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Thermal Comfort and Occupant Behaviour in Office Buildings in South-East China

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Abstract

Natural ventilation is a passive cooling method that has significant potential to reduce building energy consumption and to positively contribute to indoor environmental conditions. Because the window is an important element in naturally ventilated buildings, it can be used to adjust indoor air flow. However, lack of knowledge about occupants' window control behaviour and how this relates to different window typology would result in discrepancy between actual and proposed building performance. And also, limit the potential of natural ventilation in the building. This thesis explores the relationship between indoor air velocity, occupants' window control behaviour and window design.

This study is based on field measurement and occupant comfort survey in four office buildings in a hot and humid climate in South-east China. The field study was carried in September and October of 2012. The indoor and outdoor thermal conditions, indoor air flow speed, window state and effective opening area were monitored. Occupant thermal comfort questionnaires were given to participants four times a day to record their comfort perceptions in the office. The field study gives new insights into the correlation between indoor air speed, occupants' window control behaviour and window design.

For the research 14400 set of indoor and outdoor temperature and relative humidity data, 174560 indoor air velocity records and 1344 copies of questionnaires were collected. The results of this study defined comfort zone for this climate which is consistent with Givoni's comfort zone for a hot and humid climate. The indoor air flow path is identified by measuring the indoor air velocity across different parts of the office and related window opening combinations. Besides, the effective opening area is reduced with decreased indoor air temperature when the indoor air temperature is lower than 25℃. None of the windows is closed when the indoor air temperature is higher than 28℃. During the working hours, the changing of effective opening is related to the air velocity across the

desk surface. And measured maximum indoor air velocity measured around the occupant is 1.8m/s which did not result in occupants' window changing behaviour to adjust for comfort.

In conclusion, this study proved that occupants who live in hot and humid climate can accept higher humidity level. If the air velocity can be avoided across the occupant's working surface, then a higher indoor air velocity is still accepted by occupant as within their comfort threshold. So, there are great potentials for occupant to extend their comfort threshold and adapt to the local climate. Besides, window opening type and position has a significant impact on indoor air velocity and pattern. It would also influence convective cooling affect and occupant thermal comfort. This is evident from the indoor air velocity measurement results and the occupant comfort survey results. In addition, accessibility is important to window design. In the naturally ventilated office building, if occupants find it difficult to operate the window, this will have an influence on the natural ventilation potential in the building and cause the occupant discomfort. Thus, the findings of this study will help architects and engineers to design naturally ventilated office buildings in South-east China.

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Nomenclature

Symbol	Meaning	Unit
ΔC_p	Reference Pressure	(pa)
ΔP	Pressure difference two sides of the opening	(p)
ΔT	Temperature difference between indoors and outdoors	(K)
A	area of each opening	(m^2)
Ab	Opening area for thermal buoyancy driven	(m^2)
Aw	Opening area for wind driven	(m^2)
C	Convection including respiration	(W)
C_d	discharge coefficient	(-)
Cp	Wind pressure coefficient	(-)
C_p	Air specific heat capacity	(J/kg·K)
Clo	Clothing level	(clo)
E	Evaporation including respiration	(W)
f(β)	A value depending on the wind direction	(-)
g	Gravitational acceleration	(m/s^2)
h	Height	(m)
H	Total internal heat gain	(w/m_2)
M	Metabolic heat production	(W)
MRT	Mean radiant temperature	(^OC)
ρ	Density of the air	(kg/m^3)
Q	Quantity of heat being stored	(kW)
Q	Air flow rate	(m^3/s)
Qb	Air flow rate for buoyancy dominated condition	(m^3/s)
Qw	Air flow rate for wind dominated condition	(m^3/s)
R	Net radiation exchange	(W)
RH	Relative humidity	(%)
T	Change of equivalent comfort temperature	(^OC)
T_i	internal temperature	(^OC)
T_m	Monthly mean outdoor temperature	(^OC)
T_n	Predicated neutral temperature	(^OC)
T_o	Outdoor temperature	(^OC)
U	Wind velocity	(m/s)
v	Air velocity	(m/s)

Introduction

Global warming has been recognised as having significant effect on the ecosystem, weather, health, etc. In the past century (1901-2000), the average global temperature has risen by nearly 0.6°C. However, the temperature has increased more obviously during the last 50 years and has even been aggravated in the more recent decades (IPCC, 2007, p.124). The temperature increased by 0.2°C in the first five years of the 21st century (Hansen et al, 2006, p.14288). The geographical temperature anomaly distribution also shows the global temperature changes. The average global temperatures recorded between 1951 and 1980 were used for comparison (common period of weather record used as reference for climate study). It can be seen from the figures (Figure 0.1 and Figure 0.2) that the average global temperature distinctly increased from the 1880s, especially in the northern hemisphere with a majority population and most of the greenhouse gases.

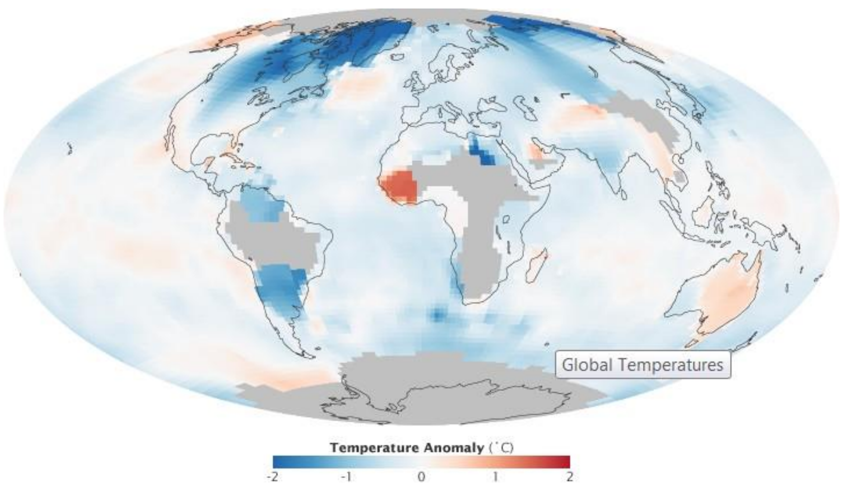


Figure 0.1: Average global temperature distribution between 1880 and 1889 (no data recorded on grey area) (NASA Earth Observatory, viewed 20 Jan 2011, http://earthobservatory.nasa.gov/Features/WorldOfChange/decadaltemp.php).

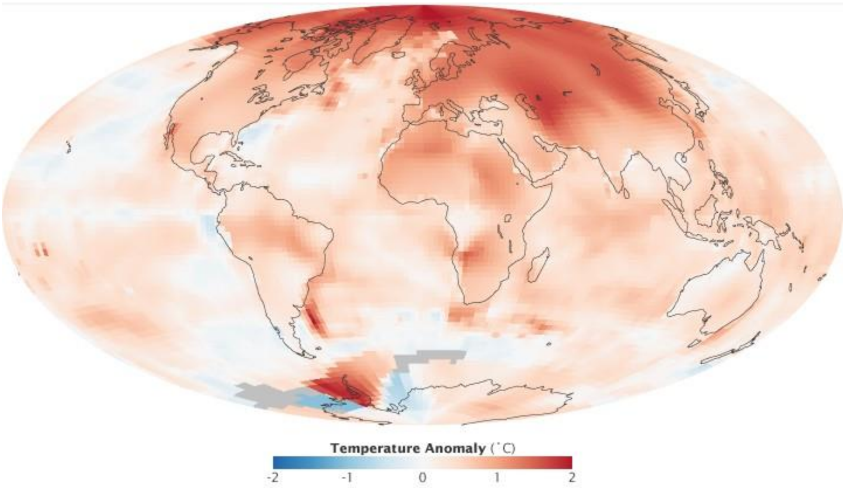


Figure 0.2: Average global temperature distribution between 2000 and 2009 (NASA Earth Observatory, viewed 20 Jan 2011, http://earthobservatory.nasa.gov/Features/WorldOfChange/decadaltemp.php).

Many scientific evidences show that the rise of global temperature is caused by the increase of greenhouse gas (Hansen et al, 1989., Kukla and Karl, 1993., IPCC, 2007). Carbon dioxide, which is the main greenhouse gas, arises in large quantities from human activities. Since the industrial revolution, the carbon dioxide emission has increased rapidly. A large amount of carbon dioxide derives from the combustion of fossil fuels such as coal, oil and gas (NRC, 2010).

In China, coal is still the main energy source, even though it produces a lot of carbon dioxide. According to the Chinese Government record, the carbon dioxide emission in 2004 was 5.07 billion tons (NDRC, 2007, p.6). Since the last century, the annual average temperature increased by 0.8°C, which is higher than the increase of the average global temperature, this number may rise up to 1.3°C-2.1°C in 2020, compared with that in 2000 (NDRC, 2007, p.5). According to the record of the National Meteorological Center of China Meteorological Administration, the highest temperature in summer was broken frequently in the decade since 2000 (CMA, 2013). Taking Hangzhou as an example – a city in Zhejiang province, which is located in South-east China – the record showed that there were only two days during the years from 1951 to 2012 with the highest temperature over 40°C, but more than fifteen days (including seven days continuously) in the year 2013. Apart from the highest temperature, the number of high temperature days (with the highest outdoor air temperature over 35°C) increased as well. The annual average amount of high temperature days from 1971 to 2000 was 21.4 days, while it increased to 35.5 days between 2000 and 2009, and the maximum is 50 days (CMA, 2013, p.1).

In addition, since the launch of the Policy of Reforming and Opening in the 1980s, the energy usage has increased steadily. The energy consumption increased from 603 million tonnes of standard coal in 1980 to 1,320 million in 2001, with an annual increasing rate of 3.8% (Wang, 2003). Since 2002, the rise of energy consumption has been much faster than the growth of GDP; it is about three times more than the USA and seven times more than Japan (Zhou and Lin, 2007). The environmental situation in China could be even more serious. Thus, the Chinese Government proposed that the carbon dioxide emissions per unit of GDP in 2020 should drop by 40% to 45%, compared with the year 2005 (2.76kgco2/USD) (NDRC, 2007, p.8).

The construction business, which is responsible for around 50% of the global energy consumption and nearly 30% of the discharge amounts of carbon dioxide, is one of the industries responsible for most greenhouse gas emissions (Edwards, 1999, p.61). In China, approximately 35% of the total energy is used in construction each year and causes nearly 20% of the total carbon dioxide emissions (Wu, 2003, p.14). The overall construction area in China accounted for almost half of the world's total in each year, and 90% of them were high-energy consumption buildings (Tu and Wang, 2004, p.15). About 20% of these new constructions are office buildings (Hong, 2009, p.426).

Of the total energy consumption in buildings in China, especially of the office buildings, the HVAC (Heating, Ventilation and Air Condition) system accounted for 40%-60%, and lighting for 20%-30% (Zhou and Lin, 2007, p.1069). The total energy consumption in office buildings in China is growing 6.9% each year; up to 12% of growing is for cooling, which has the highest increase in percentage out of the whole energy use (Fridley et al, 2008). In addition, the amount of air conditioning holdings is increasing about 20% each year in China, this number is about 23% for office buildings (Shi, 2010, p.44) (Figure 0.3). The impact of air conditioning on electricity demand in summer is a very significant issue in China. The electricity consumption is increasing continuously each summer and the extra electricity demands was about 30million kilowatt in summer 2006 (Song, 2006, p.2) and may have risen up to 80million kilowatt in 2014 (CEC, 2011, p.3). The increasingly heavier dependence on air conditioning is one of the key causes of climate change. This dependence increases our vulnerability to climate change, and reduces the ability to avoid the effects of global warming (Roaf, 2006).

Figure 0.3: Hundreds of air conditioning external units on an office building in China (News QQ, viewed 10 Jul 2013, http://news.qq.com/a/20130710/006195.htm#p=1)

Study have found that air-conditioned buildings in the UK consume nearly 50% more energy than the naturally-ventilated building through the use of mechanical systems such as fans and pumps (Baker and Steemers, 2000, p.19). A similar result was found by Hong (2009, p.427). He indicated in his report that there would be a potential of energy conservation at about 50% in Chinese office buildings, through effective energy-saving design, such as efficient natural ventilation design.

In order to encourage the adoptions of energy-saving design strategies, the environmental design standards and guides have been published. For example, the CIBSE Guide A (2006) in the UK. In addition, to this sustainable building design and assessment approaches were adopted in many countries, such as BREEAM (BRE's Environmental Assessment Method) in the UK, LEED (Leadership in Energy and Environmental Design) in the US, and CASBEE (Comprehensive Assessment System for Built Environment Efficiency) in Japan. These assessment methods are used to evaluate whether building is achieving the green building standard or not.

Currently, LEED is the most used assessment system in China. Some construction companies used it to label their building as an 'eco-building', in order to acquire higher rental or sales value. However, the cost of LEED standard buildings is much more than normal buildings in China (Chu, 2013, p.284). Additionally, in 2009 the US Green Building Council collected energy use data from 156 projects which had a LEED certificate and found that, in 84% of them, the energy consumption exceeded the LEED standard, as in fact the equipment installed to achieve the assessment point was not operated in the buildings' daily use (Zhang, 2012). Chen and Lee (2013) compared three new office buildings in China using the LEED and BREAM assessment systems to evaluate the energy efficiency of the buildings; it was found that the result of the evaluation was dominated by the efficiency of air conditioning.

The Chinese Government has realised that they need their own energy-saving standard for the construction industry. Many energy conservation standards have been developed – for instance, the Residential Building Energy Conservation Design Standard for Hot Summer and Cold Winter Regions (2001), the Public Building Energy Conservation Design Standard GB 5-189-2005 (2005), the Design Code for Office Building JGJ 67-2006 (2006), the Evaluation Standard for Green Building GB/T 50378-2006 (2006), the Specification for Acceptance of Public Building Construction Quality of Energy Efficiency DB11/510-2007 (2007), etc. However by 2005, only 23.25% of the new constructions were built complying with energy conservation standards, therefore, energy standards were enforced as a law by the Government (the Ministry of Housing and Urban-Rural Development of China), and this figure rose to 71% by 2007 (Cai et al, 2009, p.2056).

However, these energy conservation standards are still vague. Therefore, in the 12^{th} five-year plan (2011-2015) of China, the government proposed to vigorously support the development of energy-saving buildings, and detail the energy conservation standard and criteria, aiming to reduce the energy consumption by 10% in public buildings. The expect consequence is in the overall energy consumption can be reduced by 116 million tonnes of standard coal equivalent in the construction industry (GOSCPRC, 2011, p.6).

Natural ventilation is an energy conservation methods which may help reduce buildings' energy consumption, improve the thermal comfort condition and maintain a healthy indoor environment (Allard, 1998; Gratia and De Herde, 2003; Zain et al, 2007). It has great potential as a passive cooling strategy and can replace the air conditioning system to a certain extent (McCartney and Nicol, 2002). Pasquay (2004) took field measurements in Germany in three high-rise office buildings with a double-facade. The result shows that natural ventilation can provide an acceptable indoor environmental condition without air conditioning even with outdoor noise. Haase and Amato (2009) used dynamic computer simulations to analyse the impact of building location, orientation and climate on the occupant thermal comfort. The natural ventilation potential for improving thermal comfort was investigated in detail. The results showed that the annual thermal comfort improvement potential by natural ventilation is between 36% and 50% in a tropical climate, and between 18% and 29% in a subtropical climate. So a well-designed natural ventilation strategy can help to reduce the cooling load in offices.

Apart from passive cooling design methods, the understanding of occupant behaviour in buildings is also an important issue for designers. During the architectural design process, the lack of understanding of occupants' thermal comfort and behaviour may result in energy waste. Bake and Steemers (2000) found that the actual energy use in an office building is much more than the value predicted by simulation tools. This is because occupants' behaviour in the office, such as controlling the windows, lights and some other office appliances, would make the actual energy use different from the predicted value. It has also been shown by Ford etc (2010) in a practice in Valletta, Malta: the office building was naturally ventilated and combined with a passive down-draught cooling system. The occupants' response to the evaluation result shows that they were unsatisfied with indoor air quality. The indoor air was stuffy in summer and over-ventilated in winter, because the building manager intervenes the system frequently. But the occupants feel have no control on ventilation, heating, cooling and lighting. Many studies have found that lack of understanding occupant behaviour in the office would cause occupant feel uncomfortable which would also result in energy waste (Norford et al, 1994., Branco et al, 2004., Lindelof and Morel, 2006., Masoso and Grobler, 2010). So, a good understanding of occupant behaviour can help the designer to achieve design aims, reduce the energy consumption and help occupant to improve their comfort.

This study aimed to investigate natural ventilation patterns in generic office buildings in South-east China, as well as the impact of indoor air flow patterns on occupants' thermal comfort and their window control behaviour. In addition, the impact of windows' design on natural ventilation and occupant behaviour in offices was also discussed. The research questions were as follows:

What is the impact of air flow speed and air flow patterns on occupant thermal comfort in office buildings in South-east China?

What is the impact of window control behaviour on thermal comfort and natural ventilation in office buildings in South-east China?

In order to explore the questions above, there are several approaches/ steps. Firstly, a good understanding of occupant thermal comfort, as well as the effect of natural ventilation and occupant behaviour in office buildings, is needed through a literature review. Secondly, the thermal performance of generic office buildings with different window sizes in South-east China was predicted by parametric study, in order to identify the required ventilation rates to achieve comfort by natural ventilation.

Thirdly, field measurements and questionnaires were applied in selected case study buildings to provide original data, in order to identify the correlation between natural ventilation, thermal comfort and window control behaviour in office buildings, and to identify the impact of windows' design on occupant behaviour, indoor air flow pattern and thermal comfort. The field measurement and questionnaire are the main methods to approach these questions. And these are the effective and straightforward methods to understanding natural ventilation, occupant's perception and occupant window control behaviour in an office building in the field study.

This thesis was divided into seven chapters, as follows.

Chapter 1, Literature review: Review of occupant thermal comfort theory, which is divided into the heat balance model and the adaptive model. The environmental function of windows and occupant window control behaviour was presented. Then, thermal comfort thresholds in a hot and humid climate are introduced, as well as the effect of humidity and air flow speed on thermal comfort. A climate and building bioclimatic chart is also illustrated.

Chapter 2, Parametric study: In this chapter, the thermal performance of generic office buildings in South-east China with different ventilation strategies (single-side ventilation and cross-ventilation), different orientations, different window sizes and different free opening sizes is investigated by empirical expressions and computer simulation. At the same time, the natural ventilation rate for achieving a comfortable indoor environment and the natural ventilation potential are evaluated.

Chapter 3, Pilot study: Local climate conditions and the method used in the pilot study in an office building in South-east China (within hot summer and cold winter climate conditions) are described. The thermal performance of the pilot study building is demonstrated. Some findings of natural ventilation, thermal comfort and occupant behaviour are presented. Also, some shortages and issues during the field work are pointed out, as well as solutions that were taken forward when developing the case studies in the chapter that follows.

Chapter 4, Field measurement methodology: The reversed field measurement methods have presented. More measurement points are set for measuring indoor air velocity. The perception vote scale which caused confusing for respondents is changed to -3 - +3 scales. Four naturally ventilated office buildings are selected and the description is demonstrated.

Chapter 5, Natural ventilation results: The results of natural ventilation in four office buildings through field measurement in 2012 are presented in this chapter. The indoor air flow rate and patterns, both in single-side ventilated and in cross-ventilated offices, are investigated. The correlation between the design of windows and the indoor air flow patterns is established. The result of thermal performance of four buildings is presented as well.

Chapter 6, Occupants’ perception: The results of comfort survey in the four case study buildings are presented. Furthermore, the comfort zone in office buildings during summer time in South-east China is developed and compared with the ASHRAE’s adaptive comfort zone and Givoni’s comfort zone. In addition, the impact of occupant thermal sensation on occupant behaviour is pointed out.

Chapter 7, Occupants’ window control behaviour: The occupant window control patterns and frequency in the four case study buildings are established. In this chapter, occupant window control behaviour and different window types are addressed. In addition, the correlation between occupant window control behaviour and indoor environmental factors is presented.

Chapter 8: This final chapter summarises some key findings of this thesis and the correlation between natural ventilation, thermal comfort and window control behaviour. Furthermore, it also provides some suggestions for window design in office buildings in South-east China. The originality and contributions of this work has presented. Besides, the limitations of the work and several issues which need further work are pointed out.

This study is based on field measurement and occupant survey in a hot and humid climate in South-east China. The measurement collected 14400 sets of temperature and relative humidity data, 174560 pieces of indoor air velocity data and 1344 questionnaires in four office buildings over a period of three weeks. The method used to identify the indoor air flow path by the measurement of the indoor air flow speed in different parts of the office has been developed. It identified the indoor air flow path which is related to different window opening combinations and types in the cross-ventilated office. And it also identified the impact of indoor air velocity on occupants' window control behaviour and occupant thermal comfort. In addition, the defined comfort zone is consistent with Givoni's comfort zone. Occupants who live in a hot and humid climate can acclimatise to local climate. Therefore, they can tolerate higher humidity level. The occupant window control behaviour in offices which correlated with indoor air speed and air temperature has been defined. Moreover, some design suggestions were pointed out, in terms of window control behaviour and window typology in natural ventilation office buildings.

The result of this study can be used as reference for designer and researchers. Further research in the field will enable more comprehensive understanding the correlation between occupant behaviour, thermal comfort and environmental conditions. The defined comfort zone can be used to predict other environmental conditions. In addition, the method used to identify indoor air flow path can be conducted to research the air flow condition in other building types and window typologies. Furthermore, the typology and opening position of the window have a significant impact on indoor air speed and air flow pattern. They would also affect the potential for convective cooling and occupants' thermal comfort. The correlation between occupant window control behaviour and indoor environmental conditions have identified in the study. It can help designer to design a practical naturally ventilated office building which can be easily controlled by the occupant, so that occupants can improve their thermal comfort by controlling these windows themselves.

1 Thermal Comfort and Occupant Behaviour

The Chinese literature that was written in the Tang dynasty (A.D.618-A.D.907) described a room which makes the occupant feel comfortable and peaceful. This kind of room includes windows at each side, so that you can close the windows when the wind blows, while opening them when the sun shines. And the seating in the room is with blinds in front and a screen behind, so that you can draw down the blinds when it is bright in the room, while drawing up them when it is dark (Tian Ying Zi, 2009). It can be seen from this literature that the ancients in China had adjusted their indoor environmental condition through controlling windows, curtains and screens to achieve comfort in both physiological and psychological states.

In recent years, the indoor environmental condition and thermal comfort has been attracting public attention in China, as it is related to an occupant's safety, healthy, efficiency and so on. Thermal comfort is a subjective feeling whereby occupants feel satisfied with the environment (ASHRAE, 2010). And it is related to the energy balance between metabolic rate and heat loss from the human body. The heat loss is demonstrated by three types – radiation (45%), convection (35%) and evaporation (20%) (Baker and Steemers, 2000, p.9). Givoni (1976) pointed out the heat transfer between a human body and the environment, as shown in Equation 1.1 below.

$$M \pm R \pm C - E = Q$$

Equation 1.1: Heat balance between a human body and the environment.

Where Q is the heat content of the body, and M, R, C, and E are the metabolic rate, radiative, convective and evaporative heat transfers. Hausladen et al (2004, p.28) indicated that "Thermal comfort depends on the heat physiology of the person: A person must keep his core body temperature constant and therefore has to be able to transfer the excess heat produced by his metabolism into the surroundings."

In this chapter the theoretical background of thermal comfort and window control behaviour is presented. The heat balance comfort model and the adaptive comfort model are introduced. Then window control as a main environmental adaptive method is reviewed, as well as the environmental functions and characters of windows. Finally, the building bioclimatic chart, which can be used to assess occupant thermal comfort in the field study, is also introduced.

1.1 Heat balance comfort model

The heat balance comfort model was built in a laboratory or a weather chamber in which all the factors were controlled in a steady state. It is used to describe the heat balance between the human body and the ambient environment. The test subject was seen as an environmental stimuli receiver to evaluate the environmental condition when the factors changed. Based on the heat balance model, Fanger (1970) developed a Predicted Mean Vote (PMV) model, according to four environmental factors (air temperature, mean radiant temperature, vapour pressure and air velocity) and two personal adjustment factors (activity level and clothing level). The basic concept of the PMV model is to calculate the body's heat balance, the prediction of the average skin temperature and the evaporative heat loss to maintain the total balance in detail. Based on the empirical laboratory research, he developed the PMV equation as a function including six variable factors, as shown below:

$$PMV = 3.155(0.303e^{-0.114M} + 0.028)L$$

Equation 1.2: The PMV equation.

The PMV model is widely used for evaluation of indoor thermal comfort and applied in many thermal comfort standards, such as American Society of Heating, Refrigerating and Air-conditioning Engineers 55 – 2004 (ASHRAE, 2004), International Organization for Standardization 7730 (ISO, 2005) and Chartered Institution of Building Services Engineers thermal comfort standard (CIBSE, 2006).

In order to apply the PMV model in actual thermal sensation evaluation, a seven-point scale of thermal sensation was developed by Fanger (1970), ranging from -3 to +3 (Table 1.1). It presents cold to hot with 0 for the neutral point. The PMV model provides the thermal sensation vote value between people and the environment. However, people have different requirements of the actual environment compared with the weather chamber.

Thus, Fanger (1970) proposed the Predicted Percentage of Dissatisfied (PPD) to predicate the percentage of people's dissatisfaction degree. He believed that, even when the PMV was equal to 0 (Neutral), there would probably be 5% of people who were not satisfied because of their different physiological states and environmental preferences. The PPD scale is similar to the seven-point PMV scale, which is from Dissatisfied (-3) to Satisfied (+3). Figure 1.1 shows the quantitative relationship between the PMV and the PPD.

Table 1.1: Thermal sensation scales of ASHRAE and Fanger.

Thermal Sensation	ASHRAE Scale	Fanger Scale
Hot	7	+3
Warm	6	+2
Slightly warm	5	+1
Neutral	4	0
Slightly cool	3	-1
Cool	2	-2
Cold	1	-3

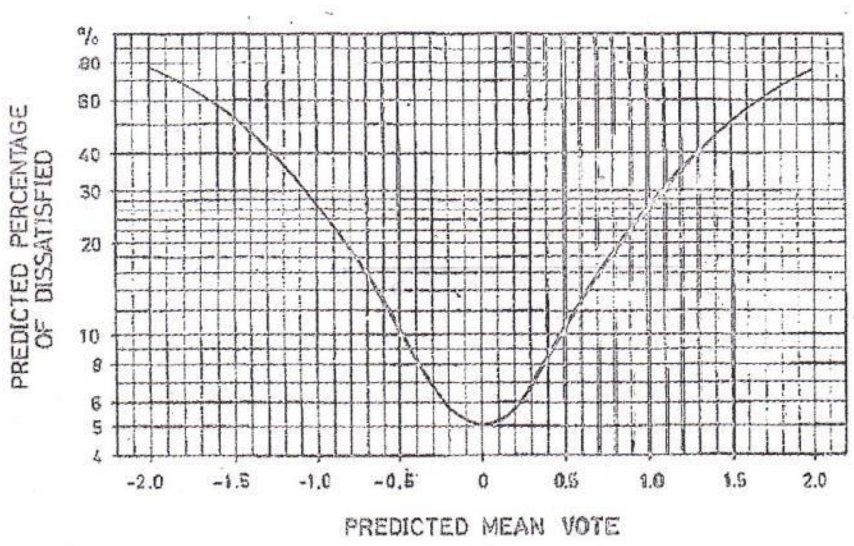


Figure 1.1: Predicted Percentage of Dissatisfied (PPD) as a function of Predicted Mean Vote (PMV) (Fanger, 1970, p.131).

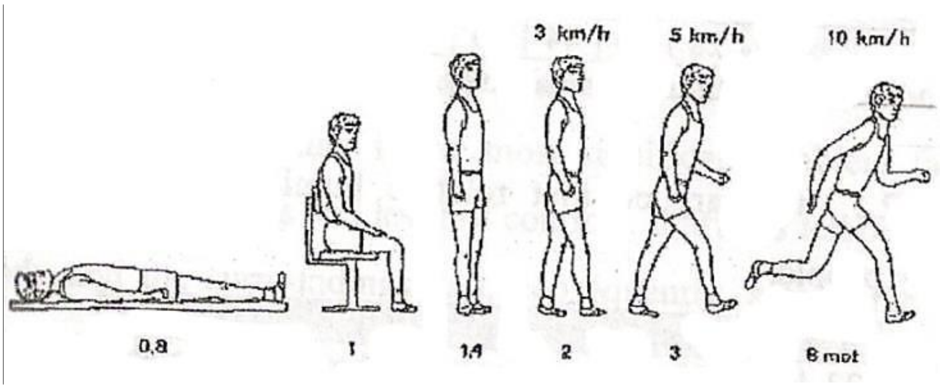


Figure 1.2: Metabolic rates according to the activity by P.O. Fanger (Lewis et al, 1992, p.61).

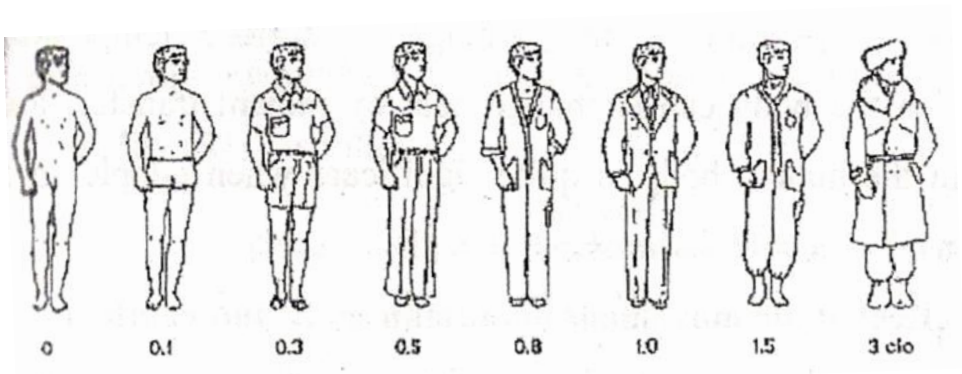


Figure 1.3: Thermal insulation values for clothing by P.O. Fanger (Lewis et al, 1992, p.61).

1.1.1 The limit of the PMV model

It is found from many field studies that there is a gap between the results from the field measurement and the PMV (Busch, 1992., De Dear and Fountain, 1994., Humphreys, 1994., Goto et al, 2007). Kwok and Chung (2003) took a field measurement in Japan in both an air-conditioned classroom and a naturally-ventilated classroom. The results showed that, in the air-conditioned classroom, the measured indoor environmental factors were in ASHRAE's comfort zone, but students felt too cold to be comfortable. Another finding was that, although the average indoor air temperature in the naturally-ventilated classroom was 3°C higher than in the air-conditioned classroom, the result of the thermal sensation vote shows the naturally-ventilated classroom is more comfortable than the air-conditioned classroom. Moujalled et al (2008) agreed with this finding. They carried out field studies in five naturally-ventilated office-buildings in the south east of France during both the hot and the cold seasons. The results showed that the occupant thermal sensation was related to operative temperature in the hot season, and the occupant was less sensitive to the temperature increasing in the naturally ventilated office building. In addition, they found that, in naturally-ventilated buildings, the PMV model was not reliable to predict occupant thermal comfort either in hot or cold seasons and the model would result in more heating/cooling time. In can be seen from the field study that occupants can actually accept a higher temperature than predicted by the PMV model in summer and a lower temperature in winter. Similar results of a discrepancy between the field measurement and PMV were also proved by other researchers (Schiller, 1990., Bush, 1992., de Dear and Fountain, 1994., Humphreys, 1994., Wong and Khoo, 2003., Liang et al, 2012). It seems that the PMV model may not be an ideal assessment model for the actual environment.

The reason for the gap between the predicted result from the PMV model and the actual thermal comfort vote result probably is that the actual environmental condition is more dynamic than the steady state environment in the weather chamber (Hensen, 1990). Oseland (1998) compared naturally ventilated office buildings in the UK with those with air-conditioning, and the results showed that the comfort threshold in naturally-ventilated office buildings is wider than in air-conditioned buildings, by about 2.4°C in summer and 2.6°C in winter. The difference of 6.3°C was found in the field study in China by Han et al (2007) during the summer time. Occupants can accept wider temperature ranges in naturally-ventilated office buildings than in air-conditioned offices. Similar findings have been indicated by other researchers, who pointed out that occupants more likely to tolerate the temperature in free-running buildings than in air-conditioned buildings (Fishman and Pimbert, 1982; Leaman and Bordass, 2000; Shove''s, 2003). The PMV model is more adaptable to predict the controlled indoor environmental condition (such as an air-conditioned room) rather than the free-running environmental condition (Yao, 1997).

In addition, in field studies, it was difficult to measure an occupant’s metabolism rate and clothing insulation value. Humphreys and Nicol (2002) pointed out that, apart from these errors in the measurement, the time gap in human thermal response may also be caused by a systematic prediction error in the PMV model. Therefore, Fanger’s PMV model can adjust occupants’ clothing value, activity level, air velocity and air temperature, but ignore their psychological perception and the environmental context, which may be important for occupant thermal sensation.

1.1.2 Neutral temperature for thermal comfort

Humphreys (1978) gathered and analysed thermal comfort survey results from 36 places worldwide. He indicated that the comfort temperature varies all over the world, and the comfort temperature range is much wider than the narrow comfort zone which is given by the heat balance model. For instance, the comfort temperature ranges from 28.1° in summer in Shanghai to 18.5° in winter in Beijing. According to Humphreys’ studies, he concluded that the indoor comfort temperature is related to the monthly mean outdoor temperature. The relationship between them is demonstrated as Figure 1.4. It means people's indoor comfort temperature is related to the season, the climate and the location.

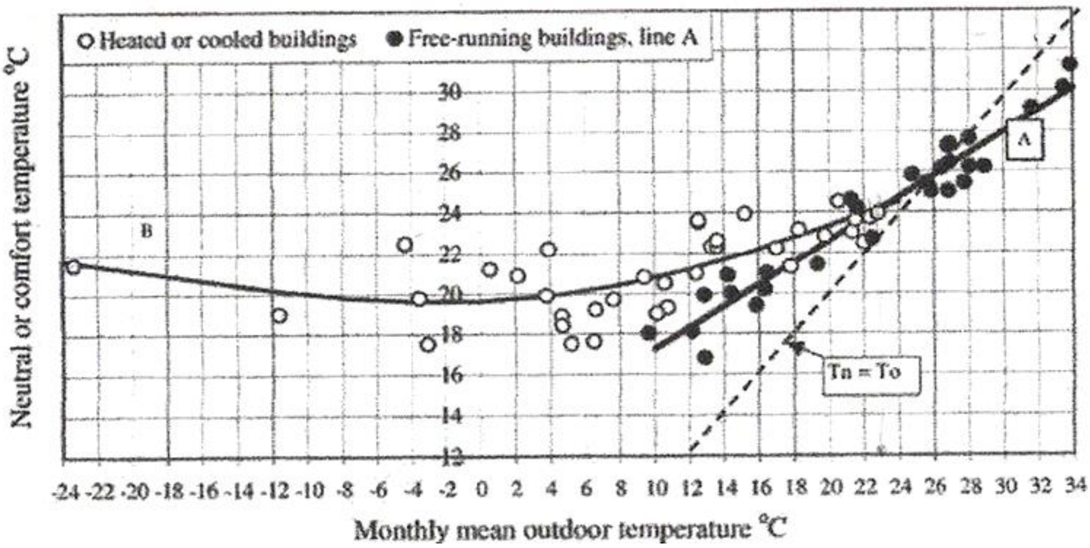


Figure 1.4: The change in comfort temperature with monthly mean outdoor temperature (Humphreys, 1978).

Humphreys also suggested a regression equation of neutral temperature for a free-running building, as shown below:

$$T_n = 11.9 + 0.534T_m$$

Equation 1.3: Humphreys's neutral temperature equation for a free-running building

Where Tn °C is the predicated neutral temperature, and Tm °C is the monthly mean outdoor temperature. The regression residual variation is 1°C which means 90% of occupants feel comfortable when the temperature varies ±1°C. This result was reviewed by Auliciems (1983). He did some more field works in different climate conditions and deleted some field works that aimed at children's comfort, and then proposed the equation with de Dear (1986) as shown in Equation 1.4

$$T_n = 17.6 + 0.31T_m$$

Equation 1.4: Auliciems and de Dear's neutral temperature equation for a free-running building.

Nicol and Roaf (1996) concluded from field measurement results in Pakistan and established the regress equation (Equation 1.5) for the relationship between the comfort temperature and the monthly outdoor mean temperature. It is similar to Auliciems and de Dear's (1986) equation. Then they took the second field measurement in Pakistan in 1999 (Nicol et al, 1999), and established the second regression equation (Equation 1.6), which is very close to the first one.

$$T_n = 17 + 0.38T_m$$

Equation 1.5: Nicol and Roaf's neutral temperature equation for a free-running building

$$T_n = 18.5 + 0.36T_m$$

Equation 1.6: Nicol et al's neutral temperature equation for a free-running building.

According to the field measurement, de Dear and Brager (1998) also presented their neutral temperature equation, as shown in Equation 1.7:

$$T_n = 17.8 + 0.31T_m$$

Equation 1.7: de Dear and Brager's neutral temperature equation for a free-running building.

A field study in five cities which were located in five typical climate zones in China was conducted by Yang (2003), and the following formula equation was proposed:

$$T_n = 19.7 + 0.30T_m$$

Equation 1.8: Yang's neutral temperature equation for a free-running building.

This equation is based on Chinese people's comfort perception which is acceptable by 90% of the occupants. The regression residual variation of ±1.5°C should be taken into account and ±2.5°C for 80% acceptability.

It can be proved from all these neutral temperature regression equations that the indoor comfort temperature for a free-running building is related to the monthly mean outdoor temperature. There is no unified comfort temperature worldwide. The thermal comfort temperature is related to the local climate condition, culture context, type of subjects, etc. Therefore, the adaptive comfort model for free-running buildings was proposed by de Dear and Brager (1998). It is more suitable for assessing occupant thermal comfort in naturally-ventilated buildings compared with the PMV model.

1.2 Adaptive thermal comfort theory

The adaptive thermal comfort model interprets people's natural inclination for changing or adapting to the living environment. Nicol and Humphreys (2002, p.564) described the basic principle as "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" and they defined it as the adaptive approach. Auliciems (1983, p.70) indicated it as "when a change occurs causing thermal discomfort, people react in such a way that their thermal comfort is re-established." Nicol and Roaf (2005) also pointed out that the comfort is the consequence of occupant interaction with the environment. In the adaptive comfort model, as an active agent, occupants adjust and acclimatise to the ambient environment through personal control (such as changing clothing, opening windows, turning the fans on, etc).

De Dear and Brager (1998) proposed an adaptive comfort model. They collected 21,000 sets of raw data from thermal comfort field studies in 160 office buildings in four continents across various climatic zones and then created a database for ASHRAE (Figure 1.5). The result proved that the PMV model is suitable to predict thermal comfort in HVAC buildings. They also demonstrated that the occupant can accept a wider temperature range in a naturally-ventilated building than assessed by the PMV model (Figure 1.6). Based on this database, ASHRAE proposed their adaptive standard ASHRAE-55 (2004), which incorporated the adaptive comfort model for naturally-ventilated buildings without any mechanical cooling system. This standard used 10% PPD to assess the acceptability of indoor comfort and showed the comfort temperature range for 80% and 90% acceptability (Figure 1.7).

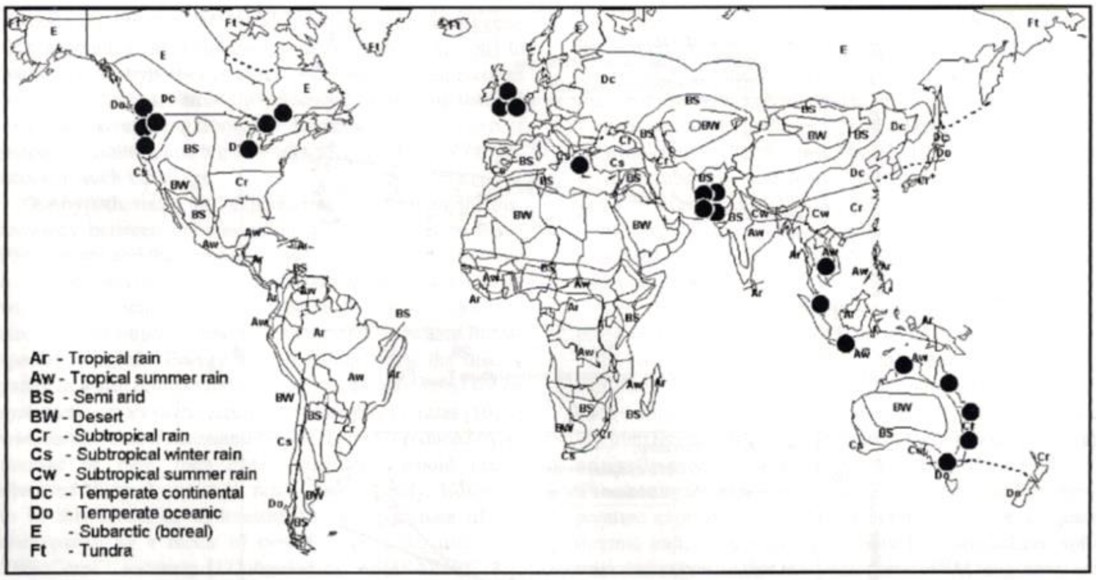


Figure 1.5: The geographic distribution of building studies (de Dear and Brager, 2002, p.551).

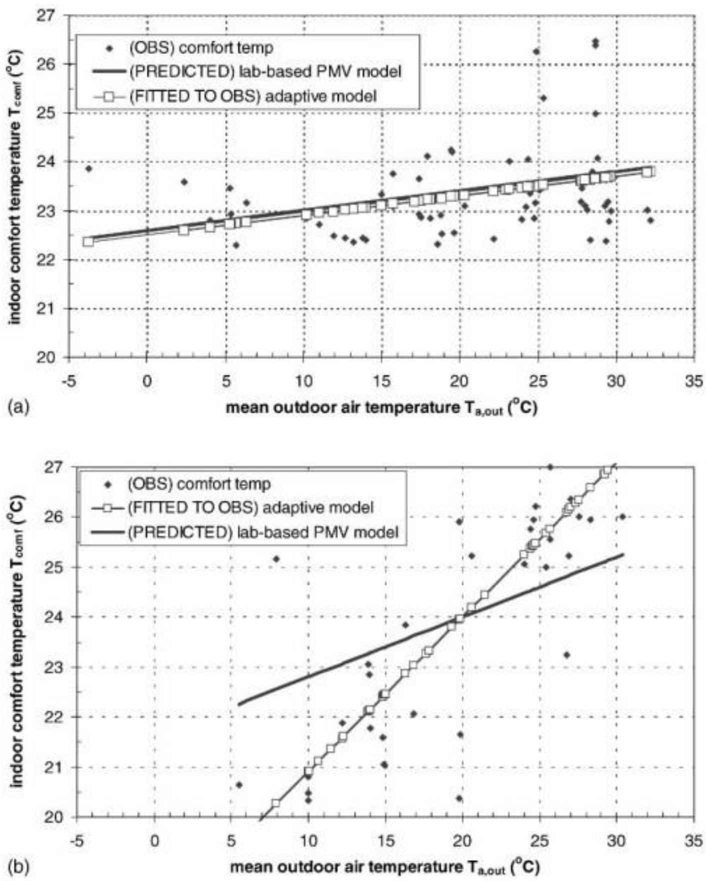


Figure 1.6: Comparison of ASHRAE adaptive models predicting indoor comfort temperatures (naturally-ventilated buildings, b) with those predicted by the PMV model (HVAC buildings, a) (de Dear and Brager, 2002, p.552).

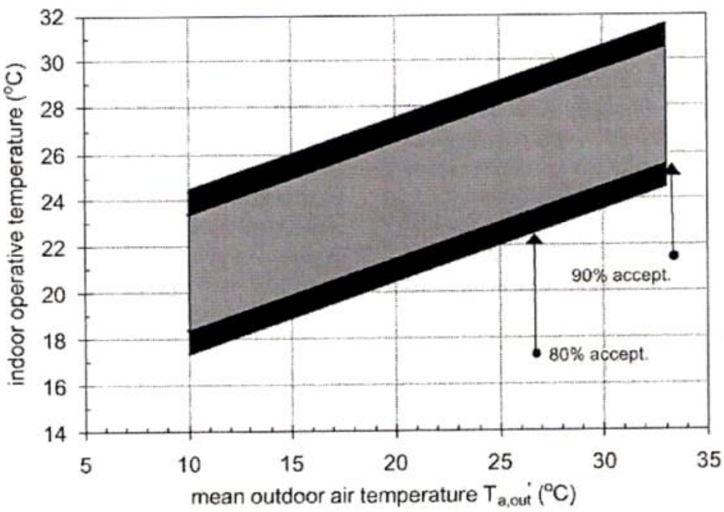


Figure 1.7: The range of thermal comfort temperature related to 80% and 90% of acceptability by the ASHRAE adaptive standard (de Dear and Brager, 2002, p.554).

1.2.1 The adaptive opportunity

Baker and Standeven (1994, 1995 and 1996) proposed the "Adaptive errors" to describe the discrepancy between predicted comfort results in free-running buildings which were guided by the general thermal comfort standard (based on the heat balance model) and the actual thermal comfort results accessed by occupants. They found that the general thermal comfort standard may guide the designer to adopt the air-conditioning system. This "error" has also been defined as an adaptive opportunity, which represents an occupant's controllability of the surrounding environment, for example, changing their clothing, controlling the windows, etc. These kinds of behaviour can help occupants to extend their comfort temperature. Figure 1.8 shows the relationship among the neutral zone, the adaptive opportunity and the environmental stimulus. When the adaptive opportunity decreases, then the area of stress (discomfort perception) increases. When the adaptive opportunity does not exist (such as in a climate chamber), then the change of environmental stimulus will cause an occupant to feel uncomfortable quite easily. So, the adaptive opportunity can help an occupant to extend their comfort zone.

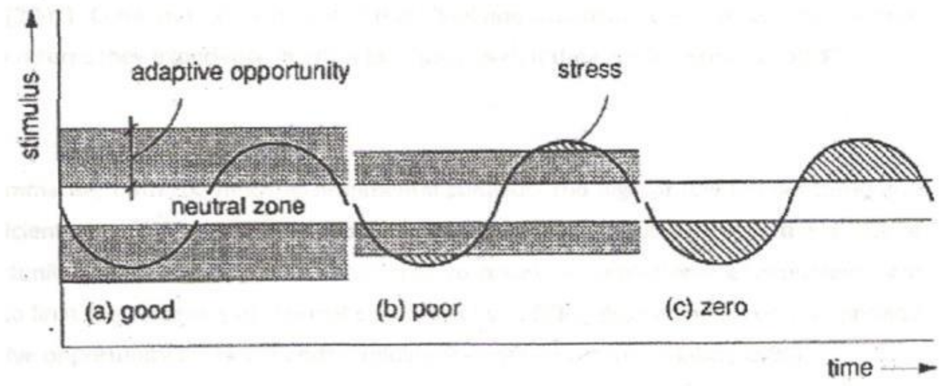


Figure 1.8: The relationship between comfort zone, adaptive opportunity and environmental stimulus (Baker and Standeven, 1996, p.180).

In another environmental condition which is well controlled (mechanic controlled) and the occupant's adaptive opportunities are limited (Figure 1.9), the neutral zone will become narrow, and the related adaptive opportunity is the same, as the occupant has to adapt this small range of environment stimuli. This adaptation is caused by the occupant psychological state, as they can expect the environment (cool or hot) to be according to their experiences. Therefore, the occupant may still feel uncomfortable. This also explains why the comfort temperature concluded by the field study is higher than the PMV results. Thus, in addition to providing a good indoor environment, the designer should also provide more opportunities for occupants to control their ambient environment (Humphreys and Nicol, 1998).

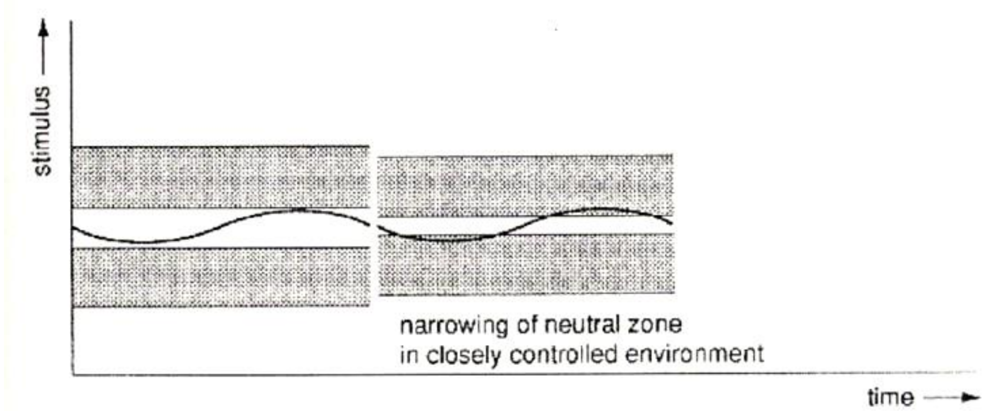


Figure 1.9: Neutral zone in closely controlled environment

(Baker and Standeven, 1996, 180).

1.2.2 Thermal comfort adaptive models

According to the field work done by de Dear and Brager (1998), the thermal adaptation model can be defined as three aspects: behavioural adjustment, physiological adjustment and psychological adjustment. The physiological adjustment is the human's physical response to the environment, such as sweating, vaso-dilation or constriction, etc. It includes two categories: genetic adaptation and acclimatisation For example, in a hot and dry climate, the capacity for sweating to increase can raise the heat load of the body and encourage heat loss from the skin; meanwhile in cold weather, the body would constrict blood vessels and pores to reduce heat loss from the skin.

The psychological adaptation is described as a consequence of expectation and habituation (Brager and de Dear, 1998). Therefore, the psychological adaptation is based on personal thermal expectation and experience (such as social, cultural, contextual factors). A study was carried out by de Dear and Leow (1990) in high-rise public housing in Singapore; 214 flats and 583 occupants were investigated in this study. They found the preferred temperature of occupants was about 2°C higher than the temperature assessed by the PMV and the ISO standard. This difference is probably caused by physiology acclimatisation and perception. Hence, the psychological adaptation can extend the thermal comfort zone (Nikolopoulou and Steemers, 2003).

Baker and Standeven (1994) have investigated seven buildings in France. It can be seen from their study that occupants change their clothing based on the climate condition in the workplace which is estimated according to the primary outdoor climate. It is correlated with the occupant's thermal expectation and experience. This is another reason for people to still feel comfortable when the ambient environment condition is outside the comfort zone which is demarcated by the heat balance model. A long-term field study by Liu et al (2013) has found that, compared with the physical impact, the psychological affection is more important on occupant adaptive behaviour, such as controlling doors, windows and air-conditioning.

The behavioural adaptation is another important method for occupants to achieve comfort, and the effect of it is more significant than other adjustment methods (Cena and de Dear, 2001). In daily life, occupants make themselves feel more comfortable through adjusting their clothing, activities and posture, or through controlling the windows, fans, etc. The behaviour adjustments include all the alterations made by the occupant to control the physical thermal balance. It can be further divided for two areas: personal adjustment (changing clothing, activity, posture, eating, drinking or changing locations etc.) and environmental adjustment (window controls, turning on fans or controlling an HVAC system etc.).

Personal adjustment includes several aspects such as changing clothing level, activity level, having hot or cold drinks, posture, etc. Changing clothing is a common adaptation method to adjust personal thermal comfort. A field work conducted by Baker and Staneven (1994) within seven buildings in France and Greece in summer time found that during the 864 hours of survey, 28 occupants had 62 times of clothing adjustment. Besides, occupants would choose the clothing level before leaving home according to external environment conditions. De Dear et al (1988) found that the clothing level is related to outdoor temperatures, and a regression equation (Equation 1.9) was established according to their study, where Clo is clothing insulation and T_o (°C) is outdoor temperature. A similar result was also agreed by Mui and Chan (2003). In another field study in Tunisia, it was found by Bouden and Ghrab (2005) that Tunisians are more likely to wear light clothes and it is easier to adapt to the environmental change. But, in the desert weather condition, the clothing level is increased. This is related to local people's living behaviour; they would wear heavy or long sleeves during the summer time in order to block the solar radiation and hot air.

$$Clo = 1.73 - 0.04T_O$$

Equation 1.9: Clothing level and outdoor temperatures.

Clothing level also influences the building energy usage. Foo and Phoon (1986) carried out a field survey in 40 office buildings in Singapore, and they found that in the air-conditioned office building, 76% of occupants set the indoor temperature below 24°C, which is lower than the summer comfort temperature defined by the ASHRAE standard (1981) and ISO 7730 (1984). However, occupants' clothing level was thicker than normal, which causes large energy waste. Based on Olesen's (2000) field study, he found that there is some difference of clothing level between females and males who are working in the same office building. Males seem to wear a suit all year round and the female clothing level was more varied, which was closely related to the outside temperature. This would result in the different temperature preference in the office in summer: men prefer 20°C–24°C with about 1clo business suit, while women prefer 23°C–26°C with about 0.5clo summer dress. In order to satisfy both the females and the males and also to achieve energy saving in the office, 23°C–24°C is suggested.

The relationship between the impact of clothing adjustment change and the energy consumption was found out by Newsham (1997) through computer simulation. He found that if occupants could choose clothes themselves, the energy consumption could be reduced by 41.1% when 90% of occupants feel comfortable. Rohles and McCullough (1981) suggested lowering the heating set point in winter and raising the cooling set point in summer, in order to reduce the energy consumption by encouraging the behavioural adjustment, such as adjusting the clothing insulation level. The behaviour adjustment could save about 22% of the heating energy consumption by lowering the heating temperature set point from 21.1°C to 18.9°C in Seattle (Heerwagen et al, 1980) and save 6%-11% of heating energy consumption by lowering every 1°C heating temperature set point in the UK (Cornwell, 1987).

