indoor neutral operative temperature regardless of the difference in the indoor and outdoor temperature, so the difference in the indoor operative temperature in the predictive and feedback control scenario fluctuated less than in the rule based control scenario.

6.4 Summary

A predictive and feedback control method was proposed to optimise the use of natural ventilation. This method was applied to a residential building model to control the window opening percentage and the indoor thermal comfort conditions.

The results showed that the outdoor temperature prediction could reduce the negative impact of control hysteresis, and the hours outside the thermal comfort bands decreased in comparison to that without using the outdoor temperature prediction.

The window opening percentage optimisation using feedback control minimised the difference in temperature between the real indoor operative temperature and the indoor neutral operative temperature during natural ventilation. Unlike the scenario without a window opening percentage optimisation, the mean absolute deviation of the real indoor operative temperature from the indoor neutral operative temperature decreased by 0.5-0.9°C, making the indoor thermal conditions more stable and comfortable.

Predictive and feedback control reduced the likelihood of overcooling and maintained a relatively stable indoor operative temperature and performed better than the rule based control.
CHAPTER 7 CONCLUSIONS

This thesis presented an investigation into the thermal comfort of high performance buildings, and natural ventilation design and operation optimisation to maximise indoor thermal comfort. Field measurements and post-occupancy evaluation (POE) surveys were carried out to understand the building performance and thermal perception of occupants in a high performance building with a mixed-mode ventilation system. The fundamental mechanisms that govern how window configuration and outdoor weather conditions influence indoor thermal comfort were then studied for a simple cross-ventilated space using Computational Fluid Dynamics (CFD) simulations. Next, the local indoor thermal comfort conditions in a high performance educational/office building (i.e. the Sustainable Buildings Research Centre, SBRC, at the University of Wollongong) using a rule-based natural ventilation strategy was analysed using CFD simulations. Lastly, an optimal window control strategy was developed to facilitate natural ventilation; The innovative work and main findings of the whole thesis were summarised.

7.1 Main contributions

- Both POE surveys and field measurements in a mixed-mode ventilated building were carried out to investigate the applicability of two representative thermal comfort models. The study can serve as a useful reference for the design and operation of mixed-mode ventilated buildings.

- The impact of each window parameter on indoor airflow conditions in naturally ventilated buildings was analysed to improve the indoor conditions. The Taguchi method was used to design the simulation scenarios for different window designs. Analysis of variance (ANOVA) was used for the percentage contribution analysis of the window parameters. Signal-to-Noise (S/N) ratio method was used to identify the near-optimal window attribute combination.

- The local thermal comfort performance in the open space of a mixed-mode ventilated building was investigated during the natural ventilation period by evaluating the local thermal stratification, thermal perception and draught. The performance of the local thermal comfort could be used to guide the optimisation of the window opening control strategy. This study developed an optimal window control strategy by combining the
prediction and heuristic decision making and feedback control to improve indoor thermal comfort.

7.2 Summary of the main findings

The findings from this thesis are summarised as follows.

7.2.1 Thermal comfort investigation of high performance buildings with advanced mixed-mode ventilation systems

Field measurements and post-occupancy evaluation (POE) surveys were carried out in a case study building to compare the thermal perception of occupants and the actual building thermal performance in the Sustainable Buildings Research Centre (SBRC). The key conclusions are presented below.

- The maximum difference in temperature between the head and ankle in the SBRC building was 2.0°C, which was less than the tolerance of 3°C specified in ASHRAE Standard 55 (2013). Thus, thermal stratification in the SBRC building was found not to significantly affect the thermal comfort of the occupants.

- Cold interior surfaces of the SBRC building in winter were hypothesised to lead to thermal discomfort due to the cold radiation effect on the occupants. Field measurements, using a thermographic camera, showed that the interior surfaces of the building were less than 19°C on a typical winter day, and given that the indoor air temperature in the occupied area was maintained at 20±1°C in winter through mechanical heating, the indoor operative temperature could be less than the minimum value (20°C) recommended by ASHRAE 55.