Goto et al (2007) indicated when the clothing insulation value was 0.5clo, every 5°C rise of the outdoor temperature would result in about 0.05clo in the reduction of clothing insulation level. Schiavon and Lee (2013) found that when people did sedentary activities (such as office work), every 1clo change is equivalent to about 6°C to operative temperature. And it was found by Liu et al (2013) in China that 0.1clo rises in clothing insulation can reduce about 0.4-0.7°C neutral temperature. In addition, the insulation level of a chair can be added 0.1clo–0.15clo when an occupant is seated, which corresponds to a 0.6°C–0.9°C increase. To sum up, the changing of clothing insulation level has an important effect on occupant thermal comfort and energy saving.

Changing posture is another way for occupants to remain comfortable. The posture will affect the effective surface area of the human body which is exposed to the ambient environment that causes heat loss. In order to adapt the environment, people's posture is relaxed and expanded in a warm or hot environment and relatively tight in a cold environment. Comparing the postures in those two conditions, a human's effective surface area varies about 20% (Baker and Standeven, 1994). Nicol and Raja (1996) conducted a field survey in a university in the UK and found that every 2% decrease of a body's effective surface area could increase the temperature by 1°C.

One of the major behaviours for the occupants to remain comfortable is to have hot or cold drinks; this was indicated by Goto et al (2007) in a long-term field study in Japan. Taking a cold drink in summer is an impactful method to drop people's metabolic heat. In their field study, Baker and Standeven (1994) found that nearly half of the subjects had a cold drink during the investigation period in summer. And it could reduce approximately 10% of the net metabolic heating by having a can of cold drink.

Occupants could achieve personal comfort by changing their location. Baker and Newsham (1989) used computer simulation to analyse the room heat gain and occupant movement in the room. They found that when the room temperature is overheated (when PPD>20%) the occupant's occupation hour was clearly reduced. Merghani (2004) did a field measurement in four houses in Khartoum. The finding showed that the indoor thermal performance has an important impact on ab occupant's indoor movement. The room that the occupant prefers to stay in in the house is more comfortable than other rooms. Baker and Standeven (1994) pointed out that the room temperature where most occupants were positioned was about 3°C lower than the average.

Therefore, for people to be free to choose their location can help them to achieve thermal comfort and energy reduction (Newsham, 1992). However, in some conditions, an occupant's position is fixed so that it cannot be changed freely (such as in the office). Then the occupant should be provided with more opportunity to control the environment, such as controlling the windows, fans or air-conditioning (Humphreys and Nicol, 1998).

Environmental adjustment includes controlling windows, fans, air-conditioning, etc. Wong et al (2002) conducted a field survey in a naturally-ventilated public house in Singapore. The 80% acceptability criteria defined by the ASHRAE-55 standard was used to evaluate occupant thermal comfort. The result showed that the fan was used frequently, and the occupants feel satisfied even when predicted thermal sensation vote in the zone of warm (+2) or hot (+3). Nicol (2004), according to his field study in a tropical climate, also pointed out that fans could raise 2°C at the upper limit of the comfort temperature within free-running buildings in hot conditions. It was proved from the field study of office buildings in Japan that fans are highly used in summer to adjust micro climates instead of air-conditioning (Goto et al, 2007; Indraganti et al, 2013). Moreover, fans can increase indoor air movement and promote heat convection between the human body and the indoor environment, which can help occupants to achieve comfort. Controlling fans can help occupants to achieve psychological and physiological comfort.

Occupants prefer to control the environment, even in the air-conditioned place. Kempton et al (1992) investigated eight apartments in New Jersey for the usage of air-conditioning, and found that three-quarters of occupants set the air-conditioning in manual mode, rather than automatic.

Even in the air-conditioned room, occupants would like more opportunities to adjust the indoor environment (e.g. control fans, windows, etc.). Adaptive thermal comfort for HVAC systems was pointed out by Darmawan (1999). It was found that occupants prefer having direct control on the indoor environment, especially by controlling the windows. A field study was carried out by Goto et al (2007), in which six HVAC office buildings with operable windows in Japan were set in this survey. They found that the comfort temperature assessed in this study was higher than that in centralised HVAC buildings but lower than in the naturally-ventilated buildings. Occupants find it more tolerable to control the windows, use personal fans or change clothing, rather than working in the office building which is fully controlled by centralised HVAC.

Apart from the usage of fans or HVAC system, occupants' control of curtains, blinds or lighting has also been paid attention in many field studies. Rea (1984), Inkarojrit (2005) and Paik et al (2006) found that the control of blinds is related mainly to occupants' visual comfort, rather than the air temperature or other environmental factors. And manual control of indoor lighting has significant impact on energy saving, especially in cell offices (Reinhart and Voss, 2003; Bourgeois et al, 2006). Thus, behavioural adaptation is a significant adjustment method that can help occupant re-establish their comfort and reduce energy consumption.

1.3 Windows function and control

The window is an important element to link the inside and outside environment of a building; it brings view, light, solar energy and fresh air that occupants desire into interior space from outside. In this section the author present the environmental functions of windows and the impact of environmental stimulus on occupant window-control behaviour. The related window-control patterns will also be pointed out.

1.3.1 The environmental function of windows

Windows can affect occupant's physiological and psychological comfort, such as mentality, motivation and productivity (Biner et al, 1993). Providing views and light is the most basic function of windows. The ancient Chinese construction regulation and literature described that: A space surrounded by a roof and walls cannot be used as a room without windows, which can bring light into the room (Baidu, 2012). In a Chinese garden, a window can also be designed as a picture frame. It is like a portal that brings all the information related to weather condition, time of the day and seasonal change (Markus, 1967). CIBSE (1987) recorded that the size of window to achieve visual requirements of occupants should be considered firstly by designers. Bringing daylight and an external view into the room seems to be the window's fundamental function.

A field study was carried out in an office building in Izmir-Turkiye by Dogrusoy and Tureyen (2007). They examined six types of window (rectangular, square, round, vertical, horizontal and window-wall) and occupants' preference in this building. The result showed that majority of occupants prefer a glass curtain wall than a horizontal or square shape and dislike the round shape, because round-shaped windows would restrict the view and the round shape is also unpopular in the office. When the area of windows is over 30% of the wall, visual satisfaction could be achieved. In addition, factors which could affect the preference rate were also collected. The result showed that the top three factors were natural light, sunlight and natural ventilation, which can demonstrate the occupant's basic demand. The visual communication factor still played an important role as it can produce a psychological effect. Yildirim et al (2007) also agree on this point. They took a field survey in an open plan office building in Ankara, Turkey. The finding shows that occupants were more satisfied with the indoor environment when sitting near a window.

Windows not only provide daylight and a view to indoor space, but also influence indoor and outdoor energy transition. The energy lost through windows is over 3% of total energy consumption in the United States, 7% in Sweden (Collins et al, 1995, p.459) and 6% in the UK (Muneer et al, 2000, p.1). A computer simulation was undertaken by Ramachandraiah and R (2008), with the same environmental conditions (outdoor temperature was set at 37.6°C). The result showed that the highest indoor air temperature will rise to 34.5°C when single glazing was plotted in the model, and reduce to 30.25°C when double glazing with a low-e coating (e=0.1) was plotted. Approximately 4°C difference can be found, compared with single glazing and low-e double glazing. It clearly presents the importance of a window's thermal insulation for indoor temperature. Therefore, a good design of window can save 40%-50% of energy consumption in non-domestic buildings (Robbins, 1986). Windows with good energy performance can reduce energy consumption and provide comfort for the indoor environment.

The opening windows can provide fresh air, which is natural ventilation. It is an important environmental factor that can affect occupants' satisfaction and also have great potential for energy saving. Good indoor air quality is important to achieve indoor comfort and health. Opening a window is the simplest way to improve indoor air quality. Allard (1998) pointed out that increasing the indoor air flow rate (within occupants' acceptable limit of course) can reduce the indoor pollution level. A large amount of incoming air through windows could drop the indoor temperature and increase the energy performance.

Walker and White (1992) investigated the mean age of air in a single-sided naturally-ventilated office to evaluate the fresh air. The result showed that the fresh air was well distributed, but there were no more details of air velocities. The measurement of velocities and temperatures in a single-side ventilated office was taken by Eftekhari (1995). He found that high velocity (0.4m/s) and low temperature is near the floor and an opposite situation showed at head level. A computer simulation study of fresh air distribution in a single-side ventilated room (3×3×15m) was taken by Gan (2000). The external wind speed was set to 0m/s; only indoor buoyancy-driven air was considered. The size and position of the window and indoor heat gain would impact on the effective depth of air distribution, which varies between 5m and 15m in this case. The small size and low position of a window opening will reduce the effective depth, so as to lower internal heat gain. Although increasing indoor heat gain can extend the effective depth and produce better indoor air quality, it is restricted by the upper threshold of indoor comfort temperature which may cause the occupant to be uncomfortable. Controlling the opening size of the window can efficiently maintain the indoor air quality.

The window is an important component for a natural ventilation cooling strategy, which can control the air flow between indoors and outdoors. Givoni (1994) indicated that the effect of a window size is related to the building's ventilation strategy. Windows have a big effect in a cross-ventilated room, but a small one in a single-side ventilated room. However, different types of windows and opening modes provide different indoor airflow patterns. Heiselberg et al (2001) indicated that the indoor air velocity is related to window type, location and opening degree. Gratia et al (2004) used computer simulation to analyse the sufficient ventilation rate as a function of size, shape and position of windows on the facade. The results in this study showed that the cooling energy can be reduced by about 40% by applying natural ventilation in the night time. Therefore, the position of the window aperture had a significant impact on natural ventilation efficiency. It is better to locate the openings at different heights in a single-sided ventilated office, the same as the inlet and outlet in a cross-ventilated office. It was found in many studies that a well-applied natural ventilation strategy had great efficiency for energy saving in summer and also provided comfort for the indoor environment (Van der Maas and Roulet, 1991; Ding et al, 2005; Gratia and Herde, 2007; Yao et al, 2009). The energy usage in naturally-ventilated buildings is 40% less than in air-conditioned buildings (Energy Consumption Guide 19, 1993). More reviews of natural ventilation for thermal comfort will be discussed below.

1.3.2 Occupant window control behaviour

Occupant behaviour in buildings can have large impact on building energy use. Window control is one of the environmental adjustment methods for occupants to restore their personal thermal comfort in the buildings. Many field studies have investigated occupant window control behaviour based on different climates, regions and environmental stimuli.

From results of those studies, the indoor and outdoor air temperatures are the main environmental factors which influence occupant window control behaviour. A field study by Warren et al (1984) in five natural ventilation office buildings in the UK during 12 weeks in the heating season reported that 76% of window state changes were caused by variable outdoor temperature. The results of stimulus of small and large openings of windows found that the large opening was driven by outdoor temperature, while in contrast the small opening was mainly impacted by indoor air quality rather than outdoor temperature. Fritsch et al (1990) conducted a field measurement in four south-facing office rooms from October to May (heating period) in Switzerland. During the measurement period, the outdoor temperature dominated the window opening in winter, and a window's opening angle would rise along with the increase in outdoor temperature.

Nicol (2001) did a survey in six countries (France, Greece, Portugal, Sweden, the UK and Pakistan) crossing Europe and Asia; the control behaviour of windows, blinds, lighting, fans and heaters was investigated. The result showed that the proportion of window opening was closely related to the outdoor temperature in natural ventilation buildings. The highest proportion of window openings was in the UK. Occupants started to open windows when the outdoor temperature reached 10°C. Nearly half of the occupants had opened their windows at 22°C, and up to 80% of them had opened windows when the outdoor temperature rose to 33°C. Therefore, the variable outdoor temperature (such as season changes) has a direct influence on the frequency of windows being open and the opening percentage. Herkel et al (2008) conducted a field study in 21 individual offices in an office building in Germany, and then indicated that the largest opening percentage and the lowest frequency occurred in summer, in order to prevent the indoor temperature becoming over-heated. Meanwhile, during spring and autumn, window positions were changed more frequently than other seasons, which may be caused by rain or wind force; however, in the heating season, the frequency of windows' change, and the percentage and duration times of opening were limited, in order to maintain the indoor temperature.

Some researchers found that the indoor temperature was the main stimulus for occupant window control behaviour. According to a field study in 15 naturally-ventilated office buildings in the UK, Raja et al (2001) found that the window control behaviour was mainly related to the indoor temperature. When the indoor globe temperature rose to 20°C, the frequency of window opening started to increase. The frequency of window opening would increase to nearly 100% when the indoor globe temperature exceeded 27°C. A similar result had also been found by Yun and Steemers (2008) based on a field study in two natural ventilation office buildings in summer in Cambridge, UK. They indicated that the indoor temperature was the main driving force for the behaviour of window control. The frequency of window control rose when indoor temperature was over 22°C, and all the windows were open when the indoor temperature exceeded 26.3°C. And the main changes of window state occurred on occupants' arrival and departure, which related to the indoor temperature's stimulation. He also pointed out that no significant correlation was found between indoor temperature and occupant window control in the previous studies, which were conducted by Warren et al (1984) and Fritsch et al (1990), during the heating season as the indoor temperature was steady, thus the outdoor temperature would have a clearer influence.

Robinson (2006) pointed out that the indoor temperature in a building would differ because of different environmental conditions, such as orientation, number of occupants, equipment, etc. Thus, the indoor temperature has more influence on occupant window control behaviour.

According to these field studies, it can be seen that both indoor and outdoor temperatures have influence on occupant window control. Rijal et al (2007, 2008) indicated that the indoor temperature can be the main environmental stimulus. Occupants opened windows to reduce the indoor temperature and prevent the room becoming over-heated, which would cause discomfort. Except for the rain or gusts of wind, which may result in windows closing, outdoor temperature has an impact on the time the window remains open. For instance, in the heating season, a window is opened to bring fresh air into the room but kept closed most of time in order to reduce heat loss. In the summer time, occupants would have large windows open to promote air exchange between the indoor and outdoor environment in order to cool the indoor temperature. In addition, when the outdoor temperature is higher than the indoor, the frequency and proportion of window openings would drop, in order to reduce the hot air entering (Fritsch et al, 1990; Herkel et al 2008). Therefore, both the indoor and the outdoor temperatures have important influence on occupant window control behaviour.

Regarding the pattern of window opening in office buildings, it has been found in many field studies that window state changes mainly occurred on occupants' arrival and departure times, but rarely happened during the work period (Herkel et al, 2008; Yun et al, 2008; Haldi and Robinson, 2009). Occupants opened the window on the time of arrival because of the higher temperature indoors in the morning, especially in summer. And the indoor air quality could be another reason. However, Yin (2006) measured the indoor CO_2 level in two naturally-ventilated office buildings at the time that occupants arrived in the morning, and the result showed that the indoor CO_2 level was slightly higher than the outdoor but still within an acceptable range, but occupants felt it to be stuffy at the time they arrived. This may be because of occupants' perception that the air flow outside may cause them to feel fresh while temporarily unable to adapt to the indoor environmental condition when they first arrive at the office. Not many researches have been done to find the relationship between window control and indoor air quality, thus further work is needed.

The ventilation during the night time is a good solution to optimise the indoor temperature and air quality in the morning. Based on a field study in summer in Cambridge, UK, Yun et al (2008) and Yun and Steemers (2008) indicated that the frequency of window state change on arrival would drop 75% if occupants kept windows open when they left the office the day before; the frequency drops also cause window opening proportion to reduce.

In addition, if a window was kept open on departure, the measured lowest indoor temperature on the day following that window being left open was 19.3°C; if a window was closed when occupants left the office, the result shows the indoor temperature was over 22°C, and occupants would then open the window when they arrived at the office. The indoor temperature in the office with night time ventilation is lower than that without night time ventilation. During the monitor time, in the night time ventilation office the indoor temperature was over 25°C for 8% of the total measuring hours, even 6% lower than the outdoor temperature, but in the office without night time ventilation the result was 40%. In conclusion, night time ventilation can provide a better indoor environmental condition for the following day and impact on window control frequency (Yun and Steemers, 2008).

During the working hours, it was proved that relatively few windows would change state, while most of the windows remained in their state (open/closed) for a long time. The reason probably is that occupants have adapted to the indoor environmental condition since they arrived at the office, so that changing window state is not important to occupants' comfort sensation (Fritsch et al, 1990). Yun and Steemers (2008) found that the frequency of window state changes in a shared office with a single window was lower than in a single occupant office. When there are two or more occupants in a room, the behaviour of changing window state as appeared to be a group decision, so the window state remains during most of the time.

As Yun and Steemers (2009) pointed out, most of the window state changes also happened when occupants left the office, and leaving the window open is an important act to encourage night time ventilation. In the night-time-ventilated office building, none of the windows was fully closed in summer when occupants left the office. There were 86% of narrow open windows' state unchanged, and 72% of large open windows would change to a narrow opening. Except where the building is designed for night time ventilation, the occupants would close the windows when they left the office. Herkel et al (2008) found that at least 84% of occupants would close the windows on departure. The main reason for occupants to close the windows when they leave the office is for security, especially on lower floors which are easily targeted by burglars. Another reason is that the wind and rain could blow off or dampen papers. Yun et al (2008) concluded that the façade design has a close impact on occupants' window control and it can help to reduce the energy consumption. For example, the top hung window has a better rain-proof function than other window types, so it can be used for night time ventilation.

To sum up, indoor temperature has a significant impact on occupant window control at the arriving time, and the night time ventilation can reduce indoor temperature so that it provides a better indoor environmental condition. But occupants would close the windows when they left the office for security reasons and to prevent wind and rain from penetrating. Therefore, a well-designed façade is needed for applying night time ventilation.

There was a large gap between the predicted energy use and the actual, found in field study by Branco et al (2004): the actual energy use ($246MJ/m^2$) was 50% higher than the predicted result ($160MJ/m^2$). The difference is due to the real performance of the technical system and occupants' use behaviour. Thence, more studies on the occupant behaviour can help to narrow the gap between the real and the predicted energy use. According to the field studies, some predicted models regarding occupant window control behaviour have been developed in order to carry it into computer simulation to evaluate building thermal performance. Fritsch et al (1990) developed a stochastic model of window opening angle based on the field investigation in offices in Switzerland in winter. The hours both during and after work time were investigated. However, this model is only suitable for the heating season rather than summer time. Based on the field work in six countries across Europe and Asia, Nicol (1990) developed a probabilistic model of occupants' control of windows, blinds, lights, heaters and fans, with the outdoor temperature been used as a main stimulus. An algorithm was proposed which can be used to predict the occupant control behaviour.

Based on Nicol's (2001) regression model and the field study in 15 office buildings in the UK, Rijal et al (2007) made some improvements and proposed the 'Humphrey algorithm'. The algorithm assumed that the window control behaviour is based on the occupants' response to achieving comfort. According to the survey data, they defined within ±2K of the comfort temperature as a 'deadband' (representing how long the window state remained unchanged) for indoor temperature, as an adaptive approach. The adaptive algorithm for window control was proposed later (Rijal et al, 2008). Haldi and Robinson (2009) pointed out that, in summer, the close relationship between the indoor and outdoor environment will reduce the efficiency of the 'Humphrey algorithm'. This is because in the 'Humphrey algorithm' this adaptive behaviour such as using fans and cold drinks was not accounted in the survey, which will affect the accuracy of the algorithm. However, the 'Humphrey algorithm' still provides a method and standard to evaluate the occupant behaviour of closing or opening windows which is related to the indoor and outdoor temperature. And it still can be applied in dynamic thermal and energy simulation tools. Based on a long-term field study in office buildings in Lausanne, Switzerland, Haldi and Robinson (2009) developed an algorithm for occupant window control behaviour correlated to indoor temperature, outdoor temperature, relative humidity, rainfall, wind speed and direction.

Yun and Steemers (2008) pointed out that Nicol's (2007) regression model can be used to predict the numerical openings of windows, but not for the single window state; for instance, how long an individual window remained open or closed. It means there is no relationship between the previous and the current window state. Based on the field work, they developed a stochastic model to predict occupant window control behaviour as a function of previous window state, indoor temperature and different time periods. Besides, Martin (1996), Herkel et al (2008) and Yun et al (2008) also developed/improved their window control algorithm related to different environmental parametrics. All these occupant window control models which correlated with different environmental factors were developed by researchers, in order to be implemented into computer simulation to help designers to predict occupant behaviour's impact on building thermal performance in order to design comfort and energy-saving buildings.

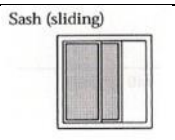
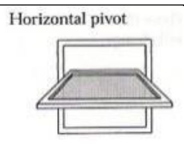
1.3.3 The effect of façade design on window control behaviour

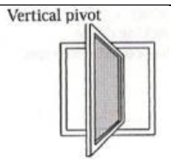
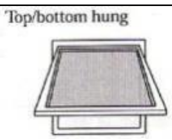
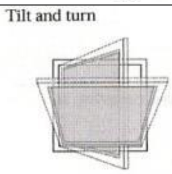
It is known that the façade design has a close relationship with occupant window control behaviour and natural ventilation. It contributes to both embodied energy and operating energy in buildings (Amato, 1996). Natural ventilation is a passive cooling method to reduce indoor temperature and help occupants achieve comfort. Occupant behaviour of window control which can influence the indoor air flow by adjusting window and it would result in indoor convective cooling effect.

Different window types provide different opening configurations, adjustable ranges of opening size, weather protection features, etc. All these different characters have various effects on air flow rate and air flow pattern. The type of window fitted in the building has a direct influence on the indoor environmental condition, and it is mainly decided by architects. A good understanding of the features of different window types can help the architect to make the right decision. Some main window types and their related features are shown in Table 1.2. The window with horizontal pivot and top/bottom hanging is relatively suitable for rainy climate conditions, as it has better protection from rain when it is open. For some places that need more ventilation for cooling the indoor temperature, the window with adjustable and large effective opening size should be considered, such as casement and vertical pivot window. On the windward side these kinds of window can be used as a wind wall, which can make the indoor air flow speed as low as 40% of the outdoor (Givoni, 1976).

Besides, the bottom-hung window can only be set to be open or closed, as the open size is fixed, and no adjustability can be made. Some types of window, such as the pivot window and the bottom-hung window, may affect the indoor furnishing, because the window will open inward (Roetzel et al, 2010). Not many studies have been done on the relationship between occupant window control behaviour and window types, open angle, and placement. Fritsch et al's (1990) field study correlated the ambient temperature with the window open angle and found that the window open angle is closely related to the outdoor temperature, and the increase of open angle is consistent with the rising of the outdoor temperature. The stochastic model was developed to predict the window opening angle. To sum up, the window type is closely related to the indoor environment, and fundamentally impacts on air change rates between the indoor and outdoor environment and occupant window control behaviour.

Table 1.2: The main window types and features (CIBSW AM10, 2005, p.26).

Sash (sliding)		These windows provide half of the opening area for ventilation. Givoni (1994) pointed out that the horizontally sliding window reduces control of the indoor air flow pattern, because the horizontal air flow fluctuation is larger than the vertical direction.
Horizontal pivot		Vertical air flow patterns are controllable in these windows types and supply high ventilation content. The structure opening area is 34% when the opening tilt angle is 20°. Givoni (1976) indicated that, if changing the tilt angle, it is possible to change the indoor air flow pattern and distribution air

		velocity.
Vertical pivot		These types of windows are similar to the horizontal pivot. The opened window can be used as a wing wall. But, rain may be a problem for these windows.
Top/bottom hung		These windows are more flexible for automatic control. The top hung window is better for day time ventilation, because the low level opening can modify the air flow pattern through to the occupant. The bottom hung and inward opening is good for night ventilation.
Side hung (casement)		Similar to the vertical pivot window, and the ventilation pattern is closely related to air velocity and wind direction. Givoni (1994) pointed out that two casement side-hung windows may obstruct the air flow, when both casements are opened.
Tilt and turn		These windows offer a poor ventilation character in both summer and winter. "It was reported that the setting of tilt angle provides too much ventilation in winter and insufficient cooling for occupants in summer" .

Karava et al (2004) stated that the window opening type, angle and shape are related to the discharge coefficients which would impact on air exchange rate, as same as the opening size and the placement of opening on the façade. Yin et al (2010) compared different window openings in a typical cellular office building in China by computer simulation in order to calculate natural ventilation potential. The result showed that the opening size and placement of an opening window on the façade has significant impact on natural ventilation rates. Thus a well-designed window opening can extend the natural ventilation time and reduce the cooling hours in summer.

Gratis et al (2004) indicated that, in a single-side ventilated office, windows at different heights can provide a much higher air exchange rate than other window placement methods, because the buoyancy driven can move the air out of the window on the higher level when the external wind speed is very small or nil. A field study was conducted by Herkel et al (2008) in 21 south-facing naturally-ventilated offices in Germany, in which windows were at different heights on the façade with the small bottom-hung window on the top levels and the large tilt and turn window at the lower level. They found that small windows have longer remaining open times but are opened less than larger windows. Therefore, the small windows are mainly used for night time ventilation, while the large window is closed. However, when the outdoor temperature was above 10°C, the open percentage of small windows is much higher than large windows; when the temperature rises over 20°C, 80% of the small windows and about 20% of large windows are fully opened. Occupants seem to prefer to open small windows rather than large ones. This kind of occupant behaviour may result in the impact on indoor air flow pattern or air flow speed. Therefore, the façade design would impact on indoor air temperature, air flow speed, and air flow pattern, which can stimulate occupants' control of windows. Still, the impact of façade design on occupant window control behaviour needs further studies.

1.4 Thermal comfort and natural ventilation

Thermal comfort threshold in hot and humid climates would be limited by high humidity, which will restrict the evaporative heat loss from the skin and cause discomfort (Szokolay, 1985). But increasing the air flow speed around occupants can boost the evaporative heat loss from the skin; it would replace the humid saturated air around the skin with fresh and unsaturated air (Szokolay, 1987). So, increasing air flow speed can help occupants to achieve thermal comfort.

1.4.1 Comfort threshold in hot and humid climates

A field study of thermal comfort was conducted by de Dear et al (1991) in Singapore. In this study a naturally-ventilated residential building and an air-conditioned office building were investigated. It was found that the upper temperature threshold is 31°C in a naturally-ventilated residential building and 26.7°C in an air-conditioned office building. Based on a similar field study by Busch (1992) in Bangkok, Thailand, the upper temperature threshold is 28°C in an air-conditioned office and 31°C in naturally-ventilation offices. And the daily mean relative humidity range is 53%-94%, with the daily mean temperature from 20°C to 35°C

(Pearce and Smith, 1984). A similar result was found by Jitkhajornwanich et al (1998) in Bangkok, that the upper temperature boundary is 31.5°C. Zhang et al (2010) indicated that in Guangzhou, China, the upper temperature boundary is 30.5°C with the relative humidity around 70% and the air temperature ranging from 28.8°C to 34.6°C in summer. Comparing these comfort temperatures with the ASHRAE adaptive standard (2004), it can be seen that all these results are higher than the comfort temperature presented by ASHRAE (2004). Givoni (1998) explained that it is because of the acclimatisation. Thermal comfort would be influenced by the ambient environment, cultural context and occupant experience. People would adapt and tolerate the local climate condition when they live in this region for a long time. Thus, people who live in the hot and humid climate can accept a higher humid and hot environment than those people from other climate conditions. This is the reason that, in a hot and humid climate, the upper boundary of acceptability of humidity and temperature is higher than the comfort threshold identified by ASHRAE (2004).

1.4.2 The effect of humidity on thermal comfort

Humidity is an important environmental factor that would influence people's thermal comfort, and is closely related to indoor health issues and energy consumption. A highly humid environment could reduce the evaporation rate, and cause germ growth, leading to the degeneration of building material. A low humidity environment could cause irritation and dryness in the eyes and respiratory tract, especially some membranes (Toftum et al, 1998; Nicol, 2004). Sunwoo (2006) suggested that the relative humidity should be above 30% to avoid dryness of the mucous membranes, which is the main cause of irritation of the eyes and upper air ways.

A highly humid environment would also affect occupant perception of the air quality (Fang et al, 1998). This was proved by Berglund and Cain (1989). They provided a space with cool and dry air to evaluate occupants' perceived air quality. The result showed that the perception of air quality dropped along with the rising of the temperature and humidity. It caused an unacceptable sense of air quality when the relative humidity was over 65%. This may be one of the reasons that occupants still felt stuffy and felt the air quality was poor in the office although the measured indoor air quality was at an acceptable level in Yin's (2006) work. A highly humid environment would also lead to health problems as it can evoke mould growth, which causes respiratory discomfort and increases the risk of allergies. The respiratory- and allergy-related health issues, especially asthma, would be increased by 30%-50% because of the dampness and mould in buildings (Fisk et al, 2007). A field survey conducted by Kishi et al (2009) in six different regions in Japan showed that the risk of Sick House Syndrome would be increased when several dampness conditions appeared, such as condensation, visual mould growth, water leakage and mouldy odour.

Apart from the influence on indoor air quality and health, the humidity would affect occupant thermal sensation under certain conditions. According to the investigation on the effect of relative humidity on thermal comfort, de Dear et al (1991) found that, in the same clothing value (0.6clo) and activity level, the subjects could not feel the difference when the relative humidity was set at 35% or 70% (temperature at 25°C-30°C). Similar to ISO EN 7730 (1994) and CEN EN 15251 Standard (2007), the effect of humidity on the thermal comfort is rarely important. The EN ISO 7730 (1994) showed the range of humidity for indoor air quality is from 30% to 70%. In China's national criteria (2005), which is based on the ASHRAE Standard, the indoor relative humidity is set at 40%-65% in summer and at 30%-60% in winter. In cold areas, the measurement taken by Kuchen and Fisch (2009) showed the same result that, when the relative humidity is between 30%-70%, the change of relative humidity was unable to cause a significant difference on the thermal comfort. Thus, there is no significant impact on occupant thermal comfort when the relative humidity varies between 30% and 70%, especially within the comfort temperature range (Nicol, 2004). And in the European context the impact of humidity is limited as well: "Humidity has only a small effect on thermal sensation and perceived air quality in the rooms of sedentary occupancy" (2007, p.16).

Humidity does not have a direct impact on occupant heat balance or physical response to the surrounding environment, but it would impact on the evaporation potential of the environment. At the high humidity level, it would reduce the evaporative capacity of the air, and decrease the ability of taking evaporative heat from the skin, which would cause the occupant to be uncomfortable (Givoni, 1998). Regarding the influence of high humidity on thermal comfort, Bo (2005) indicated that, when the relative humidity is above 70%, every 10% rise in relative humidity pushes up the air temperature by 0.4°C with the premise that the outdoor temperature is above 28°C. Nicol (2004) concluded that the primary impact of high humidity is narrowing the area of thermal comfort. Therefore, 1°C lower than the comfortable temperature should be provided when the relative humidity is high.

Givoni (1998) proposed the humidity scope for thermal comfort, which is separated by developing countries and developed countries based on his field studies in Europe, the USA and Israel. This is because people living in developed countries have better living environments than in developing countries so that they would expect a more comfortable environment; and the low expectation can increase the occupants' psychological comfort level, conversely the high expectation would decrease the comfort level (Nicol, 2004). Givoni (1998) indicated that in developing countries in summer, on the still air condition (less than 0.25m/s) the relative humidity could rise up to 80% at maximum and the absolute humidity is 17g/kg, the upper temperature threshold can rise to 29°C when relative humidity is below 50%; while on the little breeze condition (2m/s), the relative humidity could rise to 90% and 19g/kg for absolute humidity, the upper temperature threshold can rise to 32°C when relative humidity is below 50% (Figure 1.16).

The boundary for developed countries is more restricted. In summer, the upper boundary of relative humidity is at 80% for both the still air and the little breeze condition. The absolute humidity increased from 15g/kg to 17g/kg when little breeze is achieved, and the upper temperature threshold is 27°C and 30°C when relative humidity is 50% (Figure 1.17). The comfort area for humidity is also indicated in the ASHRAE 55 adaptive comfort standard (2004), the absolute humidity being used to assess the comfort zone. It pointed out that the comfort moisture range should be between 4g/kg and 12g/kg, and the upper limit of comfort temperature in summer can extend from 26°C to 27°C, if the absolute humidity can reduce from 12g/kg to 4g/kg. However, as indicated in the last section that many field works have been carried out in hot and humid climate were found that the occupant live in this climate can tolerant high humidity level than other the people from other climate condition (Busch, 1992., Jitkhajornwanich et al, 1998 and Zhang et al, 2010). Hwang et al (2009) and Liang et al (2012) have taken field survey in Taiwan were even pointed out that the indoor humidity level did not have significant impact on occupant thermal sensation, because the occupant was continuous and consistent expose in the humid climate and they can acclimatize the local climate condition.

1.4.3 The effect of air flow speed on thermal comfort

Air movement can increase the heat convection between the human body and the ambient environment, so that it takes away the heat by evaporating perspiration. The average skin temperature is 32°C-34°C when people are doing light activity, and the physical evaporation rate is based on air velocity and vapour press. The increase of air velocity can speed up the evaporation rate; while the evaporation rate will be decreased merely under high vapour pressure. Providing a cooling effect by increasing air movement can be achieved as long as the air temperature is lower than skin temperature (Szokolay, 1987). Therefore, providing air movement is an important method to reduce cooling load and achieve comfort, especially in hot and humid climates, in which the evaporation is predominant (Nicol, 2004).

Aren et al (1980) indicated people's thermal sensation in the conditions of different air velocities. In his survey (in the summer) with the environmental condition at 50% relative humidity, 29°C indoor temperature and 1m/s air velocity, the occupants still feel comfortable when they are seated (1.3met) and wearing summer clothing (0.4clo). The comfort temperature can reach 30°C, when the air velocity rises to 2m/s. A theoretical analysis by Humphreys (1970) provided an equation of the relationship between the air velocity and the change of equivalent comfort temperature, in which the air flow should steady above 0.1m/s. That is because the result is meaningless when the air velocity is below 0.1m/s as the air movement related to the body is mainly driven by the body's movement or the natural convection (Equation 1.10, Figure 1.10). Where T (°C) is the change of equivalent comfort temperature and v (m/s) is air velocity.

$$T = 7 - \frac{50}{40 + 10v^{0.5}} \,℃$$

Equation 1.10: Air velocity and the change of equivalent comfort temperature.

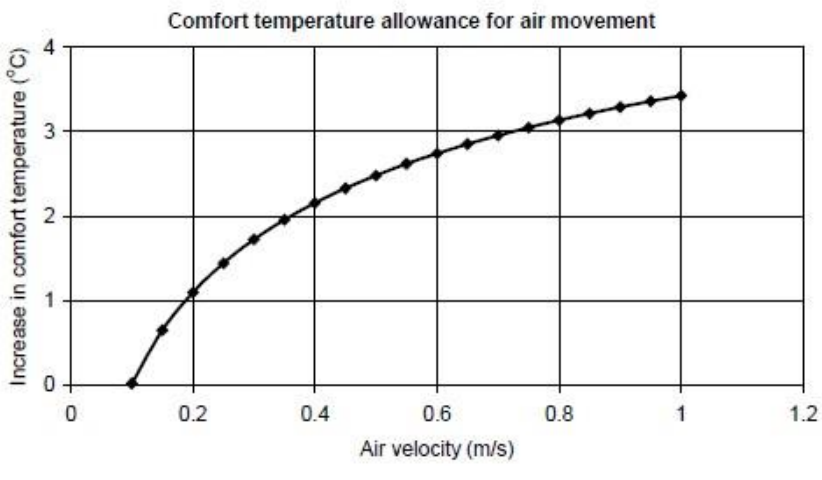


Figure 1.10: The correlation between comfort temperature and air flow speed defined by Humphreys 1970 (Nicol, 2004, p.101).

Szokolay (1985) also proposed the relationship between thermal factors and compensatory measures: the indoor air temperature would be increased by 0.6°C according to the increase of air flow by 0.005m/s, when the air velocity is above 0.15m/s. Bo (2005) found that when the temperature is above 26°C and the wind speed below 0.8m/s, thermal temperature will drop 0.55°C along with the air flow speed increasing to 0.15m/s. Givoni (1998) used a building bioclimatic chart (BBCC) to show the thermal comfort in both the developing and developed countries under the still air condition (less than 0.25m/s) and the little breeze condition (2m/s). He found that the upper temperature boundary is 3°C more in the little breeze condition. So it can be concluded that the rising of air velocity can extend people's comfort area. The air speed at 0.25m/s is suggested by CIBSE AM10 (2005) to be sufficient to maintain occupant thermal comfort in summer.

Many studies proved increasing air movement is conducive for occupants to achieve comfort (Nicol et al, 1999; Zain et al, 2007; Hwang et al, 2009). However, a high air flow speed indoors might cause some other problems, for example, paper might flap, which is not desirable, particularly in office buildings. EN ISO 7730 standard (1994) suggested that the air flow speed should not be over 1.5m/s in office buildings. According to Nicol and Humphreys' (2010) field study, the average indoor air velocity cannot reach that higher speed in generic free-running office buildings. They pointed out that the measured indoor air velocity is from 0 to 2.1m/s and the average air speed is 0.09m/s in the SCATs (Smart Controls and Thermal Comfort) data, which was gathered from 26 European offices in France, Greece, Portugal, Sweden and the UK. In the field measurement, some subjects did use air movement to reduce the effect of high temperature, but in merely 38% of cases the air velocity is above 0.1m/s with the maximum at 0.17m/s, which means the air movement was minimal. A similar result can also be found by de Dear and Auliciems (1985), that the measured average air flow speed in the building in the humid tropics climate was 0.22m/s, which was not as effective as the predicted result. Therefore, in many field studies in free-running buildings, fans are highly used by occupants to provide constant air movement so as to improve occupant thermal comfort (Sharma and Ali, 1986; Goto et al, 2007; Indraganti, 2013). In the field study in Pakistan, Nicol et al (1999) found that, when the average indoor air flow speed is about 0.45m/s with fans, the upper comfort temperature limit can increase by 2°C. In EN Standard 15251 (2007), it was suggested that in summer for those buildings without HVAC systems, the mechanical ventilation without conditioned air can be applied as a low energy method for occupants to control their environment.

1.4.4 Natural ventilation strategy in office building

Different indoor ventilation strategies will affect the indoor ventilation efficiency and air flow pattern. Three types of ventilation configuration were indicated by Baker and Steemers (2000): single-sided ventilation, cross ventilation and stack ventilation. In generic office buildings, single-sided and cross ventilation are widely used.

Single-sided ventilation is applied in a typical single room. The air enters and leaves at the same side of the room. The room can be efficiently ventilated if the depth of it is about twice than the floor height. The wind is the main driving force in summer and the thermal stack effect in winter to achieve minimum fresh air. Double opening is another form of single-sided ventilation. Due to the height difference of openings, the thermal buoyancy and wind pressure would cause the pressure difference between the two openings, and then encourage the stack effect. The double opening type will give ventilation depth for three times floor to ceiling height (Baker and Steemers, 2000). This opening type is more efficient than the single opening. Compared with two other configurations, single-sided ventilation is the simplest and the most inexpensive but is low in efficiency (Figure 2.2).

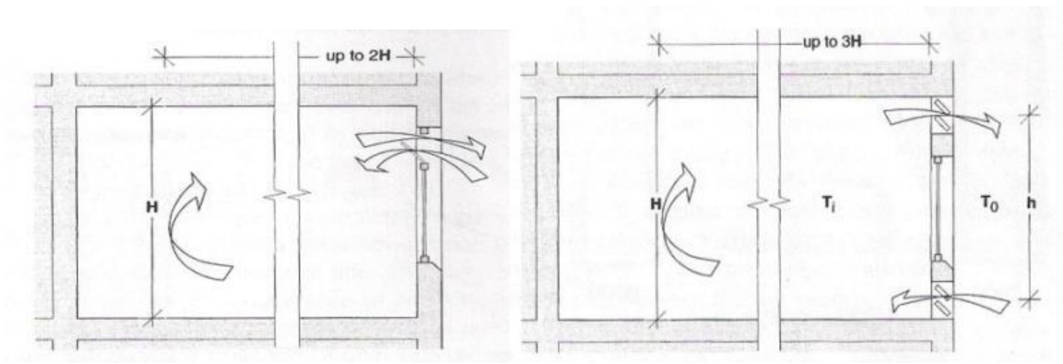


Figure 1.11: Single-sided ventilation forms (Baker and Steemers, 2000, p.58).

Cross-ventilation is a relatively effective method. The ventilation openings are on both sides of the office. Air flows from one side of the opening to the other side. Wind pressure is the main driving force. The pressure difference between two opposite openings brings air flow across the entire room, and at the same time carries off the heat and pollutants from indoors. So the windward and leeward pressures are important elements for cross-ventilation. In addition, the open layout is recommended to have a maximum depth of space about four times than the height (floor to ceiling). But the indoor furnishing or partition may restrict the air flow and affect the ventilation efficiency (Baker and Steemers, 2000) (Figure 2.3).

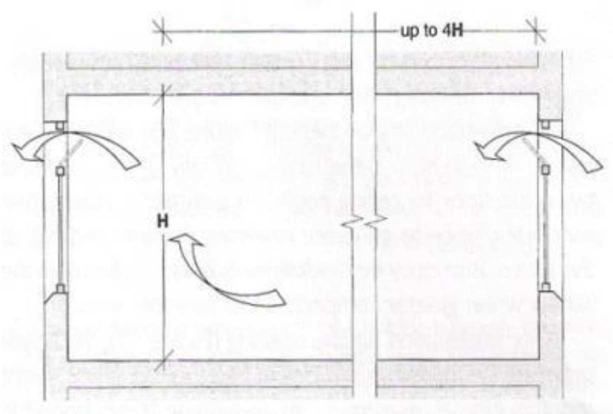


Figure 1.12: Cross-ventilation form (Baker and Steemers, 2000, p.58).

Stack ventilation is driven by the thermal buoyancy and the wind pressure. The fresh air enters the building at low level and the exhaustion at high level of the building, so the room is cross-ventilated (Figure 1.13). It is often used in buildings with a chimney or central atrium. The height of the outlet needs to be located at least half of one storage height above the top floor, in order to achieve the required air-flow rate without an enormous ventilation aperture (CIBSE AM10, 2005).

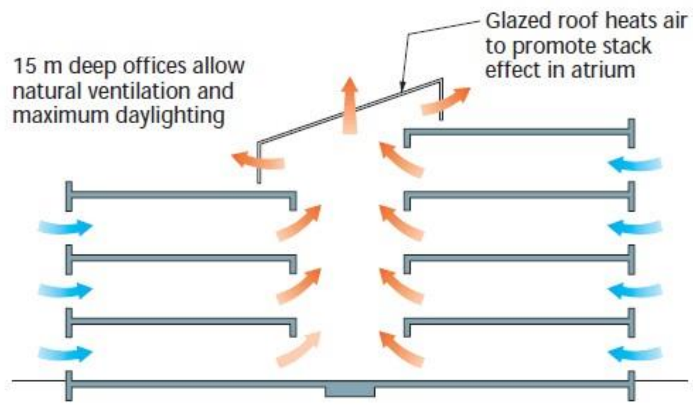


Figure 1.13: Stack ventilation form (CIBSE AM10, 2005, p.18).

1.4.5 Bioclimatic design method for building design

The bioclimatic chart demonstrated the relationship between these four environmental factors which are closely related to people's thermal comfort: dry-bulb air temperature, relative humidity, air flow speed and mean radiant temperature. Olgyay (1963) proposed the first bioclimatic chart in 1953 (Figure 1.14) which correlated occupant thermal comfort with outdoor environmental factors. The bioclimatic chart uses dry bulb air temperature and relative humidity to demarcate whether the environmental condition is in the comfort zone or not. The vertical axis is the dry bulb air temperature and the horizontal axis is the relative humidity, the shadow part shows the comfort zone. In the bioclimatic chart, the mean radiant temperature is assumed to be similar to the air temperature, so the building is well protected from solar radiation and with good thermal insulation, and a light colour for the external wall and roof. In this comfort zone, the air flow speed is considered as still, and the occupant is wearing normal seasonal clothing and doing gentle activity. However, the comfort zone in the bioclimatic chart is not absolute. It varies with air flow speed, solar radiation, changes of clothing, activity level, etc. The extended area of the comfort zone shows required air flow speed: the higher the air flow speed the more the comfort area can be extended. The lower boundary of the comfort zone also defines that the shading device needs to be considered when the temperature is above 21°C. The area below the comfort zone means the environment is cold, and the extended area shows that the radiation needs to extend the comfort area, if the temperature is below the comfort zone (Figure 1.14). Olgyay's bioclimatic chart clearly presents the correlation between environmental factors and the thermal comfort. This method can help designers to achieve a comfortable environment.

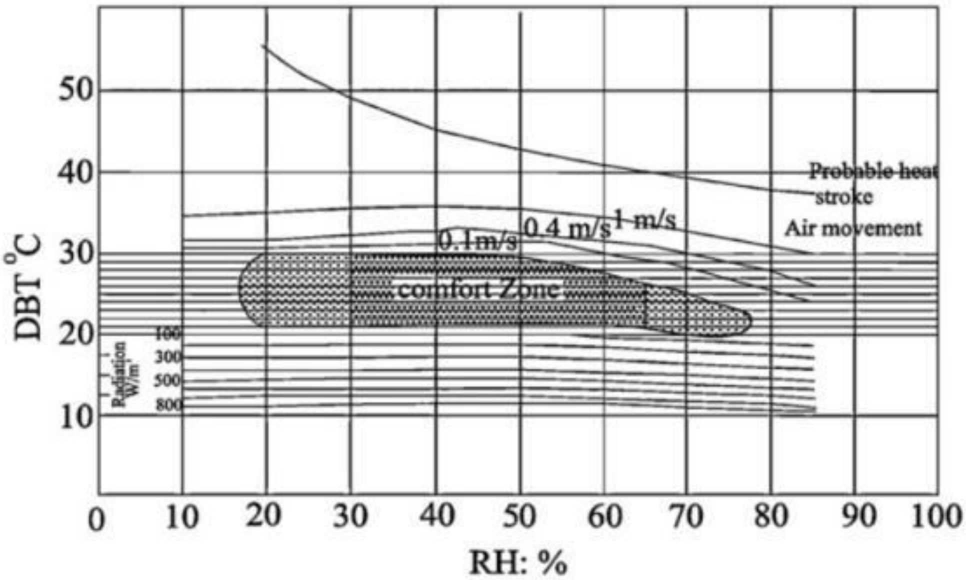


Figure 1.14: Olgyay's bioclimatic chart (Koenigsberger et al, 1974, p.51).

However, there are some limits in Olgyay's bioclimatic chart as the comfort zone in this bioclimatic chart is related to outdoor environmental conditions, not indoor ones. The indoor environmental condition could be affected by construction material, environmental design strategy, indoor furnishing, etc. Therefore, Olgyay's bioclimatic chart is suitable for naturally-ventilated buildings with a light structure and in a hot and humid climate in which the indoor and outdoor environmental condition is quite similar. But it is not really suitable for the heavy-structured buildings which may have a large temperature difference between indoors and outdoors (Givoni, 1976).

Based on Olgyay's bioclimatic chart, Givoni (1976) aimed to predict the indoor environmental condition using the outdoor prevailing environment condition and proposed his BBCC (Milne and Givoni, 1979) (Figure 1.15). All the psychrometric relationships in the chart are maintained, and different passive design methods for various climates with relative boundaries of comfort area are combined within the psychrometric chart. The methods include natural ventilation cooling, passive heating, thermal mass and evaporative cooling. The mechanism method, which needs little electric energy, was suggested when the environmental parameters are located outside those comfort boundaries. For instance, a ceiling fan could be applied if the environmental condition is out of the 'natural ventilation' area. And the comfort zone in this bioclimatic chart could achieve 80% of the occupant's perceived comfort. According to his field study, it also was pointed out that people living in different regions can acclimatise well in their local climate. For example, people living in a humid region can tolerate a high humid environment better than people in other climates. This is supported by the adaptive thermal comfort theory, which was proposed by de Dear and Brager (1998). But Watson (1983) indicated some limitations of Givoni's building bioclimatic chart: that it is not suitable for buildings with a large amount of internal heat gain, and also it is assumed that the indoor mean radiant temperature and the vapour pressure are close to the outdoor environment, and the upper boundary of the natural ventilation zone is in accordance with this assumption.

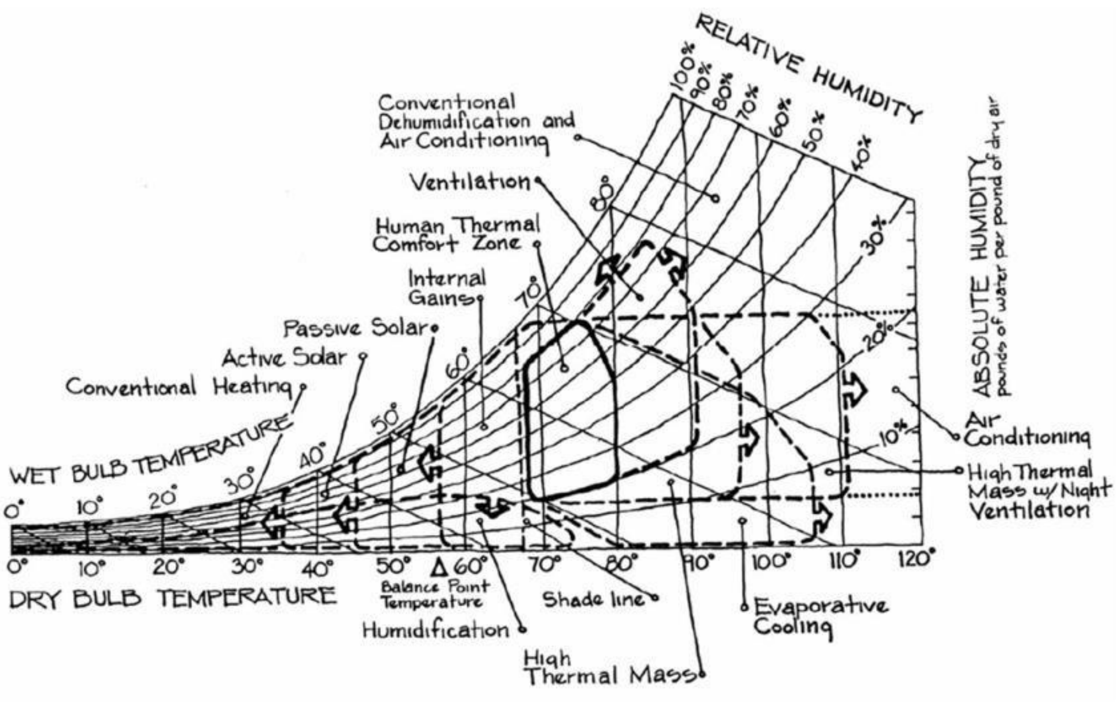


Figure 1.15: Bioclimatic chart by Givoni and Miline (Guthrie, J, 1995, p.107).

Givoni (1992, 1994) further developed the bioclimatic chart which is used to evaluate the thermal comfort in a hot and humid climate (Figure 1.16, Figure 1.17). The method of natural ventilation for cooling is highlighted, to test whether natural ventilation can help on the environmental comfort in the office. In general, Givoni (1992) divided thermal comfort envelopes by developing and developed countries into two conditions: still air (air flow speed below 0.25m/s) and light breeze (2.0m/s), according to his field study. The details of humidity and air flow scope of the comfort zone in the BBCC are presented in sections 1.4.2 and 1.4.3.

Lomas et al (2004) examined Givoni's BBCC in developed countries in an office building for cooling purposes. Compared with the condition predicted by the thermal simulation model, the differences were discussed and an environmental design strategy for different types of non-domestic building and climatic boundary on the BBCC for buildings was proposed. It is suggested in their report that the thermal simulation modelling could be used to deduce from BBCCs some different cooling ventilation strategies for different types of non-domestic building. And thermal comfort evaluation can be achieved by plotting the predicted temperature and relative humidity from thermal simulation into the BBCC.

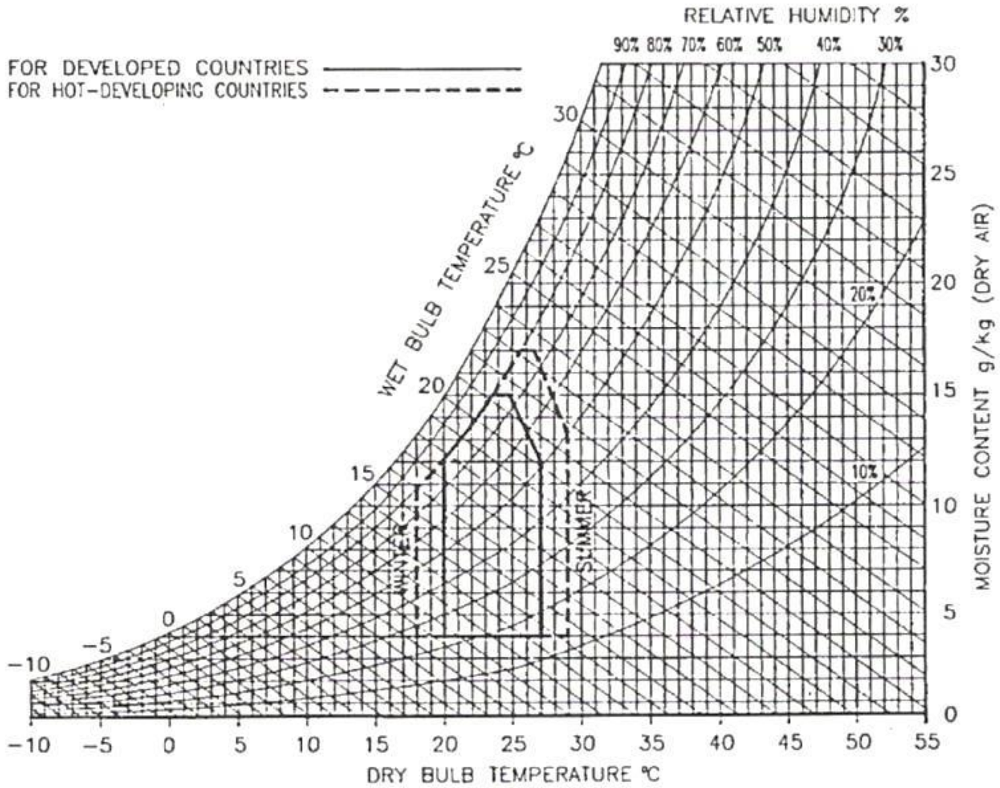


Figure 1.16: Boundaries of the comfort zone for still air conditions for summer and winter, for temperate climate and for hot climate (Givoni, 1992, p.15).

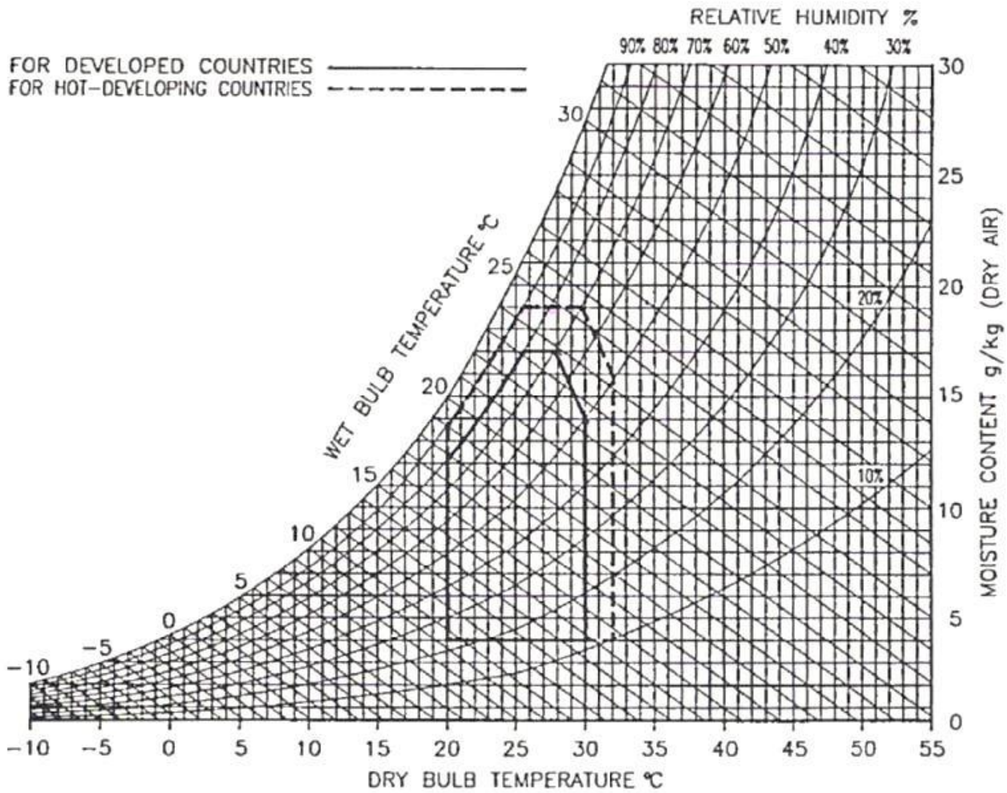


Figure 1.17: Boundaries of the comfort zone for ventilated buildings. Assumes air speed about 2m/s (Givoni, 1992, p.16).

The comfort standard for American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) has also been widely used to assess occupants' thermal comfort. The standard is mainly intended for people with sedentary activity, such as office work. The metabolic rate is less than or equal to 1.2 met, the clothing level is 0.5clo for summer and 1.0clo for winter. Based on these conditions, ASHRAE55-1992 (1992) indicated that the lower operative temperature (operative temperature: the average temperature of indoor dry bulb air temperature and radiant temperature) for thermal comfort in winter is 20°C and the upper operative temperature for thermal comfort in summer is 26°C. The upper humidity level is limited by 18°C wet bulb temperature in winter and 20°C wet bulb temperature in summer, while the lower humidity level is limited by the humidity ratio which is 4g/kg in both winter and summer. Besides, the ASHRAE55-1992 limited the indoor air flow speed as 0.2m/s, which means the average indoor air flow speed in the naturally-ventilated office would easily exceed the limit and would not be admissible under the ASHRAE55-1992 standard (Figure 1.18). The ranges are based on 80% acceptability and 10% dissatisfaction.

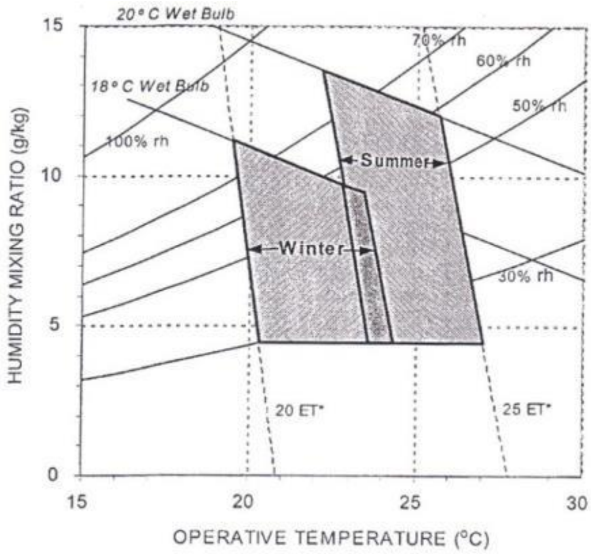


Figure 1.18: The comfort zone for ASHRAE55-1992 (de Dear and Schiller, 2001, p.101).

Because the ASHRAE standard is based on the extensive research conducted in climate chambers, many researchers found that the occupant comfort zone in the field measurement is wider than that in the ASHRAE55-1992 standard. Thus, the adaptive comfort standard is incorporated into ASHRAE55-2004 which is in accordance with de Dear and Brager's (1998) field measurement results sponsored by ASHRAE (more details were discussed in section 1.2). The comfort zone for ASHRAE55-2004 (2004) is shown as Figure 1.19. The comfort temperature for the adaptive standard is presented in section 1.1.2 with Equation 1.7. The upper humidity level is limited by a humidity ratio which is 12g/kg, and it is returned to the upper limit used in the ASHRAE55 1981 standard. But there is no recommendation for the lower humidity limit. And on the psychrometric chart, the lower humidity limit is close to 0g/kg, which is too dry and would cause discomfort. The ASHRAE Handbook (2009) suggested that the general agreement of the lower humidity ratio of 4g/kg or dew-point temperature of not less than 2°C can be used for the lower humidity limit, which has not been changed since the previous ASHRAE55 standard.

The air flow speed for the comfort zone in Figure 1.19 would not exceed 0.2m/s. If the air flow speed is above 0.2m/s, then the compensation for temperatures above the upper limit of operative temperature is shown in Figure 1.20. The increase of air flow speed is affected by the difference between the radiant temperature and the dry bulb air temperature. The curve in the figure shows different levels of radiant temperature and different dry bulb air temperature. When the radiant temperature is lower than the dry bulb air temperature, then the increase of air flow speed shows little effect on the temperature increase. Conversely, when the radiant temperature is higher than the dry bulb air temperature, then increasing the air flow speed is more effective for a given temperature rise. Increasing the air flow speed may be used to compensate for an increase by up to 3°C above the upper limit of the temperature for occupants with sedentary activity and at the same time the air flow speed limit is about 0.9m/s.

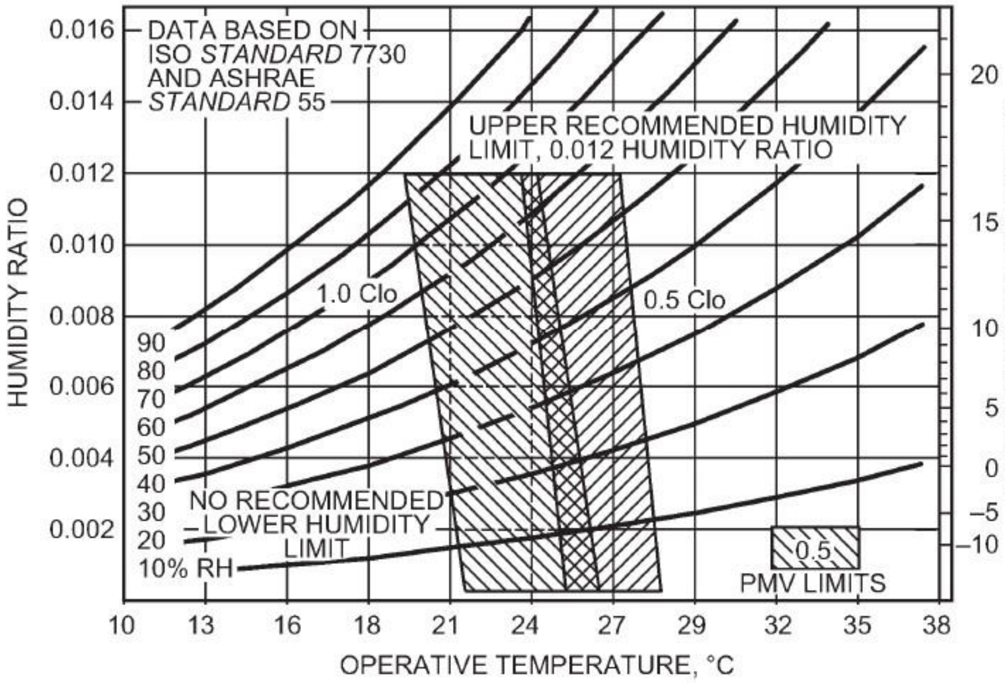


Figure 1.19: The comfort zone for ASHRAE55-2004 (ASHRAE55, 2009, p180).

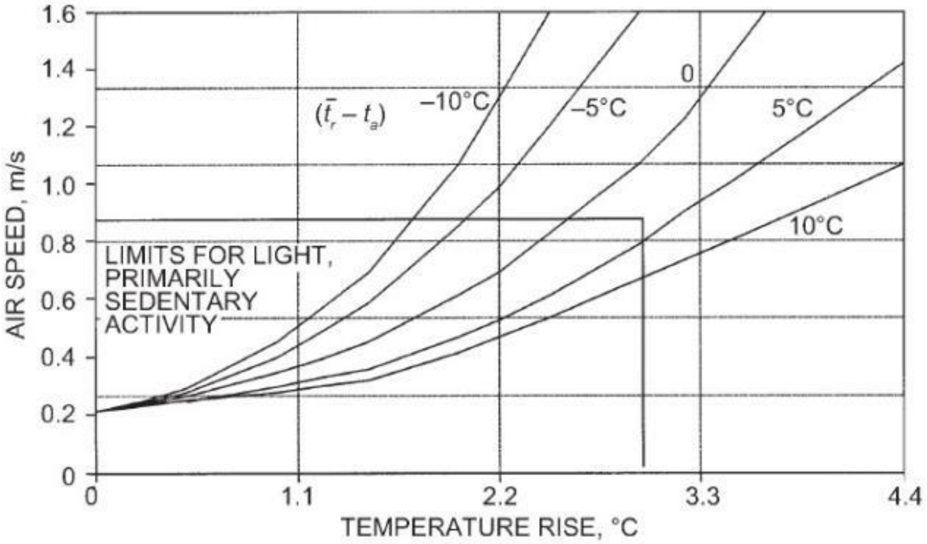


Figure 1.20: Air flow speed to compensate for temperature above the upper temperature limit in the comfort zone (ASHRAE55, 2004 p.7).

2 Parametric Study of Single-side and Cross Ventilation in Offices

In order to understand the building thermal performance related to free opening area, this chapter investigates the impact of different free opening sizes and different glazing areas of windows on thermal performance in generic office buildings in South-East China. The aims of the parametric study are to define an free opening area for natural ventilation in an office building which is related to glazing ratios, to identify air flow rates as a function of temperature difference, wind speed difference and wind direction in the office building, and to identify the frequency of indoor comfort temperature range by different glazing ratios and opening sizes in the south-east of China.

2.1 Method and apparatus

The parametric study is separated into two parts, the single-side ventilation model and the cross-ventilation model. In each model, the steady state study and dynamic study are used. In the steady state study, the empirical expression is used to calculate the air flow rate and free opening area in the office, to give a general view of the relationship between air flow rate and free opening area. Besides, different air flow speeds, different building orientations and ventilation strategies were considered. The empirical expressions are based on CIBCE AM10 (2005) and CIBCE Guide A (2006). The calculation is divided into three cases: air flow driven by thermal buoyancy, wind, and both thermal buoyancy and wind combined. In each case, the indoor and outdoor air temperature difference is divided into 3°C, 5°C and 10°C. The air flow speed is divided into 1m/s, 3m/s and 5m/s. And the opening size of the window is calculated by five levels: minimum opening size for fresh air, 25%, 50%, 75% and 100%. The method refers to a previous study on natural ventilation in office buildings (Larsen and Heiselberg, 2008).

Regarding to the dynamic state study, the EDSL TAS software (EDSL, 2011) was used to analyse the thermal performance of the office building. The software can be used to simulate the dynamic thermal performance of buildings and related systems. The Tas Building Designer simulates the dynamic building performance with integrated natural ventilation and active air flow system. The advantages of Tas for this study were advanced control functions on aperture opening and dynamic building simulation with natural ventilation calculation. Besides, in this study the simulation results were used to predict the building thermal performance differences by changing opening size. The time from May to October was applied according to the predicted result of natural ventilation potential. The weather data of the China architecture thermal environment analysis meteorology database (2005) were used for data analysis. The sizes of single-side ventilation office and cross-ventilated office were based on section 3.2. The analysis includes eight orientations and the glazing area was divided into 30%, 40%, 50% 60% and 70% at each orientation.

The construction material adopted the existing office buildings, which was according to the design standards in China and Zhejiang province (GB 50189, 2005 and DB33/1038, 2007). The detail of construction material used in the TAS (EDSL, 2011) is shown in Table 2.1. The window as a main natural ventilation component was adjusted by internal temperature. Windows were sited to open when working hours started (occupants arrived in the office) and to close when working hours finished (occupants left the office). In the working hours, which were between 9:00 and 18:00, the window would be opened at 25% when the internal temperature was above 20°C, and would be fully opened when the temperature reached 22°C. This was according to the result found by Herkel et al (2008), which was indicated in section 1.3.3. The opening area was divided into 25%, 50%, 75% and 100% of the glazing area for analysis.

Table 2.1: Construction details.

Construction type	Width(mm)	U values(W/m^{2}k)	Main material description
Floor	150	2.9	Concrete and cement mortar
External wall	300	1.7	Brick and cement mortar
Partition wall	260	2.1	Brick and cement mortar
Glazing(window)	6	5.7	Single glazing
Frame (window)	25	2.8	Wood frame

The frequency of the indoor comfort temperature range was used to analyse the hourly result and compare the difference between various conditions, so that the impact on changing the free opening area could be assessed. Besides, Givoni's (1992) building bioclimatic chart was used to define the comfort zone. The hourly data was plotted into a psychromatric chart with Givoni's comfort zone to identify the comfort distribution. The monthly average air flow rate was compared with the effective air flow rate for cooling by different orientations and temperatures to estimate whether the air flow rates could achieve the cooling effect or not. For instance, 30% of the glazing area of the office window should be fully opened to achieve a cooling effect when the temperature difference was 3°C. The free opening area could be reduced to 50% of the glazing area when the temperature differences were 5°C and 10°C. (The Tas model geometry is show in Appendix 1).

2.2 Building characteristics

Building dimension of single-side ventilated office: The building with a length and width ratio of 2:1, had a double bank, and the cellular office room size in it was 4.8m×3.6m×3m. This is based on the general building module in China.

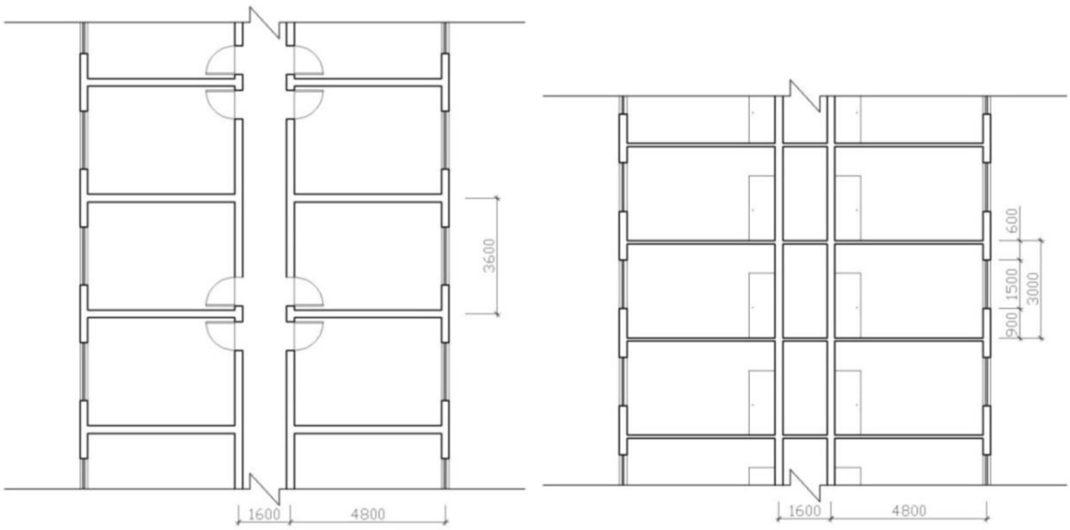


Figure 2.1: Plan and section of single-side ventilation office.

Building dimension of cross-ventilated office: The building's length and width ratio was 2:1. The cellular office room size was 4.8m×3.6m×3m, with the corridor at 1.6 metres.

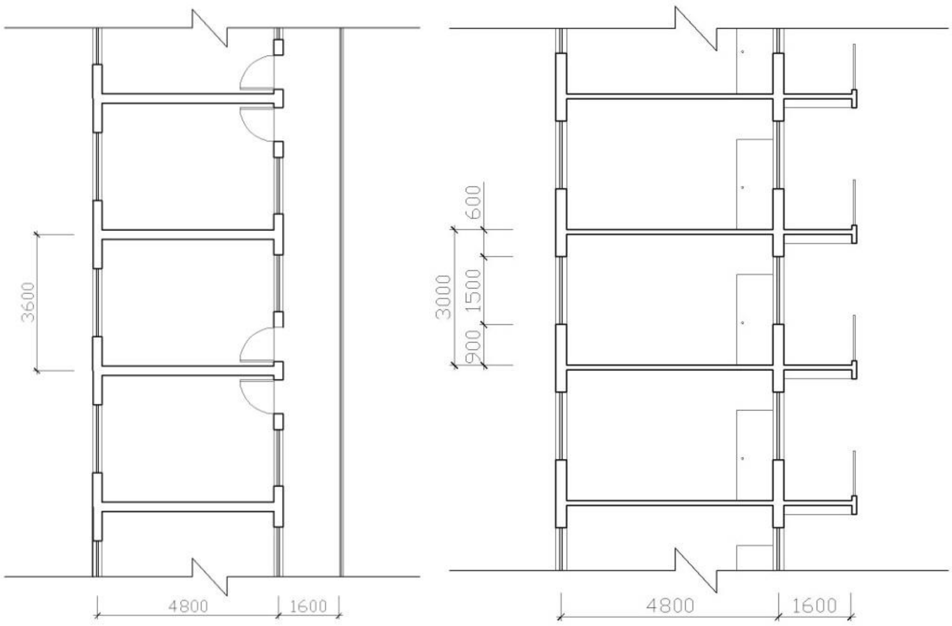


Figure 2.2: Plan and section of cross-ventilated offices.

Glazing ratios: According to the latest building regulations in China and Zhejiang province, such as the National design standard for energy efficiency of public buildings GB 50189 (2005), the National standard for office buildings JGJ 67 (2006) and the Design standard for energy efficiency of public buildings in Zhejiang province DB33/1038 (2007), the minimum glazing façade should be at least 1/6 of the office floor area and the minimum daylight factor at work level should be no less than 2%, or the daylight level should be no less than 100lux. The maximum glazing area should be no larger than 70% of the façade area, in order to reduce the energy waste.

Number of occupants: For a basic office room, the space for occupants should be at least 7m^2 per person (Zhejiang Design Standard, 2007). Therefore, there were two occupants in each analysis office.

Internal heat gain: The internal heat gain included lighting, occupants and equipment. The power for each of these heat sources was: lighting 10w/m^2, occupants 7w/m^2 per person, equipment 15w/m^2 (National standard for office buildings, 2006 and Zhejiang Design Standard, 2007).

2.3 Parameters influencing single-side ventilation in an office

The empirical expressions for buoyancy driven, wind driven and buoyancy and wind combined condition are presented, and also the equation for calculating the effective air flow rate of cooling. The result of effective air flow rate of cooling on eight directions with different glazing areas and temperature difference is demonstrated.

2.3.1 Thermal buoyancy driven

When air flow is driven by thermal buoyancy only through an opening window, it can be assumed that warm indoor air flows out on the top of the window and cold external air flows into the room through the bottom of the window. The common equation of air flow rates can be presented as:

$$Q = C_d \cdot A \cdot \sqrt{\frac{(T_i + 273)}{\Delta T g h}}$$

Equation 2.1: Air flow rate for thermal buoyancy driven in single-side ventilated room.

Where Q (m^3/s) is the air flow rate, C_d is the discharge coefficient, A (m^2) is the opening area of each aperture, T_i (°C) is the internal temperature, ΔT (K) is the internal and external air temperature difference, g (m/s^2) is the gravitational acceleration, and h (m) is the height between each opening if there are two openings in the room with a height difference or it is the height of the window for a single-opening room (Figure 2.3). The typical value of C_d is 0.25 for an opening window and 0.6 for two height different opening windows (CIBSE AM10, 2005, p46). Based on this equation, the different air flow rates between a single opening and two openings are due to different discharging coefficients. The rate in the room with two openings at different heights is about 2.4 times more than for a single opening.

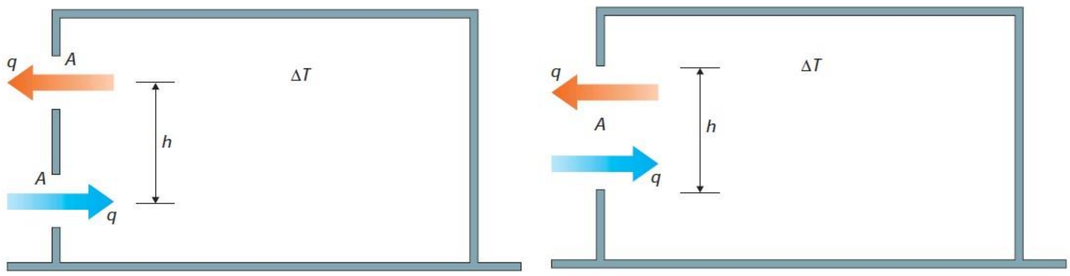


Figure 2.3: Single-side ventilation with two openings at different heights (Left) and a single opening (Right) (CIBSE AM10, p45).

2.3.2 Wind driven

For the wind driven only single-side ventilation, the air flow rate in the office can be found from the equation:

$$Q = C \cdot A \cdot U$$

Equation 2.2: Air flow rate for wind driven only mode in single-side ventilated room.

Where A (m^2) is the area of each opening, U (m/s) is the wind speed, the values of C vary from 0.01 to 0.05, which depends on the shape of the opening, the place where the reference wind speed has been measured and the wind condition around the building. The average value at 0.025 is used for calculation in the CIBSE Guide A (2006, 4-17).

2.3.3 Thermal buoyancy and wind driven combined

The thermal buoyancy and wind driven combined model is based on the empirical equation:

$$Q = C\mathrm{d} \cdot A \cdot \sqrt{\frac{2 \cdot |\Delta \mathrm{P}|}{\rho}}$$

Equation 2.3: Air flow rate for thermal buoyancy and wind driven combined model in sing-side ventilated room.

Where Q is the air flow rate (m^3/s), C_d is the discharge coefficient, A (m^2) is the opening area, ΔP (Pa) is the pressure difference between two sides of the opening, and ρ is the density of the air (kg/m^3) (CIBSE AM10). Larsen and Heiselberg (2008) divided ΔP into three parts, wind pressure difference, thermal buoyancy pressure difference, and fluctuation pressure difference. They also used a wind tunnel to measure the air flow rate in the single-side ventilation model under different environmental conditions. They concluded a new equation for the single-side natural ventilation calculation, as below:

$$Q = A \cdot \sqrt{C_1 \cdot f(\beta)^2 \cdot \left|C_p\right| \cdot U_{ref}^2 + C_2 \cdot \Delta T \cdot H + C_3 \cdot \frac{\Delta C_{p,opening} \cdot \Delta T}{U_{ref}^2}}$$

Equation 2.4: Improved equation for calculate air flow rate at thermal buoyancy and wind driven combined model.

Where f(β) is a value depending on the wind direction, Cp is the wind pressure coefficient, U (m/s) is the wind speed, ΔT (°C) is the difference of internal and external air temperature, H (m) is the height of the opening, $\Delta C_{p,opening}$ (Pa) is the pressure difference in the opening caused by flow turbulence, C1, C2, C3 are constant numbers according to wind tunnel measurement (Table 2.2), and the discharge coefficient (C_d) is included in these constant numbers.

Table 2.2: C1, C2 and C3 for different wind directions (Larsen and Heiselberg, 2008).

Direction	Incidence angle (β)	C_1	C_2	C_3
Windward	β =285-360°, β=0-75°	0.0015	0.0009	-0.0005
Leeward	β =105-255°	0.0050	0.0009	0.0160
Parallel flow	β =90°, β =270°	0.0010	0.0005	0.0111

2.3.4 Wind direction and wind pressure coefficient

The empirical equation is used to find the impact of wind speed, temperature difference and wind directions on air flow rate in a single-side natural ventilation office. The wind direction was divided into eight directions. When the wind was directly towards the opening side it was set as 0° and each direction was at intervals of 45°. Also the wind pressure coefficient was correlated (Figure 2.4 and Table 2.3) (Liddament, 1996).

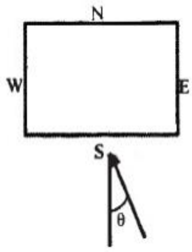


Figure 2.4: The angle of wind direction.

Table 2.3: Wind direction and wind pressure coefficient with building length and width ratio of 2:1.

	0°	45°	90°	135°	180°	225°	270°	315°
South	0.5	0.25	-0.5	-0.8	-0.7	-0.8	-0.5	0.25
North	-0.7	-0.8	-0.5	0.25	0.5	0.25	-0.5	-0.8

2.3.5 Effective air flow rates for cooling

The air flow rate for cooling can be calculated from the equation:

$$Q = \frac{H}{\rho \cdot C_p \cdot \Delta T}$$

Equation 2.5: Effective air flow rate for cooling. Where Q (m^3/s) is the effective flow rates, H (w/m^2) is the total internal heat gain, ρ (kg/m^3) is the air density, C_p (J/kg·K) is the air specific heat capacity, and ΔT (°C) is the indoor and outdoor temperature difference. According to Equation 2.5, H was the total internal heat gains including solar radiation and internal heat. Where the solar radiation was calculated from ECOTECT software, the glazing area was divided into 30%, 40%, 50%, 60% and 70% façade areas, and the solar radiation in different orientations was calculated clockwise from south to south-west in eight directions (Table 2.4).

Table 2.4: The average internal heat gain in different orientations and glazing areas.

	30% Glazing	40% Glazing	50% Glazing	60% Glazing	70% Glazing
South	53.6 w/m^2	58.9 w/m^2	64.0 w/m^2	69.3 w/m^2	74.4 w/m^2
South-east	56.1 w/m^2	62.2 w/m^2	67.6 w/m^2	74.4 w/m^2	80.3 w/m^2
East	56.3 w/m^2	62.5 w/m^2	67.9 w/m^2	74.7 w/m^2	80.7 w/m^2
North-east	53.7 w/m^2	59.0 w/m^2	63.7 w/m^2	69.6 w/m^2	74.8 w/m^2
North	50.8 w/m^2	55.2 w/m^2	59.0 w/m^2	63.8 w/m^2	68.0 w/m^2
North-west	53.8 w/m^2	59.1 w/m^2	63.8 w/m^2	69.8 w/m^2	74.9 w/m^2
West	56.8 w/m^2	63.1 w/m^2	68.7 w/m^2	75.7 w/m^2	81.9 w/m^2
South-west	56.7 w/m^2	63.0 w/m^2	68.6 w/m^2	75.7 w/m^2	81.8 w/m^2

From Table 2.4, it can be found that in some orientations the average internal heat gain was very close, such as south, north-east and north-west. Therefore, it can be divided into three groups in the effective flow rate calculation. The average internal heat gain values in south, north-east and north-west are similar enough to be one group (Group 1), while south-east, east, west and south-west are Group 2, and north is Group 3. Table 2.5 shows the result of the effective air flow rates that are needed for cooling by different orientations and temperature difference, and it also shows the air flow rate in Group 2 is the highest, which means that these orientations receive more solar radiation than the other two groups, while Group 3 is the lowest. Comparing the same glazing area at different orientations and temperature difference, the effective air flow rates for cooling were close to each other. This table was used to define whether the air flow rates could achieve a cooling purpose or not.

Table 2.5: Effective air flow rate for cooling by different orientations and temperatures.

Effective flow rate (m^3/s)	$\Delta T=3℃$	$\Delta T=5℃$	$\Delta T=10℃$

Group 1 (S, NE, NW)	30% Glazing	0.26	0.15	0.08
	40% Glazing	0.28	0.17	0.08
	50% Glazing	0.31	0.18	0.09
	60% Glazing	0.33	0.20	0.10
	70% Glazing	0.35	0.21	0.11
Group 2 (SE, E, W, SW)	30% Glazing	0.27	0.16	0.08
	40% Glazing	0.30	0.18	0.09
	50% Glazing	0.33	0.20	0.10
	60% Glazing	0.36	0.22	0.11
	70% Glazing	0.39	0.23	0.12
Group 3 (N)	30% Glazing	0.24	0.15	0.07
	40% Glazing	0.26	0.16	0.08
	50% Glazing	0.28	0.17	0.08
	60% Glazing	0.30	0.18	0.09
	70% Glazing	0.32	0.19	0.10

2.4 Initial study of air flow rates in a single-side ventilated office

In the initial study, the basic equation was used to calculate the effective air flow rate for cooling and to find the relationship between air flow rates and temperature difference, wind speed difference and wind direction in a generic office building.

2.4.1 Thermal buoyancy driven only

Figure 2.5 shows the air flow driven by thermal buoyancy in a single-opening room. It was clear that the bigger opening size and high temperature difference resulted in a higher air flow rate. In a 30% glazing area office, when the air temperature difference was 3°C, the opening needed to be 75% of the glazing area in order to achieve a cooling purpose, and 50% of the glazing area when the temperature difference was 10°C. In a 40% glazing area office, 75% of the glazing area needed to be open when the temperature difference was 3°C, and 50% when the temperature difference was 5°C. For 50%, 60% and 70% of glazing area offices, if 50% of the glazing area was open and the temperature difference was 3°C, then the effective air flow rate for cooling could be achieved. The room had two openings (Figure 2.6), and the air flow rate of it was higher than the single-opening room. If the opening size could reach 25% of the total glazing area, then the effective air flow rate for cooling could be achieved in these five cases. The two openings at different heights could reach a much higher volume flow rate than the single opening but under only the thermal buoyancy driven condition. Therefore, at no wind condition, the room with two openings had a more efficient performance than the single opening to remove the indoor heat.

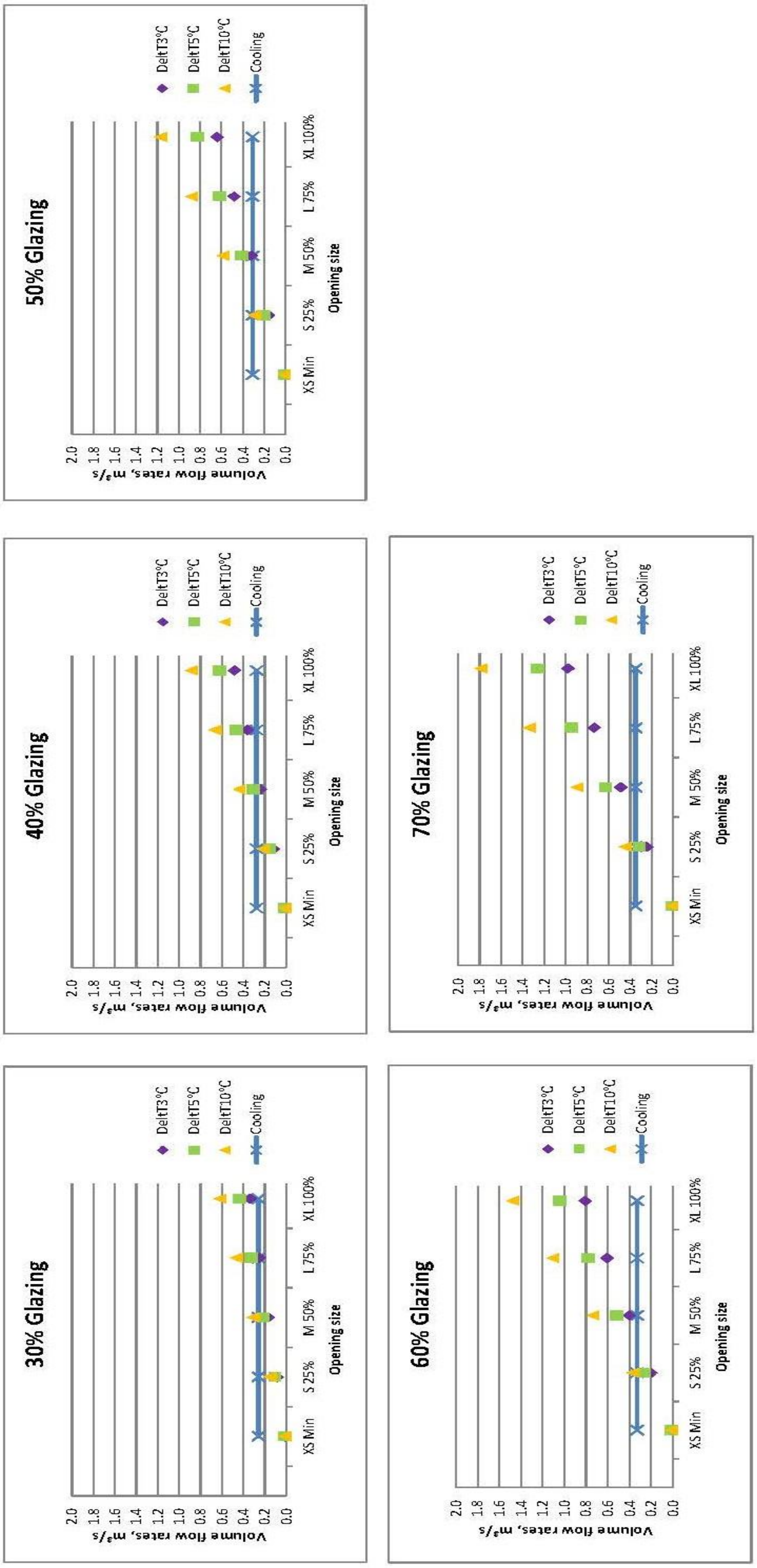


Figure 2.5: The impact of temperature difference and opening difference on air flow rates in one-opening single-side ventilation office.

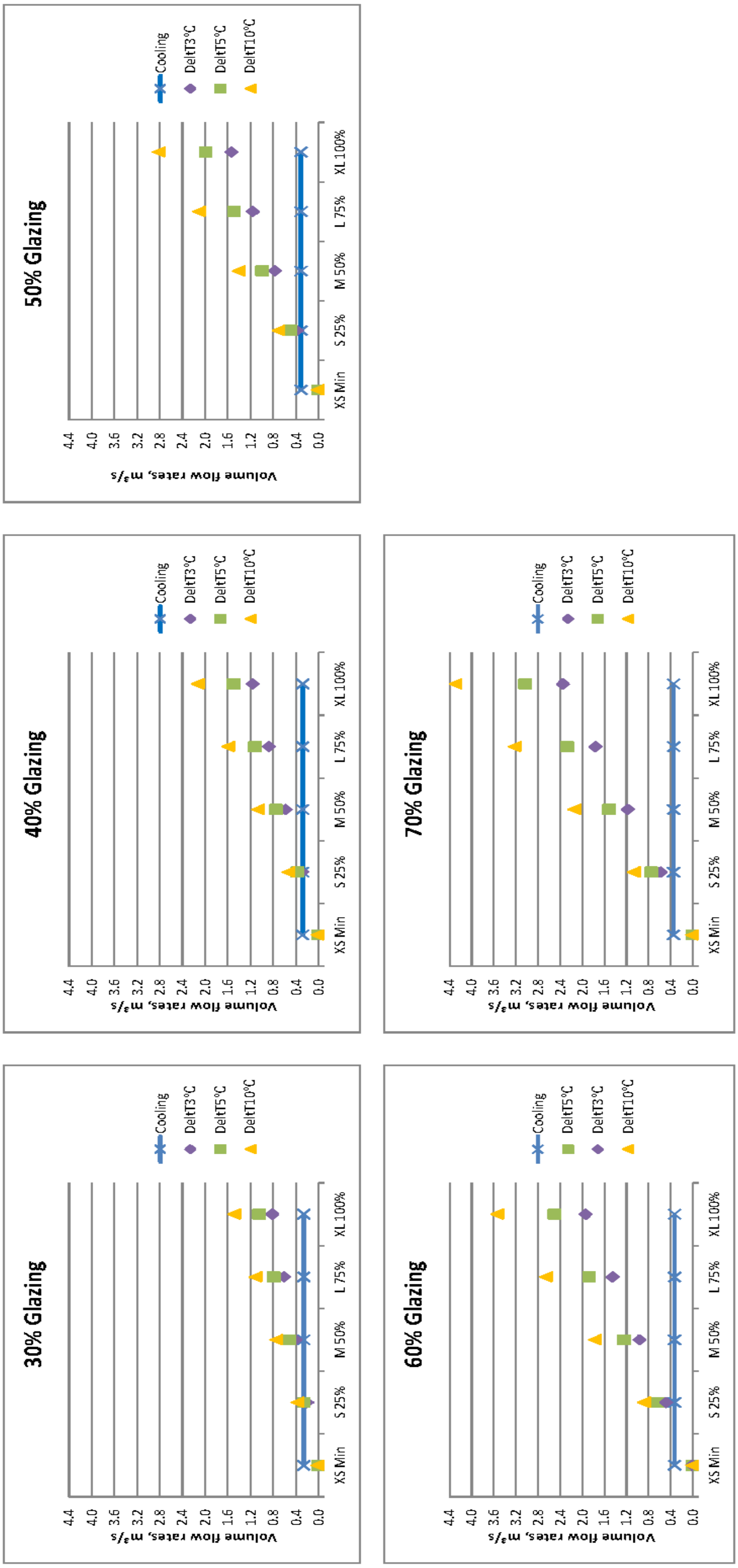


Figure 2.6: The impact of temperature difference and opening difference on air flow rates in two-opening single-side ventilation office.

2.4.2 Wind driven only and thermal buoyancy combined with wind driven condition

The result of thermal buoyancy and wind driven combined is presented in Figure 2.7 and Figure 2.8. When the air temperature difference between indoor and outdoor was 0°C, it could be considered as wind driven only. The two opening was not considered under these two conditions. Because, based on the empirical equation, at the wind driven only condition, two openings and a single opening are similar. And the thermal buoyancy and wind driven combined condition with two opening at different heights was not considered, so it is not discussed in the paper.

The result showed the air flow rate as a function of increasing wind speed and temperature difference. When indoor and outdoor temperature difference was 0°C, the wind became the main driving force. The volume flow rate was the lowest when the opening window faced the leeward side (180°). Increasing external air flow speed and free opening size would have significant effect on the volume flow rate, which would increase with the increase of wind speed and free opening size. Therefore, the opening window facing leeward under the wind driven only condition was not good for natural ventilation in room. Under the same external air flow speed, the volume flow rates were close to each other when the wind directions were 0° and 135°, 45° and 90° (Figure 2.4). But the volume flow rate at wind directions of 0° and 135° was lower than that at 45° and 90°. When the wind directions were at 45° and 90°, the volume flow rate reached the highest in the room, and it would obviously rise up along with increasing wind speed and free opening size. When the wind speed was 3m/s, and the opening size was 50% of the glazing area, it could achieve cooling demand in all cases in these two directions. Besides, when the wind speed was 1m/s, it was difficult to achieve the cooling purpose in most cases unless the room had a 70% glazing area which was fully opened. Thus, for the wind driven only condition, the wind direction at 45° and 90° could cause the highest volume flow rate in the room, while 180° is the worst direction for natural ventilation. Even by rising wind speed, it would not have significant impact on volume flow rate on 180° and the effect is limited with lower external air flow speed (1m/s).

In the wind and thermal buoyancy driven combined case, when the free opening size was still, increasing the temperature difference between indoor and outdoor or raising the wind speed would not cause significant increase in volume flow rate. The impact was little by changing these factors, especially with a small free opening size. However, when the temperature difference between indoor and outdoor was increased, the volume flow rate for cooling could be achieved more easily, and extending the free opening area was more effective on increasing the volume flow rate. Changing wind speed had a different impact on each direction, but at the same wind speed the pattern of volume flow rate on each direction with different temperature differences was similar.

When the wind speed was 1m/s, the volume flow rates at 0°, 45° and 90° were very close and the lowest was at 90°. The highest volume flow rate occurs on 135°, and on 180° the volume flow rate was slightly lower than 135°. When wind speed was 3m/s, the lowest volume flow rate was on 90°, and the volume flow rate at 0° and 180° was higher than 90° and close to each other. The highest rate occurs on 45° or 135° with temperature different changes. When the wind speed rises to 5m/s, the pattern of volume flow rate on each direction is similar to when the wind speed was 3m/s. But the volume flow rates on 0° and 180° are close and lower than other directions. The highest rate was on 45°C, then on 135° and 90°. Therefore, when the temperature difference rises, the volume flow rate on 90°, 135° and 180°, in which the three opening was on the leeward side, would drop, especially with the air flow speed at 3m/s and 5m/s. At these three directions, when temperature difference was 10°C, the volume flow rate with 3m/s and 5m/s was lower than 1m/s, so it seems the thermal buoyancy force dominates the volume flow rate. The detail of other glazing areas is shown in Appendix 2.

It can be concluded that in the wind driven only case, increasing wind speed and free opening area would result in the rise of volume flow rate, especially when the wind directions were 45° and 90° with significant impact. When natural ventilation was driven by the buoyancy and wind combined case, at low wind speed and parallel or leeward direction, thermal buoyancy had a bigger influence than wind forces. Therefore, at these conditions, increasing temperature difference was more efficient for increasing volume flow rate in a single-side ventilated office. When the wind direction was 45°, increasing temperature would not have an important impact on volume flow rate, while the wind is the main driven force.

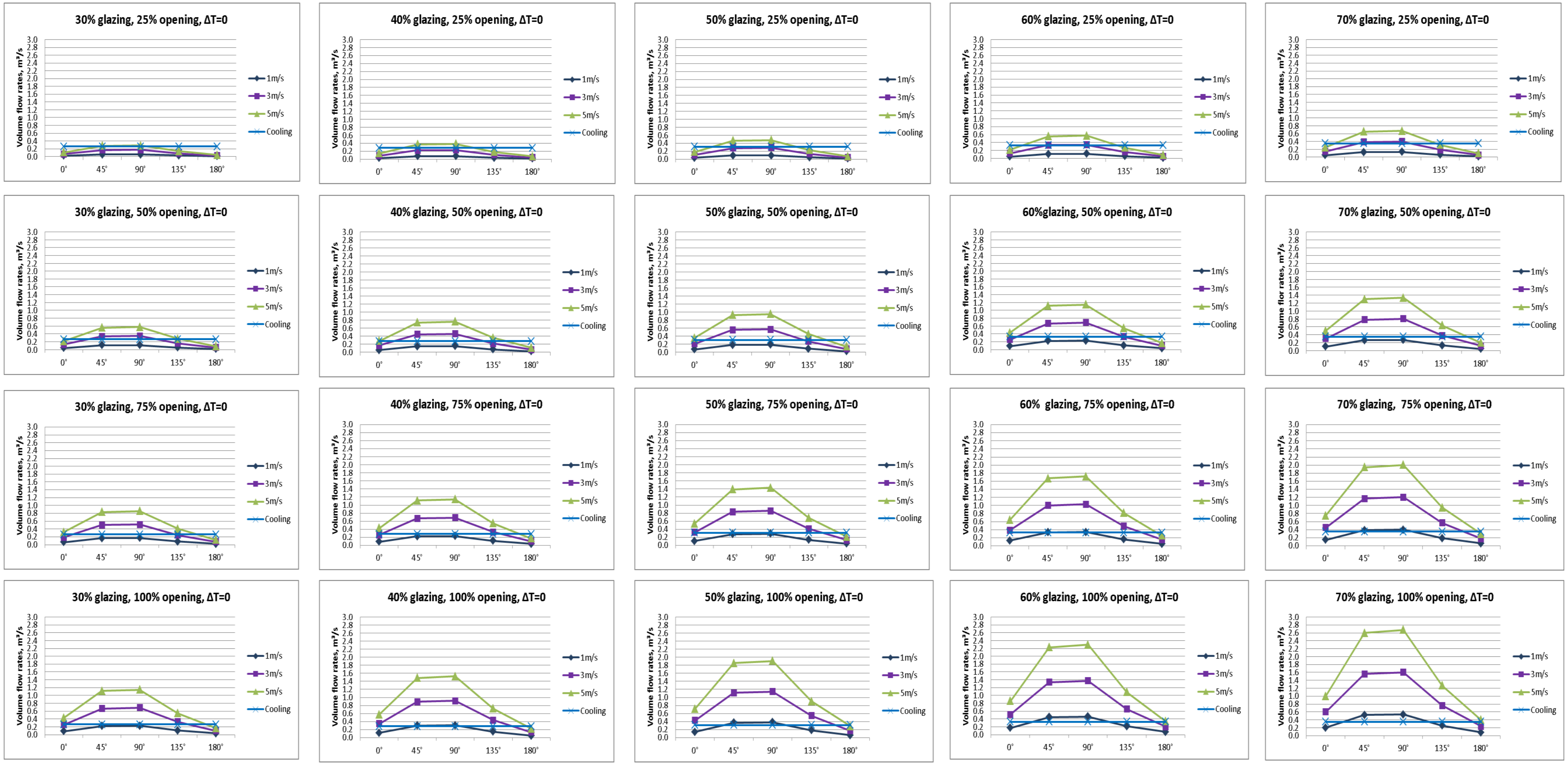


Figure 2.7: The impact on air flow rates by change in the wind speed difference at different wind directions and wind speeds; the opening is facing 0° at different glazing area.

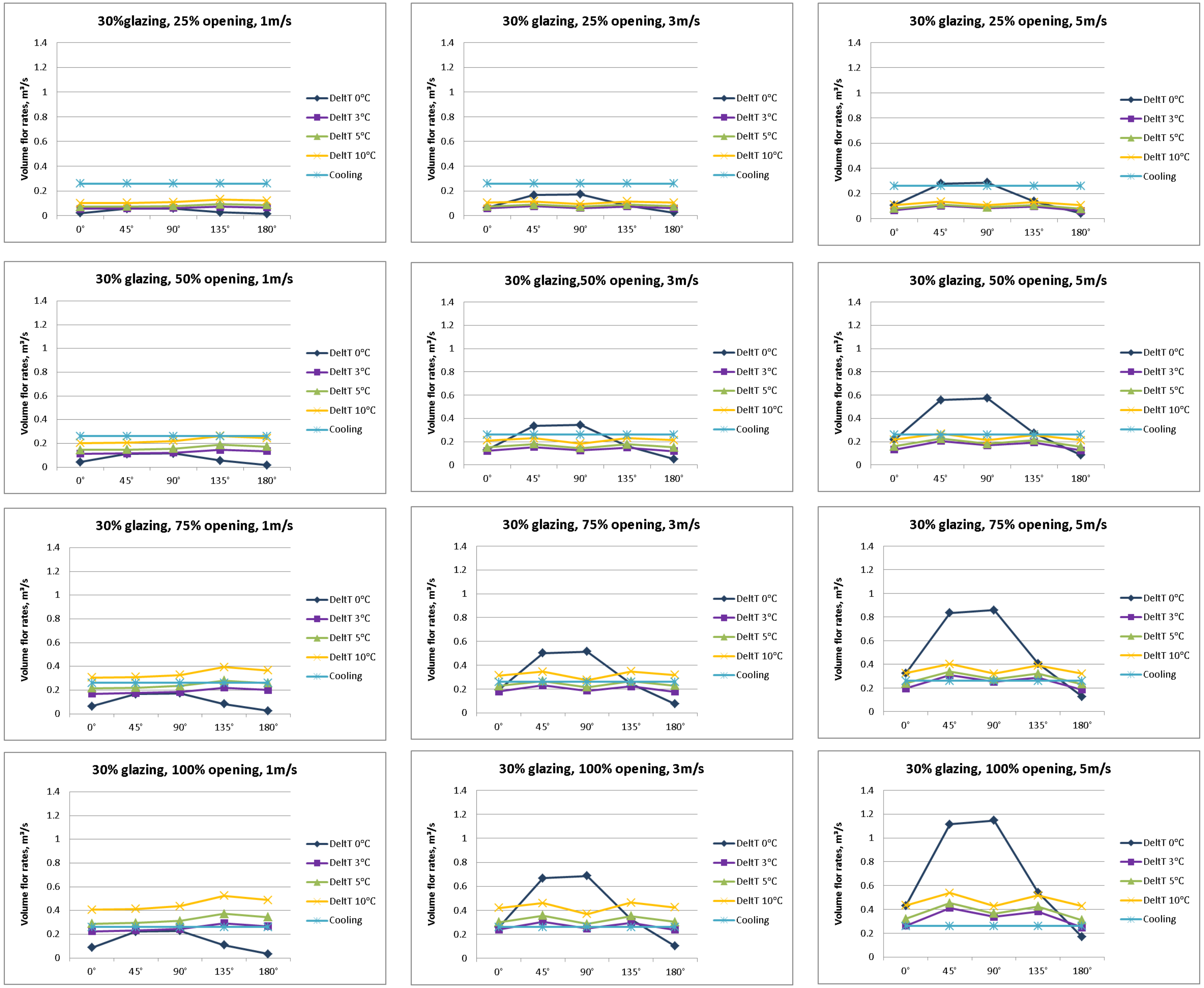


Figure 2.8: The impact on air flow rates by change in the temperature difference at different wind directions and wind speeds; the opening is facing 0° at 30% glazing area.

2.5 Hourly data analysis of single-side ventilated office

In order to provide more detailed results of the impact of natural ventilation on the thermal performance and comfort temperature in office buildings, hourly data during the natural ventilated period were used. The data also plotted into Givoni's comfort zone to identify whether it is in the comfort area. The dry bulb indoor air temperature during the working hours was used to analyse the temperature percentages in the office. The radiant temperature would have an impact on occupant comfort. Szokolay (2004) suggested that, if the difference between mean radiant temperature and dry bulb air temperature was equal or below ±3°C, then the condition would be acceptable, while if the temperature different was over ±3°C, then the mean radiant temperature may cause discomfort. Thus, in the hourly results, if the temperature difference was higher or lower than ±3°C, it would be considered as uncomfortable.

2.5.1 Temperature percentages

For the 30% glazing area office building, Figure 2.9 shows the comfort temperature frequency in the south, east, north and west orientations with the opening area increasing from 25% to 100% and from May to October (Except July and August). It can be seen that when the opening area increased from 25% to 50%, it had significant influence on the internal temperature, and the temperature frequency was extended greatly. When the opening area increased from 50% to 75%, the temperature frequency growing trend was lower than that from 25% to 50%, and the temperature frequencies were quite similar when the opening area was at 75% and 100%. This can be proved by Figure 2.7 that, in a 30% glazing office room, 75% or 100% of the window opening area is needed to achieve effective air flow rates, when the indoor and outdoor temperature varied between 3°C and 5°C and the wind speed was between 1m/s and 5m/s.

The result also showed that, in July and August, changing the opening area did not impact the indoor temperature and the comfort time was lower than 1% in the office (Figure 2.10). This was because the average internal air temperatures were above 32°C and the absolute humidity was above 20g/kg, which was out of the comfort zone. The results are shown in the psychrometric chart (Figure 2.11 and Figure 2.12). Besides, in July and August, more than 60% of the time the external temperatures were above 29°C. It seemed like, in 40% of the time the external temperature was below 29°C and the natural ventilation for cooling method may still be achievable. But in the majority of time the indoor environmental condition was far away from the comfort area; thus, the mechanical cooling system was suggested to be used to cool the internal temperature in these two months. So, July and August would not be used for further analysis.