- The thermal comfort evaluation results from Fanger’s PMV model (i.e. a static thermal comfort model) were found to be more consistent with the results from the thermal sensation vote (TSV) in winter. The ASHRAE 55 adaptive model (i.e. a dynamic thermal comfort model) provided an acceptably accurate thermal comfort condition in summer (i.e. thermal comfort conditions satisfied for 90% of the time in summer), matching the TSV responses (i.e. 94% occupants felt thermally comfortable in summer) during the summer period.
7.2.2 Numerical analysis of the influence of top-hung window configuration on local indoor thermal environment

A series of CFD simulation cases were analysed to identify which window attributes most greatly influenced indoor air velocity fields and thermal comfort in a simplified rectangular space. The main conclusions of this study were as follows.

- The outdoor air temperature, window height, and window opening angle had the most influence on the PMVe values in the region of interest in the SBRC building.

- The optimal combination of parameters selected to improve the indoor thermal comfort of the focused area of interest was: an outdoor air temperature of 20°C, a wind speed of 2.4 m/s, a wind direction of 60°, a window opening angle of 10°, the window width and height of 0.4 m and 0.4 m, respectively, window height above the ground of 1.2 m, and the fly screen type of $R_{w25}$. The results can be used as a reference point for further optimisation.

- The wind speed and window opening angle were the most important factors influencing the airflow rate. A near-linear relationship between the two factors (i.e. wind speed and window opening angle) and the airflow rate were identified.

7.2.3 Indoor local thermal comfort analysis in an open plan office with cross ventilation

The local thermal comfort conditions in cross ventilated buildings were investigated using the SBRC building and CFD modelling. The main findings were as follows.

- If a cross-ventilated building is located in the lee of an upstream building, the indoor circulating airflow may be in the opposite rotational sense to that without the upstream building being in place. For the example of the present SBRC building, when the wind approaches from the north the ‘high bay’ wing of the building is upstream of the office. In this situation, a large vortex was predicted to form between the high bay and the office wing, and a very different pressure distribution on the exterior office occurred compared to the case without the upstream high bay blockage.

- One of the most important causes of unsatisfactory thermal conditions that were simulated as likely to arise at times in the naturally ventilated SBRC building was a result of windows being open when the outside temperatures were too low. The PMVe values at all the test points in the occupied space analyses were found to be negative under all the simulated conditions when the outdoor air temperature was between 20°C
and 24°C for the assumed thermal boundary conditions, which would lead to occupants’ thermal perceptions in the building being cool or cold in the work area. Further simulations under wind conditions with a wider range of outdoor air temperatures suggested that PMVe could be maintained between -0.7 and +0.7 (associated with category C in ISO 7730 standard) when the outdoor air temperature is between 25 and 29°C.

- The risk of draughts in the open-plan office area of the SBRC building was found to be relatively high when using natural ventilation during the periods with relatively low outside temperatures. The unsatisfied draught rate (DR >30% for Category C according to the ISO 7730 standard) was found to be reduced by 47% when the outdoor air temperature increased from 20 to 24°C. Further simulations under particular wind conditions (i.e. for a 5m/s southerly wind and fully opened windows) with a wider range of outdoor air temperatures suggested that the draught risk could be controlled when the outdoor air temperature is higher than 25°C.

- More than 50% of the simulated cases suffered from excessive draughts (DR>30%) when the wind speed is more than 4.0 m/s.

7.2.4 Development and simulation of an optimal natural ventilation control strategy

A predictive and feedback control method was proposed to optimise the use of natural ventilation. This strategy was tested on a model of a residential building (i.e. the Solar Decathlon house) and the major findings are presented below.

- Predicting the outdoor temperature was a good way of reducing the negative impact of transient weather change. The thermal discomfort time when the indoor operative temperature is outside the thermal comfort band was reduced in comparison to the case without using outdoor temperature prediction.

- A decision tree control strategy was generated to determine the best ventilation mode for a given set of circumstances. One-third of the total internal nodes (used for dataset sorting) in the decision tree model were related to the outdoor air temperature, indicating that the outdoor air temperature is the most critical parameter influencing indoor thermal comfort during natural ventilation.