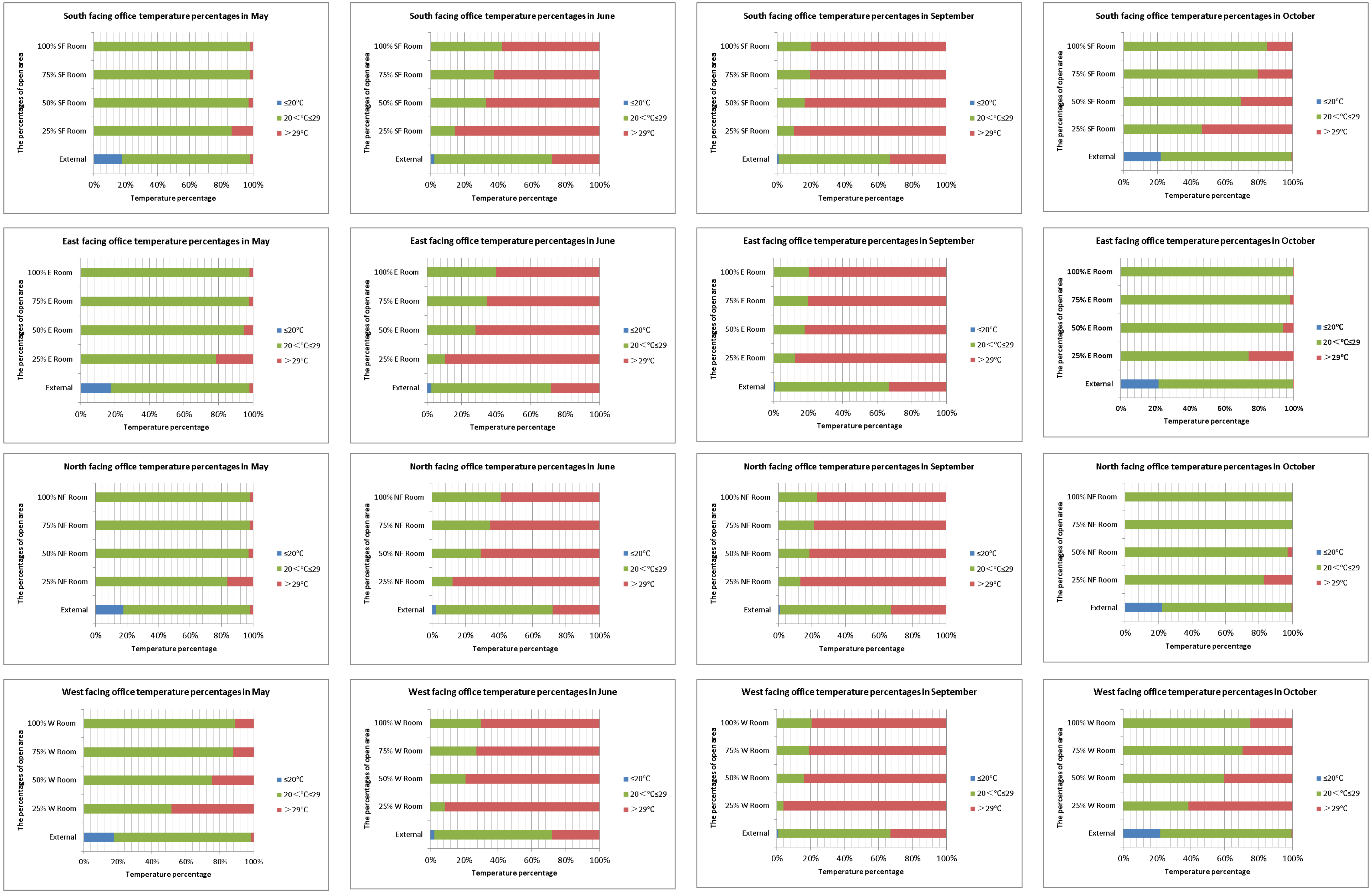


Figure 2.9: The temperature percentage in 30% glazing and single-side ventilated office in south, east, north and west orientations in May June, September and October.

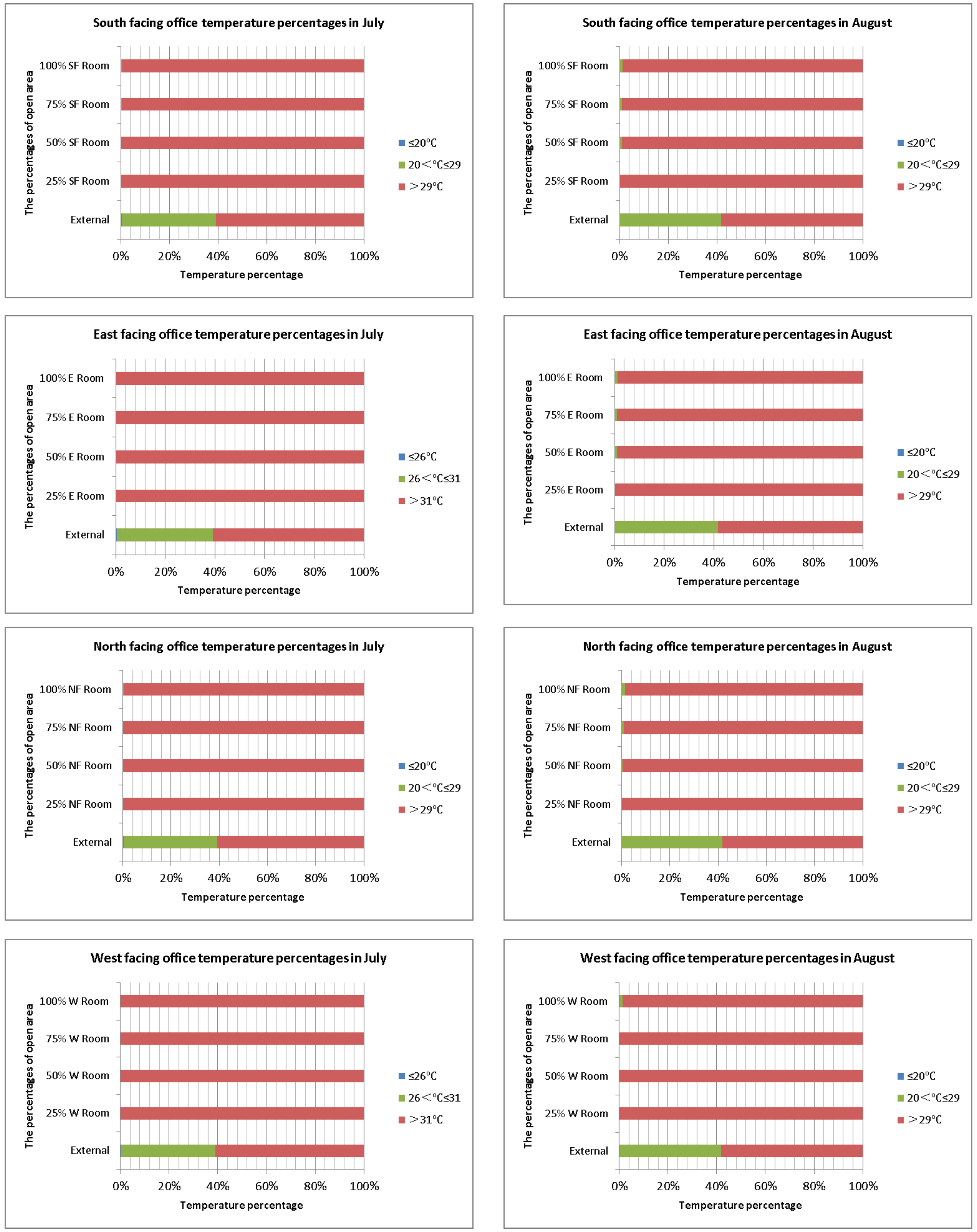


Figure 2.10: The temperature percentage in 30% glazing office in south, east, north and west orientation offices in July and August.

Figure 2.11: Indoor temperature distribution in July at 30% glazing area east orientation office room with 100% opened window.

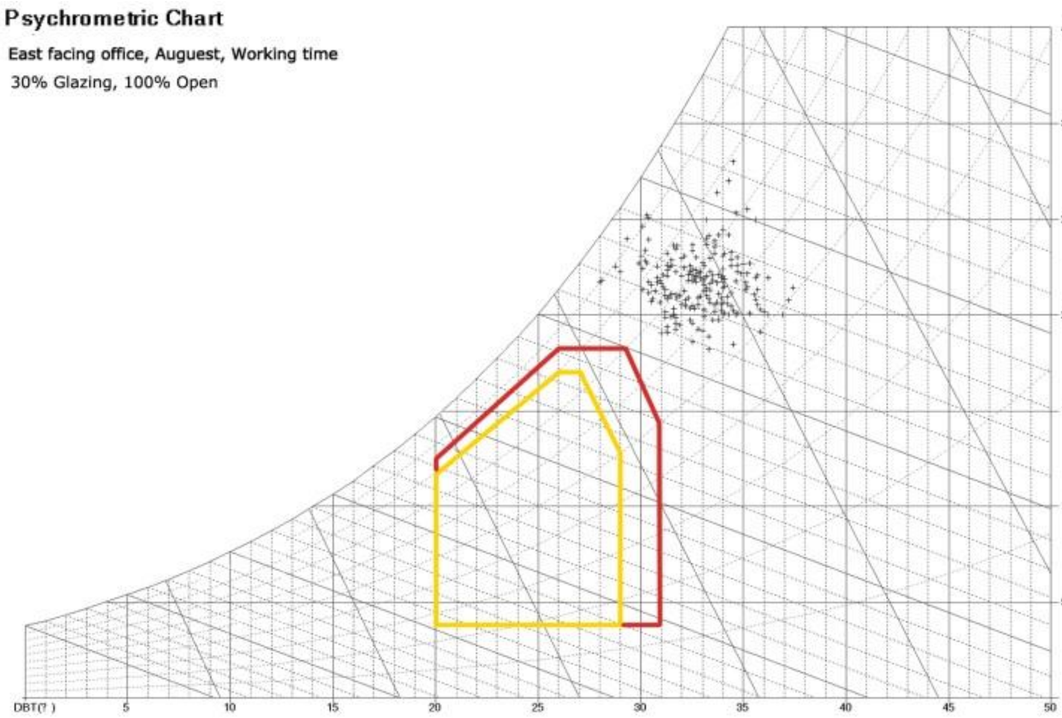


Figure 2.12: Indoor temperature distribution in August at 30% glazing area east orientation office room with 100% opened window.

In May and October the internal temperature conditions seemed optimistic if the opening area could be extended to 75% or above (use the west facing as an example, Figure 2.13). Some of the temperatures in working hours were still located on the outside of the yellow comfort zone, because of the high humidity ratio (Figure 2.14 and Figure 2.15). But if the internal air flow rate could be increased to 1.5m/s, then most of the temperatures in working hours could be covered in the extended comfort zone. In October, in 24% of working hours the temperature in a west-facing office was above 29°C, and the highest temperature occurred at later afternoon when the low angle sunlight came from the west (Figure 2.16).

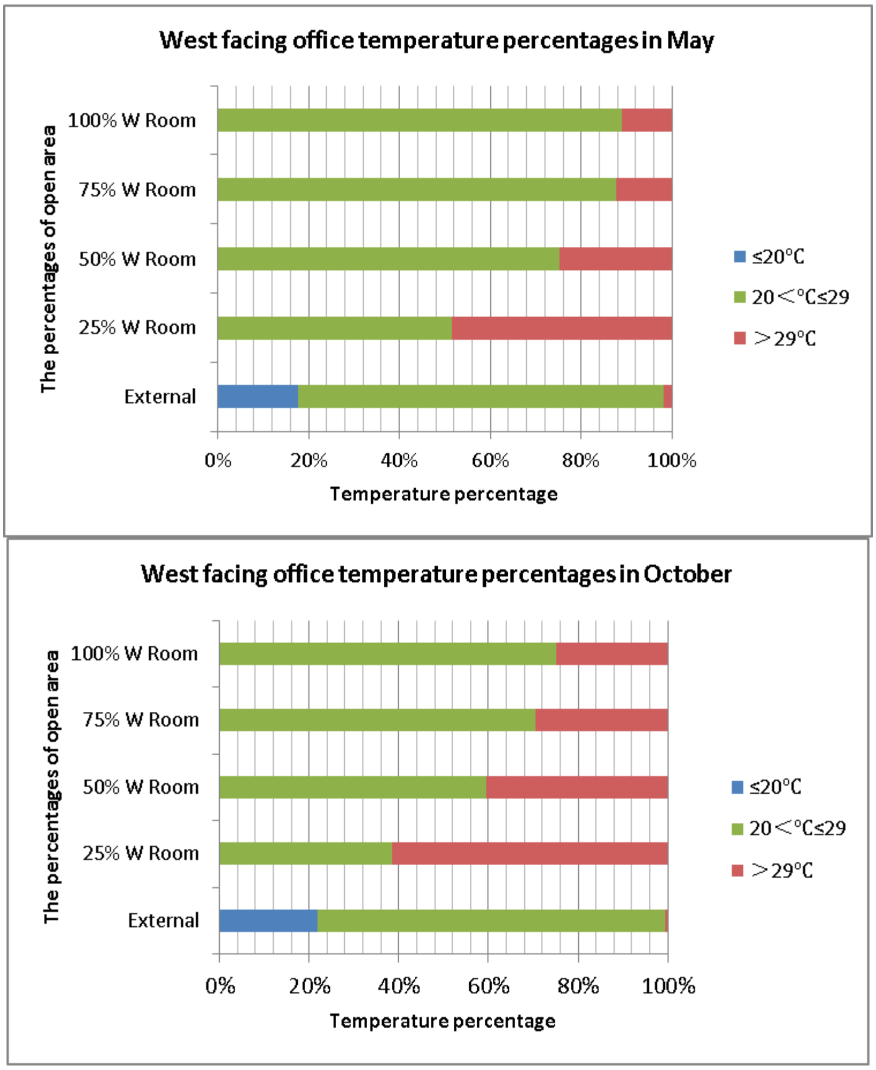


Figure 2.13: The percentage of temperature in May and October in a west-facing office.

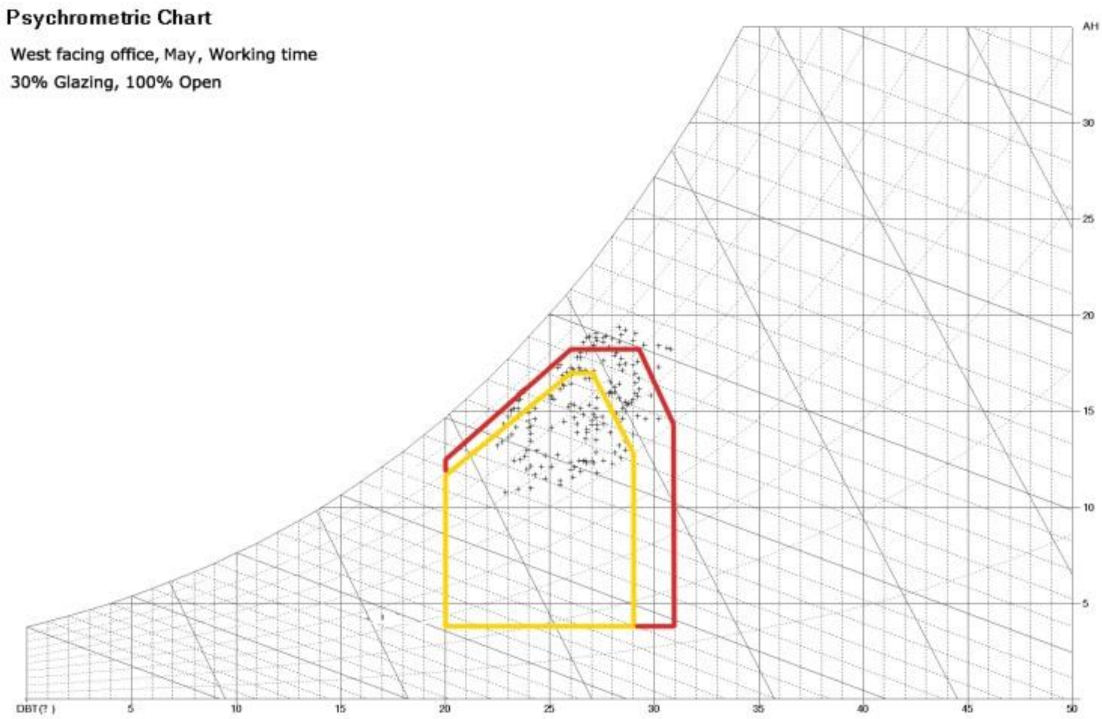


Figure 2.14: Indoor temperature distribution in May at 30% glazing area west orientation office room with 100% opened window.

Figure 2.15: Indoor temperature distribution in October at 30% glazing area west orientation office room with 100% opened window.

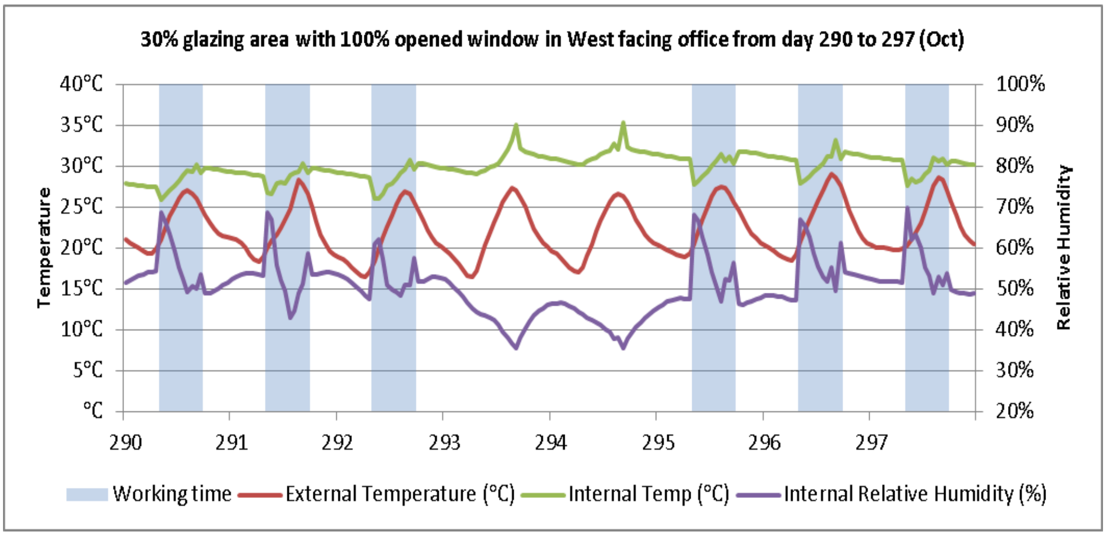


Figure 2.16: Internal and external temperature and indoor relative humidity in west-facing office in October, from day 290 to 297.

In May, when the glazing area increased from 30% to 70%, changing the free opening area from 50% to 100% of the glazing area did not influence the indoor temperature proportion. Therefore, the extended effective open area which caused air volume flow rate to increase could offset the increase in solar radiation by extending the glazing area. But on the 25% open case, the percentage on the comfort temperature range in the 70% glazing office was 4% higher than the 30% glazing office. This may be because the effective open area in the 70% glazing office was larger than the 30% glazing office.

In June, when window was 50% and 75% opened, the percentage of temperature was the same in these two types of office. And the result of 25% open was as same as May; the percentage in the 70% glazing office was 8% higher than the 30% glazing office. However, the situation on the 100% open case was the opposite. The 30% glazing office was 3% higher than the 70% glazing office. The small glazing area with a large opening performed better than a large glazing area with a large opening.

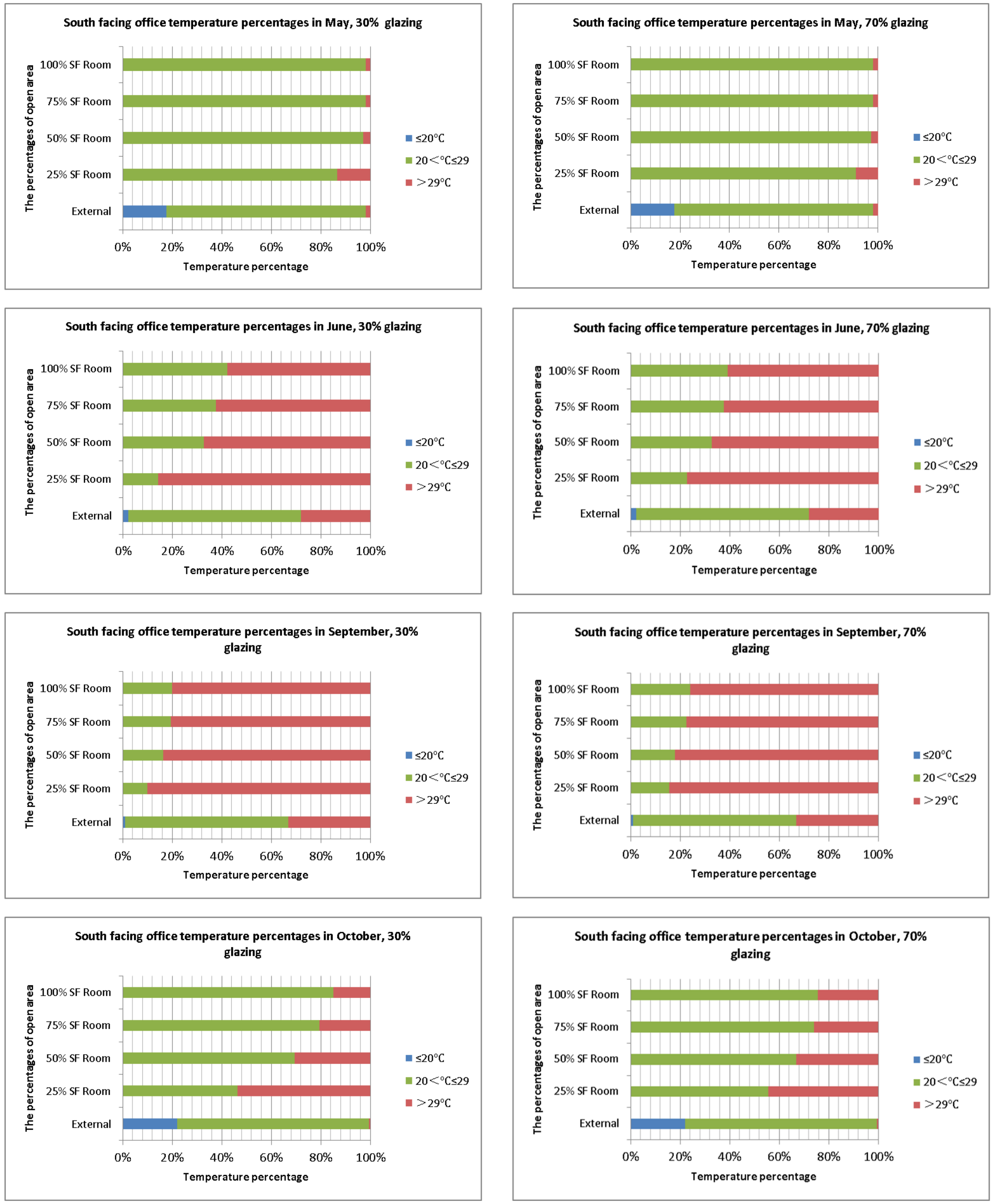


Figure 2.17: Comparing indoor temperature percentage between 30% and 70% glazing office facing south in May, June, September and October.

In September, the glazing area increased with the percentage of comfort temperature rising. The comfort temperature percentage in a 70% glazing office was about 4% higher than the 30% glazing office in 25%, 75% and 100% cases. And on the 50% open case the comfort temperature percentage was about 1% higher than the 30% glazing office. Therefore, extending the effective open area can increase the comfort temperature percentage in September.

In October, the comfort temperature in the 25% open case in a 70% glazing office was 9% higher than the 30% glazing office. But in the 50% open case the comfort temperature percentage was reduced by 2%. This situation was worse in 75% open and 100% open cases, in which the value was reduced by 6% and 9%. Thus, in October the situation was similar to June; increasing the glazing area would reduce the comfort temperature percentage, and the office obtained heat more than it released.

Generally, in a south-facing office during these four months, the 30% glazing office with fully openable window had a higher comfort temperature percentage than the 70% office. And in the 30% glazing office, the minimum effective open area should be larger than the 25% glazing area. The total comfort temperature percentage in the 30% glazing office was about 2.2% higher than the 70% glazing office, which amounted to 18.2 working hours. The details of the temperature percentage change in the office with other orientations were shown in Table 2.6.

Table 2.6: The indoor comfort temperature percentage change results when glazing area increased from 30% to 70%, and increased comfort time in the office.
(¤: means result was same)

	May	June	September	October	Increased comfort time
South	25% ↑4% 50% ¤ 75% ¤ 100% ¤	25% ↑8% 50% ¤ 75% ¤ 100% ↓3%	25% ↑6% 50% ↑1% 75% ↑2% 100% ↑4%	25% ↑9% 50% ↓2% 75% ↓6% 100% ↓9%	30%＞70% **18.2h**(2.2%)
South east	25% ↑4% 50% ¤ 75% ¤ 100% ¤	25% ↑10% 50% ↓1% 75% ¤ 100% ↓4%	25% ↑5% 50% ↑2% 75% ↑3% 100% ↑4%	25% ↑4% 50% ↓3% 75% ↓5% 100% ↓6%	30%＞70% **11.8h**(1.4%)
East	25% ↑4% 50% ↓1% 75% ↓2% 100% ↓2%	25% ↑9% 50% ↑2% 75% ↓1% 100% ↓4%	25% ↑4% 50% ↑2% 75% ↑2% 100% ↑3%	25% ↑7% 50% ↓2% 75% ↓2% 100% ↓3%	30%＞70% **11.7h**(1.4%)
North east	25% ↑4% 50% ↓1% 75% ↓1% 100% ¤	25% ↑9% 50% ↓1% 75% ¤ 100% ¤	25% ↑4% 50% ↑3% 75% ↑4% 100% ↑4%	25% ↑5% 50% ↓1% 75% ↓1% 100% ¤	30%＜70% **7.2h**(0.8%)
North	25% ↑3% 50% ¤ 75% ¤ 100% ¤	25% ↑9% 50% ↑3% 75% ¤ 100% ↓5%	25% ↑5% 50% ¤ 75% ↑3% 100% ↑3%	25% ↑5% 50% ¤ 75% ↓2% 100% ¤	30%＞70% **0.4h**(0.2%)
North west	25% ¤ 50% ↓8% 75% ↓8% 100% ↓8%	25% ↑9% 50% ↑3% 75% ↑1% 100% ↓2%	25% ↑4% 50% ↑4% 75% ↑3% 100% ↑4%	25% ↑5% 50% ↓3% 75% ↓6% 100% ↓5%	30%＞70% **23.6h**(2.8%)
West	25% ↑8% 50% ↓5% 75% ↓15% 100% ↓11%	25% ↑9% 50% ↑4% 75% ↑1% 100% ¤	25% ↑10% 50% ↑2% 75% ↑1% 100% ↑1%	25% ↑11% 50% ↓1% 75% ↓4% 100% ↓5%	30%＞70% **29.5h**(3.6%)
South west	25% ↓1% 50% ↓7% 75% ↓8% 100% ↓6%	25% ↑9% 50% ↑2% 75% ¤ 100% ↓1%	25% ↑6% 50% ↑2% 75% ↑3% 100% ¤	25% ↑11% 50% ↓1% 75% ↓6% 100% ↓10%	30%＞70% **34.0h**(4.1%)

The results showed that, when the window can be fully opened, in seven orientations the comfort time in the 30% glazing office was more than the 70% glazing office. Except when the office was facing north-east, the comfort time in the 70% glazing office was 7.2 hours more than the 30% glazing office, so having a large glazing area and large effective open area can improve an indoor environmental condition. For the other orientations, a small glazing area with a large effective open area was better. Especially in the south-west, west and north-west directions, there was 23 hours' difference during the working hours when changing the glazing area from 30% to 70%. On the south-west orientation, the comfort time can be increased to 34 hours, which was about 4 working days. On these orientations, reducing solar radiation was more efficient than increasing the free opening area. On the north orientation, the result was close in these four months. In 30% glazing or 70% glazing, there was not much difference in indoor comfort temperature. In addition, the indoor comfort temperature difference between 30% glazing and 70% glazing also showed that the less comfort hour difference it has, the more comfort hour it has in the office. Therefore, north and north-east orientation offices had more comfort time than the offices in other orientations.

2.6 Parameters influencing cross-ventilation in an office

For a cross-ventilated office, the buoyancy driven model is similar to a single-side ventilation office, so the buoyancy driven expression is not present in this case; only wind driven and wind driven and buoyancy combined empirical are presented. Besides, the effective air flow rates for cooling in a cross-ventilated office are also demonstrated.

2.6.1 Wind driven

For the wind driven cross-ventilation, the air flow rate can be found from the equation:

$$Q = C_d \cdot A \cdot U \cdot \left(\Delta C_p\right)^{0.5}$$

Equation 2.6: Air flow rate for wind driven cross-ventilation modle (CIBSE Guide A, p4-16).

Where Q (m^3/s) is the air flow rate, C_d is the discharge coefficient, A (m^2) is the opening area, U (m/s) is the wind speed, the values of ΔCp are the wind pressure difference between windward and leeward (CIBSE Guide A).

2.6.2 Thermal buoyancy and wind driven combined

The thermal buoyancy and wind driven combined cross-ventilation model was complicated, so the calculation was divided into two parts, the thermal buoyancy dominate or the wind dominate. It was decided by the equations:

Buoyancy dominated

$$Q_b, \left(U/\sqrt{\Delta T}\right) < 0.26 \cdot (A_b/A_w) \cdot \left(h/\Delta C_p\right)^{0.5}$$

Equation 2.7: Air flow rate for buoyancy dominated condition (CIBSE Guide A, p4-16).

Wind dominated

$$Q_w, \left(U/\sqrt{\Delta T}\right) > 0.26 \cdot (A_b/A_w) \cdot \left(h/\Delta C_p\right)^{0.5}$$

Equation 2.8: Air flow rate for wind dominated condition (CIBSE Guide A, p4-16).

Where U (m/s) is the wind speed, ΔT (°C) is the indoor and outdoor temperature difference, Ab (m^2) is the opening area for thermal buoyancy driven, Aw (m^2) is the opening area for wind driven, h (m) is the height of the opening for thermal buoyancy, and ΔCp is the windward and leeward wind pressure difference (CIBSE Guide A).

2.6.3 Wind pressure coefficient

The wind pressure coefficient is presented in section 2.3.4.

2.6.4 Effective air flow rates for cooling

The same method as presented in section 2.3.4 was used to calculate the effective air flow rate for cooling in a cross-ventilated office. The corridor was not considered for this stage and it would be discussed as a shading device in the office building on an hourly data analysis stage. Table 2.7 shows the internal heat gain in the office in different directions and glazing size, because it had a window on both sides of the office, and the heat gain was higher than that in the single-side ventilation office. As a rule of thumb (CIBSE AM10, 2005, p4), the average heat load is about 40 W/m^2 with natural ventilation systems, which is lower than the predicated result shown on Table 2.7. This indicated that there will have overheating issue in offices, especially in the office with large glazing area. Other passive design method should be considered. However, occupants who live in hot and humid climate may be able to adapt a warmer environmental condition. According to Equation 2.5, the effective air flow rate for cooling is shown in Table 2.8, and also it is divided into three groups based on internal heat gain.

Table 2.7: The average internal heat gain in different orientations and glazing areas.

	30% Glazing	40% Glazing	50% Glazing	60% Glazing	70% Glazing
South&North	67.4w/m2	77.4w/m2	86.6w/m2	97.2 w/m2	106.8w/m2
South-east*North-west	71.9 w/m2	83.3 w/m2	93.4 w/m2	106.2w/m2	117.2w/m2
East&West	75.1 w/m2	87.6 w/m2	98.6 w/m2	112.4w/m2	124.6w/m2
North-east&South-west	72.4 w/m2	84.0 w/m2	94.3 w/m2	107.4w/m2	118.6w/m2

Table 2.8: Effective air flow rate for cooling by different orientations and temperatures.

Effective flow rate (m^3/s)		ΔT=3℃	ΔT=5℃	ΔT=10℃
Group 1 (S&N)	30% Glazing	0.32	0.19	0.10
	40% Glazing	0.37	0.22	0.11
	50% Glazing	0.41	0.25	0.12
	60% Glazing	0.46	0.28	0.14
	70% Glazing	0.51	0.31	0.15
Group 2 (SE&NW, SW&NE)	30% Glazing	0.34	0.21	0.10
	40% Glazing	0.40	0.24	0.12
	50% Glazing	0.45	0.27	0.13
	60% Glazing	0.51	0.31	0.15
	70% Glazing	0.56	0.34	0.17
Group 3 (E&W)	30% Glazing	0.36	0.21	0.11
	40% Glazing	0.42	0.25	0.13
	50% Glazing	0.47	0.28	0.14
	60% Glazing	0.54	0.32	0.16
	70% Glazing	0.59	0.36	0.18

2.7 Initial study of air flow rates in a cross-ventilated office

The calculated result based on empirical expression was presented. Because the buoyancy and wind driven combined model was separated into buoyancy dominated and wind dominated, the wind driven only condition is therefore not present. And in the wind dominated condition, the wind direction at 0° and 45° is considered, because when the wind direction is 90° the wind pressure difference is 0, so buoyancy driven would dominate the natural ventilation. And at a direction of 135° and 180°, the pressure difference is the same as 0° and 45°.

2.7.1 Buoyancy dominated natural ventilation

According to Equation 2.7 and wind pressure coefficient (Table 2.3), the air flow rates at different temperatures and different opening sizes were calculated. The result shows that under a thermal buoyancy dominated condition, the bigger opening size and higher temperature difference result in a higher air flow rate (Figure 2.18). From 30% to 50% of glazing area, opening 50% of the glazing area can approach effective air flow rates and achieve a cooling effect, when indoor and outdoor temperature difference is 3°C. At the same temperature difference, 70% of the glazing area needs an opening of 25% of the glazing area to achieve a cooling effect. If indoor and outdoor temperature difference was 10°C, opening 25% of the glazing area can achieve a cooling effect in these five glazing areas. As for single-side ventilation, the volume flow rate increases with free opening area and temperature difference rise.

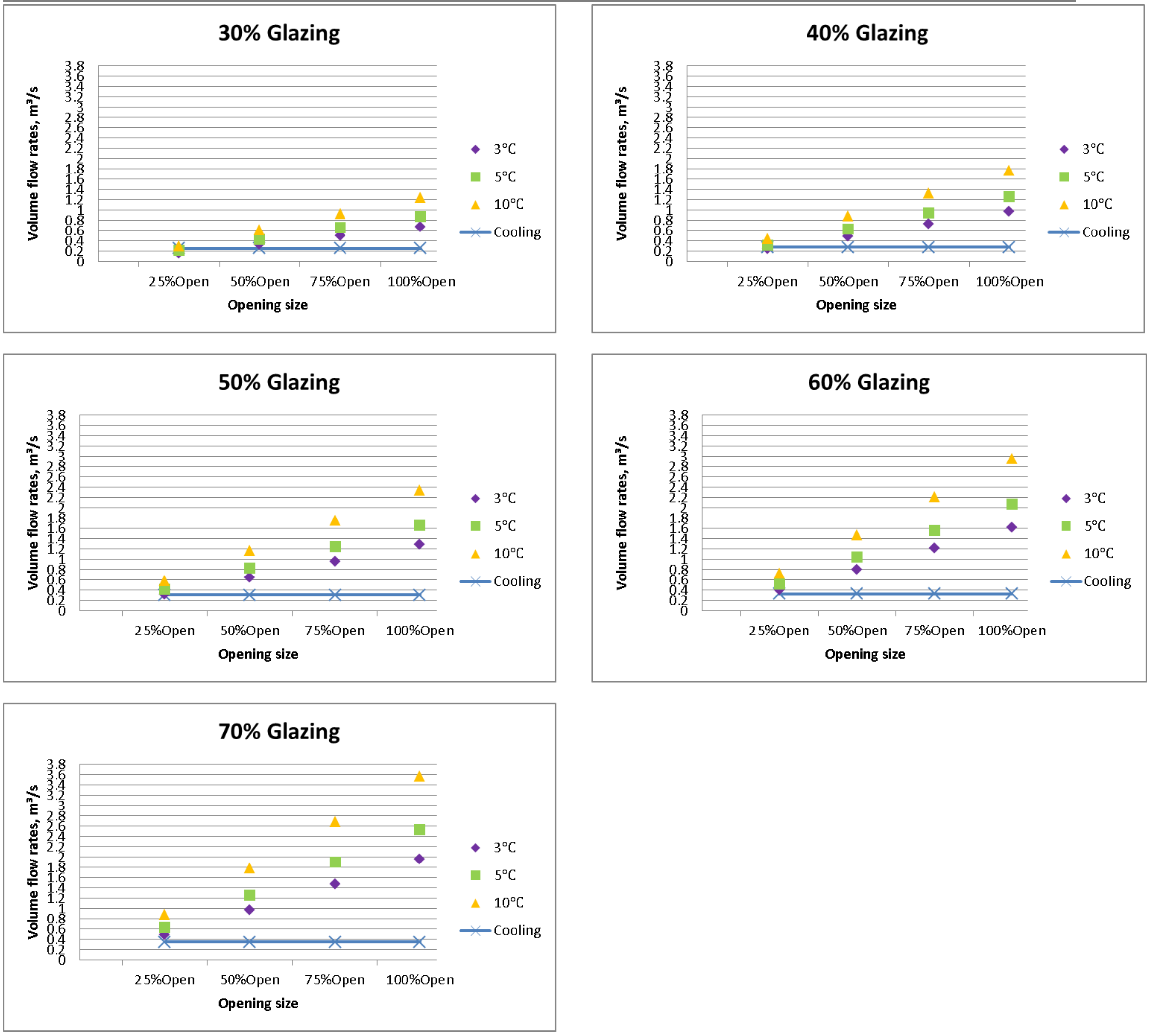


Figure 2.18: The impact of temperature difference and opening difference on air flow rates in a cross-ventilated office.

2.7.2 Wind dominated natural ventilation

Figure 2.19 shows the impact on air volume flow rate by changing the wind speed and wind direction in a cross-ventilated office when using wind dominated natural ventilation. The figures show that increasing wind speed and opening area resulted in the rise of air flow rate. At 1m/s wind speed, opening 25% of the glazing area at all glazing sizes can just attain an effective air flow rate for cooling. When the opening size was larger than 25%, the effective air flow rate for cooling was easier to approach. So opening 25% of the glazing areas can basically achieve the cooling purpose in a cross-ventilated office. Besides, when the wind direction was 0°, the volume flow rate was slightly higher than direction 45°. In a cross-ventilated office, increasing air flow speed had a more significant impact on volume flow rate than increasing indoor and outdoor temperature difference, especially with a large free opening area.

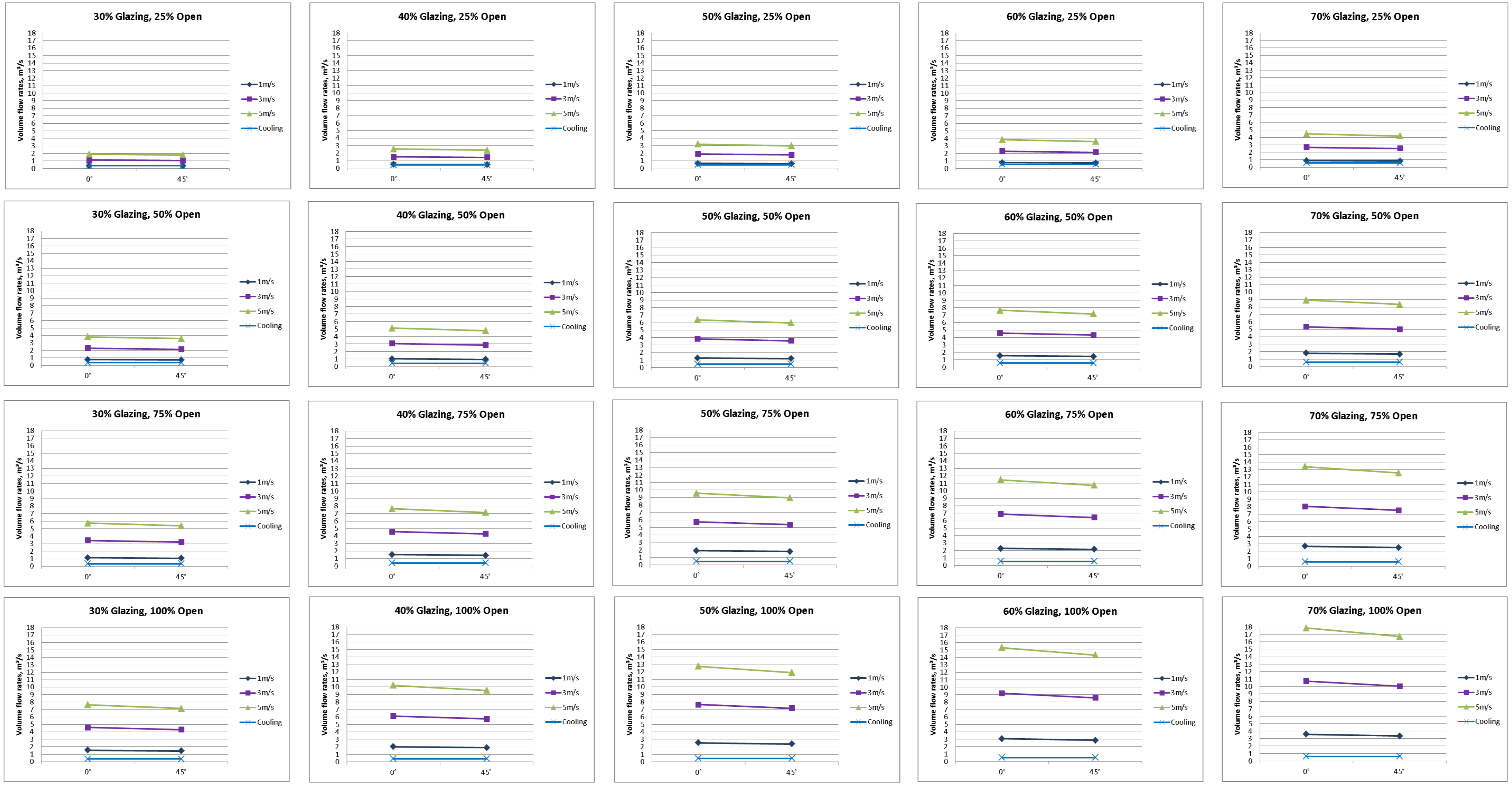


Figure 2.19: The impact on air flow rates by changing the wind speed difference at different wind direction and wind speed; the opening is facing 0° at different glazing area.

2.8 Hourly data analysis of a cross-ventilated office

Dynamic analysis gave more detailed results of the impact of natural ventilation on office buildings' thermal performance. The corridor was considered in the analysis. The changing of the glazing area and opening size on both sides of the office were the same. In the cross-ventilated office, the corridor at one side of the office seems to act as a shading device and may be able to extend the comfort temperature. But according to the results, the corridor does not significantly impact on indoor thermal performance. For instance, in October, the corridor at the south side was about 1% higher than the north side (Figure 2.20 and Figure 2.21). In the other months, the value was the same. Therefore, four orientations were considered in the hourly data analysis.

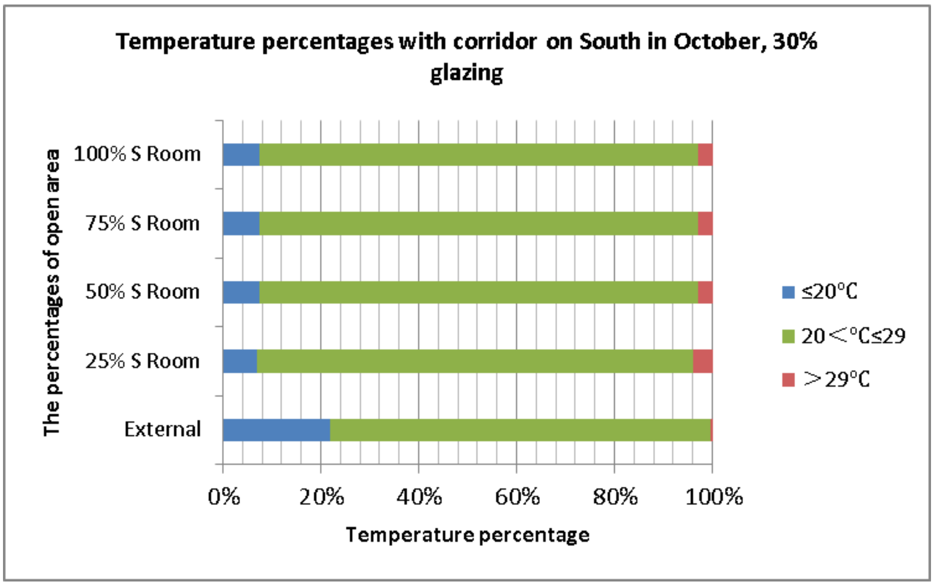


Figure 2.20: Temperature percentages in a cross-ventilated office with a corridor in the south.

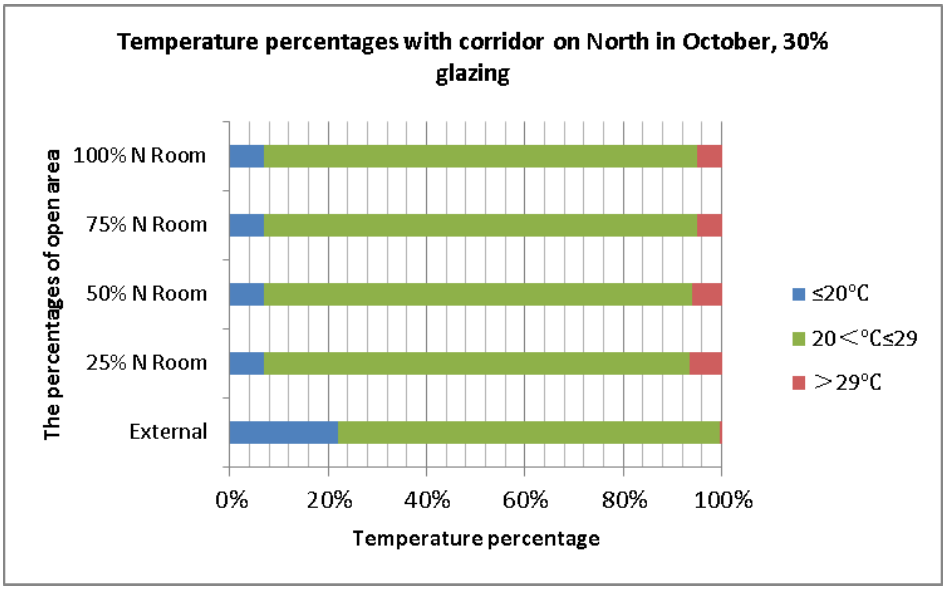


Figure 2.21: Temperature percentages in a cross-ventilated office with a corridor in the north.

2.8.1 Temperature percentages

The result of temperature percentages in a 30% glazing and cross-ventilated office on four directions are shown in Figure 2.22. In the cross-ventilated office, the result of opening 25% of the glazing area and 100% of the glazing area did not have too much difference. As for the single-side ventilation office, the comfort temperature percentage in July and August was very little, so it was not demonstrated. In May, the situation in the office was the best in the four months. In the south/north orientation office and the south-west/north-east orientation office, the indoor comfort temperature percentage was more than outdoor comfort temperature percentage. This is because the indoor temperature was never lower than 20°C during the working hours, and changing the open area would not impact on the change of indoor temperature percentages. The comfort temperature percentage resulted in the south-east/north-west and east/west facing office being slightly lower than the other two offices, but it would not have a significant impact on indoor comfort temperature. In the east/west facing office, increasing the free opening area from 25% to 100% could cause the comfort temperature percentage to rise by 4%. In a word, in May, the thermal comfort would not be an issue in the office on each orientation (Figure 2.23). In most of the working hours, the temperature was in the comfort zone, but the relatively high humidity may have caused discomfort sometimes.

In June, the maximum comfort temperature percentage in the south/north facing office was about 50% in the entire working hours, which was much lower than the value in May. Compared to the south/north orientation, the temperature percentage in the other orientations was slightly lower. The maximum difference was 8% in the east/west orientation. In addition, the indoor temperature percentage was increased gradually with increasing effective open area. The result of the 25% open office was 8% lower than the 100% open office, and this difference was the same as the difference in the other orientations. Although within 50% of the time the indoor temperature was in the comfort range, according to the psychrometric chart, for most of the time the data were located outside of the comfort zone because of relatively high humidity. This was the main problem for the indoor comfort during June.

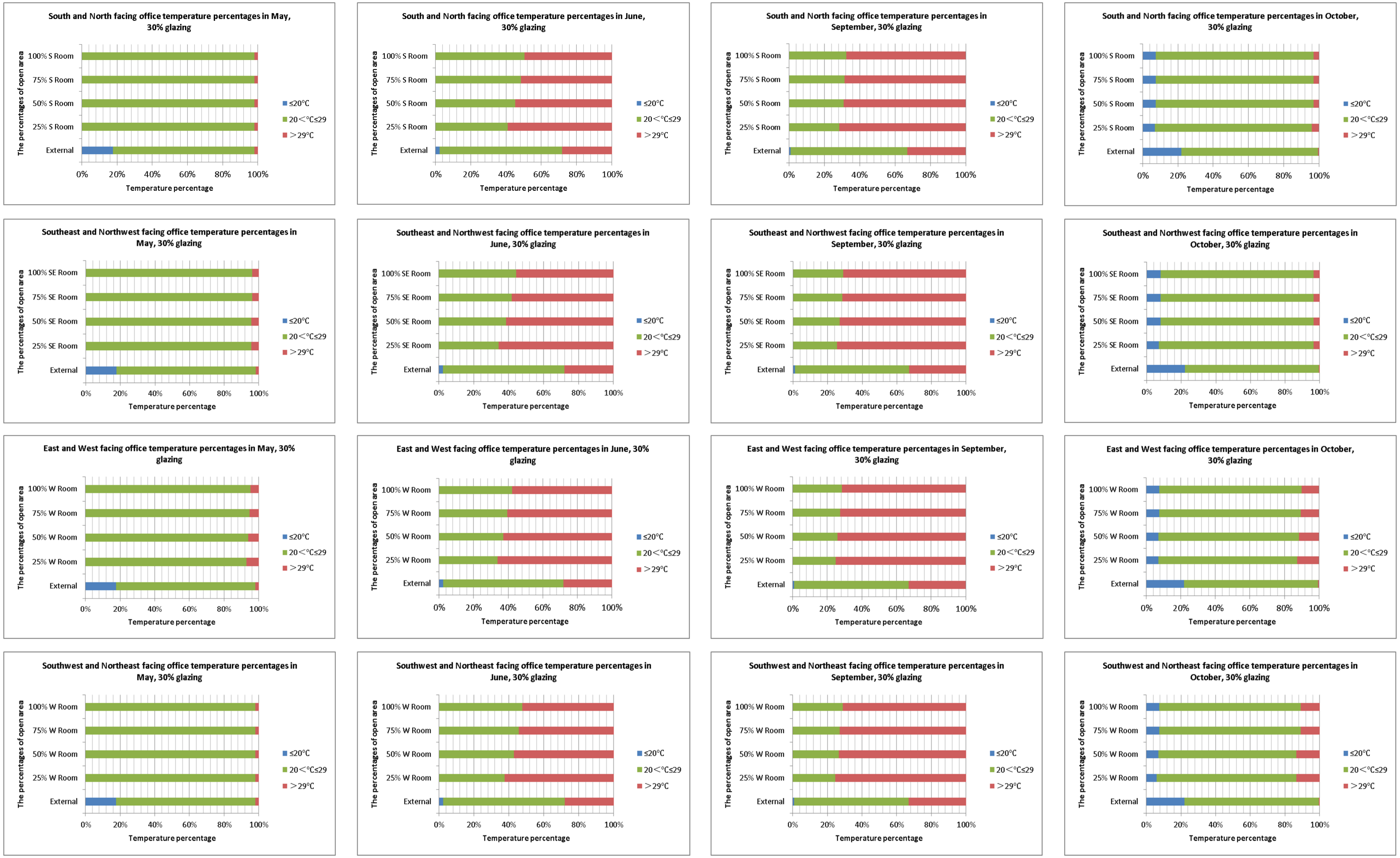


Figure 2.22: The temperature percentage in a 30% glazing and cross-ventilated office in eight orientations in May June, September and October.

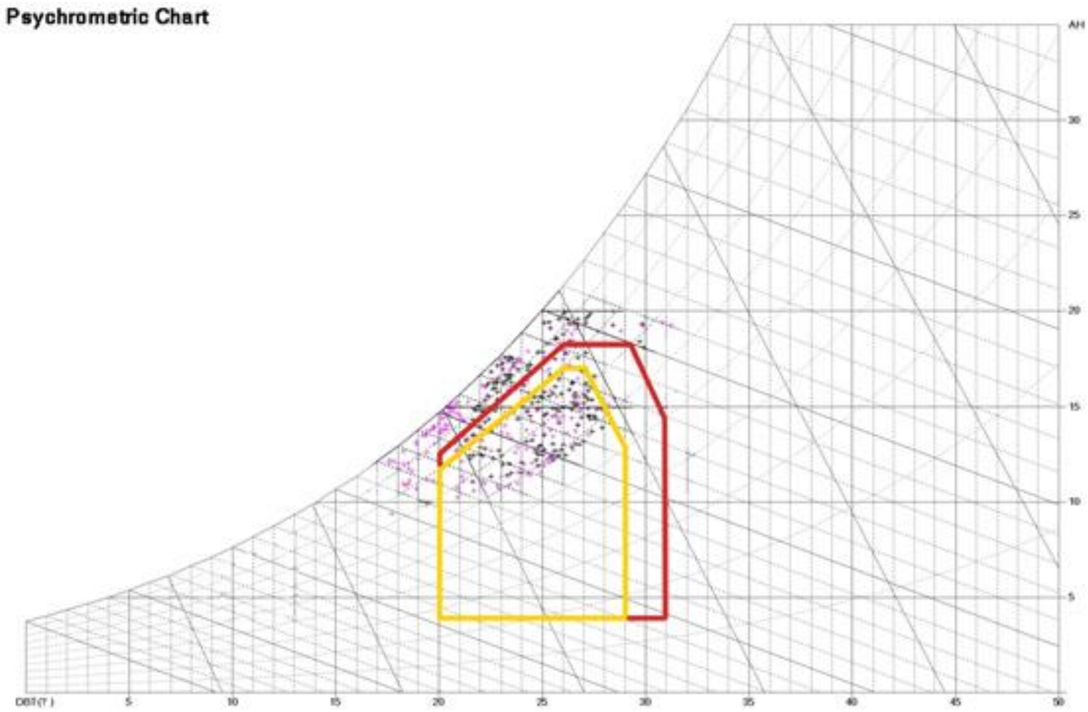


Figure 2.23: Indoor (Black) and outdoor (Pink) temperature distribution in May at 30% glazing and south/north orientation office with 100% opened window.

Figure 2.24: Indoor (Black) and outdoor (Pink) temperature distribution in June at 30% glazing and south/north orientation office with 100% opened window.

In September, the comfort temperature percentage was the lowest within these four months. The maximum value was 32% in south and north facing offices. The temperature percentages in the other three directions were the same, i.e. 4% lower than the south-east orientation. The difference between each orientation was small, the same result as changing the effective open area. The 100% open window could increase the comfort temperature percentage by 4% more than the 25% open window. In September, it had the lowest comfort temperature percentage, but many data were located within the comfort zone (Figure 2.25). As in June, the relative humidity was the main problem.

Figure 2.25: Indoor (Black) and outdoor (Pink) temperature distribution in September at 30% glazing and south/north orientation office with 100% opened window.

In the office during the working hours, the indoor temperature was slightly higher than the outdoor temperature (Figure 2.26). But the office was naturally well-ventilated, because in the morning there was an obvious indoor temperature decrease, which was related to the occupant behaviour of opening the window when they arrived in the office that caused the office to be cross-ventilated. But because the outdoor temperature during the noon time was over 30°C, it was very difficult to reduce the indoor temperature. Besides, the window was closed after working hours so the indoor temperature dropped very slowly, which caused a higher indoor temperature in the early morning when occupants arrived in the office, as the outdoor temperature after working hours was much lower than the indoor temperature. The night time ventilation can be considered to reduce the indoor temperature after working hours and to reduce the indoor temperature in the morning.

In October, in about 6% of the time the indoor temperature was lower than 20°C, which may have caused occupants to feel cold and uncomfortable. But in most of the time, the indoor temperature was in the comfort temperature range. The result of south/north and south-east/north-west was the same. In about 4% of time the indoor temperature was above 29°C, and changing the effective open area would not cause any difference. The results of the comfort temperature percentage in the east/west and south-west/north-east orientation were close to each other and 6% lower than other orientations. In addition, increasing the free opening area would have a small influence on temperature percentage rise, which was about 2%. In the psychrometric chart (Figure 2.27), the data were mainly in the comfort zone, so in the majority of time the thermal comfort could be achieved in the cross-ventilated office in October.

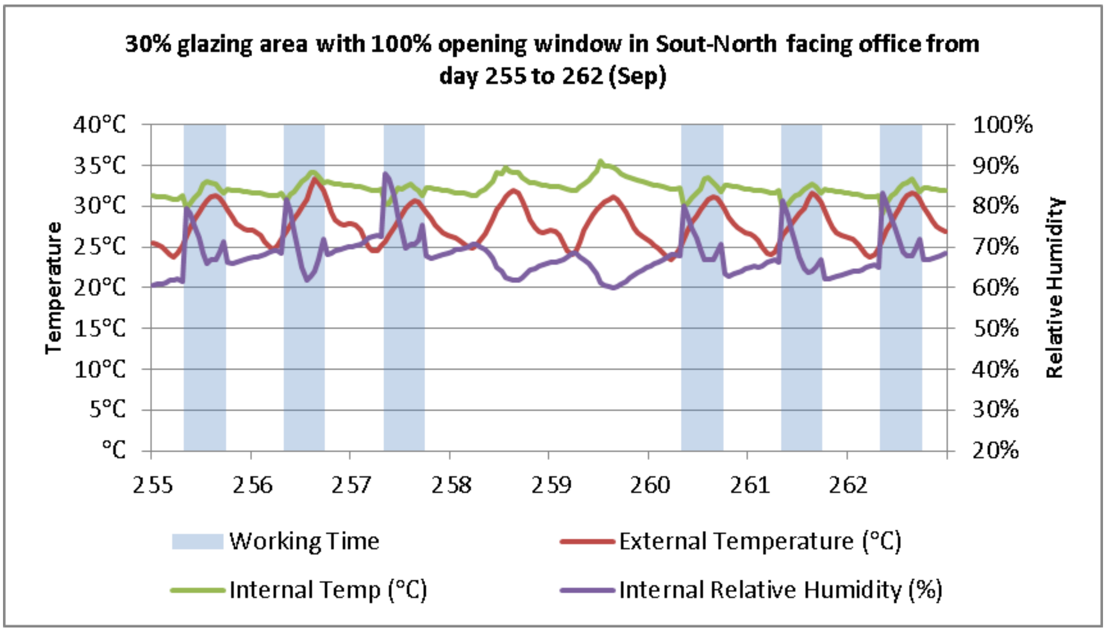


Figure 2.26: Internal and external temperature and indoor relative humidity in south/north facing office in September.

Figure 2.27: Indoor (Black) and outdoor (Pink) temperature distribution in October at 30% glazing and south-north orientation office with 100% opened window.

To sum up, in the cross-ventilated office, if the effective open area on both sides of the office was larger than 25% of the total glazing area then there was not much difference in indoor temperature variation. The result was the same as predicted by the empirical expression. Especially in May, changing the free opening area from 25% to 100% would not have any influence on the indoor temperature during the working hours. In these four orientations, the total amount of comfort temperature percentage in the south-north orientation was the most, while in the east-west orientation it was the worst. However, the amount of indoor temperature percentages between each orientation was little. Therefore, in the cross-ventilated office, the orientation of the office would not cause much indoor temperature difference.

2.8.2 The optimum glazing area and orientation in these four months

Figure 2.28 shows the indoor temperature percentage difference between a 30% glazing office and a 70% glazing office on the south-north orientation. In the single-side ventilation office the small glazing office with a large effective open area had more comfort temperature percentage than the large glazing office. The situation in the cross-ventilated office facing south-north was similar, but the gap was much smaller than the single-side ventilation office.

In May, the temperature percentage in 30% and 70% glazing offices was the same. Therefore, in this month, if the office could be cross-ventilated, it would not cause a thermal comfort problem in the office. In June, the comfort temperature percentage in the 30% glazing office was slightly higher than the 70% glazing office. The increased amount of percentage on different open areas was similar, at the value of 5%. Increasing the glazing area would reduce comfort temperature percentage. In September, the result of comfort temperature percentage difference was the same as June. The comfort temperature percentage in the 30% glazing office was more than the 70% glazing office, with a gap of 4%. In October, the comfort temperature percentage in the 30% glazing office was 3% lower than the 70% glazing office. The result was slightly different in the 70% glazing office when the glazing area was 25% open. The percentage of temperature dropped about 3% when the temperature was lower than 20°C. Therefore, the total amount of comfort temperature percentage did not decrease. In this month, reducing the effective open area when indoor temperature tends to cool can extend the comfort temperature as well. Generally, the comfort temperature in the 30% glazing office was higher than the 70% glazing office. Reducing the glazing area from 70% to 30% could extend the comfort temperature percentage by 3.5% (28.6 hour).

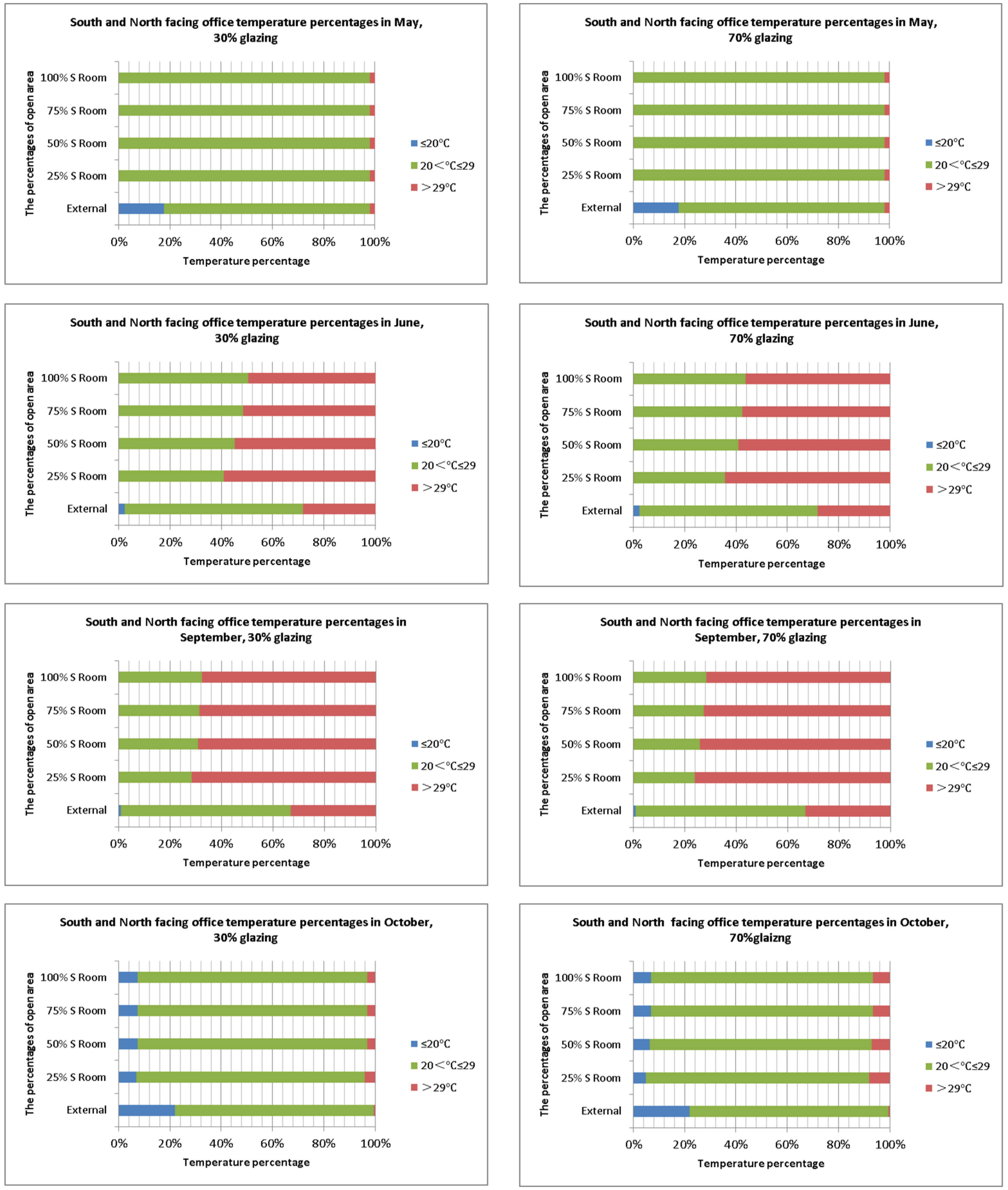


Figure 2.28: Comparing indoor temperature percentage between 30% and 70% glazing office facing south-north in May, June, September and October.

The result of the temperature percentage in other orientations is shown in Table 2.9. The temperature percentage result between the 30% and 70% glazing offices in the south-east/north-west orientation was the same, such that none of the values changed. The result in the north-east/south-west orientation was the same, so changing the glazing area would not cause the change of indoor temperature percentage.

Table 2.9: The indoor comfort temperature percentage change results when glazing area increased from 30% to 70%, and increased comfort time in the office.
(¤: means result was same)

	May	**June**	**September**	**October**	**Increased comfort time**
South - North	25% ¤ 50% ¤ 75% ¤ 100% ¤	25% ↓5% 50% ↓5% 75% ↓6% 100% ↓6%	25% ↓4% 50% ↓4% 75% ↓4% 100% ↓4%	25% ↑4% 50% ↓4% 75% ↓4% 100% ↓4%	30%>70% **28.6h**(3.5%)
South east-North west	25% ¤ 50% ¤ 75% ¤ 100% ¤	25% ¤ 50% ¤ 75% ¤ 100% ¤	25% ¤ 50% ¤ 75% ¤ 100% ¤	25% ¤ 50% ¤ 75% ¤ 100% ¤	30%=70% **0h**(0%)
East-West	25% ↓37% 50% ↓34% 75% ↓29% 100% ↓25%	25% ↓18% 50% ↓16% 75% ↓16% 100% ↓15%	25% ↓8% 50% ↓8% 75% ↓9% 100% ↓8%	25% ↓27% 50% ↓24% 75% ↓24% 100% ↓22%	30%>70% **144h**(17.5%)
North east-South west	25% ¤ 50% ¤ 75% ¤ 100% ¤	25% ¤ 50% ¤ 75% ¤ 100% ¤	25% ¤ 50% ¤ 75% ¤ 100% ¤	25% ¤ 50% ¤ 75% ¤ 100% ¤	30%=70% **0h**(0%)

The result in the east-west orientation was different and the situation was the worst (Figure 2.29). Reducing the glazing area from 70% to 30% could increase the comfort temperature percentage by 17.5%, which was about 144h (18 working days). Especially in May and October, there were large comfort temperature percentage differences in the office. The amount of percentages in the 70% glazing office was much lower than in the 30% glazing office. Increasing the glazing area would cause an indoor temperature rise, and the solar radiation may have a significant impact on indoor temperature. Extending the effective open area in the 70% glazing office had more impact on indoor temperature than in the 30% glazing office. Increasing the effective open area from 25% to 100% can increase 16% of the comfort time, but the comfort temperature percentage was still lower than the value in the 30% glazing office. This situation was even worse than the west facing single-side ventilation office. The reason probably is that the air flow speed on the east-west direction was lower than other orientations and the extended glazing area received much heat from solar radiation, so the heat received by the office was far more than it could move out. Therefore, on the east and west facing office the large glazing façade should be avoided.

However, based on Figure 2.30, the result showed that the office was naturally well ventilated. During the working hours the indoor air temperature was very close to the outdoor temperature. But the indoor radiant temperature was much higher than the indoor air temperature. And the temperature difference was more than 3°C. Because there was a large glazing area at both sides of the office, the radiant temperature rose up fast in the morning by the direct sunlight from the east and reached the peak in the afternoon. During these times the indoor temperature was not considered to be in the comfort temperature, which resulted in a low comfort temperature percentage. Therefore, solar radiation was the main problem in the east-west facing office.

To sum up, in the cross-ventilated office, the south-north direction was the optimum orientation and the east-west was the worst. In addition, the same as the single-side ventilation office, the 30% glazing office performed better than the 70% glazing office in the orientation of south-north and east-west. The result between the 30% and 70% glazing offices in the south-east/north-west and north-east/south-west office was the same.

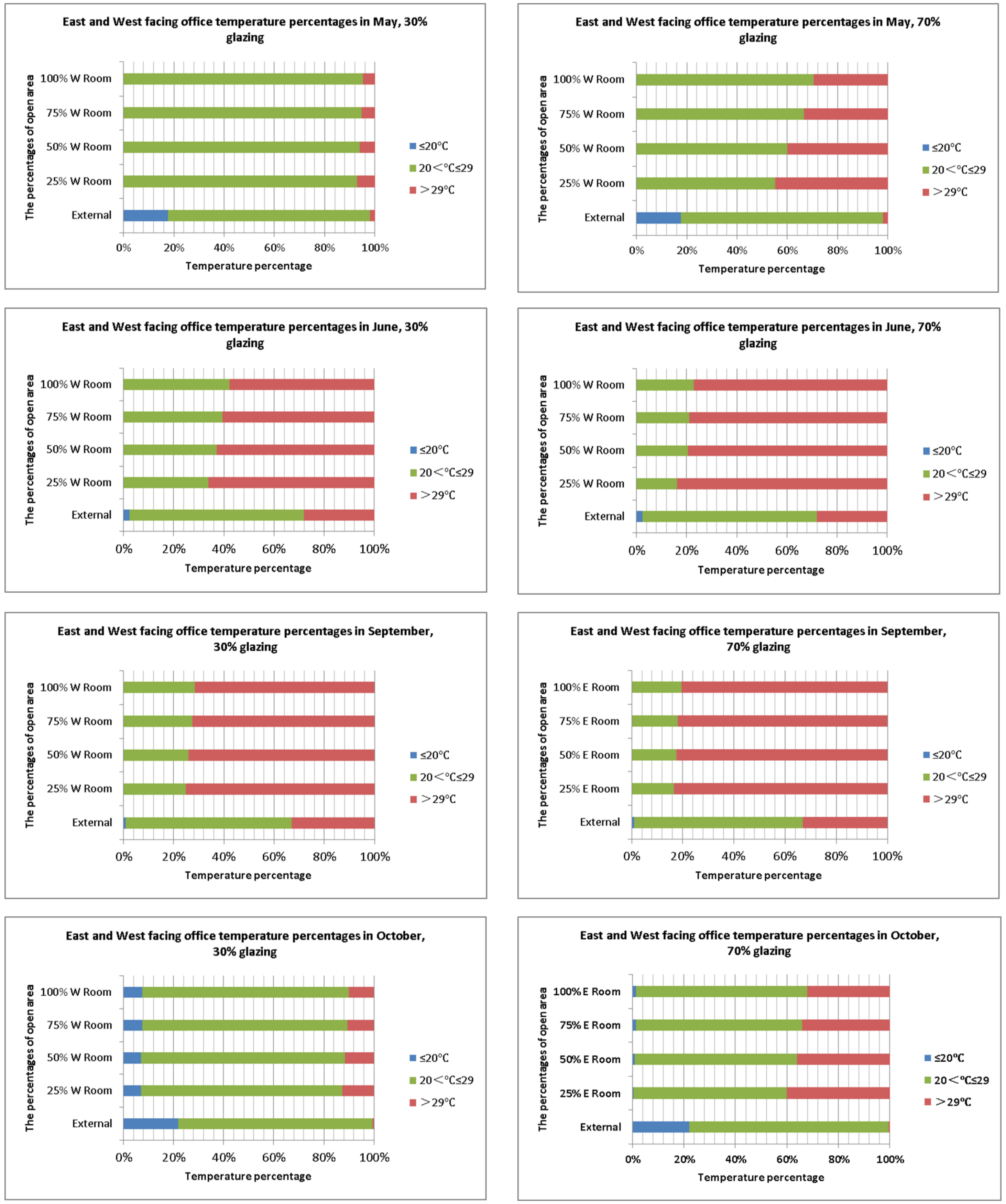


Figure 2.29: Comparing indoor temperature percentage between 30% and 70% glazing office facing east-west in May, June, September and October.

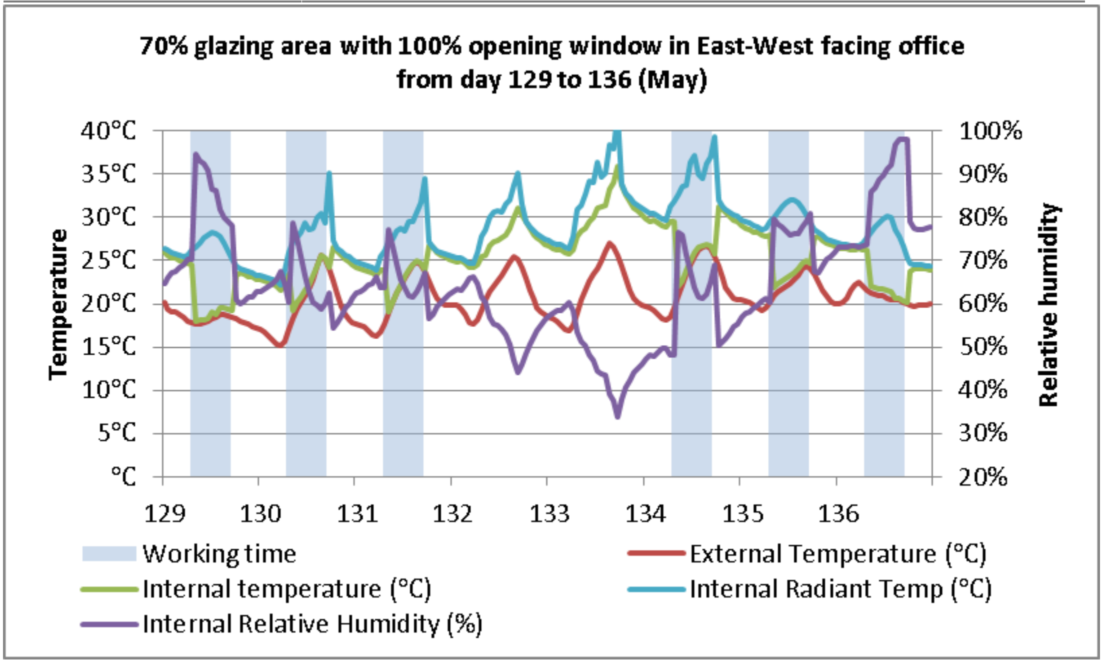


Figure 2.30: Internal and external temperature and indoor relative humidity in east-west facing office in May.

2.8.3 The temperature percentage between a single-side ventilated and a cross-ventilated offices

Comparing the temperature percentage between a single-side ventilation office and a cross-ventilated office in May, June and September, the indoor comfort temperature percentage in the cross-ventilation room was more than that in the single-side ventilation office. And in some orientations when the window was fully opened, the comfort temperature percentage in the single-side ventilation office was very close to the cross-ventilated office, for instance, south, north and the orientation inclines to east (Figure 2.31).

But the situation in October was different. In the south and north orientations, if the office was single-side ventilated and facing north, of which the free opening area could achieve 50% of the glazing area, then the indoor comfort temperature percentage was higher than that in the cross-ventilated office. The same results can be found in single-side ventilation offices which were facing east and north-east. In these offices, there was a common feature which was that the comfort temperature percentage in the opposite orientation was much lower than these offices. This was because, in the cross-ventilated office, the façades were facing both directions and would receive solar radiation from both directions. The indoor temperature percentage in cross-ventilation was like an average value of two single-side ventilation offices facing opposite orientations. That was the reason why the comfort temperature percentage in the cross-ventilated office was lower than the single-side ventilation office in some orientations. In October, the solar radiation from the west was the main issue which increased the indoor temperature. Furthermore, the temperature percentage of the indoor temperature below 20°C in the cross-ventilated office was more than the single-side ventilation office. The cross-ventilated office seemed over-ventilated, which may cause the occupants to feel cold and uncomfortable in the office. Reducing the effective open area could drop the air flow rate in the office and reduce the heat loss when the indoor temperature was low. In most of the time within these four months, the comfort temperature percentage in the cross-ventilated office performed better than the single-side ventilation office.

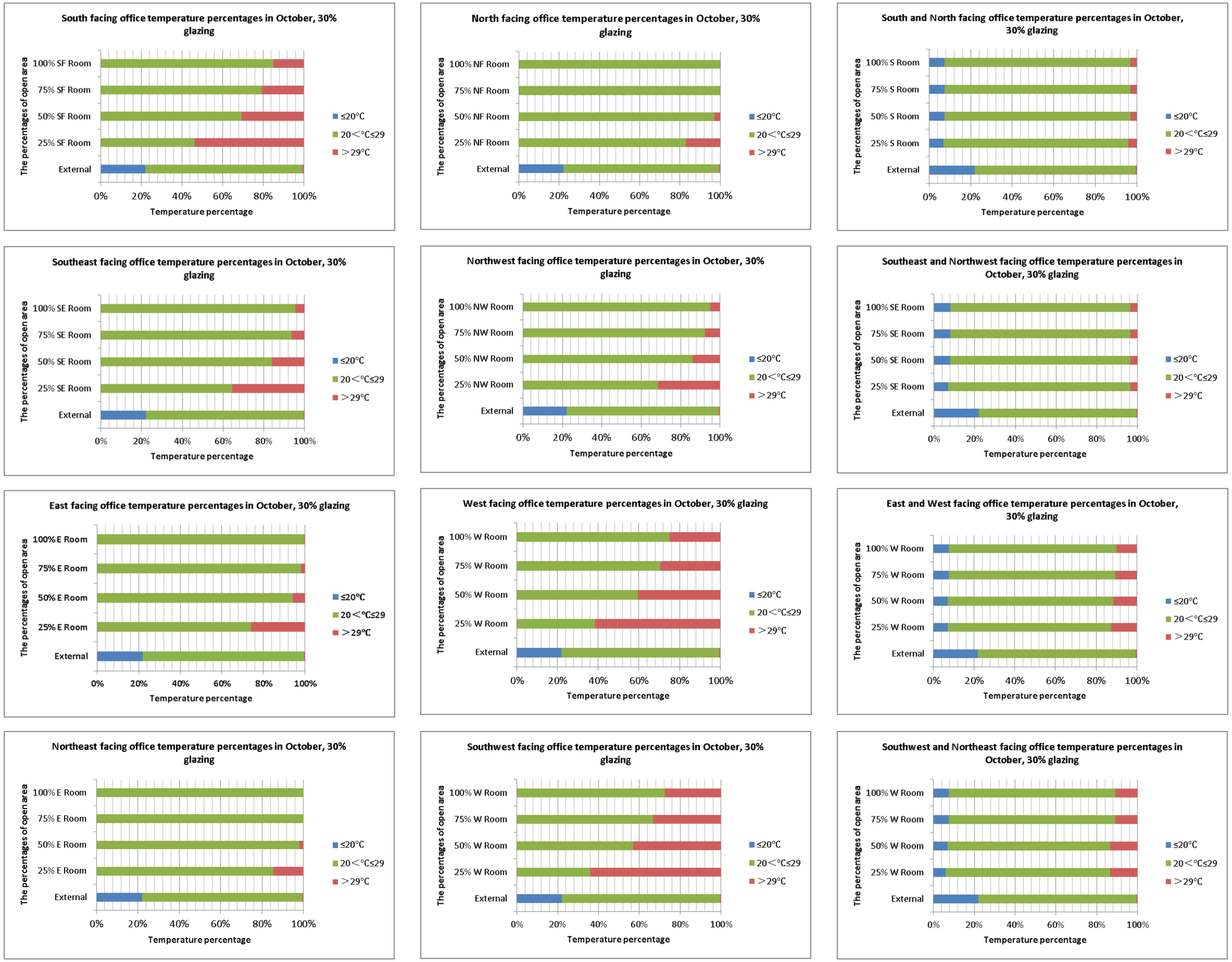


Figure 2.31: The temperature percentage in October in single-side ventilation office and cross-ventilated office with different orientations.

2.9 Discussion and conclusions

In the initial study, based on empirical expression, the effective air flow rate for the cellar office building was calculated. The results showed that, out of eight orientations and glazing areas from 30% to 70%, in some orientations the effective air flow rates were close to other. So the results were divided into three groups- south, north-east and north-west in Group 1, south-east, east, west and south-west in Group 2, north in Group 3 with the lowest effective flow rates. Those values were used to estimate the air flow rate whether a cooling effect had been achieved or not. Figure 2.5 shows that, in a 30% glazing office room, 3°C temperature difference, the window needs to be fully opened to achieve a cooling effect. The opening area could be reduced to 75% when temperature difference rises to 5°C.

The impact of changing indoor and outdoor temperature difference, wind speed and both temperature difference and wind speed was evaluated by empirical equations. The result shows that, in the temperature difference only condition, air flow rate increased as temperature difference rose. In the wind only condition, it is clear that increased wind speed and opening area resulted in air flow rate rise. At the same wind speed, when the incident angle was at 45° and 90°, the air flow rate reached the highest point, and the lowest point occurs when wind blows directly towards the opening area or directly to the leeward side. When the wind and temperature are combined, the results show that change in temperature difference has a large impact on the air flow rate at lower wind speed, which is 1m/s in the calculation. In addition, at the directly windward and leeward side, change in temperature difference is more effective than change in wind speed. Wind speed had more impact when the incident angle was at 45° or 135°.

The hourly data of a 30% glazing area office room showed the predicted indoor environment from May to October. The result was indicated by comfort temperature frequency and the psychrometric chart. The results demonstrated that, in July and August, the indoor and outdoor temperature and humidity ratio are far away from the comfort zone, and natural ventilation cannot help occupants to achieve comfort, so the mechanical cooling system should be applied in these two months. In May and October, if the window is able to be 100% open, the comfort temperature could be achieved in the majority of time. In June and September, for more than half of the working hours the temperature was higher than the upper boundary of the comfort zone, but most of the external temperature was in the comfort temperature range. Therefore, reducing the indoor temperature was still achievable by raising the air flow rate.

In addition, in these four months, the 30% glazing office had more comfort time than 70% glazing office, especially in south-west, west and north-west facing offices. The small glazing area with a large free opening area can achieve a better indoor environmental condition. Besides, the smaller comfort temperature percentages between a 30% and 70% glazing office represented a better comfort temperature percentage in the office, for which the north orientation has the highest value in these orientations, then the north-east.

In the cross-ventilated office, except when the wind was parallel with the open area, the wind pressure difference was mainly dominating the natural ventilation. And when wind speed was 1m/s, opening 25% of the glazing area could achieve the cooling purpose in the predicted office. This result was proved by hourly data analyses as well. In the cross-ventilated office, changing the open area from 25% to 100% had a very limited impact on indoor temperature percentages. The indoor comfort temperature percentage was positive in the cross-ventilated office, especially in May and October, although in June and September the maximum comfort temperature percentage could achieve 50% and 30% with optimum orientation. But according to the data distributed in the psychrometric chart, the high indoor relative humidity caused most of the data to be located on the outside of the comfort zone, which may have resulted in the occupants being uncomfortable.

The result of increasing the glazing area in the cross-ventilated office was similar to that in the single-side office. On the south-east/north-west and south-west/north-east orientations, changing the glazing area did not cause the change of indoor temperature percentage. But on the south-north and east-west orientations, the comfort temperature percentage was decreased with increasing the glazing area. Especially in the east-west orientation, increasing the glazing area led to the indoor comfort time reducing to 144 hours. The high indoor radiant temperature was the reason for the indoor comfort temperature percentage to drop in the 70% glazing office. Therefore, in this orientation, controlling solar radiation would be more efficient than increasing the effective opening area.

In most of the time, the comfort temperature percentage in the cross-ventilated office was more than that in the single-side ventilation office. But in October, the comfort percentage in the cross-ventilated office was lower than in the single-side ventilation office, which was facing the south, north and east inclined orientations. That is because the cross-ventilated office received solar radiation and air flow from two directions. The indoor temperature result in the cross-ventilated office was more like the average result of two opposite single-side ventilation offices. If one orientation received more heat than the other, it would increase the temperature in the cross-ventilated office as well. Thus, the indoor comfort temperature percentage was lower than the single-side ventilation office in some orientations.

3 Pilot Study in an Office Building in Hangzhou

This chapter describes the climate condition in both hot summer and cold winter and the detailed method of the pilot study in an office building in Hangzhou, which is located in South-East China. The aim of the pilot study was to examine the methodology and to find any deficiencies in the method that may need to be addressed before the development of the case studies. Field measurement and questionnaire were the methods used in the field work. Besides, the thermal performance of the building was demonstrated. Some findings of the natural ventilation, occupant's perception and occupant window control behaviour were presented. Additionally, results for a period when air-condition was used due to an unexpected hot wave were also presented. At last, shortfall and issues in the field work were pointed out and appropriate solutions were provided.

3.1 Local climate

Hangzhou was used as a case study city; it was located in the hot summer and cold winter climate zone in China. The definition of climate zone was according to the building design standard (Chinese National Standard, 1993), based on the average temperature in the coldest and hottest month, and also the number of days when the average temperature was below 5°C or above 25°C (Table 3.1). Hangzhou is in the south-east part of China, at the latitude of 30.1° North and the longitude of 120.07° East. In summer, the prevailing wind comes from the south-east direction, bringing hot and humid air from the ocean; meanwhile, in winter, cold and arid wind comes from the north-west part of the continent. The highest solar angles in Hangzhou are 36°64 for winter solstices, 83°25 for summer solstices, and 59°9 for the equinoxes. The typical year weather data produced by China Meteorological Administration and Tsinghua University were used for local weather condition analysis, which was from China's architecture thermal environment analysis meteorology database (China Meteorological Administration and Department of Building Science and Technology, Tsinghua University, 2005). This database recorded the weather data from 1971 to 2003 from over 270 weather stations in China.

Table 3.1: Climate classification criteria (Chinese National Standard, 1993).

Climate zone	Main index	Complementary index
1,Very cold	ATCM≤-10℃	NDAT5≥145days
2,Cold	ATCM=0-10℃	NDAT5=90-145days
3,Hot summer and cold winter	ATCM=0-10℃,ATHM=25-30℃	NDAT5=0-90days, NDAT25=40-110days
4,Mild	ATCM=0-13℃,ATHM=18-25℃	NDAT5=0-90days
5,Hot summer and warm winter	ATCM≥10℃,ATHM=25-29℃	NDAT25=100-200days
Notes: ATCM: average temperature in the coldest month; ATHM: average temperature in the hottest month; NDAT5: number of days that average temperature is below 5°C; NDAT25: number of days that average temperature is above 25°C.		

According to the typical year hourly weather data of Hangzhou, the mean annual temperature was 17.4°C. The hottest months were July and August, with mean temperatures of 28.6°C and 29.9°C. The coldest months were January and February, with mean temperatures of 5.5°C and 6.3°C. However, the temperature in Hangzhou can decrease to -2.6°C in winter (the lowest record in the database is -12.7°C), while it can rise up to 36.7°C (the highest record in the database was 42.9°C) in summer (Figure 3.1). The average relative humidity was 82.3% in summer and 66.1% in winter. However, the relative humidity can reach up to 99% in summer and drop to 20% in winter.

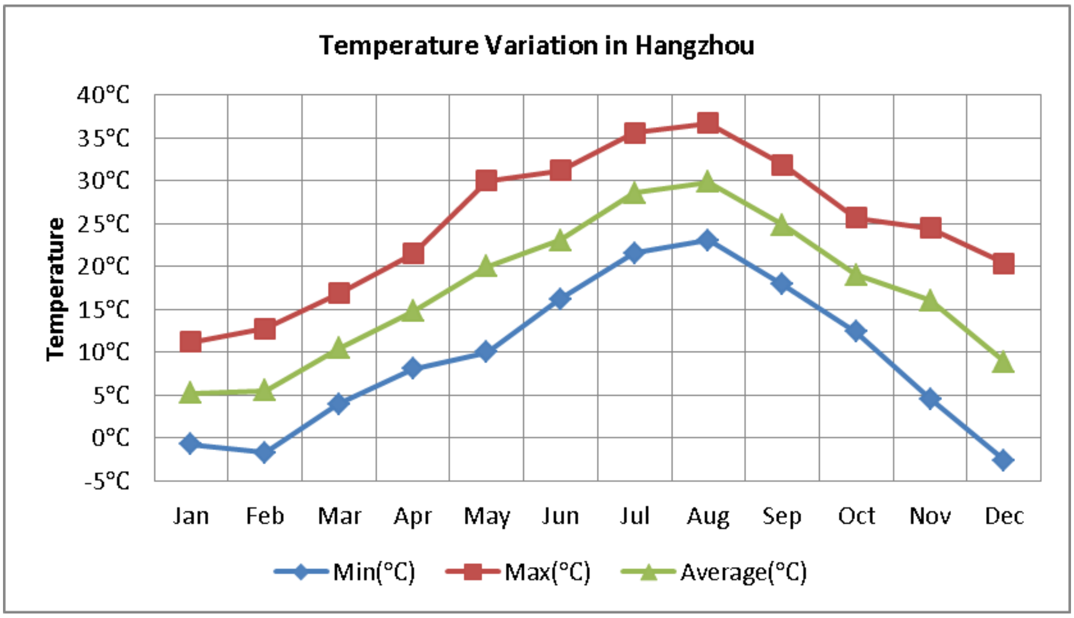


Figure 3.1: The typical annual temperature in Hangzhou produced by author based on China's architecture thermal environment analysis meteorology database.

Figure 3.2 illustrates the percentage of comfort time during the working day (the main working day was from 9am to 6pm in China) each month (shown as yellow columns). Moreover, the red columns show the percentage of comfort time when natural ventilation was achieved. Thus, natural ventilation in office buildings could help in extending the comfort zone in the office, especially in the months of May, June, September and October. The building bioclimatic charts were used to present the year round comfort distribution in terms of weather data in Hangzhou; the detail of the building bioclimatic charts was presented in Section 1.4.5. The figure were created using data from China's architecture thermal environment analysis meteorology database (China Meteorological Administration and Department of Building Science and Technology, Tsinghua University, 2005) and analysed through Ecotect[1] software; it shows hourly temperatures and relative humidity distribution from May to October (Figure 3.3, Figure 3.4 and Figure 3.5). The yellow line demonstrates the comfort zone for the still air condition and the red line

[1] Ecotect: It is an environmental analysis software which can be used to simulate building's environmental performance in the design stage.

shows the extended area of the comfort zone if natural ventilation could approach when the indoor air flow speed was 1.5m/s, according to Givoni's (1994) work. The green dot shows the working hours and the blue was the time after working hours. It shows that, in May and June, thermal comfort can be achieved in most of the working hours, through naturally ventilated. During July and August, the weather was very hot and humid. In a very limited time period comfort can only be achieved through the use of active system such as air-conditioning. In this period, the effectiveness of natural ventilation was limited. In September and October, during most of the working hours, outdoor temperature were within the selected thermal comfort range, although the outdoor temperature was below the lower comfort boundary after working hours. Therefore, the field study should be taken during May, June, September and October.

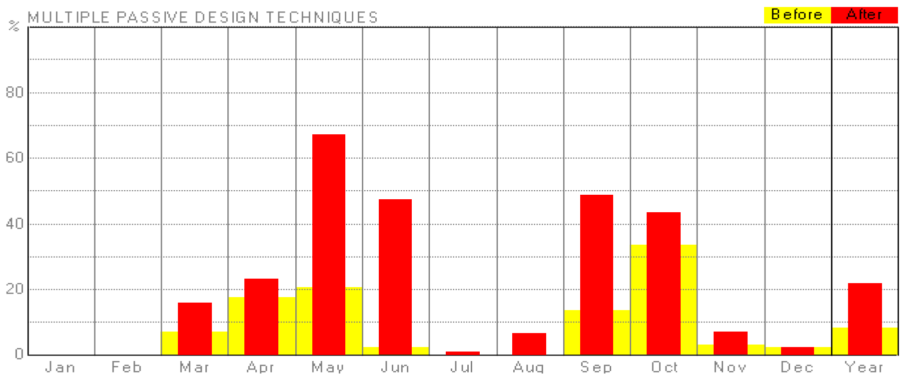


Figure 3.2: The natural ventilation potential in each month relate to percentages of comfort time during the working hours in each month (9am-6pm). The figure produced by author based on China's architecture thermal environment analysis meteorology database.

Figure 3.3: Outdoor air temperature and relative humidity distribution in May and June. (Yellow: still air condition, red: air flow speed about 1.5m/s)

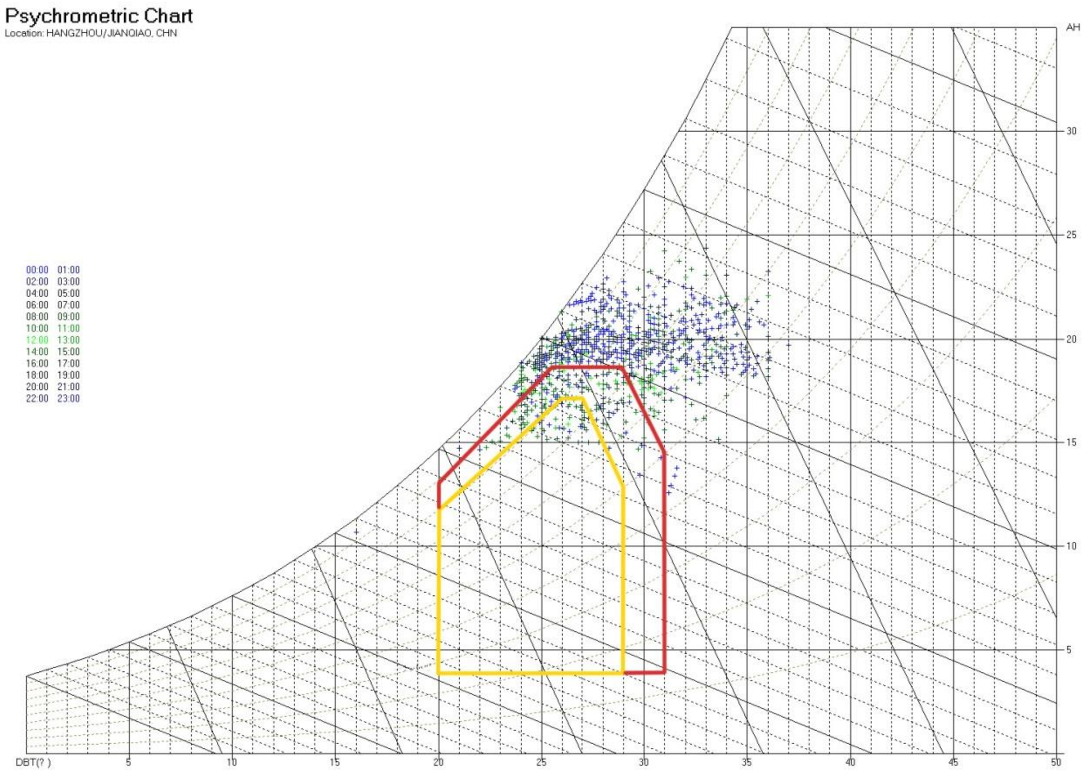


Figure 3.4: Outdoor air temperature and relative humidity distribution in July and August. (Yellow: still air condition, red: air flow speed about 1.5m/s)

Figure 3.5: Outdoor air temperature and relative humidity distribution in September and October. (Yellow: still air condition, red: air flow speed about 1.5m/s)

3.2 Building characteristics

Understanding the characteristic of office buildings can help to identify the potential of natural ventilation and the pattern of it. This could impact on occupants' behaviour in the office. According to the parametric study the comfort temperature in the office with large glazing area was lower than small glazing offices, so in the large glazing office the occupants may more frequently using window or other method adapt to the environment. The office used in the pilot study was a 21-floor building with a glass curtain wall (Figure 3.6), which was located in the south part of Hangzhou city near Qiantang River and facing south-east (Figure 3.6). Also, this was the only building that author have the permission to take measurement and questionnaire in that period. The building character can be seen from the plan that the building on the 20th and 21st floors was 46m long and 21m deep. The distance between each pillar was 8.5m (Figure 3.7 and Figure 3.8) with the height of 2.8m from floor to suspended ceiling (Figure 3.9). The main structure of the building was concrete with a glass curtain wall as the façade. The internal materials were: wood structure with gypsum plaster partition wall or glass partition wall, plywood suspended ceiling, laminated wood floor in the office and marble floor in the corridor. Detailed building plan was show in Appendix 3.

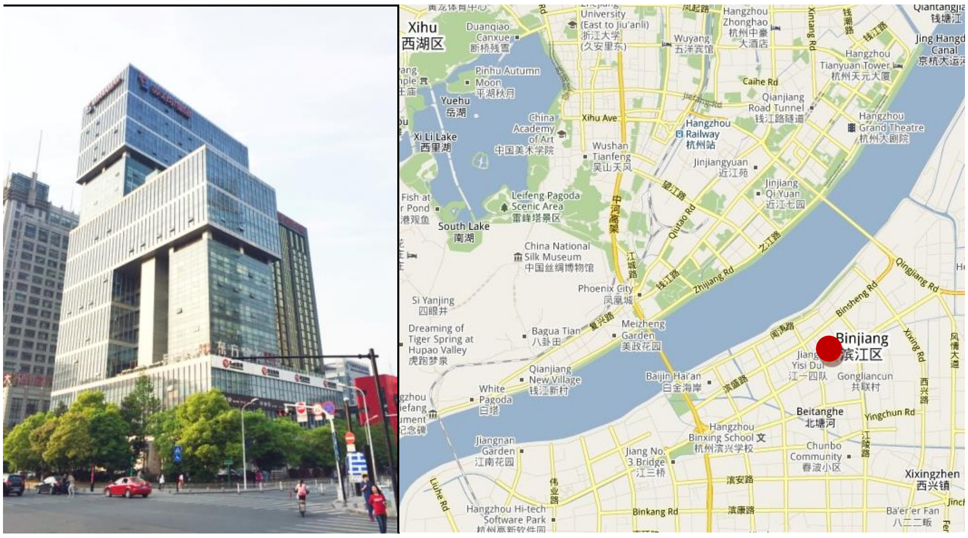


Figure 3.6: The rendering image (produced by architect) on the south-east facade of the office building (left) and the location in the city (right).

Figure 3.7: The plan of 20th floor.

Figure 3.8: The plan of 21st floor.

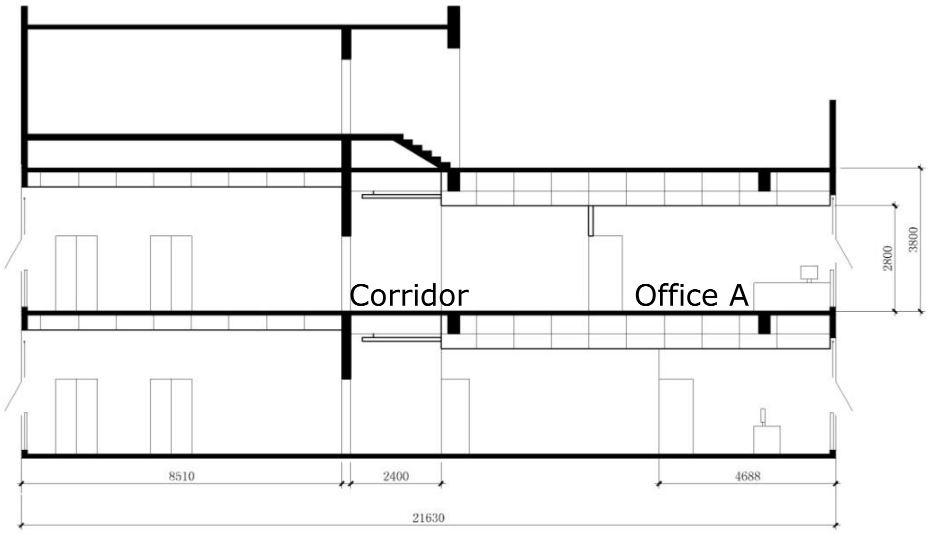


Figure 3.9: The section of 20th and 21st floor, cut through Office A and service core.

Office A (Figure 3.10, Figure 3.11 and Table 3.2) selected for monitoring was located on the 21st floor, while B and C were on the 20th floor. These were typical office rooms in the office building. Office B was facing south-east and office C was facing north-east and north-west. Office A was facing south-east, which was the smallest office but with the most of occupants and computers. The room sizes of offices B and C were very similar. Each of them has two occupants and two computers, total of eight occupants were monitored in the offices. The glass area in offices A and B were the same, and there were two top-hanging windows, both facing south-east in each office. But in office B, only one window was openable. Office C has the largest glass area among the three, with three windows, two facing north-west and one facing north-east. Due to the climate situation in Hangzhou, which was regularly over comfort zone, air conditioning was installed in the office to cool down the indoor temperature in summer and produce heat in winter. In this office building, the variable refrigerant flow air-conditioning system was used, which has two internal units in each office, installed in the ceiling. The power of each unit was about 2.2kw/h (Figure 3.12). Occupants can adjust the air conditioner individually. There was no specific natural ventilation strategy designed in the building and no mechanical fresh-air system was installed.

Figure 3.10: The interior image of a typical office room in the building.

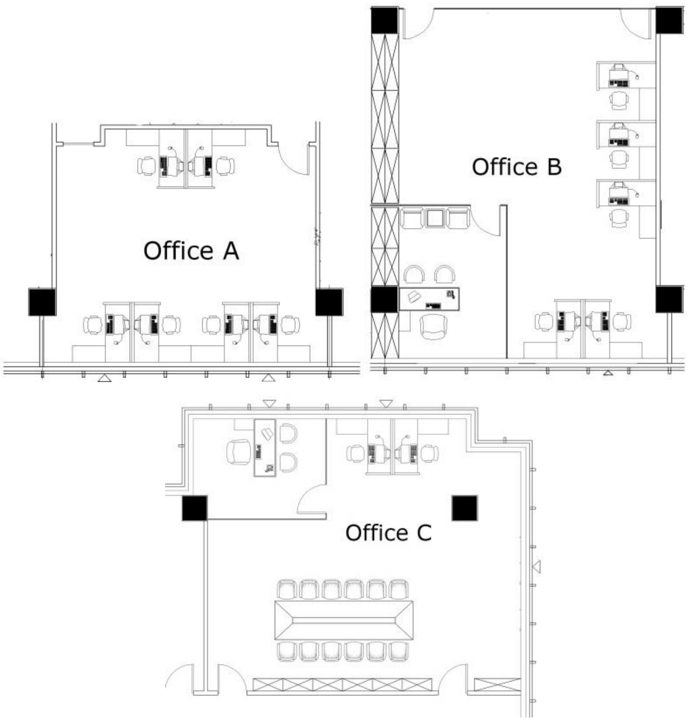


Figure 3.11: The plans of offices A, B and C.

Figure 3.12: The air-conditioning units in the office.

Table 3.2: The detailed characters of the three offices.

		Office A	Office B	Office C
Orientation		South-east 165°	South-east 165°	North-west 345°
Number of occupants		4	2	2
Number of computers		4	2	2
Dimensions	Width (m)	8.4	8.4	11
	Depth (m)	6.8	10	8.8
	Height (m)	2.8	2.8	2.8
Glazing area	Width (m)	8.4	8.4	19.8
	Height (m)	3	3	3
	Glazing Ratio%	90	90	90
	Glass type	Low-E	Low-E	Low-E
Window type		Top hung	Top hung	Top hung
Maximum openable area (m^2)		0.48	0.48	0.72

3.3 Methods and apparatus

Field measurements and occupant satisfaction surveys were used in this pilot study. These were efficient and straightforward method to investigation natural ventilation, occupant’s perception and window control behaviour. Monitored environmental factors included indoor and outdoor dry bulb air temperature, indoor and outdoor relative humidity, indoor and outdoor air flow speed and window state (open or close). The measured environmental factors were used to derive building thermal performance, natural ventilation stats and window control patterns in the office building. The contents of the occupant questionnaire were developed from previous research on post-occupant evaluation and occupant behaviour by well-established researchers (Cohen et al., 2001; Yun and Steemers, 2008). The aim of the occupant survey was to establish the occupants’ environmental perception that was related to indoor environmental stimulus. The relationship between environmental factors and occupant behaviours could be found from the collected data. The measurements were taken in May 2011 for two weeks, in three offices in the building mentioned in Section 3.2 in Hangzhou, China. (The detailed specification and efficiency of the instruments were shown in Appendix 4). For the pilot study 43210 set of indoor and outdoor temperature and relative humidity data, about 21600 indoor air velocity records and 160 copies of questionnaires were collected

3.3.1 Air temperature and relative humidity measurement

Tinytag (TGP-4500) was used to measure indoor and outdoor temperature and relative humidity. This model of Tinytag can record temperature between -25°C and +85°C and relative humidity between 0% and 100%. The accuracy of the temperature reading was ±0.25°C between 0°C and 40°C. The accuracy for relative humidity was ±3%RH at 25°C. The data can be exported to Excel.

A data logger was set up in each office to record the dry bulb indoor air temperature and relative humidity at two minutes intervals. The position of each data logger was on the desk near an occupant in order to measure the exact environmental condition around the occupant (Figure 3.13, Figure 3.14). The data logger was carefully located on the desk avoiding any impact by direct sunlight and other heat source (e.g., computer). The recorded internal temperatures and humidity levels were combined with window control records for analysis. These were used to correlate the indoor thermal performance and the relationship with window control, and also, the correlation of these with occupant indoor environment perception. The time of turning on or off the air-conditioning system was recorded by observation in fifteen minutes intervals.

Figure 3.13: The position of indoor temperature and relative humidity data logger on the desk.

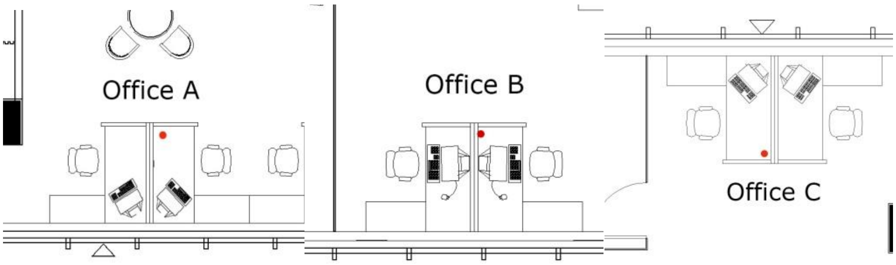


Figure 3.14: The position of the data logger in each office (red dot).

In order to monitor the microclimate conditions of the site, the outdoor dry bulb air temperature and relative humidity were recorded by a similar data logger (Tinytag TGP-4500) on the top of the office building. The data logger was well sheltered, avoiding direct sunlight and rainfall (Figure 3.15). The data were recorded in two minutes intervals.

Figure 3.15: The position of outdoor temperature and relative humidity data logger on the roof.

3.3.2 Air flow speed measurement

A portable AIRFLOW thermal anemometer (TA-2-2) and an anemometer (DVA 30 VT) were used to measure the air velocity at the opening area of the window and in the offices. The TA-2-2 thermal anemometer's working velocity range was from 0 to 2m/s, with accuracy of ±3% FSD at 20°C and 1013mbar. The velocity range for DVA 30 VT was 0.25-30m/s and the accuracy was ±1% FSD at air density 1.2kg/m^3. The TA-2-2 thermal anemometer was used for measuring the air speed near the occupant and DVA 30VT was used for measuring the air speed at window opening area. The measured effective opening area was used during the field study and the effective opening area measurement was based on the criteria in CIBSE AM10 (2005) (Figure 3.16). The effective window opening area and door were divided into nine grids for measuring and the results were recorded on paper each time. The average air speed was used for analysis (Figure 3.17). Each opening window was measured in 15-minute intervals. The indoor air flow speed was recorded at three points: one was close to the ceiling, one close to the occupant and one near the floor. The air velocity measurement was used to understand the thermal air movement condition, the influence for indoor thermal performance and the impact on occupant thermal comfort and window control behaviour.

A DVA 30 VT anemometer was used to measure outdoor air velocity on the top of the roof. Because of the prevalent wind direction and the building design (facing south-east), the measurements were taken facing south-east. The data were recorded at half-hour intervals and three times in each measuring. However, the recording was stopped sometimes because of the rain.

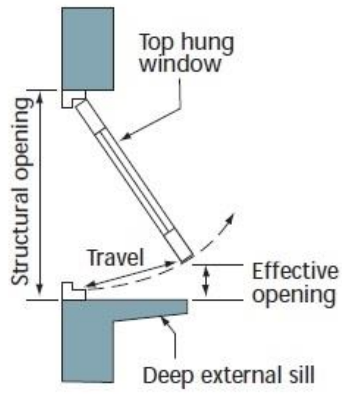


Figure 3.16: Structure opening and effective opening for a top hung window (CIBSE AM10, p22).

1	2	3
4	5	6
7	8	9

Figure 3.17: The opening area was divided into nine grids.