- The implementation of window opening percentage optimisation using feedback control minimised the temperature difference between the practical indoor operative
temperature and the indoor neutral operative temperature during natural ventilation. The mean absolute deviation (MAD) of the indoor operative temperature from the indoor neutral operative temperature in the scenario with window opening percentage optimisation was reduced by between 0.5°C and 0.9°C as compared to the scenario without using window opening percentage optimisation.
REFERENCES


References


References


58. de Dear RJ, Brager GS. Developing an adaptive model of thermal comfort and preference. 1998.


References


References


References


140. Shaaban AA, Morcos SM, Khalil EE, Fouad MA. Effect of Ventilation Rate and Gaseous Contaminant Density on Indoor Air Quality in a Chemical. 2014.


References


References


References


References


APPENDIX A A PLAN VIEW OF THE SUSTAINABLE BUILDINGS RESEARCH CENTRE
APPENDIX B A PLAN VIEW OF THE SOLAR DECATHLON HOUSE
APPENDIX C USER DEFINED FUNCTIONS

(1) PMVe, PPD and DR

#include "udf.h"
DEFINE_ON_DEMAND(comfort)
{
  Domain *d;
  Thread *t;
  cell_t c;
  real CLO; // Clothing (clo)
  real MET; // Metabolic rate (met)
  real WME; // External work, normally around 0 (met)
  real TA; // Air temperature (°C)
  real TR; // Mean radiant temperature (°C)
  real VEL; // Relative air velocity (m/s)
  real RH; // Relative humidity (%) 
  real PA; // Water vapour pressure (Pa)
  real TU; // Turbulence intensity (%) 
  real FNPS; // Saturated vapour pressure, kPa
  real ICL; // Clothing insulation, m2K/W
  real TCL; // Clothing surface temperature, °C
  real M; // Metabolic rate, W/m2
  real W; // External work, W/m2
  real MW; // Internal heat production in the human body, W/m2
  real FCL; // Clothing area factor
  real HCF; // Forced convective heat transfer coefficient, W/m2K
real HCN; // Natural convective heat transfer coefficient, W/m²K
real HC; // Convective heat transfer coefficient, W/m²K
real TAA; // Air temperature, K
real TRA; // Mean radiant temperature, K
real HL1; // Heat loss difference through skin
real HL2; // Heat loss by sweating (comfort)
real HL3; // Latent respiration heat loss
real HL4; // Dry respiration heat loss
real HL5; // Heat loss by radiation
real HL6; // Heat loss by convection
real TS; // Thermal sensation transfer coefficient
real EPS; // Small value
real i; // Iterator
real TCLA; // First guess for surface temperature of clothing
real P1,P2,P3,P4,P5; // Calculation terms
real XN,XF; // Iterative solutions
real PMV,ePMV, PPD, DR; // Predicted mean vote, extended predicted mean vote, predicted percentage dissatisfied and draught