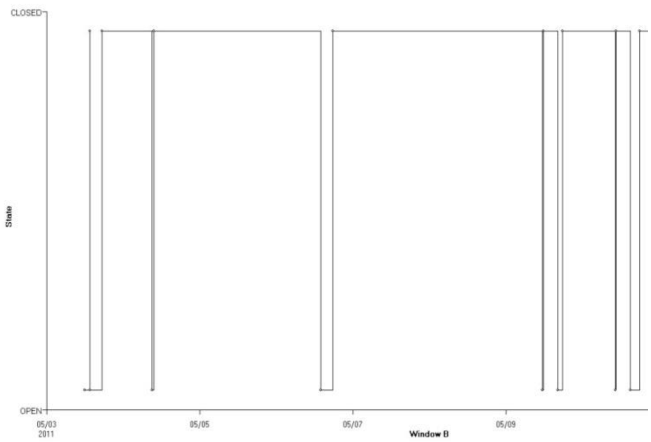
3.3.3 Occupant thermal comfort survey

The working day for the occupants was 9:00-17:30 including a 1-hour lunch time from 12:00 to 13:00, and the offices were fully occupied during the measuring time. In the morning, occupants normally arrive in the office at about 8:40. The questionnaires were given twice a day. First distribution was at 11:00 in the morning and the second distribution was at 17:00, half an hour before going off duty. The questionnaire aimed to identify the occupants' overall evaluation of indoor environmental conditions and personal comfort states. At the beginning, the clothing and activity level of occupants were recorded. The questionnaires also included occupants' perception of the indoor temperature when they just arriving in the office, the indoor temperature and indoor air quality. For temperature assessment, it provided a seven-point scale from too cold (1) to too hot (7) and the comfort assessment was from very uncomfortable (1) to very comfortable (7). This evaluation was focused on occupants' perception in three periods of the day: the time of first arrival, the morning and the afternoon. The sample of the questionnaire was given in Appendix 5.

3.3.4 Occupant window control monitoring

The size of the window, and the extent of the effective opening area were measured first. The window state was recorded by state monitors and loggers (NOMAD, OM-51). These window state monitors were set on the window frame to record window state changes – from close to open or from open to close (Figure 3.18). The extent of the opening area was measured and recorded by author. The data were recorded every half second and the time accuracy was ±100ppm at 20°C. The output records include the window state (close/open), the changing time and the duration. These data were correlated with indoor environmental conditions to analyse the relationship between occupants' behaviours and influential environmental factors. There were two export formats for window state data. The first was shown as image (Figure 3.19), which shows the continuous state of the monitored window. The Y-axis shows the status of windows as open or closed, the X-axis shows the time, while the change point of the window state was shown by small dots on it, which shows the continuous state of the monitored window. The other approach was based on the exported data with form of text (Figure 3.19); each line shows the windows' change time and state, and the time difference between the two lines was the duration time of the window's state. So, the window states were recorded during the whole monitored period. This was used to demonstrate occupants' window control patterns and the impact on natural ventilation. At the same time, the correlations with other environment factors could be found.

Figure 3.18: The position of window state data logger.



Date Time	State
05/03/11 12:04:32.0	OPEN
05/03/11 13:42:17.0	CLOSED
05/03/11 13:42:18.5	OPEN
05/03/11 13:42:19.0	CLOSED
05/03/11 13:42:20.0	OPEN
05/03/11 13:48:34.5	CLOSED
05/03/11 13:48:51.5	OPEN
05/03/11 17:36:37.5	CLOSED
05/04/11 09:15:30.0	OPEN
05/04/11 09:41:58.5	CLOSED
05/06/11 14:01:46.5	OPEN
05/06/11 17:46:59.0	CLOSED
05/09/11 11:22:11.5	OPEN
05/09/11 11:42:45.5	CLOSED
05/09/11 16:11:41.5	OPEN
05/09/11 17:41:19.5	CLOSED
05/10/11 10:14:35.0	OPEN
05/10/11 10:27:30.5	CLOSED
05/10/11 15:02:08.5	OPEN
05/10/11 17:51:33.5	CLOSED
05/11/11 08:53:59.5	OPEN
05/11/11 17:53:15.5	CLOSED
05/12/11 16:10:11.0	OPEN
05/12/11 18:33:23.0	CLOSED
05/16/11 09:38:11.5	OPEN
05/16/11 11:14:09.5	CLOSED
05/16/11 14:03:30.0	OPEN
06/25/11 00:25:25.5	OPEN

Figure 3.19: The export example in image format (Left) and text format (Right).

3.4 Environmental factors results

The following was based on dry bulb air temperature and relative humidity measured results during the two weeks in May 2011 in an office building. The local climate condition and related thermal performance in three office rooms were presented.

3.4.1 Outdoor environmental conditions

During the measuring time, the outdoor temperature varied from a minimum of 14.5°C to a maximum of 36.1°C, with the mean daily average temperature of 25.3°C. There were large temperature fluctuations during the measuring time, which was because the heat wave hit the city and lasted for four days, and the highest temperature of each day was above 30°C during these four days. But after the heat wave with the incoming rainy day of 11th May, the outdoor temperature dropped rapidly from about 36°C to 20°C. The outdoor relative humidity varied from 18.8% to 88.3%. The outdoor relative humidity was relatively high in the first three working days and the rainy day, then it decreased quickly after the rainy day and reached its lowest point, which was 18.8%. Therefore, during the working hours, the highest and lowest temperatures were 36.1°C and 16.5°C with the mean daily average temperature of 26.3°C, while the highest and lowest relative humidity were 83.1% and 18.8% (Table 3.3 and Figure 3.20). In the measurement, the prevailing wind was from the south-east and the wind speed was between 0.00m/s and 6.98m/s, with an average wind speed of 1.47m/s. It was expected that the large variation in outside wind velocity, outside temperature and humidity would influence the indoor environmental condition and occupant behaviour.

Table 3.3: Maximum, minimum and average outdoor dry bulb air temperature and relative humidity.

	Measuring period	Working period
Maximum temperature	36.1℃	36.1℃
Minimum temperature	14.5℃	16.5℃
Mean daily average temperature	25.3℃	26.3℃
Maximum relative humidity	88.3%	83.1%
Minimum relative humidity	18.8%	18.8%
Mean daily average relative humidity	53.5%	50.9%

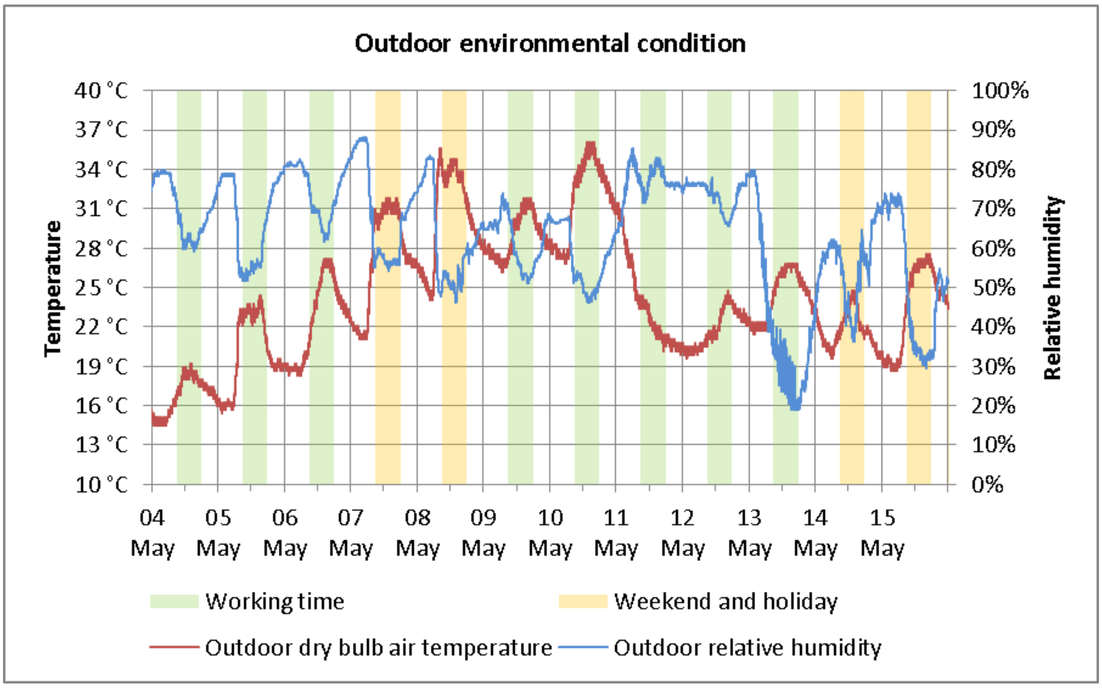


Figure 3.20: Outdoor dry bulb air temperature and relative humidity variation during the monitored period.

3.4.2 Thermal performance of three offices

In office A, in the first five days the office room was naturally ventilated. But the air-conditioning system was used when the heat wave arrived and continued to the end of the measurement, so in this certain period of time the office rooms would not be considered as naturally ventilated (Figure 3.21). During the natural ventilation time, the minimum indoor temperature was 22.8°C and it rose up to 29.9°C at the weekend, and the relative humidity was between 42% and 63.7%. The office temperature increased gradually with the rising outdoor temperature, but seemed more steady. The daily indoor temperature fluctuant was about 3°C and this fluctuant was much lower in the working hours. For the outdoor temperature the minimum fluctuant was 4.9°C. Besides, there was a large temperature difference between indoor and outdoor environments. At the first working day, the indoor temperature was 6°C higher than the outdoor. In the next two days, the outdoor temperature increased, getting close to the indoor temperature during the day time, but during the night time the difference between indoor and outdoor was still around 5°C. The peak temperature occurred during the weekend, when the outdoor temperature was about 4°C higher than indoor and remained so for four days. It can be seen that there was a great cooling potential during the night time.

On 9th May, the indoor temperature was 28.9°C before the air-conditioning was switched on by an occupant to achieve thermal comfort. During the air-conditioned period, both the indoor temperature and the relative humidity were more dynamic than those in the naturally ventilated period, because the occupant adjusted the comfortable indoor environment through controlling the air-conditioning, while the windows were still opened at the same time in order to obtain fresh air, which also brought the outdoor hot air into the room. Because of the air-conditioning, the lowest daily indoor air temperature occurred during the working hours in these days. The indoor air temperature began to increase when occupants left the office and switched off the air-conditioning, and it reached the highest at night time. This situation remained throughout the rest of monitored period; even when the outdoor air temperature was lower than the indoor temperature on the hottest day (10th May). Figure 3.22 shows the environmental condition on weekdays during the air-conditioning period. It can be clearly seen that, on the first two days, the indoor air temperature continually rose up until it became close to the outdoor air temperature, but the indoor temperature decreased very slowly when the outdoor temperature was below it. On 10th May, after working hours, the indoor air temperature continued to rise up until early morning the next day and was quite stable at around 30°C, until occupants arrived at the office and switched on the air-conditioning. This may be because of the heavy building structure which can store too much heat during the hottest day but was then difficult to move it out. So when the air-conditioning was turned off, the building structure would heat the indoor air. The closed windows also impeded the indoor hot air moving out of the building when the outdoor air temperature was lower than the indoor.

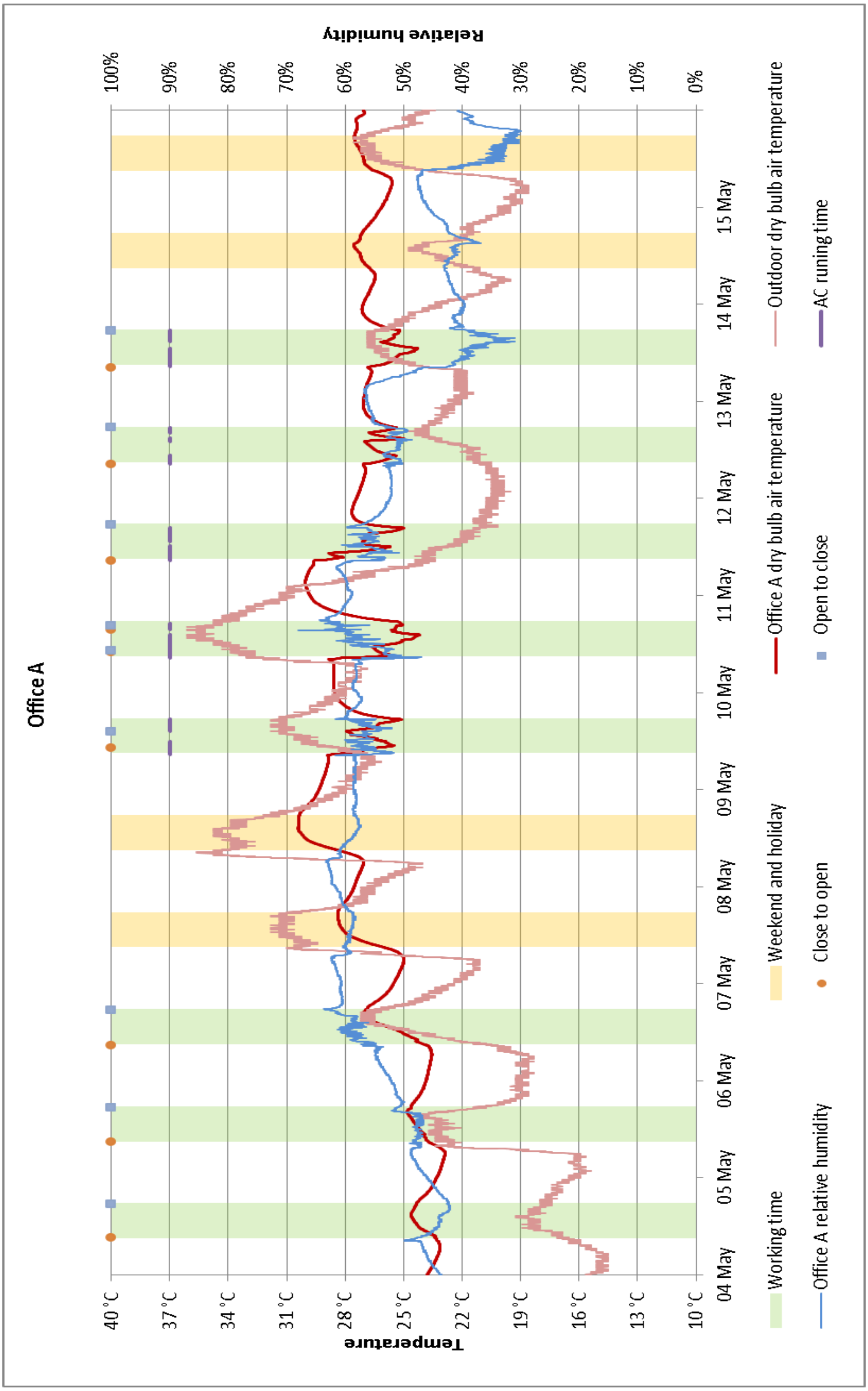


Figure 3.21: Office A dry bulb air temperature, relative humidity, window state and air-conditioning running time during the monitored period.

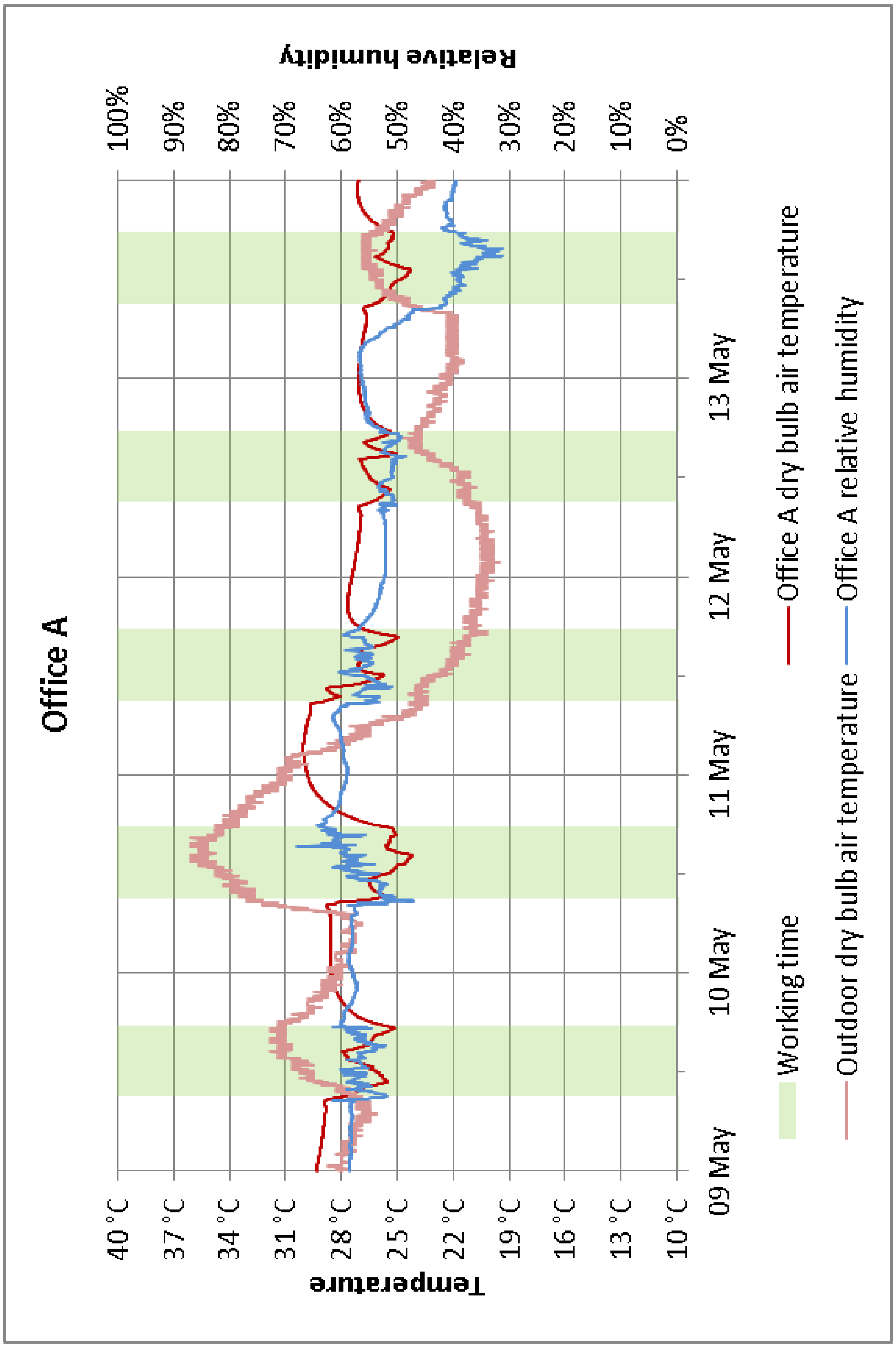


Figure 3.22: Office A environmental condition during the air-conditioned period.

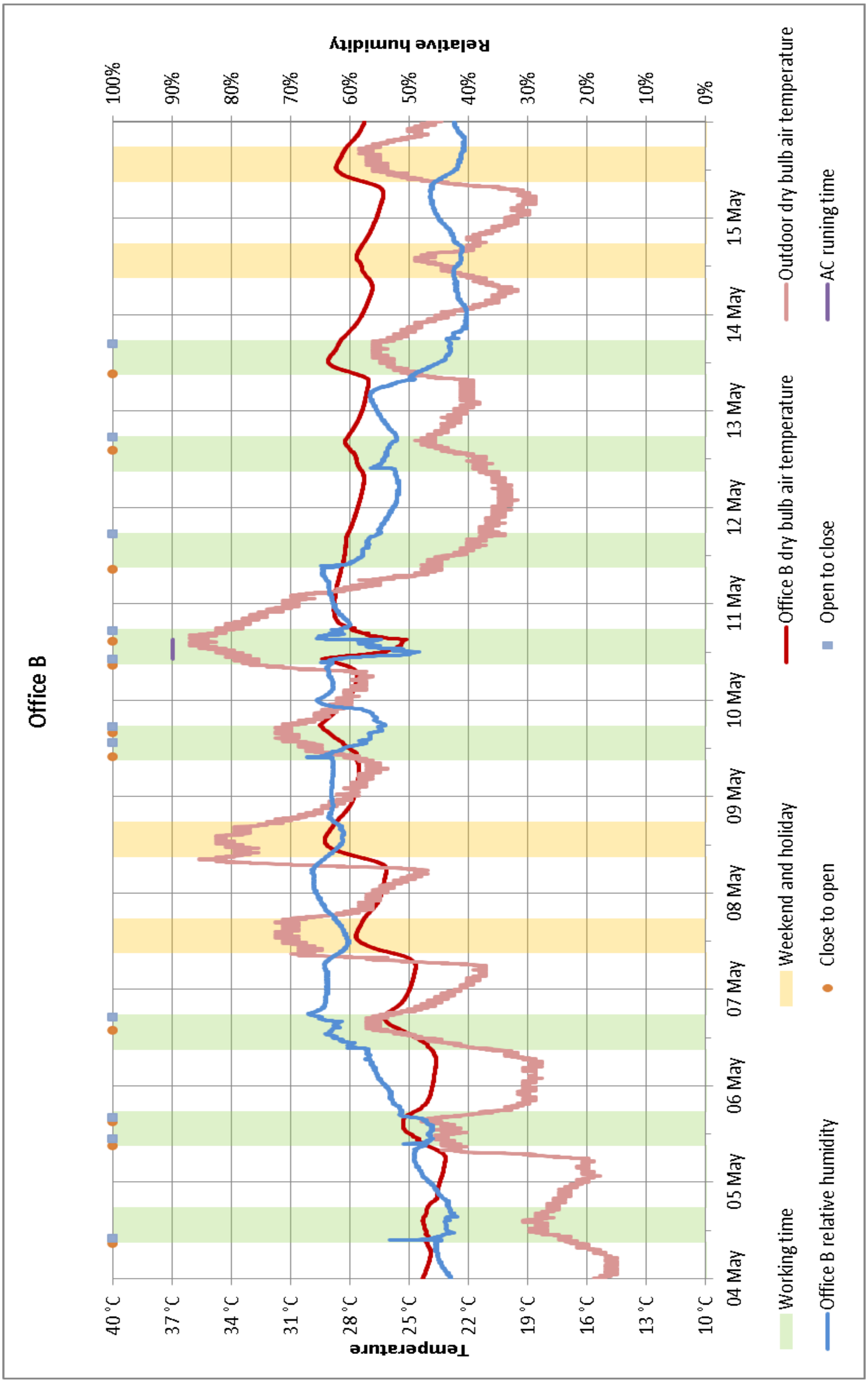


Figure 3.23: Office B dry bulb air temperature, relative humidity, window state and air-conditioning running time during the monitored period.

Office B was naturally ventilated for the majority of time, while the air-conditioning was used in a very short period on 9th May and all the working hours on 10th May. In general, during the natural ventilation period, the indoor air temperature wave in office B was similar to office A, and it increased gradually with the outdoor air temperature and after the hottest day the indoor air temperature was relatively steady, which was around 28°C. Besides, the measured average indoor dry bulb air temperature during the natural ventilation time was very close as well, which was 26.7°C in office A and 26.3°C in office B.

Office C was located at the corner of the building which has windows on two orientations, so it may be possible to achieve cross-ventilation. The air-conditioning was used only on the hottest day. Figure 3.24 presents dry bulb indoor air temperature and relative humidity variation in office C. It shows that the indoor air temperature was more fluctuant than the other two offices, and it had the lowest daily indoor temperature compared with other offices. Besides, the indoor air temperature was more close to the outdoor air temperature than other offices and the indoor air temperature dropped more than other offices during the unoccupied period. This may be because of the cross-ventilation achieved in office C, which was more efficient on moving the indoor hot air out of the office. Besides, one of the windows was kept open after working hours, so the night time ventilation may have been affected. Because one facade was facing north-west, the solar radiation has greater impact later in the afternoon, which was when daily indoor temperature peaks in the office. There were clearly temperature fluctuations on 11th, 12th and13th; this may because of the impact of natural ventilation on indoor dry bulb air temperature, and this will be discussed later.

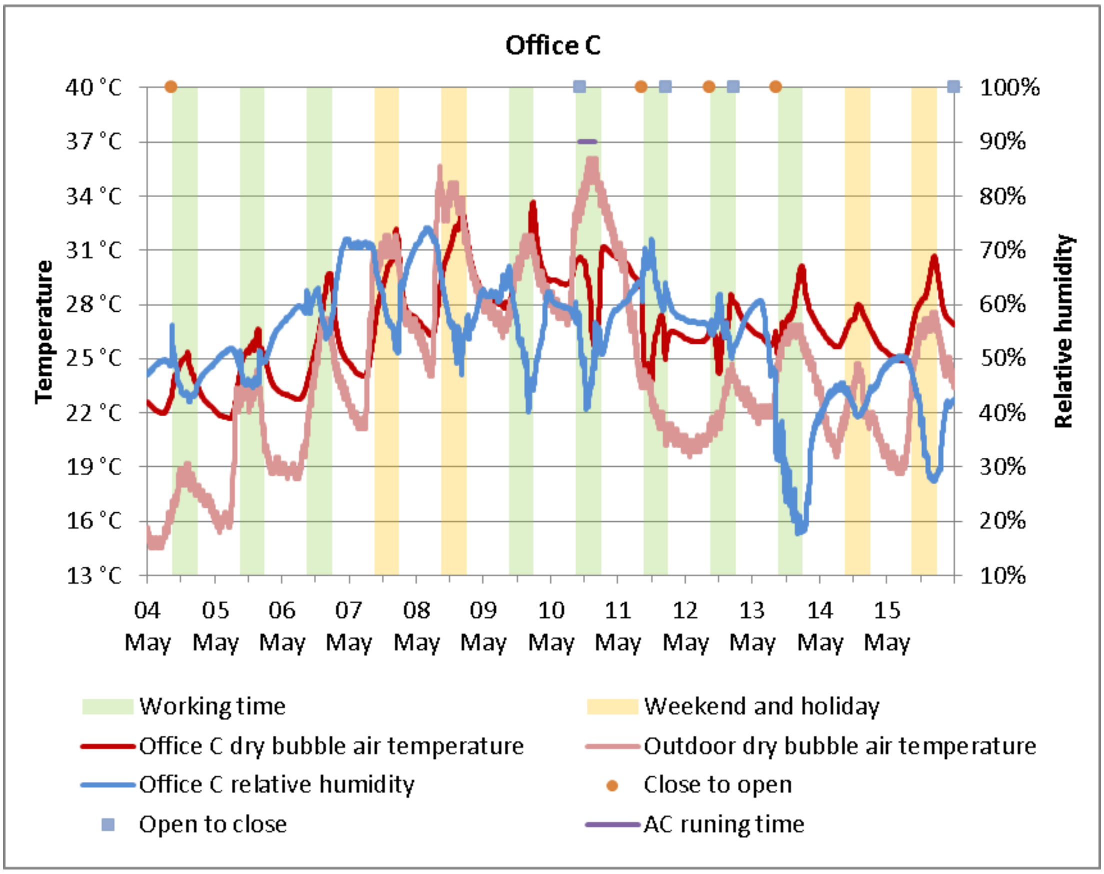


Figure 3.24: Office C dry bulb air temperature, relative humidity, window state and air-conditioning running time during the monitored period.

Figure 3.25 presents the percentage of hours over and equal to the certain dry bulb air temperature during the working hours in three offices. In 20% of the working hours, the outdoor temperature was over 29°C, higher than that in the three offices, so when the outdoor temperature went over 29°C, the outdoor temperature was higher than the indoor. Comparing these three offices, it can be seen that office A has the lowest average indoor air temperature during the occupied period, during which none of the monitoring hours was over 29°C. This result can be predicated because the air-conditioning was used in most of the working hours. The indoor temperature was controlled between 23°C and 28°C. In office B, the highest indoor temperature did not exceed 30°C. Compared with office C, which has similar air-conditioning operation hours, the percentage of working hours were very close when the indoor temperature was lower than 26°C, but the percentage of hours over 27°C and 28°C was higher than office C, and it dropped very quickly when the temperature was over 29°C. In about 50% of the hours the temperature was between 27°C and 29°C. It can be found that, between 9th and 13th, the indoor temperature was quite steady and waved around 28°C. Office C had the highest indoor temperature during the working hours which was close to 34°C; the occupants seemed more tolerant to high indoor temperatures than other offices. In 12.5% of the working hours the temperature was over 30°C. The indoor air flow condition may be one of the reasons that occupants could accept higher indoor temperatures than others.

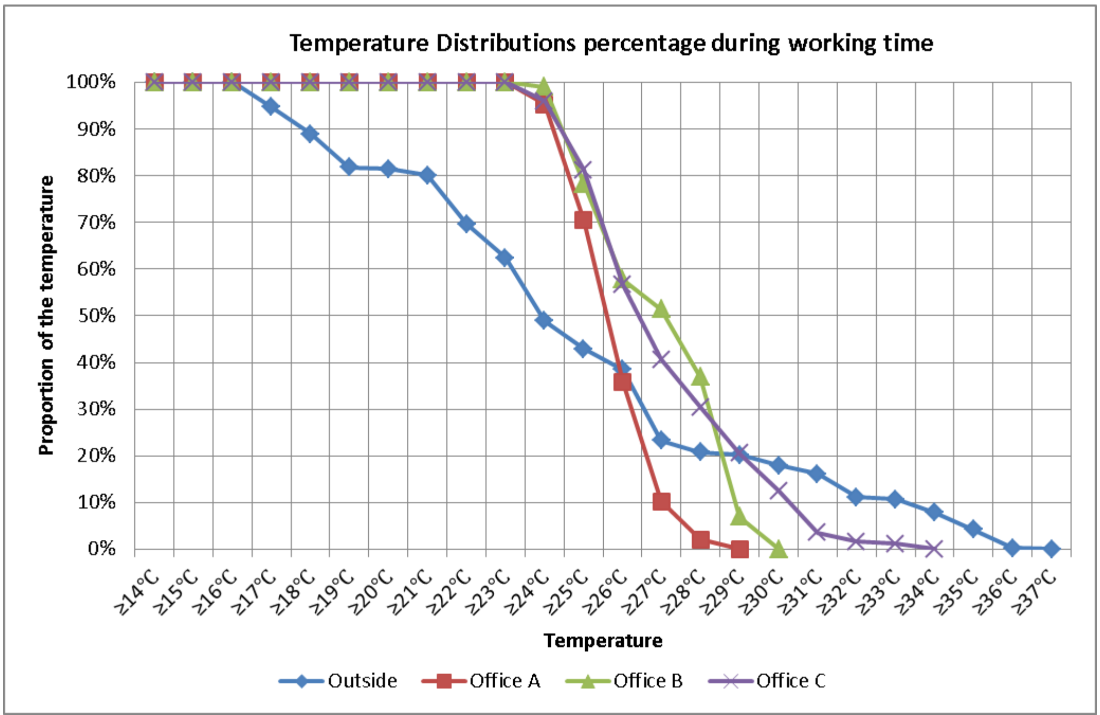


Figure 3.25: Percentages of hours over a certain temperature during working hours.

3.5 Natural ventilation results

Natural ventilation was driven by wind pressure and thermal buoyancy. According to the character of the office building, there was no height difference between each window in the office room; so, wind pressure was the main driving force for the natural ventilation in the office. An opening window was the main aperture for air flow moving in and out of the building. Thus, the measured air flow speed at opening windows in the office was presented and natural ventilation potential in the office building.

3.5.1 Potential for natural ventilation

When the temperature outside was lower than inside, natural ventilation was an effective way to reduce the indoor temperature. In order to understand the potential capacity of natural ventilation for this building, the temperature difference between indoor and outdoor has been compared in this study. It was found that the indoor temperature was higher than the outside between 76%-94% of the time during the work period when air-conditioning was off (Figure 3.26). Thus, natural ventilation was an effective way for cooling during this time. According to Figure 3.27, in the unoccupied time, the percentage of indoor temperature higher than outdoor temperature was 80%-93%, which was higher than the occupied time. The biggest temperature difference could rise to 10°C in the evening. This may be because the thermal capacity of the building structure released heat at night, but occupants closed the windows when they left the building, so the indoor hot air could not be moved out efficiently at night. If the night time ventilation strategy was so designed or occupants could leave the window open when they left, the office could potentially be cooled down at night and impact on occupant comfort perception the next day.

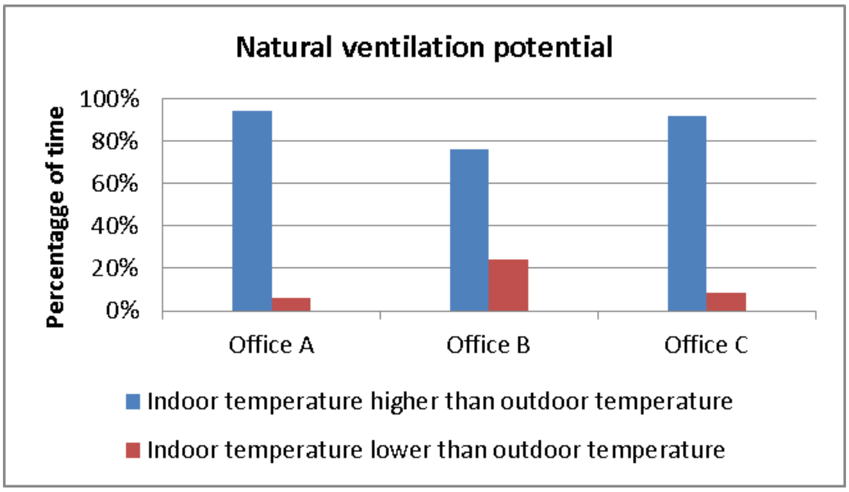


Figure 3.26: The percentage of an hour that indoor temperature was higher than outdoor temperature during the occupied time and without air-conditioning.

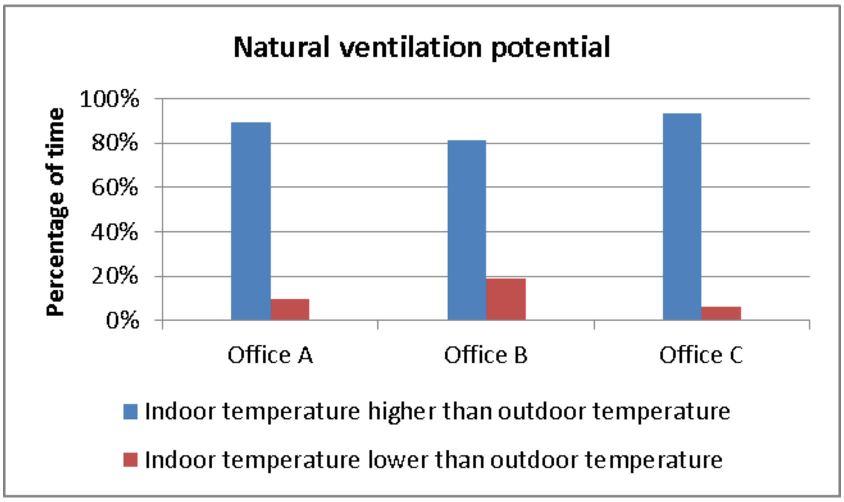


Figure 3.27: The percentage of an hour that indoor temperature is higher than outdoor temperature during unoccupied time.

3.5.2 The predicted effective opening area for cooling

The depth of this office building was large than the 'design rule of thumb' (useful depth up to about four times floor to ceiling height) (Baker and Steemer, 2000) that can achieve cross-ventilation, so both rooms A and B were ventilated from one side only, while room C which was located at the corner of the building could achieve cross natural ventilation. In order to generally understand the required opening size in each office and the amount of natural ventilation needed for cooling, the Optivent[2] (Ford et al, 2007) test was used. The character of the office and window were based on Table 2.1. In the test, it was assumed that the occupant is doing office work (85w), each computer was 100w, and each light was 40w. The daily averaged solar radiation on windows was calculated from Ecotect software and the temperature difference was based on measured average indoor and outdoor temperature. The wind was considered as the main

[2]: Optivent: It is an EXCEL based natural ventilation steady-state calculation software for the early design stage of buildings. It can be used to predict the convective cooling potential of naturally ventilated office, according to room dimension, opening position/size and indoor/outdoor environmental conditions. This software was based on CIBSE (2005), ASHRAE (2005), Etheridge and Sandberg (1996) and Givoni (1994).

driving force, which was based on the measured result with the average wind speed at 1.5m/s.

Office A was the smallest room with four occupants and four computers. The solar radiation rate on the glass curtain wall was 1990wh/m^2 and the indoor temperature was 4°C higher than the outdoor. The results show that the required air flow rate for cooling was 1.63m^3/s, and the opening area should be as much as 3.2m^2 in order to take the indoor heat away effectively. Office B has the same orientation and glass area as office A, but a bigger indoor floor area. There were two occupants and two laptops in the office, with the same solar radiation rate and outside air velocity. When the indoor temperature was 2.7°C higher than the outdoor, the required air flow rate for cooling was 2.10m^3/s and the opening area for ventilation needs was about 4m^2. Office C was the largest room with the largest area of glass curtain wall, which was double that of offices A and B. As it faces to the north-east, the solar radiation rate was about 2208wh/m^2. There were two occupants and two computers in it. Under the 3°C temperature contrast, the required air flow rate for cooling was 2.69m^3/s and the required opening area was 4.3m^2 (Table 3.4).

Table 3.4: The predicted air flow rate and opening size for cooling.

	Required air flow rate for cooling	Required opening size for cooling
Office A	1.63m^3/s	3.2 m^2
Office B	2.10m^3/s	4.0 m^2
Office C	2.69m^3/s	4.3 m^2

Compared to the actual effective opening size, the maximum open area for each office was about 0.48m^2 in office A, 0.48m^2 in office B and 0.72m^2 in office C, which was far less than the predicted area. At the same time, the depth of the building also reduces the efficiency of natural ventilation. Therefore, according to the predicted result, the heat cannot be moved out of the room promptly, and it may influence the occupant's thermal comfort and window control behaviour. Although there was great potential for natural ventilation in the office building, the maximum opening size was fixed, so natural ventilation as a cooling method would be very difficult.

3.5.3 Air flow speeds at opening windows

The locations of measured windows and doors in each office were shown in Figure 3.28, and the air flow speed was presented in Table 3.5. As a high-rise office building, when the wind hits the building, it may go upward along the facade, the opening top hung window acting like a wind catcher which can lead the air flow into the office. So, even in the single-sided ventilated office, the air flow speed measured at an opening window was positive. In office A, there were two openable windows (windows A1 and A2), with the maximum opening area of $0.24m^2$ on each window, and the average air flow speed was 1.0m/s and 1.1m/s. It can be calculated that the average air volume flow rate was about $0.50m^3/s$ of air entering or leaving office A through windows A1 and A2. The area of door A which connected office A to the corridor was about $1.4m^2$, although the building was deeper than the design 'rule of thumb' for cross-ventilation. It can be seen from the result that the average air flow speed measured when opening the door was 0.35m/s, meaning the air flow rate was $0.49m^3/s$. The air flow rates through the windows and door (linking office and corridor) were similar. The air flow from outside could pass though the corridor and move out from the window near the elevator. However, the air velocity measured in the corridor which was near the elevator was close to naught. The average air velocity though the fire escape door (the door was perpetually being opened by occupants for going upstairs and downstairs) was about 1m/s. So, the air flow from office A may be moved out through the fire escape stairs, but this situation was undesirable in terms of fire safety.

There were two openable windows in office B, but the occupants could only use one of them. Therefore, only this window (window B1, Figure 3.28) was measured. The average wind speed was 1.03m/s, and the average air flow rate was $0.25m^3/s$. In office B, the air flow rate was not measured on door B ($1.4m^2$), because the door was closed most of the time.

There were two windows (windows C1 and C2) at the north-west surface of office C, and one (window C3) at the north-east. According to Table 3.5, the average air flow rates measured on windows C1, C2 and C3 were 0.26m^3/s, 0.27m^3/s and 0.32m^3/s respectively, which were slightly higher than in offices A and B. There were two entrances in office C, but only door C was kept open during the occupied period and the rate measured on door C was 0.36m^3/s.

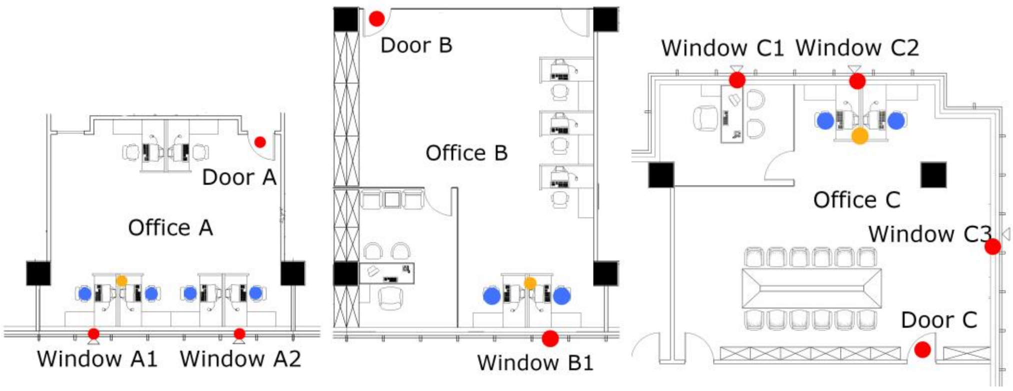


Figure 3.28: The position of measured window and door in each office. (The red points show where air speed were measured, the blue points show where occupants were sitting and yellows point show the data logger's location.)

Table 3.5: Measured average effective opening size, average air flow speed and average air flow rate.

Office	**Window or door**	**Average effective opening size**	**Average air flow speed**	**Average air flow rate**
Office A	Window A1	0.24m2	1.00m/s	0.24m^3/s
	Window A2	0.24m2	1.10m/s	0.26m^3/s
	Door A	1.4m2	0.35m/s	0.49m^3/s
Office B	Window B1	0.24m2	1.03m/s	0.25m^3/s
	Door B	1.4m2	N/A	N/A
Office C	Window C1	0.24m2	1.11m/s	0.26m^3/s
	Window C2	0.24m2	1.13m/s	0.27m^3/s
	Window C3	0.24m2	1.33m/s	0.32m^3/s
	Door C	1.4m2	0.36m/s	0.50m^3/s

Except for the air flow speed at the opening window, the indoor air flow speed was also measured at three points in the office: near the ceiling (point O), near the occupant (just above the desk) (point P) and near the floor (point Q) (Figure 3.29). The result was demonstrated in

Table 3.6. Because the air flow speed near the floor (point Q) was too small, it was not used in the analysis. In order to compare the proportion between each office, the air flow speed at the opening window was assumed as 1, and then the internal measured air flow speed was defined at the same proportion.

The result showed that in the three offices the air flow speed measured near the ceiling was close to that at the opening window and the air flow speed near the desk was much lower than point O. Since the air flow passed through the window and moved up, this result may be impacted by the window type. The opening area for the top-hung window was on the bottom, while the tilted window panel worked as a wind wall, so the air flow would be directed to the top of the room. This also caused the air flow around the occupant to be relatively lower. The air flow speed at measure point P in offices A and B was close and slow, but in office C it was slightly higher. This may be because the pressure difference at two windows in the cross-ventilated office was larger than the windows at the single-sided ventilated office. It would drive the air flow into the office more efficiently. The air flow speed would be higher than the single-sided ventilation office which may influence occupant thermal comfort. But this influence would be limited as the air flow speed around the occupant was still slow.

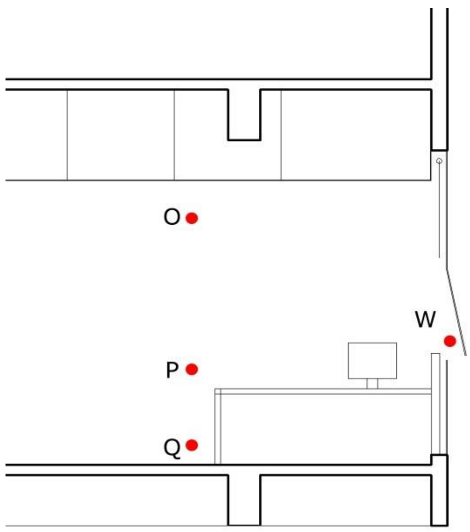


Figure 3.29: The measurement points in the office.

Table 3.6: The proportion of measured indoor air flow speed in three offices (average air flow speed).

	Point W	Point O	Point P
Office A	1 (1.00m/s)	0.95 (0.95m/s)	0.18 (0.18m/s)
Office B	1 (1.03m/s)	0.97 (1.00m/s)	0.20 (0.21m/s)
Office C	1 (1.19m/s)	0.97 (1.15m/s)	0.26 (0.31m/s)

3.5.4 The impact of natural ventilation on indoor air temperature

Compared with the predicted result and the measured result, it can be seen (Table 3.7) that the natural ventilation cannot achieve a cooling purpose in these offices, because the effective opening area was much smaller than the requirement of the cooling purpose. As offices A and B seemed to be single-side ventilated, the daily indoor temperature swing during the natural ventilated period was lower than in office C in which the cross-ventilation may be achieved.

Table 3.7: Required air flow rate for cooling compare with recorded air flow rate.

	Required air flow rate for cooling	Recorded air flow rate
Office A	$1.63m^3/s$	$0.50m^3/s$
Office B	$2.10m^3/s$	$0.25m^3/s$
Office C	$2.69m^3/s$	$0.53m^3/s$

Although the influence of natural ventilation on indoor air temperature was very limited, high air flow speed still had a direct impact on the indoor air temperature. It can only be found out in office C between 11th and 13th May. According to Figure 3.30, it can be seen that, on 11th May, the outdoor air temperature dropped rapidly and was much lower than the indoor air temperature at about 6°C. When occupants arrived in the office and opened the windows, the indoor air temperature decreased rapidly until it reached the outdoor air temperature. The highest average hourly air flow speed in the morning was 2.9m/s, and the average air flow rate was about $1.40m^3/s$, which was lower than the predicted air flow rates for cooling at $2.69m^3/s$. The reason for the rapid indoor air temperature drop was the drizzling in the morning which meant the solar heat gain was much lower than predicted. But, during a sunny day, the varying air flow rate has little impact on indoor air temperature. In the afternoon of 13th May, the increasing air flow speed could not cause the drop of indoor air temperature; this was because the internal heat gain from direct sunlight in the afternoon was more than the heat moving out of the office by air flow. This condition occurred in most of the monitored period. Besides, because of the indoor air flow patterns, the occupants would not be disturbed by high air flow speed at an open window.

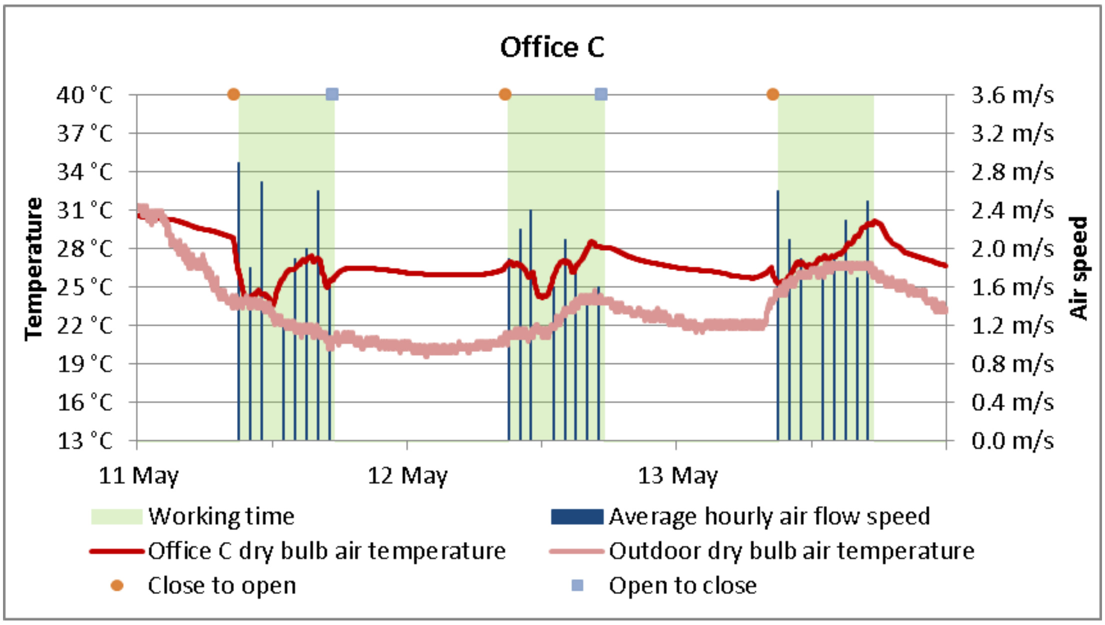


Figure 3.30: The indoor air temperature and average air flow speed in office C from 11th May to 13th May.

There was night time ventilation potential in the office buildings. The largest air temperature difference between indoor and outdoor can reach up to 10°C during the night. If windows could be kept open after working, the indoor temperature could be reduced to a certain extent and the indoor environmental condition for the next day could be improved. In these three offices, only a window was kept open during the night in office C between 4th and 10th May. And the difference of average indoor and outdoor air temperature can be found between leaving a window open and making them fully closed at night time. In office C, when a window was open after working hours, the average indoor air temperature was 2.82°C higher than the outdoor air temperature; while when windows were fully closed, the average indoor air temperature was 4.49°C higher than the outdoor air temperature. Comparing the average indoor and outdoor air temperature difference at the same period in office C with offices A and B, which were 4.61°C and 4.69°C, the average air temperature difference in office C is about 1.8°C lower than in offices A and B. This means that the indoor air temperature during the night time in office C was lower than in offices A and B, which was close to the outdoor air temperature. Therefore, an open window at night could reduce the indoor air temperature. If the night time ventilation strategy has been designed or a window which was suitable for night time ventilation has been installed and kept open, the night time cooling could be achieved to improve the environmental condition for the next day. .

3.6 Occupants' perceptions results

According to measured indoor dry bulb air temperature and relative humidity, the data have been plotted into Givoni's comfort zone to identify whether or not they were located in the comfort zone. Figure 3.31 shows the temperature and relative humidity distribution on a psychrometric chart during the working period without air-conditioning operating in office A. Because of the use of air-conditioning, the indoor air temperature was below 30°C during the natural ventilation time and the relative humidity was between 40% and 70%. In the majority of working hours during the natural ventilation period, the indoor temperature can be considered as comfortable; if the air velocity around occupants increased to 1.5m/s, the comfort can be achieved all the time.

Figure 3.31: Dry bulb air temperature and relative humidity distribution in Office A during working hours without air-conditioning operating.

As for office A, the indoor air temperature in office B was below 30°C and the relative humidity was between 40% and 70%. In a great number of times the relative humidity was between 60% and 70%, which was higher than office A, but it would not have a significant impact on occupant thermal comfort. The dry bulb air temperature and relative humidity distribution in office C was wider than in offices A and B. The temperature varied between 23°C and 34°C, and the relative humidity was between 20% and 70%. In the majority of time, the temperature and relative humidity were located in the comfort zone and some of them were in the red zone. But in some working hours, the temperature and humidity were still outside of the comfort zone.

According to the psychrometric charts in these three offices, in most of the working hours the indoor temperature and relative humidity were in the comfort zone and it can be predicted that occupants would feel comfortable and be satisfied with the indoor environmental condition. Perhaps occupants would feel comfortable or satisfaction all the time during the natural ventilation period even when the temperature and relative humidity were outside of the comfort zone. This may be because if occupants perceived the office as uncomfortable, then they would use air-conditioning to restore the comfort sensation. Therefore, the overall dry bulb temperature and relative humidity distribution in these three psychrometric charts can be considered as the indoor environmental condition being acceptable to occupants.

Therefore, in offices A and B, if the indoor dry bulb air temperature was not exceeding 30°C, occupants would still be satisfied with the indoor environmental condition. In office C, the occupants could accept much higher indoor air temperature. Whether occupants feel comfortable or not will be found by comfort vote.

Figure 3.32: Dry bulb air temperature and relative humidity distribution in office B during working hours without air-conditioning operating.

Figure 3.33: Dry bulb air temperature and relative humidity distribution in office C during working hours without air-conditioning operating.

3.6.1 Occupant perceived comfort vote and thermal sensation vote results

The occupant perceived comfort and thermal sensation vote were recorded by questionnaires. In the average thermal sensation vote (Figure 3.34), the numbers from 1 to 7 mean from very cold to very hot, while the number 4 was the neutral point, meaning neither cold nor hot. The figure shows that, during the measuring period, the thermal sensation vote was mainly around neutral. This means, generally, occupants feel slightly warm in the office. Only the vote at arriving time in office A and in the afternoon in office C, and the thermal sensation vote were close to warm (5). In office A, the thermal sensation vote at arrival time was higher than the morning and afternoon, which would be caused by the use of air-conditioning. The afternoon thermal sensation vote in office C was because of the rise of indoor air temperature caused by direct sunlight in the late afternoon.

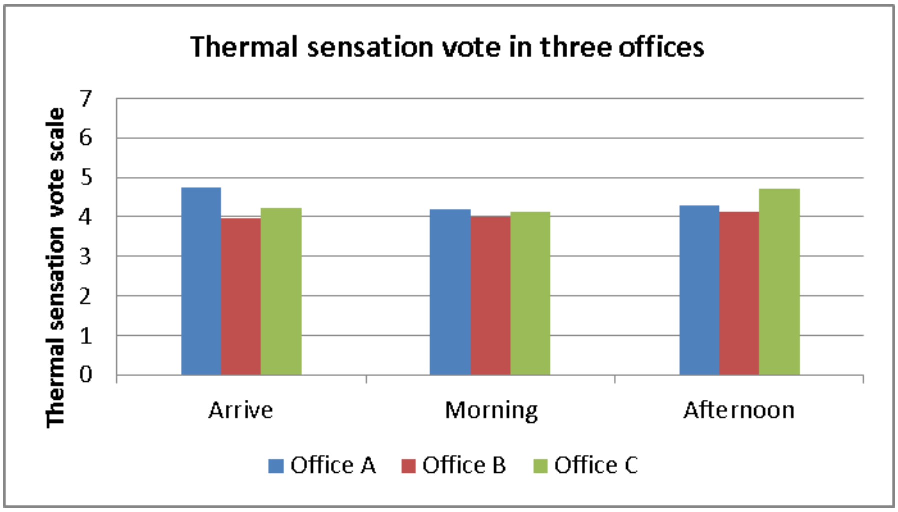


Figure 3.34: The average occupant thermal sensation vote results during working period.