d=Get_Domain(1);
EPS=0.00015;
CLO=0.5;
MET=1.2;
WME=0.0;
RH=70.0;
ICL=0.155*CLO;
M=MET*58.15;
W = WME * 58.15;
MW = M - W;
if (ICL <= 0.078) FCL = 1.0 + 1.29 * ICL; else FCL = 1.05 + 0.645 * ICL;
thread_loop_c(t,d)
{
begin_c_loop(c,t)
{
TA = C_T(c,t) - 273;
TR = 24;
VEL = sqrt(pow(C_U(c,t), 2) + pow(C_V(c,t), 2) + pow(C_W(c,t), 2));
FNPS = exp(16.6536 - 4030.183 / (TA + 235));
PA = RH * 10.0 * FNPS;
HCF = 12.1 * sqrt(VEL);
TAA = TA + 273.0;
TRA = TR + 273.0;
TCLA = TAA + (35.5 - TA) / (3.5 * (6.45 * ICL + 0.1));
P1 = ICL * FCL;
P2 = P1 * 3.96;
P3 = P1 * 100;
P4 = P1 * TAA;
P5 = 308.7 - 0.028 * MW + P2 * pow(TRA/100, 4);
XN = TCLA / 100.0;
XF = XN;
for (i = 0; i < 150; i++)
{
XF = (XF + XN) / 2.0;
HCN=2.38*\text{pow}(\text{fabs}(100.0*XF-TAA),0.25);
if (HCF>HCN) HC=HCF; else HC=HCN;
XN=(P5+P4*HC-P2*\text{pow}(XF,4))/(100+P3*HC);
if (\text{fabs}(XN-XF)<E\text{PS}) \text{ break; }
}
TCL=100.0*XN-273.0;
HL1=3.05*0.001*(5733.0-6.99*MW-PA);
if (MW>58.15) HL2=0.42*(MW-58.15); else HL2 = 0;
HL3=1.7*0.00001*M*(5867.0-PA);
HL4=0.0014*M*(34.0-TA);
HL5=3.96*FCL*(\text{pow}(XN,4)-\text{pow}(TRA/100.0,4));
HL6=FCL*HC*(TCL-TA);
TS=0.303*\text{exp}(-0.036*M)+0.028;
PMV=TS*(MW-HL1-HL2-HL3-HL4-HL5-HL6);
ePMV=0.9*PMV;
PPD=100.0-95.0*\text{exp}(-0.03353*\text{pow}(ePMV,4)-0.2179*\text{pow}(ePMV,2));
TU=\text{pow}(2*\text{C\_K(c,t)}/3,0.5)/VEL;
if (VEL<0.05) DR=0; else DR=(34-TA)*\text{pow}(VEL-0.05,0.62)*0.37*VEL*TU*100+3.14);
if (DR>100) DR=100;
C\_UDMI(c,t,0)=ePMV;
C\_UDMI(c,t,1)=PPD;
C\_UDMI(c,t,2)=DR;
}
end\_c\_loop(c,t)
(2) Wind speed

#include "udf.h"

DEFINE_PROFILE(inlet_y_velocity, thread, index)
{
    real x[ND_ND];
    real y;
    face_t f;
    begin_f_loop(f,thread)
    {
        F_CENTROID(x,f,thread);
        y=x[2];
        F_PROFILE(f,thread,index)=-0.71/1.66*pow(y,0.22);
    }
    end_f_loop(f,thread)
}

DEFINE_PROFILE(inlet_x_velocity, thread, index)
{
    real x[ND_ND];
    real y;
    face_t f;
    begin_f_loop(f,thread)
    {
        F_CENTROID(x,f,thread);
    }
}
\[ y = x[2]; \]

\[ F\_PROFILE(f, thread, index) = 0.71 / 1.66 \ast pow(y, 0.22); \]