The daily average thermal sensation vote was presented in Figure 3.35. The light colour shows the vote during the air-conditioned time. In office A, occupants feel neither hot nor cold in the natural ventilated period. Only the vote in the afternoon of 6th May was close to warm, because of a sensible rise of indoor temperature compared. In the air-conditioned period, it was clear that occupants feel hot when they have just arrived at the office. The thermal sensation vote gradually decreased when the air-conditioning started running, and the lowest daily thermal sensation vote was in the afternoon. The vote was lower than neutral and close to slightly cool sometimes.

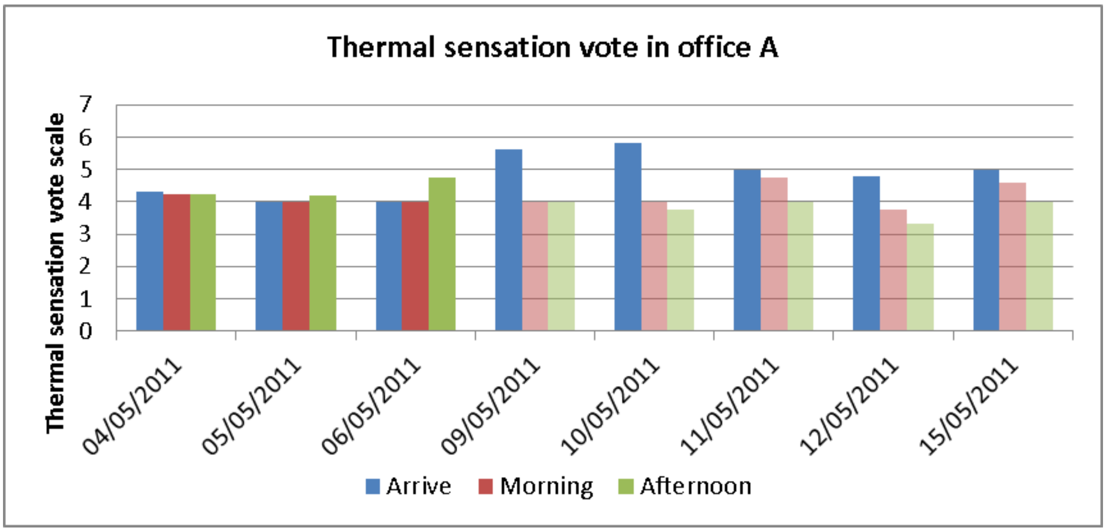


Figure 3.35: Average daily thermal sensation vote in office A
(light colour shows air-conditioned period).

In office B, the thermal sensation votes in the morning were the same in these eight days, which was neutral. Before 10th May, the lowest thermal sensation vote was at arriving time and gradually increased. After 10th May, the highest vote occurred at arriving time and the votes in the morning and afternoon were the same, both at neutral lasting for three days. This may be because the indoor temperature during the working hours was quite stable in these three days. But at arriving time, the indoor temperature was not the highest in a day, as the higher thermal sensation vote may be related to other elements or it may be because when occupants have just arrived from a relatively cooler outside environment, then the temperature contrast leads to a higher vote at arriving time.

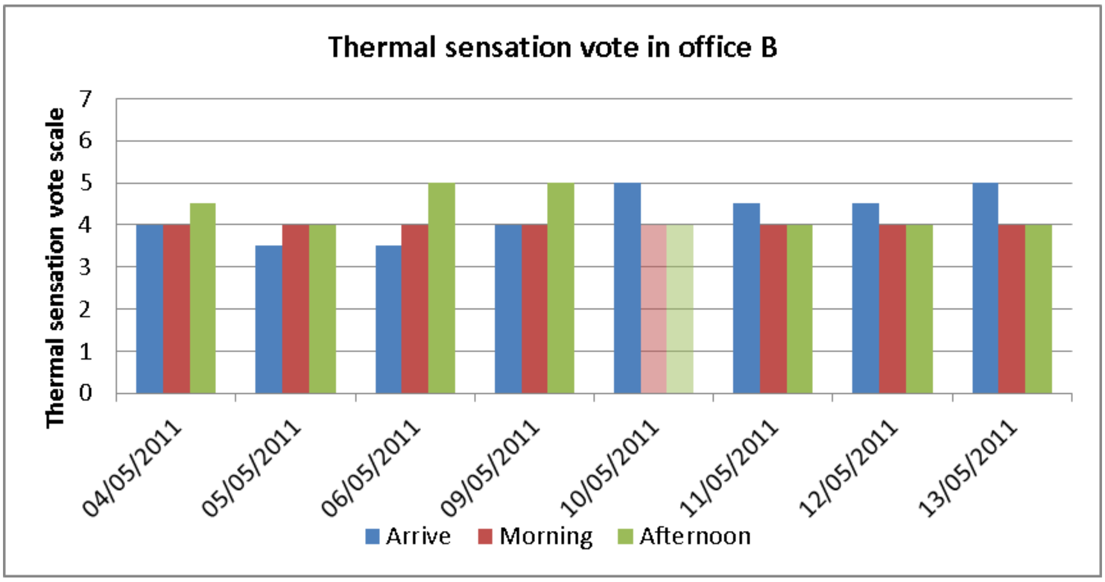


Figure 3.36: Average daily thermal sensation vote in office B
(light colour shows air-conditioned period).

In office C, the thermal sensation vote shows a significant rise in the afternoon, which was because office C, which faces north-east, would be affected by the direct sunlight in the late afternoon, especially after 3pm, which causes a significant indoor temperature increase. Especially in the afternoon of 9th May, the thermal sensation vote reaches its highest, the same as the indoor dry bulb air temperature, which was about 33.6°C, just before the occupants left the office. On 11th May the vote in the morning was lower than the rest of that day. There were obvious indoor temperature drops after occupants open the window in the morning, which caused occupants to feel cool in the morning. The impact of indoor air flow rate will be discussed later.

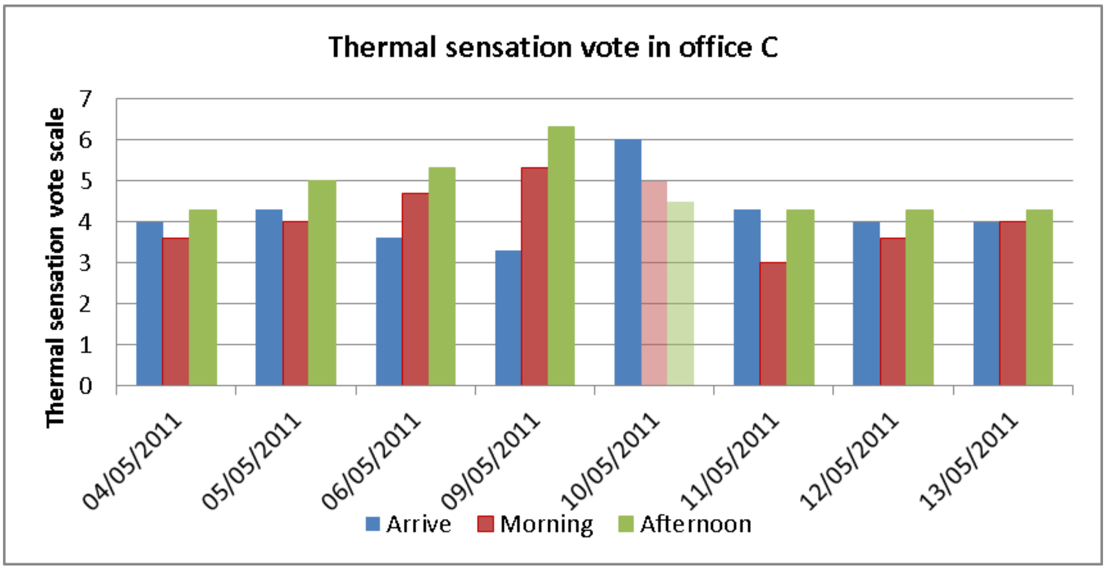


Figure 3.37: Average daily thermal sensation vote in office C
(light colour shows air-conditioned period).

When correlating the thermal sensation vote with related temperature in the office building in the natural ventilated time, it can be seen (Figure 3.38) that in general the indoor temperature tended towards hot and the majority votes were between 3 and 5, whereby it can be considered that the temperature was still acceptable. When the indoor air temperature rises above 26°C, some occupants would feel hot, and 30°C seems to be an top thermal threshold for occupants in the office. Few votes were taken above this temperature because air-conditioning was operating, and the occupant was voting on being very hot when the office was still naturally ventilated.

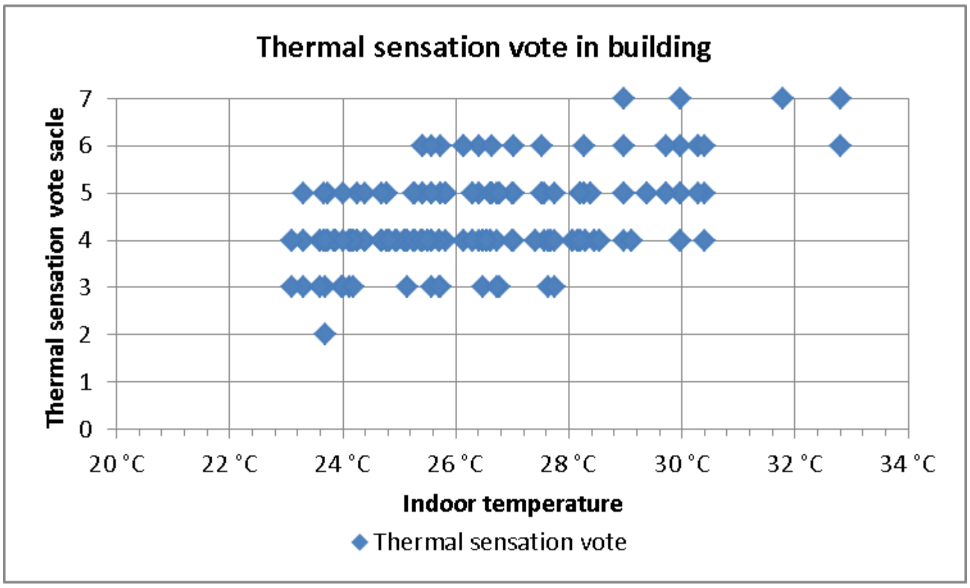


Figure 3.38: Thermal sensation vote with indoor dry bulb air temperature in office building during natural ventilated period.

The average perceived comfort vote during the measuring time was shown in Figure 3.39. The scale of the numbers from 1 to 7 means from very uncomfortable to very comfortable, and the number 4 was the neutral point. Generally, according to the perceived comfort vote result, occupants were satisfied with their working environment during the monitored period. The perceived comfort vote was the lowest at arriving time and highest in the morning. Comparing all the offices, the occupants in office B provided the highest average comfort vote, meaning they were more satisfied with the indoor environmental condition than occupants in other offices. The occupant comfort votes in office C were lower than office B at a different time of the day, but the average vote was the lowest in the afternoon. For office A, the average vote was the lowest at the arriving time and it was lower than the neutral point, which means occupants were slightly uncomfortable when they had just arrived at the office. After arrival, the vote result increased gradually, and reached the highest point in the afternoon, and were close to office B. The perceived comfort vote pattern was different in office A compared with other offices, which may be because of the use of air-conditioning for the majority of time. The air-conditioning was switched on when occupants arrived in the office, so occupants felt more comfortable in the afternoon than in the morning. Generally, occupants in offices B and C were more satisfied with their indoor environment than in office A, which was air-conditioned most of time.

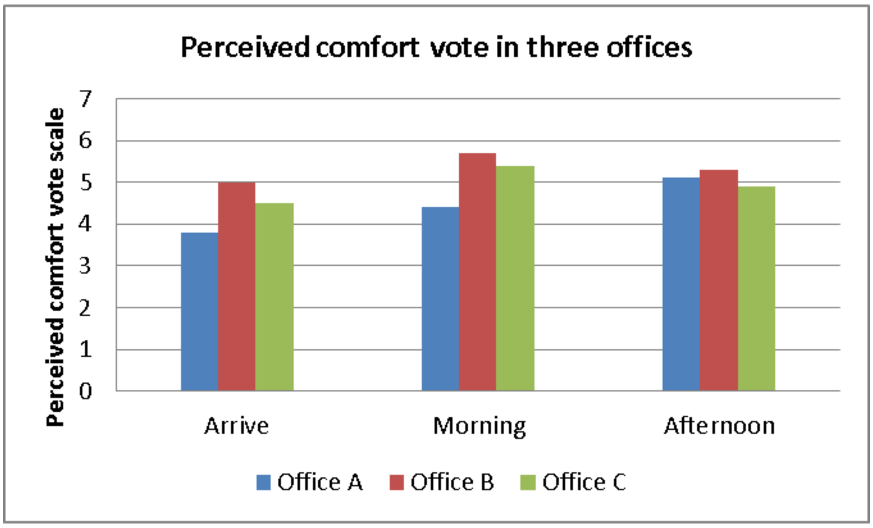


Figure 3.39: The average occupant perceived comfort vote during working period.

During the natural ventilated period, in most of the working hours, occupants felt comfortable in these three offices. According to Figure 3.40, in office A, only on 6th May, the comfort votes at arriving time and in the afternoon were lower than the neutral point, but still higher than point 3 (slightly uncomfortable). During the air-conditioning time, the occupant perceived comfort vote does not seem higher than the vote during the natural ventilation time, and in some of the air-conditioning time the vote was lower than the natural ventilation period, especially in the morning. But it can increase occupant perceived comfort vote to a certain extent by reducing the indoor temperature.

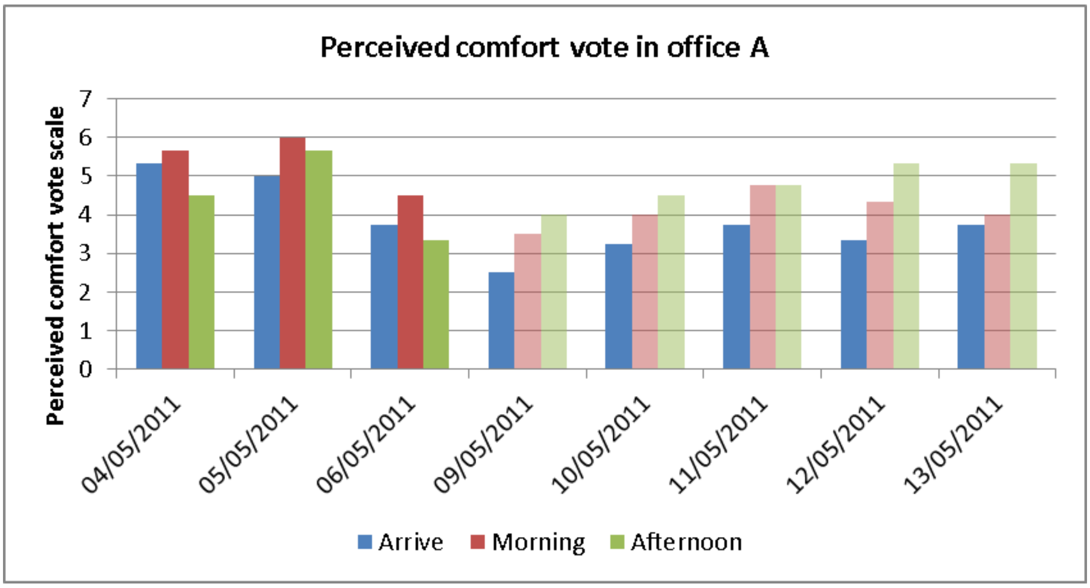


Figure 3.40: Average daily perceived comfort vote in office A
(light colour shows air-conditioned period).

In office B (Figure 3.41), occupants felt comfortable in the overall working hours although they felt warm sometimes. On 9th May, the vote was relatively lower than other days; this may be because the indoor temperature was higher than previous working days. Although the indoor dry bulb air temperature did not decrease after 10th, it appeared occupants had been used to the indoor environment. In general, the occupants in office B were more satisfied with the indoor environmental condition than other offices. This may be because the indoor air temperature was more stable than other offices and occupants could easily adapt the indoor environmental condition.

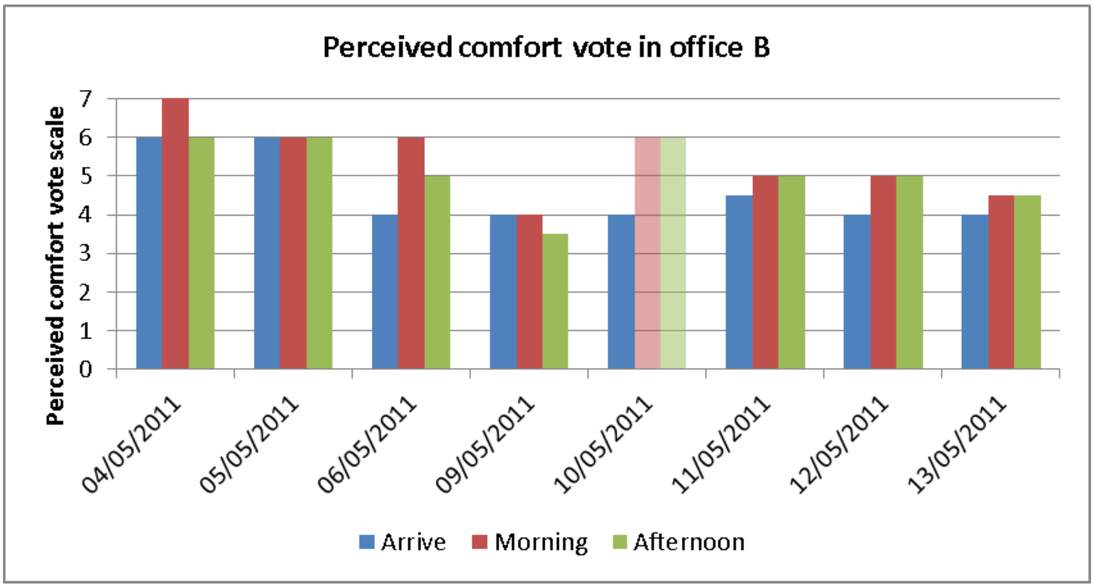


Figure 3.41: Average daily perceived comfort vote in Office B (light colour shows air-conditioned period).

In office C, occupants preferred the natural ventilation condition than air-conditioning. Office C has the lowest comfort vote in the three offices on 6th and 9th, and occupants felt hotter than other working days. Especially on 9th, the air temperature rose up to 33.6°C, so occupant perceived comfort vote and thermal sensation vote tended to be very hot and uncomfortable, but air-conditioning was still not used. According to the interview results, 88% of occupants in the office building prefer the natural ventilation indoor environment over air-conditioning, because, in the air-conditioned environment, the air quality was poor and the environment was dry, and skin surface and lips would become uncomfortable. Using air-conditioning was the last choice for them to restore the comfort. That was a reason for the window to be kept open when the air-conditioning was running. In addition, occupants in office C can tolerate the high indoor temperature, possibly because the high temperature occurred just before they leave the office and the indoor temperature rises rapidly from 31°C to 33.6°C in half an hour. In this half-hour, occupants may be able to tolerate the high temperature; another reason may be because the occupants will leave the office soon and would be disinclined to turn on and off the air-conditioning in half an hour, even if it were hot and uncomfortable.

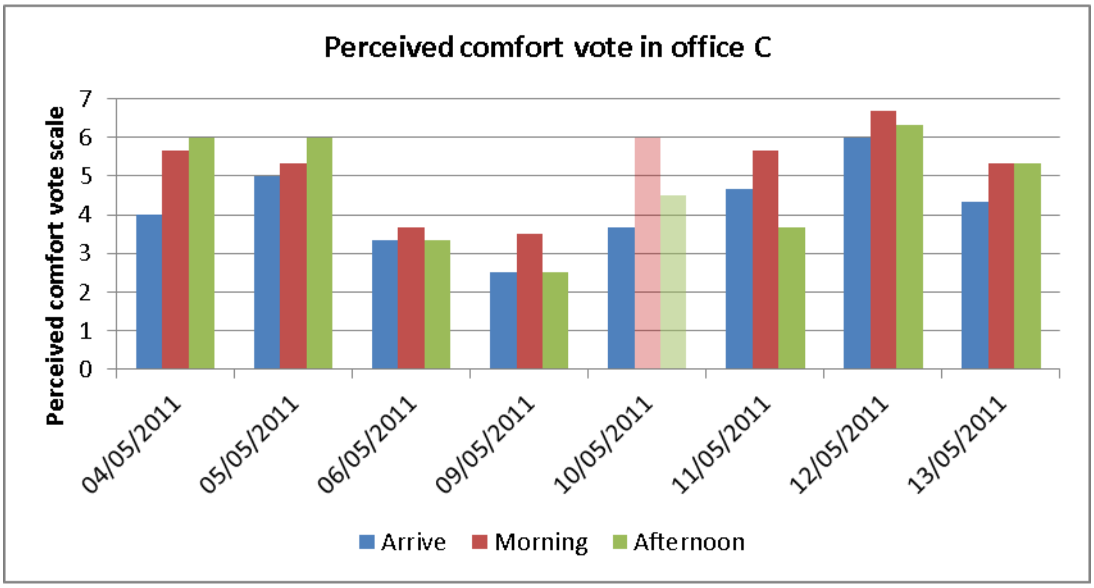


Figure 3.42: Average daily perceived comfort vote in office C
(light colour shows air-conditioned period).

Figure 3.43 shows the perceived comfort vote correlates with indoor dry bulb air temperature during the natural ventilation period in three offices. In the main time, occupants felt comfortable in the office and very few votes were below the neutral point. The vote at 7 (very comfortable) was mainly between 23°C and 26°C. When the indoor air temperature was over 30°C, none of the occupants felt comfortable.

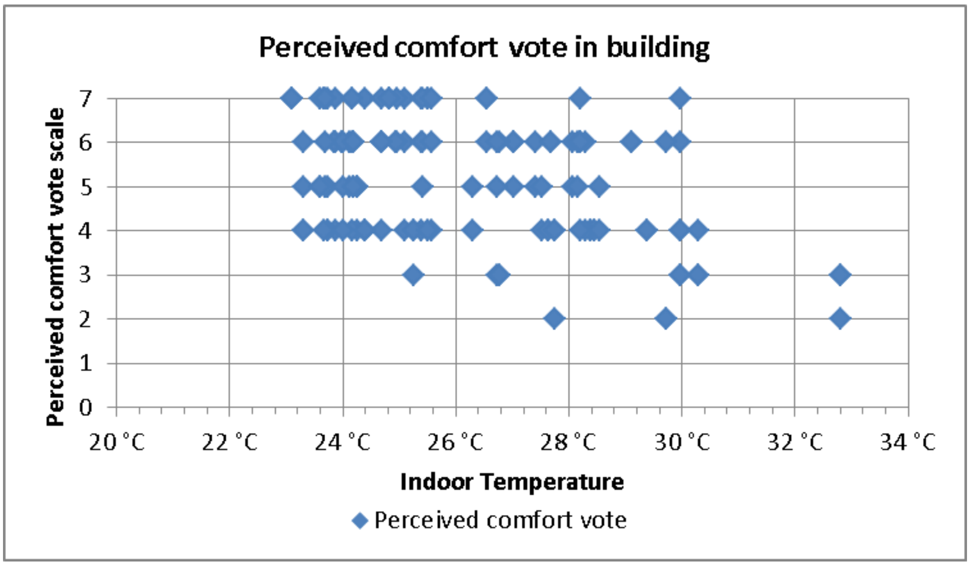


Figure 3.43: Perceived comfort vote with indoor dry bulb air temperature
in office building during natural ventilated period.

Therefore, compared with the perceived comfort vote and thermal sensation vote, these two figures were related to each other. Occupant perceived comfort votes in office B were the most positive and in the thermal sensation vote the results were most close to neutral. Also, office A has the lowest average perceived vote at arriving time; it corresponds with the highest thermal sensation vote. A similar vote result can be found at office C in the afternoon, which was because the impact of solar radiation in the afternoon raises indoor temperature and causes discomfort. The statistical test results suggest that the perceived comfort vote results positively correlated with the thermal sensation vote results (i.e. R^2=0.42) (Figure 3.44).

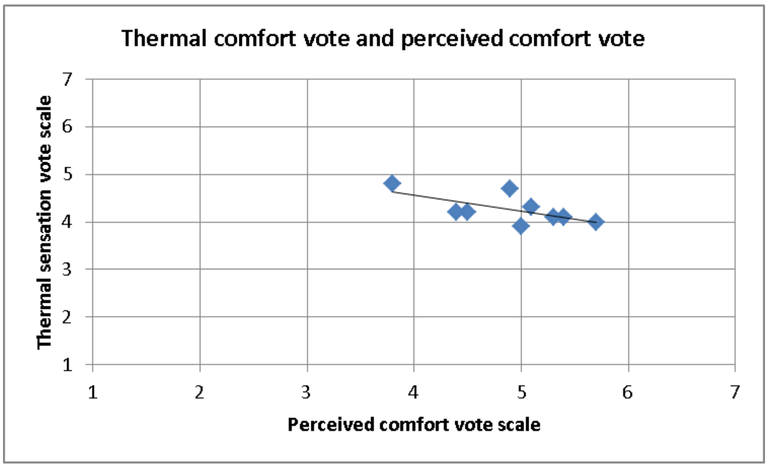


Figure 3.44: Relationship between occupant thermal sensation and perceived comfort.

To sum up, during the monitored period, the occupant thermal sensation vote tends towards warm and hot, corresponding to the perceived comfort vote which shows occupant felt. Thus, in the natural ventilated office, occupants still feel comfortable in a warm environment when the indoor air temperature was below 30°C. And occupants were not satisfied with the air-conditioned indoor environment because they felt dry when air-condition was running.

3.6.2 Occupant perceived indoor air quality results

Owing to the restrictions of equipment, the indoor air quality evaluation was mainly through questionnaires of indoor air quality as perceived by occupants, together with the predicted result based on calculation of indoor ventilation rate. The perceived air quality vote calculated from 1 to

7 corresponding to occupant perceived as very stuffy to very fresh (Figure 3.45).

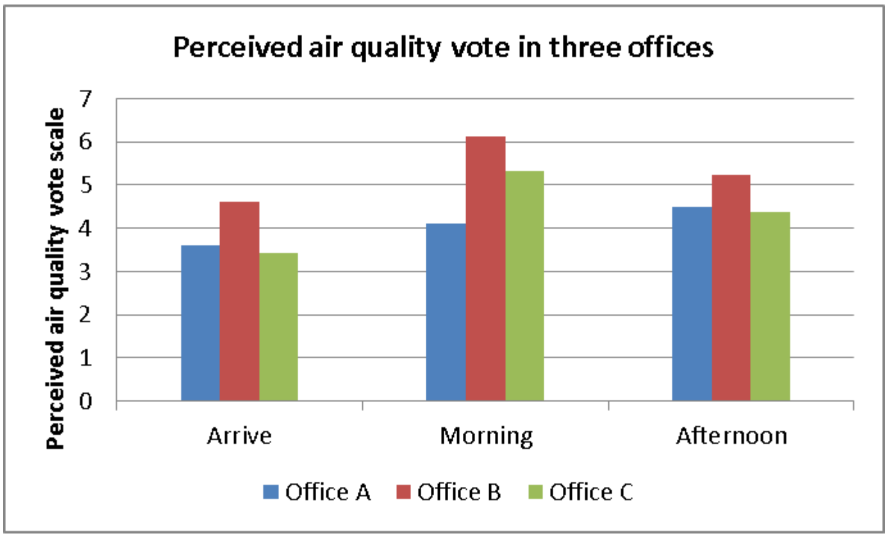


Figure 3.45: The average occupant perceived air quality vote during whole working period.

It can be seen from the vote result that the perceived indoor air quality was the lowest when occupants had just arrived in the office and it was better in the morning than in the afternoon in offices B and C, but the other way round in office A, which gradually increased from arrival time to the afternoon. According to the building design standard in China (2005), in office buildings the minimum fresh air required per person per hour was 30m³, or the air change rate would be 1.2-2.7 times per hour, the greater of which will be conceded as the basis. According to building configuration (Table 3.2) and measured air flow speed (Table 3.5), the fresh air required in each office and predicted result were shown in Table 3.8. It can be seen from the result of the assumption that the air change rate far exceeds the need of occupants. Therefore, the perceived indoor air quality cannot reflect the actual indoor air quality.

Table 3.8: The required and predicted air volume flow rate for indoor air quality in each office.

	Office A	Office B	Office C
Required air volume flow rate	$120m^3/h$	$60m^3/h$	$60m^3/h$
Predicted air volume flow rate	$907m^3/h$	$405m^3/h$	$1555m^3/h$

However, some relationship between the occupants' perceived thermal sensation and the indoor air quality can be seen from the comparison, in offices A, B, and C. Taking A as an example (Figure 3.46), when occupant thermal sensation vote was at neutral (neither cold nor hot) or cool, the vote of air quality was shown as generally higher. As the indoor temperature gradually increased, the vote on air quality became gradually lower. This phenomenon shows that occupants' perceived indoor air quality was fresher when they were in an indoor environment of neutral or cool than hot. Therefore, the average vote of perceived indoor air quality and the average vote of perceived comfort were quite similar. So, in hot and sticky air conditions, occupants may confound the perceived comfort and perceived air quality. It may be because the heat loss from the respiratory system decreased and caused an uncomfortable sensation in this environmental condition. But the reason for occupants to a feel lower air quality in a warmer room than in a colder room will need further study.

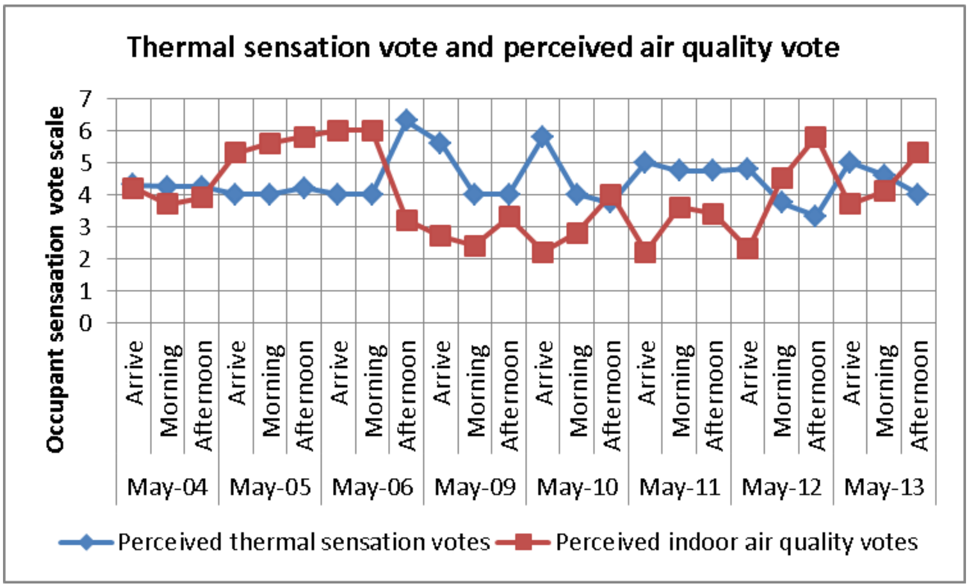


Figure 3.46: Correlation between thermal sensation vote and perceived air quality vote results in office A.

To sum up, according to the data plotted in the psychrometric charts during the naturally-ventilated time, in the majority of time the air temperature and relative humidity was located in the comfort zone (still air condition); also, some of the data can be coved by extended comfort zone which causes increasing indoor air velocity. In addition, the indoor relative humidity was between 30% and 70% in three offices, which would not have significant impact on occupant thermal comfort. Based on the occupant sensation survey result in the natural ventilation period, if indoor air temperature was below 30°C, it can be accepted by occupants most of time. So, the occupant sensation survey result for occupant thermal comfort was close to the psychrometric charts result, and 30°C can be defined as the top threshold of indoor air temperature for thermal comfort in the office building. Besides, occupants cannot accurately perceive the indoor air quality.

3.7 Occupant window control behaviour results

The window control results were divided into three parts with the window states being at arrival time, during the working period, and at the leaving time, to find out occupant window use patterns (Figure 3.47). The working period here means the period after occupants arrived at the office until the end of the working day before they left (lunch time was not included). Figure 3.47 showed that occupant behaviour of controlling the window happened mainly at the time when they arrived at the office in the morning and when they left, but rarely during the working hours. Besides, the window has three states – open to close, close to open and no change, which means no adjustment on the opening size during the working hours, such as from large opening to small. This may be because the opening size was small; changing opening size would not have much impact on the indoor environment or occupant thermal comfort, thus, no opening size change has been made.

The proportion of window opened by occupants when they just arrived at the office was 80% in both offices A and C, which was higher than other times of the day. Office B was 20% lower than other offices; the occupants in the office seem not to be anxious to open the window when they arrived in the office. Occupant-opened windows can be found from the contradistinction of occupant perceived thermal comfort, that at arrival time the comfort level was slightly lower than in the working hours, and the vote for the indoor air quality at the arrival time was even the lowest in the whole day in the three offices. Therefore, the relatively high indoor temperature and the poor air quality sensation at occupant arriving time will, to a certain extent, affect the occupants' behaviour of window opening.

In the working period, the windows' state in office C does not change most of time, and it was kept opened because in the majority of working hours office C was naturally ventilated. In office A, the proportion of 60% of window state does not change, which was slightly lower than office C; and 30% of window state changing was from open to close, because the usage of air-conditioning would cause the window to close. However, during the observation period, the window was kept open most of time, even when the air-conditioning was running. The explanation from occupants was that they need fresh air and were not satisfied with the sealed air-conditioned environment. The similar condition was also found in office B for a short period. This behaviour of window control would increase the cooling energy amount in the building. This may because there was no mechanical fresh air system in the buildings; besides, the occupants were not worried about the electricity fees which would be paid by the company. This result was investigated by Kempton et al (1992) in an apartment in New Jersey about use of air-conditioning. Thirteen air-conditioned rooms were not charged for electricity bills during the summer. The results showed that the energy usage in 115 days was 1247kwh, which was much higher than the previous record (24kwh in 115 days) when the bill has to be considered. In office B, the proportion of window state changes was similar; this was related to the window state at arriving time, so 40% of the window state firstly changing from close to open happens during the working period and also the window was closed more frequently.

Most of the window states would not be changed during the working hours; it seems changing window state would not impact on occupant comfort sensation. Window type and opening size would influence occupant window control behaviour in three offices. The small opening size restricts the air flow rate in the office and the hot air cannot be successfully moved out of the office, so changing the opening size in the office cannot effectively influence the indoor temperature. High indoor air velocity would disturb occupants' working and cause discomfort, but the air flow passing through the open window would go up to the top of the office and have little impact on occupants. Thus, changing the window state was more likely to be for fresh air rather than to adjust the indoor temperature.

At the leaving time, in the three offices, occupants prefer to close the window rather than keep it open. None of the window states would be changed from close to open. But one of the windows, which was in office C, would be kept open when they leave the office. Closing the window when occupants were leaving the office was not requested by the company; the main reason was for weather protection, to prevent wind or rain affecting the paper on the desk which was close to the window. This can explain why the window in office C was kept open after work, because it was far away from the desk and there was no other furniture around it. Occupants also explained that keeping the window open would improve the next day's indoor air condition.

To sum up, most of window state changes occur on occupant arriving time and leaving time. The window state changes from close to open at arriving time mainly relate to poor comfort perception and indoor air quality sensation. During the working hours, most of the window states would not be changed after occupants made changes at arriving time. And most of the windows were kept open until occupants leave the office; this was mainly for fresh air purposes rather than indoor temperature. Windows will be closed in order to prevent the influences of wind and rain on the office during the unoccupied time. In this office building, indoor air temperature and air flow rate have very limited impact on occupant window control behaviour, and the window type was the main element that leads to this result.

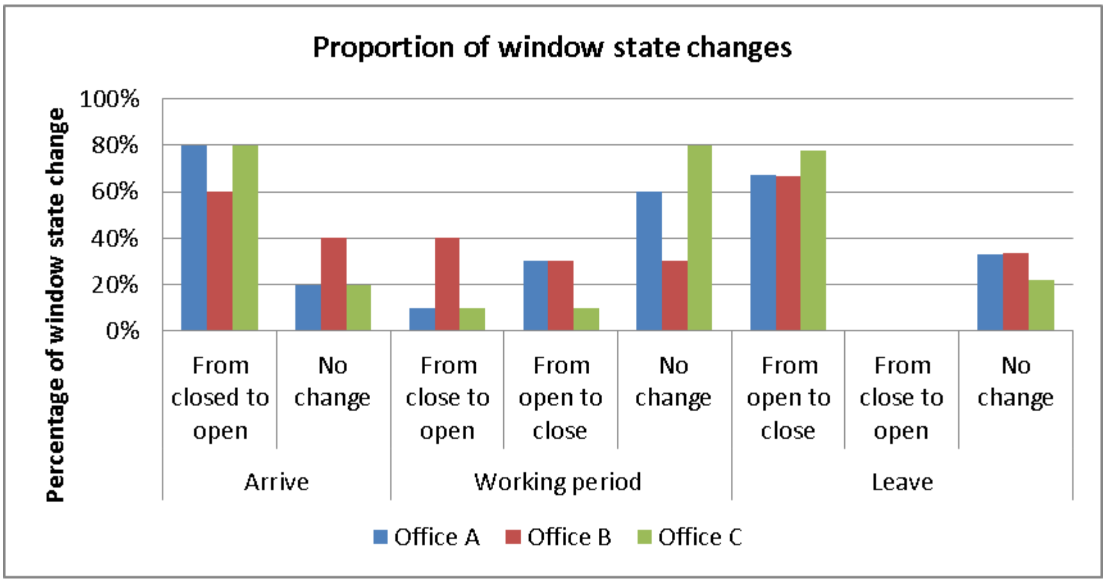


Figure 3.47: The proportion of window state changes in three offices.

3.8 Discussion and conclusions

The pilot study aims to examine the methodology in the field work and to establish the correlation between air flow rate and air flow patterns on occupant thermal comfort and occupant window control behaviour. The result shows the small opening size would limit indoor air flow rate which would restrict indoor heat from moving out in a naturally-ventilated office. This would result in indoor temperature being much higher than outdoor temperature and cause occupants to be uncomfortable. The air flow passing through a top-hung window can move up to the top of the room and the air flow speed around occupants was much lower than the opening area. Even under high wind speed the occupant who was doing office working near the window would not be disturbed by high air flow speed. Also, the low air flow speed at the occupied area has limited effects on extending the occupant thermal comfort area. So, in these three offices occupant opening window behaviour was more for fresh indoor air purposes rather than adjusting indoor temperature and air flow speed. And it was the same reason that occupants keep windows open during the air-conditioning time.

Besides, window state changes mainly happened at occupant arrival time and leaving time. At arriving time most windows were turned from close to open which was caused by a hot thermal sensation vote and a poor air quality sensation vote. The occupant perception of indoor air quality vote result would lead to occupants changing the window state, but the occupant air quality sensation vote cannot evaluate actual indoor air quality, and it was related to thermal sensation vote. The environmental element impact on occupant indoor air quality sensation vote needs further study. At leaving time, due to weather protection reasons, windows were closed when occupants left the office. If the window were to be left open, night time ventilation could reduce the indoor temperature and improve the indoor environmental condition to a certain extent the next day. But opening the window should prevent the impact of rainfall or gusty wind on the indoor furniture, office stationery and papers. So, window type and aperture position needs to be well designed in the office to achieve night time ventilation and for occupants to be happy to keep the window open after work.

Based on the results of occupant perceived comfort vote and thermal sensation vote during naturally ventilated working hours, the indoor temperature was tending towards hot, but occupants were still satisfied by the indoor environmental condition and in most of the time when occupants felt uncomfortable the air-conditioning was operated. Thus, the top indoor air temperature threshold can be defined as 30°C; it was close to Givoni’s (1998) comfort zone which can be identified on the psychrometric chart. Although air-conditioning can decrease the indoor temperature, most occupants were not satisfied with an air-conditioned indoor environment.

Because of the small opening size and the window type, the correlation between occupant window control behaviour and indoor air flow rate, and indoor air temperature cannot be established. Further measurement needs to be taken. In the next field measurement, more window types with different natural ventilation types in an office building need to be measured to establish the impact of window type on indoor air flow rate and air flow patterns. The external air flow speed and direction were too dynamic to correlate to indoor air flow speed and patterns in the field measurement. For the indoor air flow speed, more measurement points will be considered in order to identify detailed indoor air flow patterns and impacts on occupant thermal comfort. Besides, according to occupant response to the vote scales in the questionnaire, the scale from -3 to 3 with 0 as the neutral point will be used in the field work, instead of the scale from 1 to 7 with 4 as the neutral point, because some of the occupants suggested that the description of the scale with the scale from -3 to 3 would be easier to understand rather than 1 to 7. In addition, the 1 to 7 scale also resulted in ambiguous analysis result; the bar chart cannot present the relationship between comfort perception result and indoor environmental condition.

The questionnaire was distributed twice a day, at later morning or later afternoon. The questions were about their comfort perception in the morning or afternoon, which will recollect their perception during the in the whole morning or afternoon. For instance, occupant may feel uncomfortable when they arrived the office; then they may find a way (e.g. changing window state, drinking hot or cold water or changing clothing level) to restore their comfort. The comfort perception of occupants changed with the changing of the indoor temperature, and their behaviour for improvement. Therefore, if the comfort perception was only collected at later morning or later afternoon, the occupant perception vote result can only reflect the overall perception experience rather than the instant feeling of the indoor environment. And also, it would be difficult to relate occupants’ perception with the indoor environmental factors and their behaviours. In the next chapter, the revised methodology would be proposed with four new case study office buildings been described.

4 Methodology for Field Measurement

In this chapter, the characteristic of measured office buildings and revised measurement methods are presented. The field measurement was aimed at establishing occupants' comfort zone and their window-control behaviour in office buildings in South-East China; and to establish the impact of window effective opening area and typology on indoor air velocity, air flow patterns and air temperature. Based on the result of the pilot study, more buildings and window types were chosen. The results of natural ventilation in office buildings, occupant thermal comfort and window control are presented in the following chapters.

4.1 Methods and apparatus

The field study includes: indoor environmental conditions measurement, thermal comfort survey and occupant window control monitor. Based on the field measurement method in the pilot study, revised methods were presented. The indoor environmental condition measurement and occupants' thermal comfort survey were used to establish occupants' comfort zone. Measured indoor air temperature, relative humidity, indoor air flow speed and window state were used to identify the impact of indoor environmental condition on occupants' window control behaviour.

4.1.1 Air temperature and relative humidity measurement

The methods for measuring indoor and outdoor air temperature and relative humidity were as same as pilot study (presented in section 3.3). Because of small quantities of Tinytag (TGP-4500), similar apparatus (LUGE L92-1+) were added in the measurement, the details of new apparatus are show in Appendix 4. The places of the apparatus in the field work are presented as follow.

The outdoor air temperature and relative humidity were measured by a data logger (Tinytag TGP-4500) on the top of an office building. The data logger was well sheltered from direct sunlight and rainfall (Figure 4.1). The data were recorded in two-minute intervals. At the same time, the data, such as wind direction, wind speed, rainfall, air pressure, temperature and relative humidity, were downloaded from the weather monitor station which was about five hundred metres away from buildings A, B, and C and about two kilometres away from building D (presented in section 4.2). The data were recorded in ten-minute intervals.

Figure 4.1: Outdoor air temperature and relative humidity measurement.

For indoor temperature and relative humidity measurement, a data logger (Tinytag TGP-4500 or LUGE L92-1+) was set up in each office and recorded the indoor air temperature and relative humidity at two-minute intervals. The data loggers were located on the desk near the occupant in order to measure the exact environmental condition around the occupant (Figure 4.2). Also, the data loggers were carefully placed to avoid any unnecessary impact such as direct sunlight or other heat source (e.g., hot water). Because of lack of instruments, only one indoor radiant temperature data logger (LUGE L92-1+) was set up in an office building which was close to the indoor air temperature data logger. The analysis combined the recorded internal temperatures and relative humidities with the questionnaire and window control records to present the relationship between indoor thermal performance and window control, together with occupants' indoor environment perception.

Figure 4.2: Indoor temperature and relative humidity measurement.

4.1.2 Air flow speed measurement

In order to define the impact of window typology on indoor air flow patterns, and also the impact of indoor air flow speed on occupant thermal comfort and window-control behaviour, the indoor air flow speed measurement was separated into interval measurement and continuity measurement.

The interval measurement measured the indoor monitor point at intervals. The air velocity was measured by Anemometers (AIRFLOW TA-2-2 and Tes-1341). The AIRFLOW TA-2-2 was used for measuring air speed around the occupant, desk level and the Tes-1341 was used for measuring the air speed at window's or door's opening area. The office was vertically divided into three parts: near the ceiling (Point O, about one metre below the ceiling), near the desk surface (Point P) and near the floor (Point Q) (Figure 4.3). In addition, on the horizontal aspect another two measured points were added – one is near the partition wall and the other is close to the occupant (Point R and Point S) (Figure 4.4). In office buildings A and B, the air flow speed at the corridor side window or door (Point T) was measured (Figure 4.3). At the same time of measuring Points O to T, the air velocity of the effective opening area (Point W) was recorded. The air speed measurement at opened door or window were the same as the method in pilot study which was divided the effective opening area into nine grids for measurement and using average air speed for analysis (Figure 4.5). Each measuring point was taken for three minutes and recorded in thirty-minute intervals (Table

4.1). The recorder registered as much data as possible; the average air flow speed was used for the analysis of indoor air flow patterns and the effect of window typology on indoor air flow speed. Because of limited instruments and assistants, the measurement was taken only during working hours for three continuous days at two or three offices in each building. Therefore, at the first three days the measurement was taken in office A, then office B in the next three days etc.

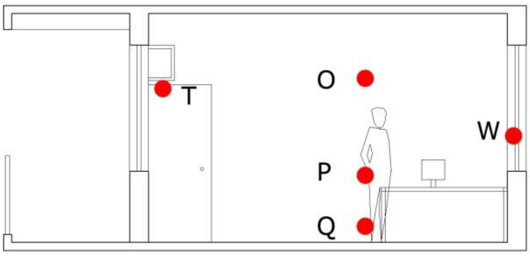


Figure 4.3: Section of the office and measurement points.

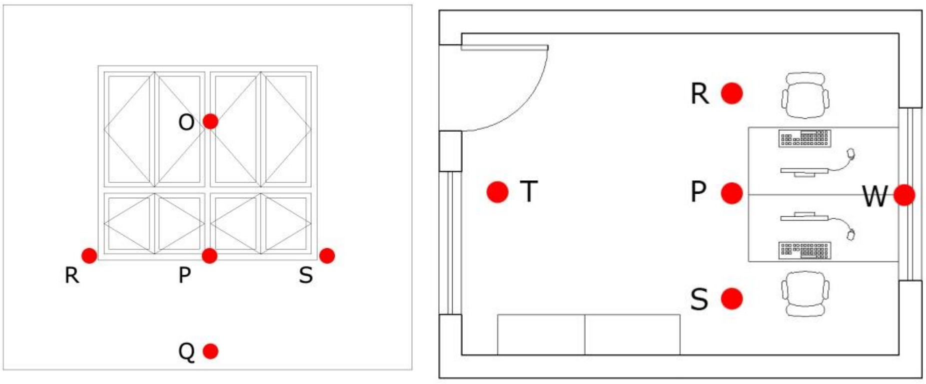


Figure 4.4: Measurement points in the office room

(left: window elevation, right: office plan).

1	2	3
4	5	6
7	8	9

Figure 4.5: The air speed measurement at opened door or window were divided by nine grids.

Table 4.1: Indoor air velocity measurement timetable for cellular office.

Measuring Point	Time in 30-minute intervals							
	1-3 min	4-6 min	7-9 min	10-12 min	13-15 min	16-18 min	19-30 min	Repeat
Point W								
Point O								
Point P								
Point Q								
Point R								
Point S								
Point T Window								
Point T Door								

For continuity of measurement, two offices in an office building (A1, A2, B1, B2, C2, C3, D1 and D3) were selected for measurement during working hours in four days (the 10th Oct to the 15th Oct in office buildings A and B, the 13th and the 14th was the weekend; the 16th Oct to the 19th Oct in office buildings C and D). Points W, R, P, and S, which were close to the desk surface and occupant, were measured at the same time. The data were recorded at two-minute intervals. Besides, the air flow speed was also recorded before the window state was changed by the occupant. The air flow speed was used to analyse the impact on occupant window-control behaviour.

4.1.3 Occupant thermal comfort survey

The measurement of indoor and outdoor temperatures and relative humidity, together with questionnaires were used to address occupants' thermal comfort threshold in the office building.

The working hours for occupants were from 8:30 to 17:30 including three hours' break time from 11:30 to 14:30 in the summer (from June to October). The offices were fully occupied during the measuring time. It would be marked on the questionnaire if any occupant was not in. To avoid the occupants filling in all the questions at once, the questionnaires were handed out four times a day, to ensure the result would be as accurate as possible. In addition, each occupant's background information was recorded one day before the survey start (such as: age, gender et al).

For each single day, the first distribution was at 8:50 in the morning to allow occupants to reach a stable metabolic rate. There was no lift in buildings A, B and C, so occupants had to climb the stairs, which would increase occupants' metabolic rate and impact on their comfort sensation when they arrived in the office. The second distribution was taken at 11:00 (half an hour before lunch break). The third and fourth distributions were given at 14:50 and 17:00 respectively.

The questionnaire aimed to identify the occupants' evaluation of indoor environmental conditions and personal comfort states. It had two parts, the background record part and the evaluation part. The background part was given on the first day of the survey and the evaluation part was sent out daily. At the beginning, based on the check list in ASHRAE standard 92 (1992), the occupants' clothing and their activity level were estimated and recorded. The questionnaire also included an occupant's perception of comfort, indoor temperature, indoor relative humidity and indoor air quality. The assessment scale was changed from 1 – 7 to -3 – +3, because the occupants suggested a -3 – +3 scale was easier to understand. For comfort assessment, a seven-point scale was provided, from very uncomfortable (-3) to very comfortable (3), for the thermal sensation assessment it was from cold (-3) to hot (3), for humidity sensation, the vote was from too dry (-3) to too humid (3), and for air quality it was from very stuffy (-3) to very fresh (3). Zero is the neutral point. These records were related to indoor temperature and relative humidity to establish occupant comfort threshold. Because of lack of instruments indoor CO_2 level was not measured, the results were based on occupants' perception. There were total of 24 occupants were surveyed in four buildings, including sixteen males and eight females. The age range was between 25 and 60 years old. There were 1344 questionnaires in total achieved in four office buildings and about 14400 sets of data were collected. A sample of the questionnaire is given in Appendix 6.

4.1.4 Occupant window control monitoring

Occupant window control behaviour monitoring is to establish the correlation between window-control behaviour and indoor environmental conditions. The way to record the window state is the same as in the pilot study. However, the window state monitor only recorded the state as "open to close" or "closed to open", while the effective opening area and the window state changing (such as from large to small or from small to large) could not be recorded by state logger. Therefore, these data were recorded by the author and his assistants, and the corresponding time was marked. So, the window area and the time were logged. Each window state recorder monitored a surveyed office in one office building. In the field measurement the discharge coefficients for each opening was difficult to measure, the effective opening area was measured for analysis rather than free opening area.

4.2 Description of Office buildings

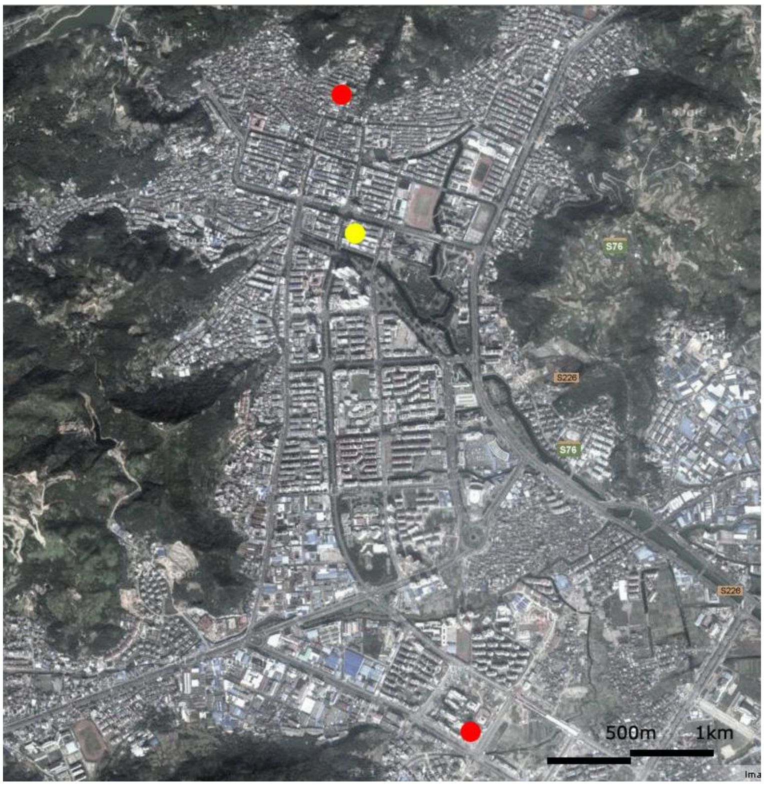


Figure 4.6: The red points show the location of monitored offices, the yellow point shows the nearest weather monitoring station.

The measurement was taken between 24th September and 18th October 2012, in Yuhuan, Zhejiang province, South-East China, with the latitude and longitude of 29° and 120°. The city is located in the climate zone of hot summer and cold winter. Twelve cellular offices in four naturally-ventilated office buildings were selected for analysis. The office buildings A, B, and C were close to each other (Figure 4.6, the red point on the top). Building B was in the middle of these three buildings. Building A was about 40 meters on south of building B and building C was about 20 meters north of building B. As building C was on a slope, the ground of it was about 3 meters higher than the ground in building B. Building A was about 60 meters away from a deserted city road which was on the south. Office D (Figure 4.6, the red point on the bottom) was about 3 kilometres far away from them without any tall buildings around. However, there was a four-lane dual carriage city road on the east side of the building, which is not busy at the moment (as it was in a new district) but may lead to a noise problem in the future. The yellow point shows the closest weather monitor point of the local weather station. The local microclimate was show on Appendix 7. The typical offices characteristics in four buildings were show on Table 4.2.