\}

end_f_loop(f, thread)
## APPENDIX D PRESSURE COEFFICIENTS OF THE OPENINGS IN THE SOLAR DECATHLON HOUSE

<table>
<thead>
<tr>
<th>Angle</th>
<th>Facade-E1</th>
<th>Facade-E2</th>
<th>Facade-E3</th>
<th>Facade-E4</th>
<th>Facade-N1</th>
<th>Facade-N2</th>
<th>Facade-N3</th>
<th>Facade-N4</th>
<th>Facade-S1</th>
<th>Facade-S2</th>
<th>Facade-S3</th>
<th>Facade-S4</th>
<th>Facade-S5</th>
<th>Facade-S6</th>
<th>Facade-S7</th>
<th>Facade-W1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.333</td>
<td>-0.437</td>
<td>-0.47</td>
<td>-0.797</td>
<td>0.817</td>
<td>0.864</td>
<td>0.835</td>
<td>0.827</td>
<td>-0.34</td>
<td>-0.339</td>
<td>-0.312</td>
<td>-0.243</td>
<td>-0.24</td>
<td>-0.258</td>
<td>-0.329</td>
<td>-0.353</td>
</tr>
<tr>
<td>45</td>
<td>-0.629</td>
<td>0.085</td>
<td>0.127</td>
<td>0.404</td>
<td>0.527</td>
<td>0.449</td>
<td>0.08</td>
<td>0.432</td>
<td>-0.434</td>
<td>-0.696</td>
<td>-1.371</td>
<td>-0.278</td>
<td>-0.476</td>
<td>-0.636</td>
<td>-0.642</td>
<td>-0.263</td>
</tr>
<tr>
<td>90</td>
<td>-0.15</td>
<td>0.942</td>
<td>0.956</td>
<td>0.946</td>
<td>-0.608</td>
<td>-0.403</td>
<td>-0.197</td>
<td>-0.136</td>
<td>-0.115</td>
<td>-0.137</td>
<td>-0.178</td>
<td>-0.22</td>
<td>-0.282</td>
<td>-0.251</td>
<td>-0.614</td>
<td>-0.102</td>
</tr>
<tr>
<td>135</td>
<td>0.792</td>
<td>0.327</td>
<td>0.328</td>
<td>0.151</td>
<td>-0.45</td>
<td>-0.388</td>
<td>-0.329</td>
<td>-0.333</td>
<td>-0.046</td>
<td>0.161</td>
<td>0.538</td>
<td>0.183</td>
<td>0.399</td>
<td>-0.009</td>
<td>0.739</td>
<td>-0.267</td>
</tr>
<tr>
<td>180</td>
<td>0.196</td>
<td>-0.664</td>
<td>-0.718</td>
<td>-0.402</td>
<td>-0.314</td>
<td>-0.209</td>
<td>-0.301</td>
<td>-0.307</td>
<td>0.289</td>
<td>0.345</td>
<td>0.17</td>
<td>0.769</td>
<td>0.933</td>
<td>0.555</td>
<td>0.661</td>
<td>-0.435</td>
</tr>
<tr>
<td>225</td>
<td>-0.429</td>
<td>-0.402</td>
<td>-0.395</td>
<td>-0.404</td>
<td>-0.338</td>
<td>-0.349</td>
<td>-0.354</td>
<td>-0.306</td>
<td>0.224</td>
<td>0.365</td>
<td>0.053</td>
<td>0.85</td>
<td>0.858</td>
<td>0.958</td>
<td>-0.278</td>
<td>0.161</td>
</tr>
<tr>
<td>270</td>
<td>-0.181</td>
<td>-0.092</td>
<td>-0.098</td>
<td>-0.08</td>
<td>-0.122</td>
<td>-0.176</td>
<td>-0.493</td>
<td>-0.674</td>
<td>-0.577</td>
<td>-0.523</td>
<td>-0.487</td>
<td>-0.51</td>
<td>-0.482</td>
<td>0.18</td>
<td>-0.190</td>
<td>0.357</td>
</tr>
<tr>
<td>315</td>
<td>-0.216</td>
<td>-0.291</td>
<td>-0.303</td>
<td>-0.274</td>
<td>0.25</td>
<td>0.287</td>
<td>0.797</td>
<td>0.712</td>
<td>-0.47</td>
<td>-0.47</td>
<td>-0.453</td>
<td>-0.38</td>
<td>-0.395</td>
<td>-0.432</td>
<td>-0.195</td>
<td>0.151</td>
</tr>
</tbody>
</table>
## APPENDIX E OCCUPANT ACTIVITY AND EQUIPMENT USAGE

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Heat gain</th>
<th>Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Occupant 1</strong></td>
<td>60w</td>
<td>23:00-08:00 in the master room; 08:00-17:00 in the study room; and 17:00-23:00 in the living room</td>
</tr>
<tr>
<td><strong>Occupant 2</strong></td>
<td>60w</td>
<td>23:00-08:00 in the master room and 17:00-23:00 in the living room</td>
</tr>
<tr>
<td><strong>Light</strong></td>
<td>4w/m²</td>
<td>18:00-23:00 in all rooms</td>
</tr>
<tr>
<td><strong>Computer</strong></td>
<td>90w</td>
<td>09:00-17:00 in the study room</td>
</tr>
<tr>
<td><strong>TV</strong></td>
<td>120w</td>
<td>19:00-23:00 in the living room</td>
</tr>
<tr>
<td><strong>Fridge</strong></td>
<td>60w</td>
<td>24 hours in the living room</td>
</tr>
<tr>
<td><strong>Oven</strong></td>
<td>1500w</td>
<td>08:00-08:30, 12:30-13:00 and 18:00-18:30 in the living room</td>
</tr>
<tr>
<td><strong>Washing machine</strong></td>
<td>300w</td>
<td>09:00-10:00 in the laundry</td>
</tr>
</tbody>
</table>