Table 4.2: Typical offices and windows in measured four buildings.

		Office A1	Office B1	Office C1	Office D1
Dimensions	Width (m)	3.6	3.6	3.9	4.3
	Depth (m)	4.8	4.8	6.3	6.5
	Height (m)	3.0	3.1	3.0	2.7
Glazing area	Size (m^2)	2.9	3.5	3.3	7.2
	Glazing Ratio (%)	28	35	30	58
Window type		Casement	Casement /Top hung	Sliding	Top hung
Maximum openable area (m^2)		2.50	3.12	1.60	0.25
Other windows in the office Type Size(m^2) Openable area(m^2)		Casement 2.40 2.00	Pivot 1.10 0.95	N/A	N/A

The offices in Building A (Figure 4.7, Figure 4.8 and Figure 4.9), which was built in the 1980s, were all cellular offices at a single side of an open-air corridor. Two offices on the third floor in this building were used for measurement and named as A1, A2. The offices were facing south. There was one casement window with a wooden frame and normal single glass on each side of the office and a door with a top light window. All the windows could be opened, with a roller blind behind. The glazing area was 28% (2.88m^2) on the south-facing façade and 24% (2.40m^2) on the north-facing façade. The maximum effective opening area on the south façade was 2.50m^2 while 2.00m^2 on the north, but the size could be extended to 4.20m^2 on the north façade if both door and top light window were open. Each office had two occupants sitting near the window. There were two females in office A1 and two males in office A2. The detailed office plans, sections and window size are shown in Appendices 8 and 9.

Figure 4.7: Office building A and internal view of office room.

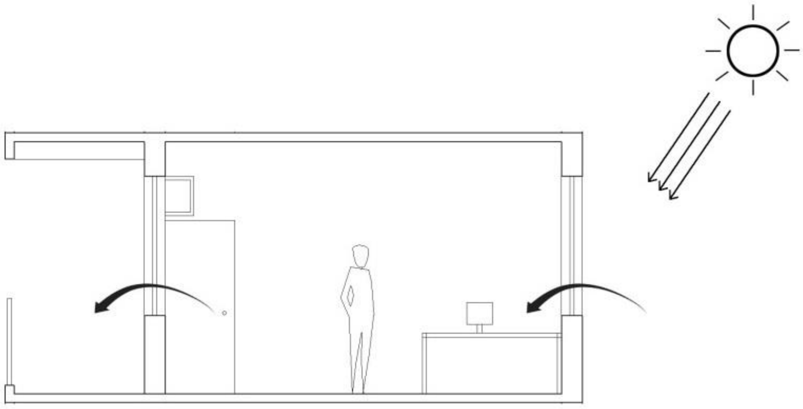


Figure 4.8: Draft section of office A.

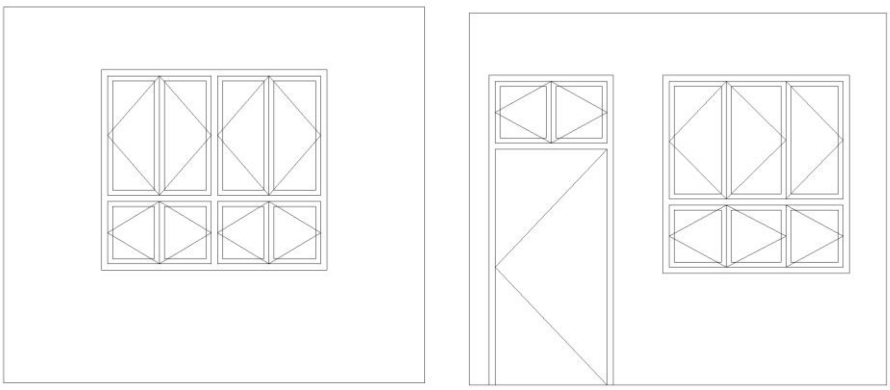


Figure 4.9: Windows in building A.

Office building B (Figure 4.10, Figure 4.11 and Figure 4.12) was built in the 1970s. The office rooms in it were at both sides of a corridor. There were four offices on the second floor named as B1, B2, B3 and B4, used for analysis, all of which were facing south. In each office, there was a horizontal pivot window near the top light window on the partition wall facing the corridor side, the glazing size was 1.1m^2 and the maximum opening area was about 0.95m^2. Besides, a window with two top-hung opening windows and four casement windows on the other side facing the outside. The window frame was made of steel. The glazing area was 35% (3.52m^2) of façade and the maximum opening area was about 3.12m^2. Two roller blinds were behind the window. There were two occupants in each office sitting near the window. There were two males in office B1, two males in office B2, one male and one female in office B3 and one male and one female in office B4.

Figure 4.10: Office building B and internal view of office room.

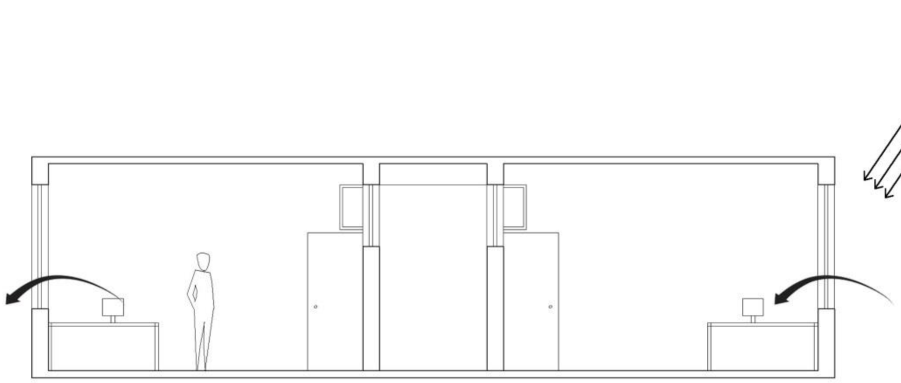


Figure 4.11: Draft section of office B.

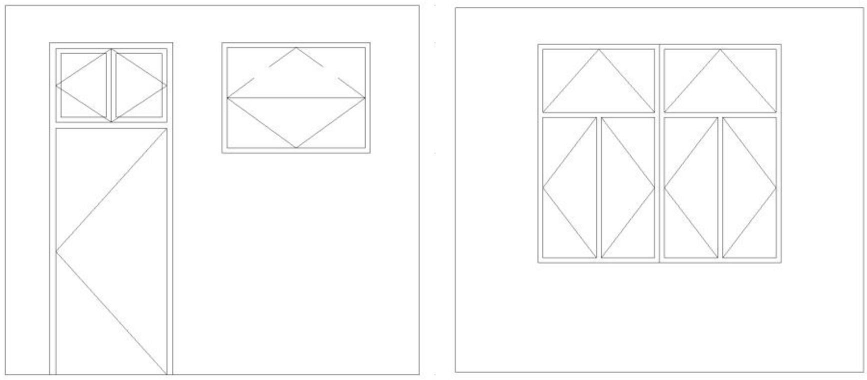


Figure 4.12: Windows in building B

Office building C (Figure 4.13, Figure 4.14 and Figure 4.15) was built later, in the 1990s, in which the cellular offices were at both sides of a corridor, with aluminium-framed sliding windows in each office. The glazing area was about 30% (3.28m^2) of the façade, and the maximum opening area was about 48% (1.60m^2) of the glazing area. Three offices (C1, C2 and C3) on the third floor were chosen for measurement. All these three offices were facing south. Two roller blinds were behind the window. There were two males in office C1, two females in office C2 and one male and one female in office C3.

Figure 4.13: Office building C and internal view of office room.

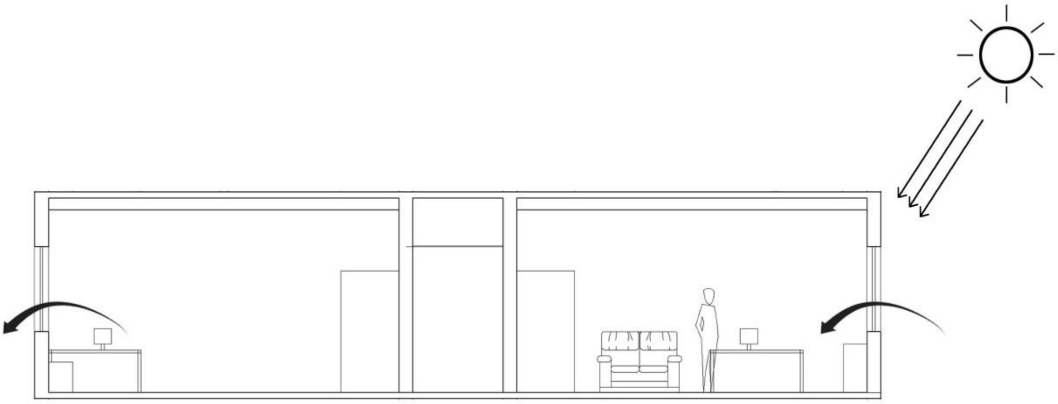


Figure 4.14: Draft section of office C.

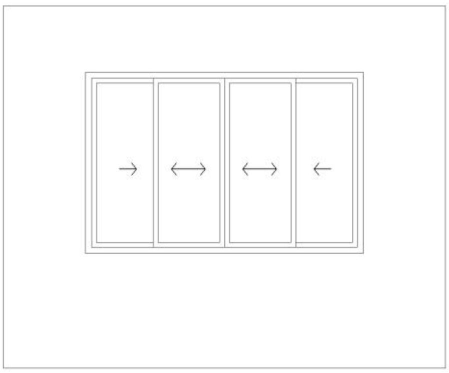


Figure 4.15: Windows in building C.

Office building D (Figure 4.16, Figure 4.17 and Figure 4.18) was a tall building with 14 floors and a central core, which was built in 2009. Each office in this building had two top-hung windows on a glass curtain wall with thermal-break aluminium frames and green coating toughened glass. The glazing area was 58% ($7.20m^2$) of the façade area and the maximum opening area was about $0.25m^2$, which was about 3% of the glazing area. Curtains have been hung in this building. Three offices (D1, D2 and D3) on the third floor were used for measurement. Office D1 was facing east by south, office D2 was facing west by north, and office D3 was facing north by east. There were two females in office D1, one male and one female in office D2 and one male and one female in office D3 as well.

Figure 4.16: Office building D and internal view of office room.

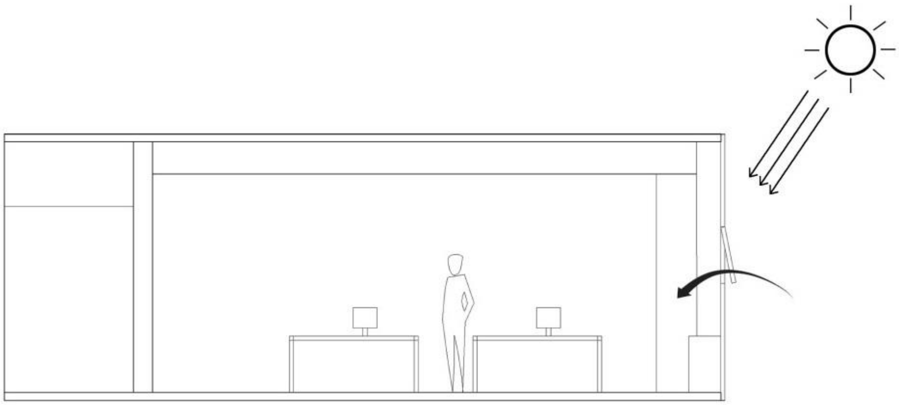


Figure 4.17: Draft section of office D.

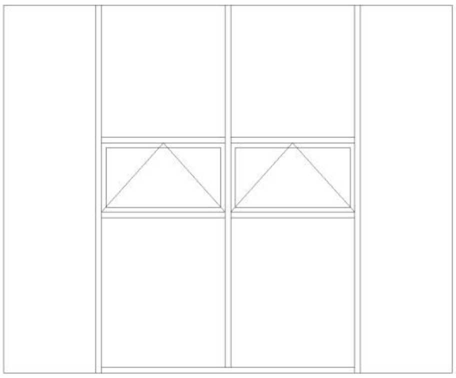


Figure 4.18: Windows in building D.

4.3 Wind speed data

Based on the pilot study, the measured wind speed and direction on top of the building did not have a significant impact on indoor air flow patterns and air flow speed on opening a window, because wind direction is unpredictable and dynamic on top of building. Therefore, during this measurement, the external air direction and air flow speed were collected from the closest weather monitor station, and were used as a reference to provide a general view of the local wind direction and speed. The data were recorded at 10-minute intervals. Figure 4.19 of a wind rose shows the frequency of the outdoor wind direction and speed. The prevailing wind direction was North-East (30°) and the average speed was about 4m/s. Direction North-East (60°) had the highest average wind speed, which was nearly 6m/s. North facing and North-East facing offices may have a higher indoor air flow speed. Although the wind direction frequency for South and South-East was much lower than North-East, the average wind speed was closer to North-East, which was about 4m/s. Figure 4.20 shows the frequency of wind speed, which was the highest when the wind speed was between 1m/s and 3m/s. Only in 10% of the time was the wind speed below 1m/s, and in 4% of time the wind speed was over 10m/s. Therefore, in those three weeks, the wind condition was good.

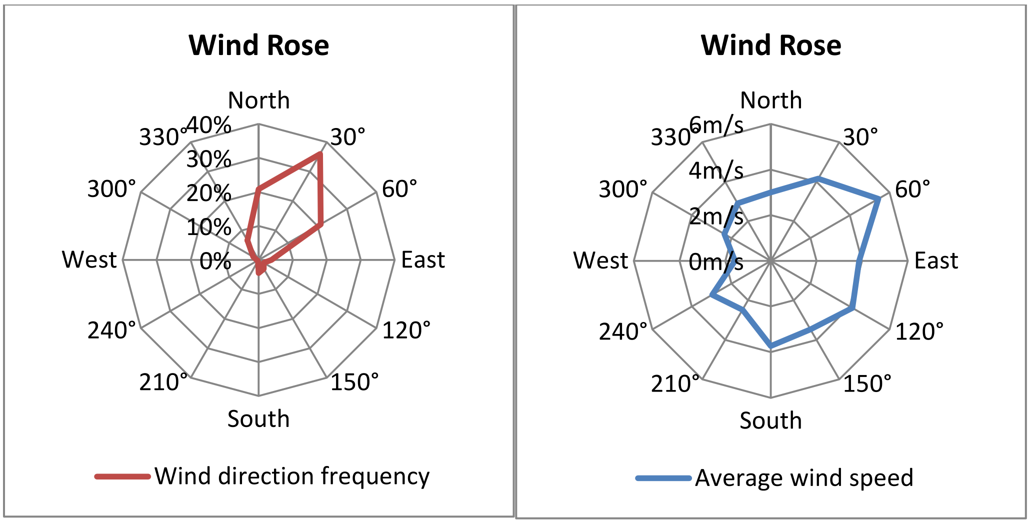


Figure 4.19: Wind rose showing direction frequency (Left) and average wind speed for each direction (Right) in three weeks.

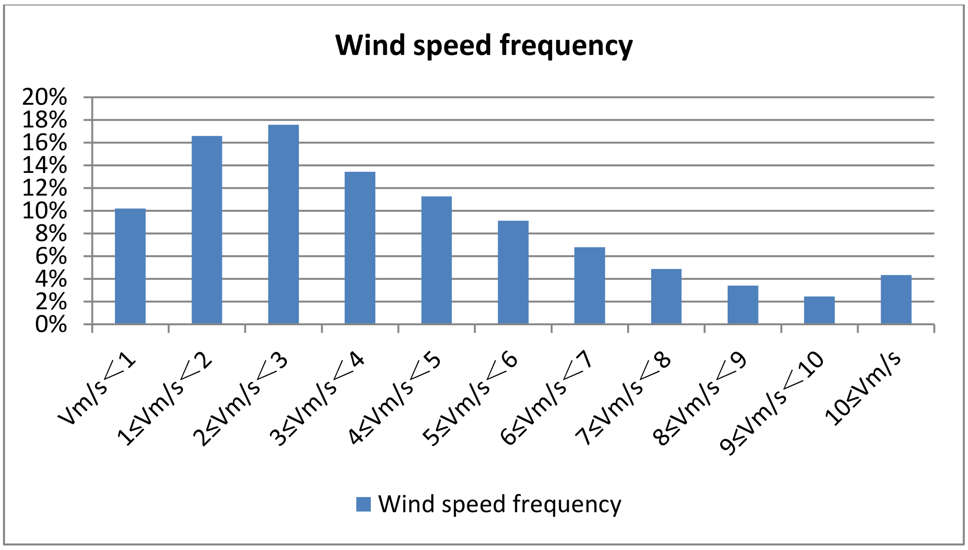


Figure 4.20: The frequency of wind speed.

5 Environmental Factors

This chapter shows the measured results in the four buildings. The thermal performances of twelve measured offices are presented. The window state record and indoor air flow rate were used to identify the impact of natural ventilation on indoor air temperature. The natural ventilation types in each office are also defined and the results of single-side ventilation and cross-ventilation type were compared. Besides, according to measured indoor air flow speed on different measurement points in the office, the influence of window typologies on indoor air flow speed and air flow path were established, which would influence occupants' thermal comfort and window control behaviour. In order to indicate natural ventilation type clearly in each office, the SSV and CV were used to representative single-side ventilation and cross ventilation.

5.1 Indoor temperature and relative humidity

5.1.1 Office building A

In office building A, during the working period, office A1 (SSV) could be seen as a single-side ventilated office, since the window and the door would not open at the same time. Also, the internal roller blind was dropped down most of time to block the solar radiation on both sides of the office. Even when the window was opened, the effective opening area was limited. In office A2 (CV), both the window and the door were opened most of time. It could help office A2 to achieve cross-ventilation. In addition, both offices had the same number of occupants and computers, so the internal heat gain from occupants and equipment could be seen as the same. The results of internal environmental conditions in these two offices are shown in Figure 5.1.

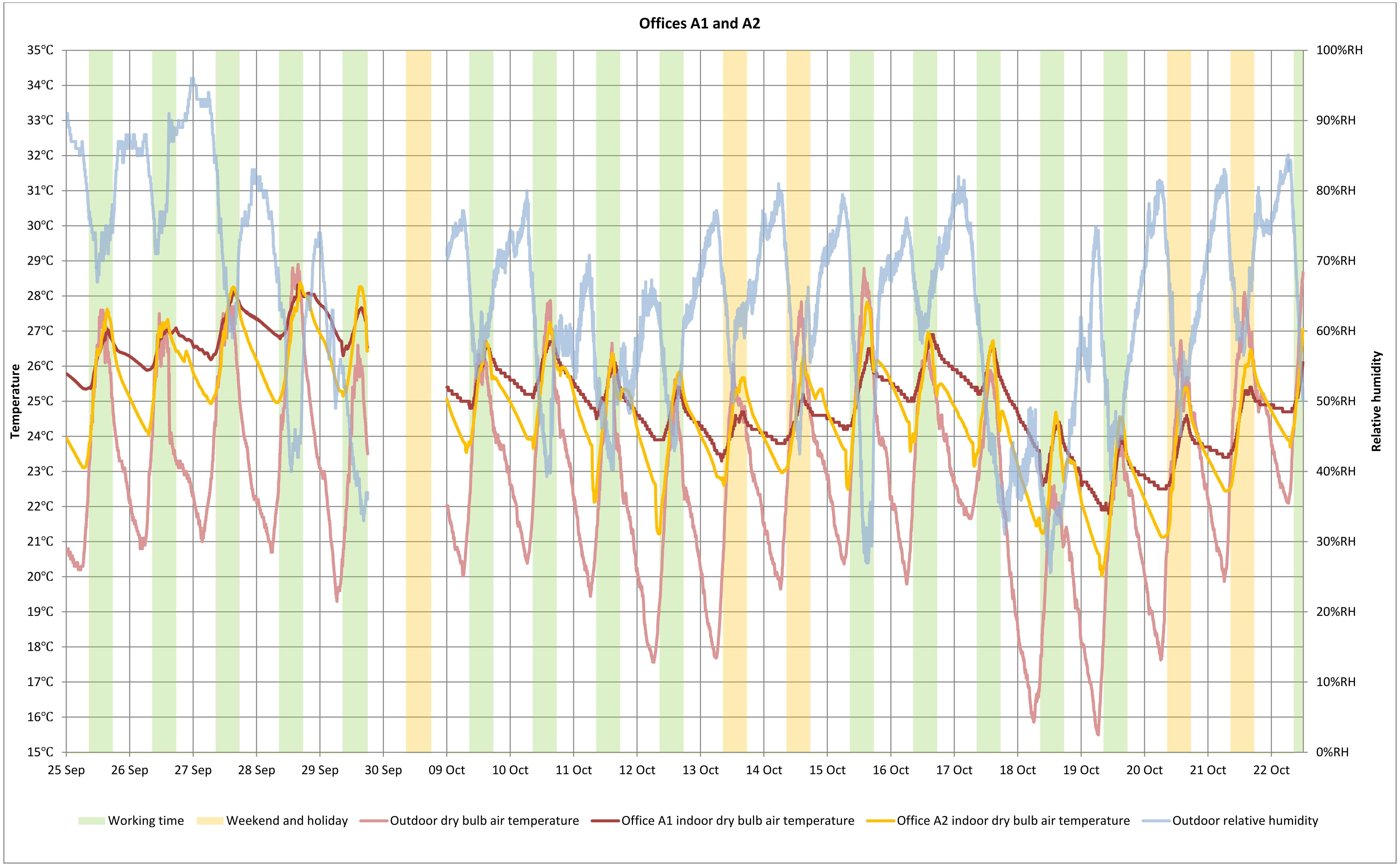


Figure 5.1: Measured indoor dry bulb air temperature and outdoor dry bulb air temperature in office building A.

During the whole monitored period, the outdoor dry bulb air temperature varied between 15.5°C and 29.9°C, which showed a large difference between day and night. Comparing the indoor dry bulb air temperatures, the temperature difference between day and night in office A2 is greater than in A1. The highest daily indoor dry bulb air temperature in office A2 is higher than in A1, and the air temperature variation in office A2 was close to the outdoor air temperature. This may be because it was cross-ventilated in working hours in office A2, so that the indoor heat could be moved out from the office more efficiently, but the outdoor hot air could also be brought into the room. In the cross-ventilated office, the indoor dry bulb air temperature was much more easily influenced by the outdoor temperature.

Compared to office A2 (CV), occupants in office A1 (SSV) used an internal roller blind to block the direct sunlight from the south, the lowered roller blind blocking the open window and reducing the effective opening area (Figure 5.2). Sometimes occupants closed the window and left the door open. In addition, the north-facing window was not opened during the monitoring time and the curtain was fully closed. It can be seen that blocking solar radiation was also an efficient method to reduce indoor temperature in the day time. This result had also been found in a previous parametric study.

Figure 5.2: The curtain on a south-facing window in office building A.

Although the highest dry bulb indoor air temperature in office A1 was lower than office A2, the average indoor air temperature in office A1 was 0.45°C higher than office A2 during the working hours. Because office A1 was single-side ventilated, it was less efficient for moving the internal heat out of the office than office A2; especially after the indoor temperature reached its peak, the air temperature in A2 dropped much faster than office A1. This situation continued even during the off-working hours, because no window was opened after working hours. This situation may be related to the curtains which also prevent heat loss in office A1. This may cause the indoor dry bulb air temperature at night in office A1 to be higher than office A2.

There was an obvious temperature drop every morning just before working hours in office A2, which was because of the cross-ventilation caused by occupants opening doors and windows as soon as they arrived. It happened more frequently and obviously in the cross-ventilated office (A2) than in the single-side ventilated office (A1). The amount of air temperature drop between different days may be related to the air flow speed passing through the office. In these two days (the 11^{th} and the 12^{th}) (Figure 5.3), based on the weather station record, the recorded average wind speed was 5.8m/s on the 11^{th} and 4.7m/s on the 12^{th}, which were much higher than the other days (varying between 1m/s and 3m/s). Except for the 17^{th}, the average wind speed was 5.3m/s, but the indoor air temperature that dropped at occupant arriving time was smaller than the air temperature drop on the 11^{th} and the 12^{th}. The wind direction may influence the air speed that passed through the office. Nevertheless, the results in office building A showed that the internal heat can be removed more efficiently by cross-ventilation.

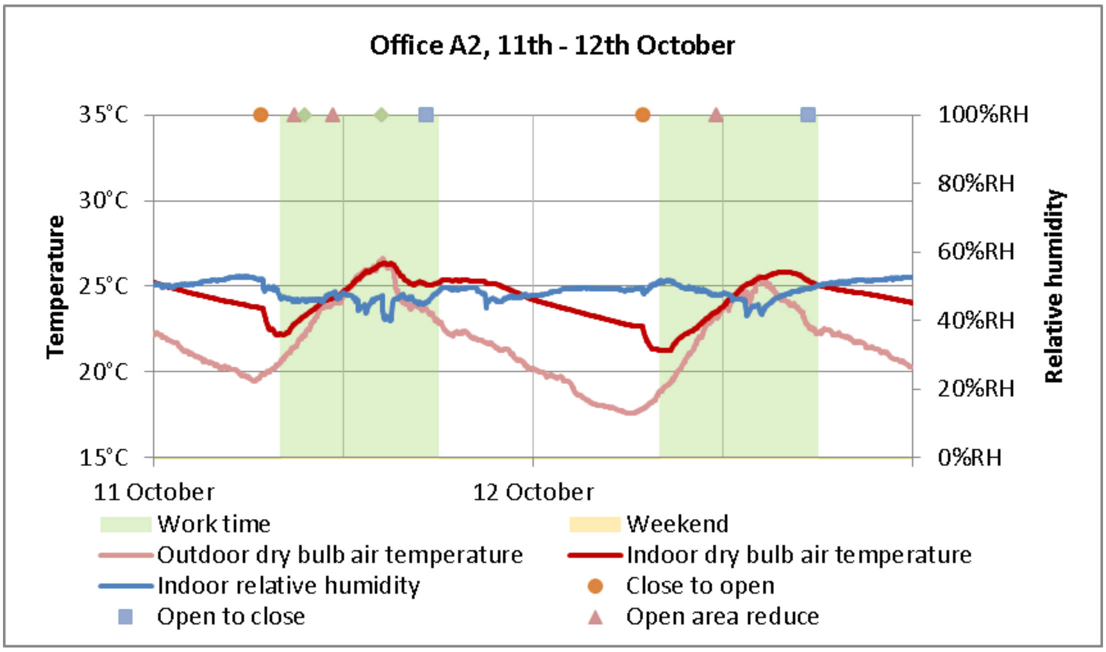


Figure 5.3: Indoor environmental condition in office A2 (CV) during 11th and 12th of October.

In office A2, there was a slight temperature rise just after the occupants left the office and closed the windows and the door. This situation was not found in office A1, which may be caused by the heat release from the building structure. When the window was shut the heat could not be moved out of the office and the indoor temperature would heat up until achieving a new heat balance between the building structure and the indoor air. In office A1, the natural ventilation could not help to reduce the indoor air temperature efficiently, and the indoor air temperature drop rate was very close to the heat loss rate from the building structure, so the indoor air temperature stopped rising when occupants left the office. In addition, after working hours the indoor air temperature dropped more slowly than the outdoor air temperature, so there was a large temperature gap between indoor and outdoor. The maximum dry bulb air temperature difference between outdoor and indoor in office A1 was 7.59°C, and 6.17°C in office A2. If night-time natural ventilation could be provided, the indoor temperature could be further reduced in office building A.

In order to establish the impact of the indoor air flow speed on indoor air temperature, the continuous indoor air flow speed was measured on four days (the 10th Oct to the 15th Oct, except the 13th and the 14th which were weekends) in office building A2, and the effective opening area was recorded at the same time. According to measured air flow speed on the opening area, the air volume flow rate and required air flow rate for cooling were calculated to assess the natural ventilation cooling ability.

The results were shown in Figure 5.4. The dark purple column indicates the indoor surface temperature, the blue column indicates the air volume flow rate, and the yellow column shows the required air flow rate for cooling. If the blue column were higher than the yellow one, it would mean at that point natural ventilation could efficiently move the heat out of the office and cool the indoor environment. If the yellow column were negative, the indoor air temperature would be lower than the outdoor air temperature and the large air volume flow rate would raise the indoor air temperature. By calculating the required air flow rate for cooling, the minimum indoor and outdoor air temperatures were limited at 2°C. Based on empirical expression, when the temperature difference was smaller than 2°C, the required air flow rate for cooling in the office would be extremely high and it would increase with decreased indoor and outdoor temperature difference. In fact, in the natural ventilated office, if indoor and outdoor temperature difference was small, it would mean the room was well natural ventilated. And increasing indoor air flow speed would have more influence on occupant comfort sensation rather than indoor temperature. Besides, in the figure there is a gap between the morning and the afternoon. This is because, during the lunch break, the air flow speed and surface temperature were not measured.

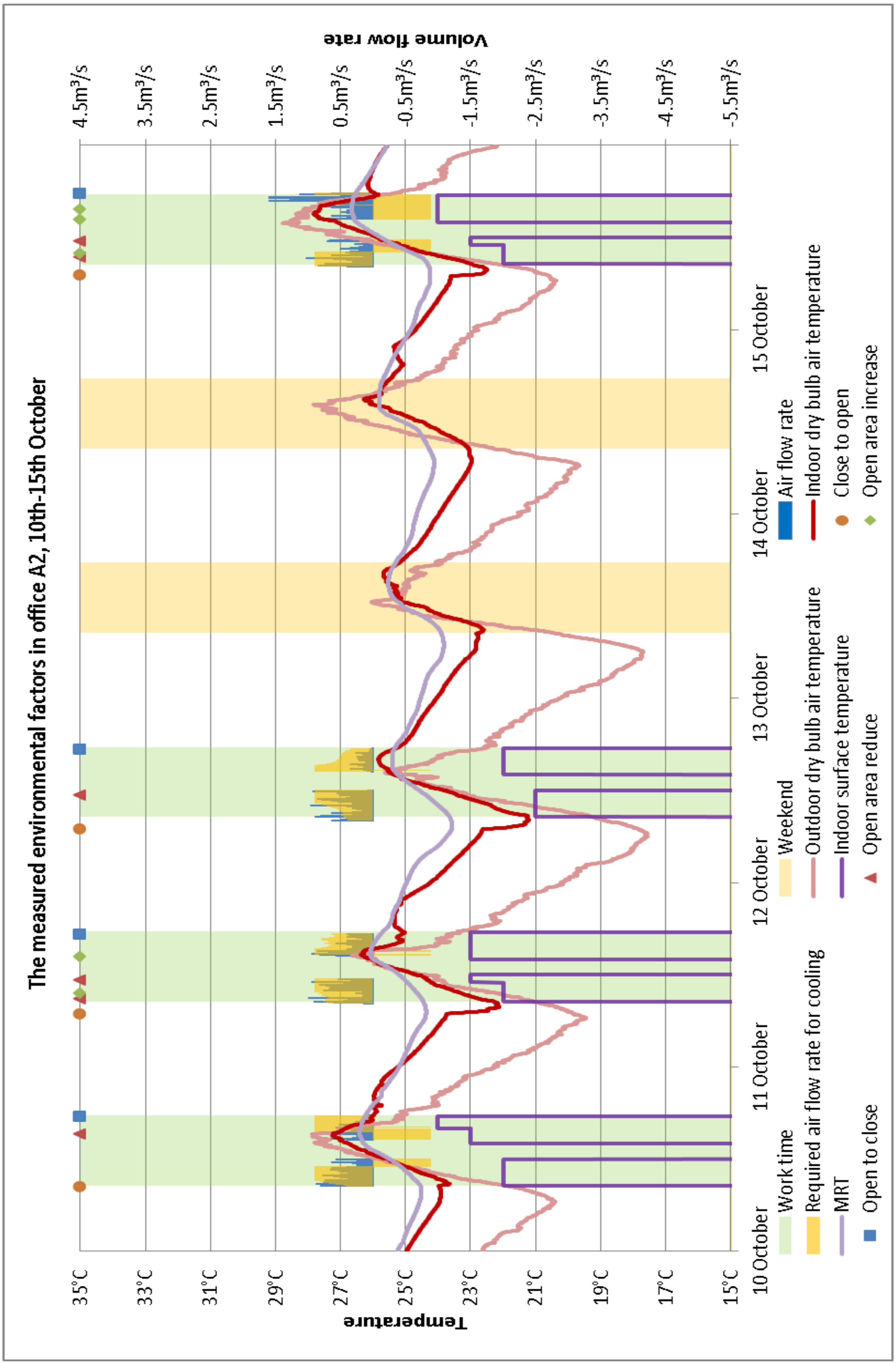


Figure 5.4: Measured indoor temperature and indoor air volume flow rate in office A2 (CV).

A significant indoor air temperature variation occurred in office A2 at the time when occupants arrived in the office. The air temperature difference and high air flow speed were the main reasons. The occupants arrived in the office much earlier than the working hours, so the air flow speed in the office was not measured for a short time after the occupants opened the window. According to the measured results in the morning, in the majority of time the air volume flow rate was very close to the required air flow rate for cooling and sometimes was slightly higher, so the indoor warm air could be moved out efficiently and the indoor air temperature was very close to the outdoor air temperature.

When the air volume flow rate was lower than the required amount for cooling in a period of time, the indoor air temperature would increase. But in four days, in the morning after the air temperature drops when occupants arrive, the air volume flow rate was not always higher than the required air flow rate. The indoor air temperature was still close to the outdoor air temperature, so the cooling requirement could still be achieved. This may be a difference between the theoretical study and the field measurement results. If the air volume flow rate was much lower than the required air flow rate, it would reduce the heat loss in the afternoon when the outdoor air temperature dropped. In the afternoon on the 12th of October, occupants reduced the effective opening area in the later morning and kept it unchanged until they left the office. The indoor air temperature was still increasing when the outdoor air temperature reached its peak. And in the afternoon, the decrease of indoor air temperature was slower than the outdoor. The small effective opening area reduced the air volume flow rate in the office and impacted on the indoor air temperature.

Besides, the indoor surface temperature and indoor radiant temperature were measured. The average indoor mean radiant temperature in working hours was 25.41°C, which was slightly higher than the average indoor air temperature (25.09°C), and the highest daily temperature was lower than the indoor air temperature. The indoor radiant temperature increase and decrease rates were much slower than the air temperature.

The slower decrease rate would influence the indoor air temperature when the occupants left the office. The air temperature started rising when the door and windows were closed, until it became close to the indoor radiant temperature. Therefore, when the natural ventilation stopped, the heat loss rate dropped rapidly and the heat accumulated in the office, so that the heat received by the indoor air was more than it lost. In the afternoon on the 12th of October, when the occupants left the office, the indoor air temperature was very close to the indoor radiant temperature, and there was no variation of it. Moreover, the reduced air volume flow rate was related to a small effective opening size in the morning, causing the cooling ability of the natural ventilation to drop. So even when occupants fully closed the windows and door, the heat loss rate in the office would not have much difference compared with the afternoon.

Because of the measurement intervals, the indoor surface temperature in these four days generally presented the indoor thermal condition. The maximum indoor surface temperature was 24°C and the lowest was 21°C. The surface temperature in office A2 was the lowest in the four buildings. The highest surface temperature was about 3-4°C lower than the highest indoor air temperature. And in the morning the surface temperature was lower than that in the afternoon, with the maximum difference about 2°C. The surface temperature variation in office A2 was larger than the other offices.

In summary, according to De Dear’s comfort equation (Equation 1.7) the comfort range in September were between 24.8°C and 29.8°C and between 23.4°C and 28.4°C in October. During the measured period, in most of the time the indoor air temperatures in office A1 and A2 were in the comfort range, the highest daily indoor temperatures were all below the high boundary of comfort range. The indoor temperature conditions in office A1 was better than office A2. Because in the office A2, the indoor air temperature was rapidly drops when occupants opened door and window at arrive time. This situation causes the indoor air temperatures were lower than low boundary of the comfort range in a period of time in the morning, which may causes occupants felt cold. Besides, the indoor air temperature drops at occupants arriving time in office A2 were clearly showed that when the indoor air flow rates were higher than the rates for cooling required can efficiently reduce the indoor temperatures. Although, office A1 was single-side ventilated, the indoor air flow rates would not achieved the cooling required (detail presented in section 5.2.1), the indoor air temperature was much stable than office A2 by using curtain roll. This method also keeping indoor air temperature varies in the comfort range. Generally, based on the indoor temperatures in these two offices, both rooms were provided acceptable indoor conditions. Whether occupants satisfy the indoor conditions were showed in chapter 6 which presented occupants' perception results.

5.1.2 Office building B

In office building B, the office rooms B1 and B3 were cross-ventilated. As the window on the corridor side was used, when the door was closed the office could still be cross-ventilated. But the corridor windows in offices B2 and B4 were not used, so they could be seen as single-side ventilation rooms when their door was closed. In office B2 (SSV/CV), due to work requirement, the door was used quite often, so the natural ventilation condition changed with the change of the door state. It was more like a hybrid natural ventilation condition, but in most of the time the room was cross-ventilated. Office B4 was cross-ventilated in a very short time when occupants arrived at the office; then the door would be closed because the door holder was broken. The cross air flow would slap the door and disturb occupants' working. When the door was closed, the office room became single-side ventilated. In office B2, one occupant kept the roller blind in a low position and it covered half of the window during the whole monitoring time; while in office B4 both roller blinds were kept in a low position. Furthermore, the data in the last two days of the first week were not recorded in office B2, because something was wrong with the data logger. The result is shown in Figure 5.5.

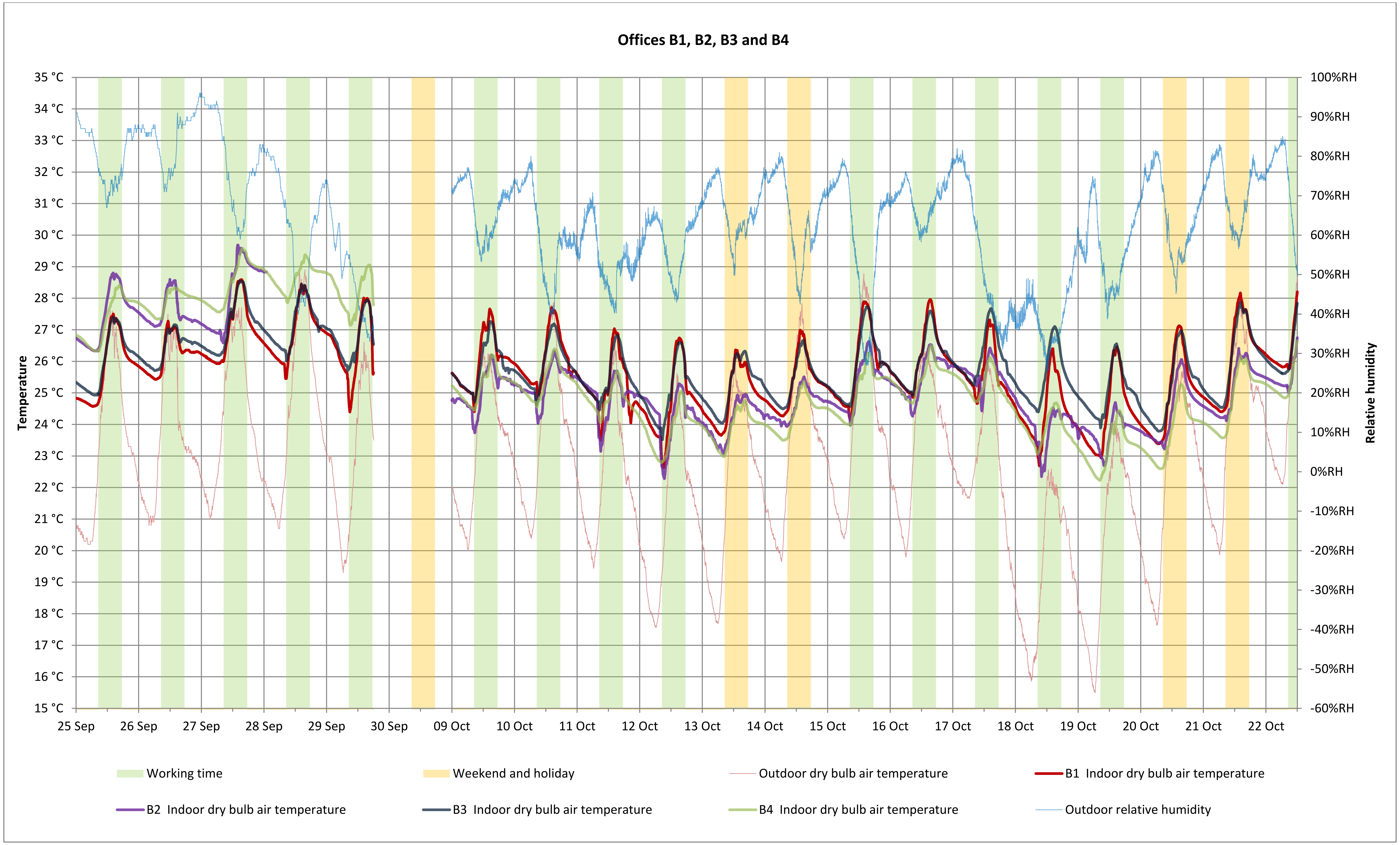


Figure 5.5: Measured indoor dry bulb air temperature and outdoor dry bulb air temperature in office building B.

According to the results, the average indoor dry bulb air temperatures in working hours were 26.2°C in office B1, 25.5°C in office B2, 26.3°C in office B3, and 26.1°C in office B4. The indoor air temperatures in cross-ventilated offices B1 and B3 were higher than in the hybrid and single-side ventilated offices B2 and B4. The indoor air temperatures in two cross-ventilated offices were very close to each other; while it was the lowest in office B2 among the four offices, which was 0.5°C lower than in office B4. As for office building A, in office building B the highest daily indoor air temperature in the cross-ventilated office was higher than in the single-side ventilation office.

However, the situation was different in the first week. In the first week, the indoor dry bulb air temperatures in offices B2 and B4 were higher than in B1 and B3. The reason for this situation may be related to the small effective opening area – the occupants only allow a small opening during the working hours. When the opening area was larger, the indoor air temperature dropped. It can be found on 26th Sep in office B2 that the indoor air temperature dropped about 1°C when the window opened. But in most of time during the first week, the window state was not changed, even when the air temperature reached 29.5°C. The comfort sensation will be discussed in a later chapter, about if the indoor environmental condition can be accepted or not by the occupants in the office.

The temperature variation character in offices B1 (CV) and B3 (CV) was very similar to the situation in office A2 (CV). The indoor air temperature dropped in the morning when occupants opened the window, and then increased with the rise of the outdoor air temperature. But unlike the air temperature in office A2 which was very close to the outdoor air temperature, it was higher than the outdoor air temperature by more than 1°C in offices B1 and B3 during those seven days. Especially on 18th Oct, the indoor dry bulb air temperature in offices B1 and B3 was about 4°C higher than the outdoor air temperature. On the same day the temperature difference in office A2 was about 2°C. It seems that the hot air can be moved out more efficiently in office A2.

However, in office building B, there was another office on the opposite side of the measured office room. The air flow may come from the opposite office and leave the building at a measured office room. This condition may also move the hot air from the opposite office into the measured office. If the heat cannot be moved out efficiently, it would raise the indoor air temperature in a monitored office. So a higher air exchange rate was needed in order to move the hot air out of the office building. But in office building B there were only two casement windows used by occupants. The maximum effective open area was similar to office building A, because of the occupant control; especially in the second and third week the effective open area was kept to a small opening state most of time. In addition, the heat loss from office building B was slower than office building A. Comparing the indoor air temperature between the two office buildings when occupants left the office, the indoor air temperature dropping slope in office A2 was more rapid than in offices B1 and B3 which were cross-ventilated. Due to the occupant behaviour and building characters, the superiority of cross-ventilation has not been displayed and the advantage of a corridor-side window cannot be identified.

Instead, offices B2 and B4 had a lower indoor air temperature. Office B4 was single-side natural ventilation dominated. The indoor air temperature of it was lower than a cross-ventilated office because of using the indoor roller blind and small opening area, which was similar to office A1. Besides, it had the lowest average indoor air temperature after working hours. The average indoor dry bulb air temperature during working hours in office B2 was 0.5°C lower than office B4, but after working hours the indoor air temperature in office B4 was lower than office B2. Especially in the second and the third weeks, the average indoor air temperature in office B4 was 0.8°C lower than in office B2. Compared with offices B1 and B3, the indoor air temperature decrease curves were very similar. Therefore, during the night time, the heat loss in office B4 was the same as in other offices, so the lower indoor air temperature was related to the relatively lower indoor air temperature in the working hours. Thus, in office B2, for some reason the indoor air temperature did not drop a lot during the night (e.g. 19th Oct) and the air temperature curve seemed different from the other offices. It may be because the occupant did not switch off the computer when they left the office, thus the heat from a running computer slowed down the indoor air temperature's decrease.

Although the indoor air temperature in office B2 dropped slower than other offices, the thermal performance during the working hours in office B2 is much better. In the morning it had the same characteristic as a cross-ventilated office in that the indoor air temperature had a sudden drop when occupants arrived, which also happened in office B4 sometimes. In office B2 the indoor air temperature dropped more than the other office rooms when occupants opened the window. This is because the effective opening size of the window was bigger than in other offices, which encouraged the internal heat to move out of the office. Besides, the highest daily indoor air temperature in it was lower than in other offices, sometimes even lower than the outdoor air temperature, which may be caused by the roller blind reducing the solar radiation.

Office B2 achieved the best indoor temperature condition in the four offices, in which controlling natural ventilation may be the main reason. When occupants arrived in the office, the outdoor temperature was lower than the indoor, so the occupant behaviour of opening the door and windows could help the room to achieve cross-ventilation and then reduce the indoor temperature efficiently. When occupants closed the door, the office room became single-side ventilated so the air exchange between inside and outside would be reduced. The rolled-down blind can reduce the solar radiation to some extent and slow the increase of the indoor air temperature. At the same time, as the outdoor air temperature was higher than the indoor, the low air exchange rate could also reduce the hot air moving from outdoor into the office room. Therefore, the indoor air temperature in B2 was lower than other offices. In addition, reducing the air exchange rate when the outdoor air temperature was higher than the indoor could also slow the rise of the indoor temperature. This situation proved that, in the parametric study, the external shading device was not efficient in those office buildings in this climate condition, as the external hot air increased the indoor air temperature. However, the unconscious control by occupants of the door and windows helped to prevent the increase of indoor air temperature.

As for office A2, when occupants left the office and closed the window, the indoor air temperature slightly increased in office B4. As office building B had a great potential for night ventilation, the largest temperature difference between indoor and outdoor was 8.7°C in office B4.

In office building B, continuous air flow speed measuring time was the same as office building A. The indoor air temperature drop in the morning in office B2 was obvious, because after the night-time cooling the indoor air temperature was still high. The lower outdoor air temperature in the early morning had a great impact on the temperature decrease. The air volume flow rate in office B2 was higher than in office A2, and it caused the indoor air temperature to drop in the morning. However, the highest daily indoor air temperature of B2 was lower than A2; decreasing the effective opening area and blocking solar radiation can reduce the highest daily temperature. It was proved that in the morning on 10th October there was a sharp drop of indoor air volume flow rate when occupants reduced the effective opening area. The volume flow rate rapidly decreased from 1.5m^3/s to 0.4m^3/s. It also happened in the mornings on 11th and 15th October (Figure 5.6). Therefore, reducing the air volume flow rate could slow down the increase of indoor air temperature.

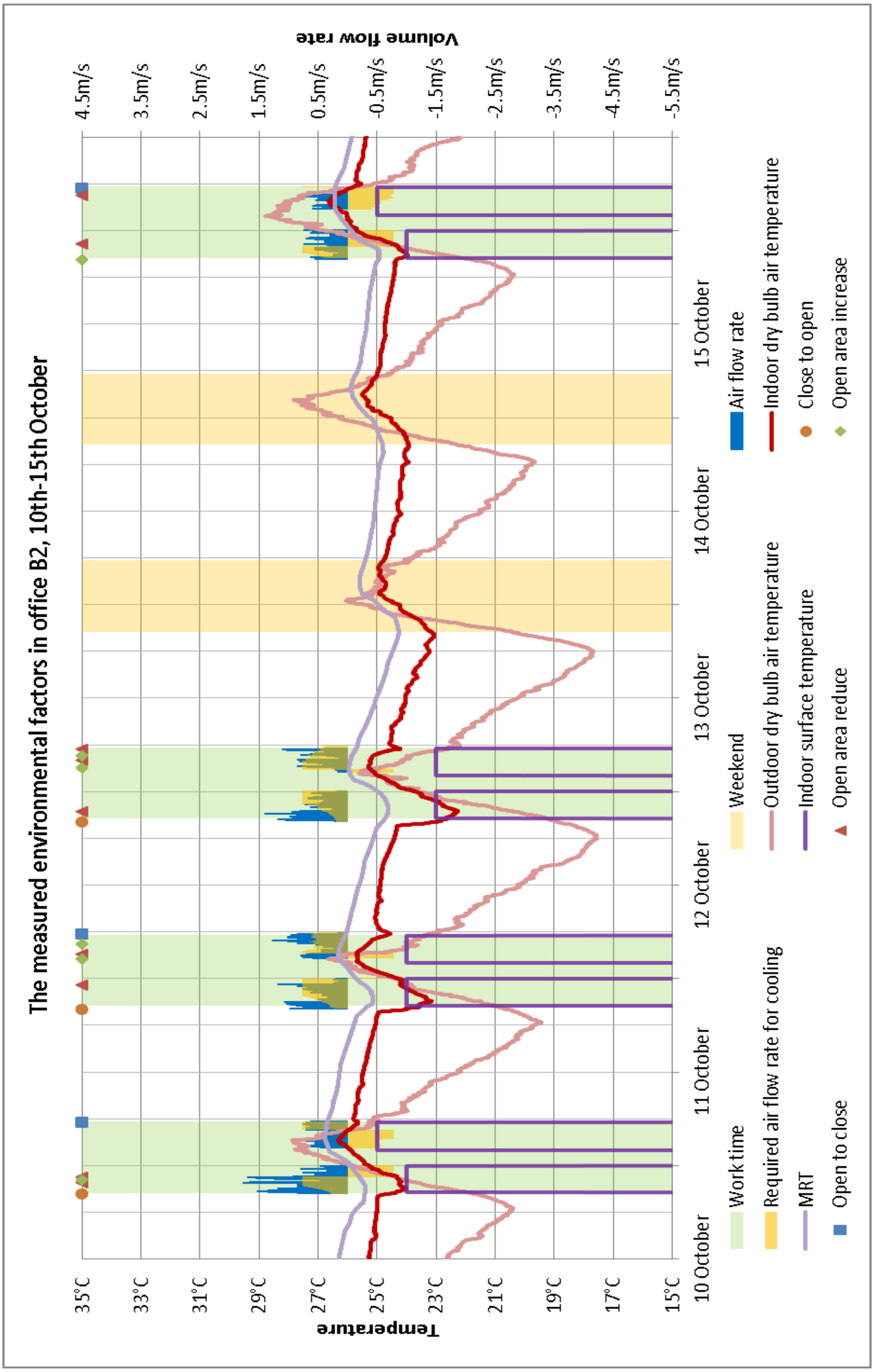


Figure 5.6: Measured indoor temperature and indoor air volume flow rate in office B2 (SSV/CV).

However, compared with offices A2 and B2, reducing the effective opening area would not increase the indoor air temperature, and increasing the effective opening area would not help reduce the indoor area temperature. On the 10th and 11th October in office A2, reducing the effective opening area neither slowed the air temperature increase rate nor over-heated the office room, which may have benefited from good air volume flow rate. But on 12th October, the effective opening area was kept to a small opening and the air volume flow rate was lower than the previous day. Thus, the indoor air temperature was higher than the outdoor in the afternoon. Moreover, in the afternoon in office B2, even when the air volume flow rate was higher than the required amount for cooling and also the window opening had become larger, the indoor air temperature drop was still slower than the outdoor. This could also prove that it was difficult for the building structure, which stored the heat during the day time to move it out at night.

In office B2, the average indoor radiant temperature during the working hours was 25.79°C and the indoor air temperature was 24.89°C. The radiant temperature was 0.9°C higher than the air temperature. After the working period, the decrease curve of radiant temperature and air temperature was nearly parallel. Comparing the temperature between the off work time and the time just before the working period in the next morning, the temperature varied by 1°C in these four days. The building was not insulated, but the heat in the office was very difficult to lose during the night time, so that the building structure may store much heat during the day and be used as a heat source at night. Therefore, more indoor heat was received than lost, and the indoor temperature drop was very slow. The indoor surface temperature in office B2 varied between 23°C and 25°C, and the daily temperature difference was 1°C. The indoor surface temperature was higher than the temperature in office A2 and more stable. Especially on the 11th and the 12th, the indoor surface temperature did not change through the working hours. It was proved that the temperature of the building structure was quite stable.

5.1.3 Office building C

In office building C, office C1 (SSV) was single-side ventilation dominated because of a broken door holder; once the door was closed by air flow the occupants would not open it until someone needed to get in or out of the office. Offices C2 (CV) and C3 (CV) were cross-ventilated, and in office C3 the roller blind was used very frequently. The measured indoor dry bulb air temperature results are show in Figure 5.7.

In these three offices, the average indoor dry bulb air temperature in working hours was 27.88°C in office C1, 26.95°C in office C2, and 26.31°C in office C3. The average indoor air temperature in office C1 was higher than other two offices, and office C3 had the lowest indoor air temperature, about 1.5°C lower than office C1. Although the indoor air temperature in office C1 was higher than other offices, at early morning just before the occupants arrived in the office, the indoor air temperatures were very close through a night temperature drop. The ability of the building structure to absorb and release heat was very stable. In office C1, the indoor air temperature during the day time was much higher than other offices, after working hours the temperature would drop gradually; however, in office C3, the indoor air temperature would gradually increase or keep stable; the situation in office C2 was between these two offices, sometimes the indoor air temperature would increase and sometimes decrease. Until the next morning, the indoor air temperatures were close to each other. So, the natural ventilation situation in the day time directly influenced the indoor air temperature in each office.

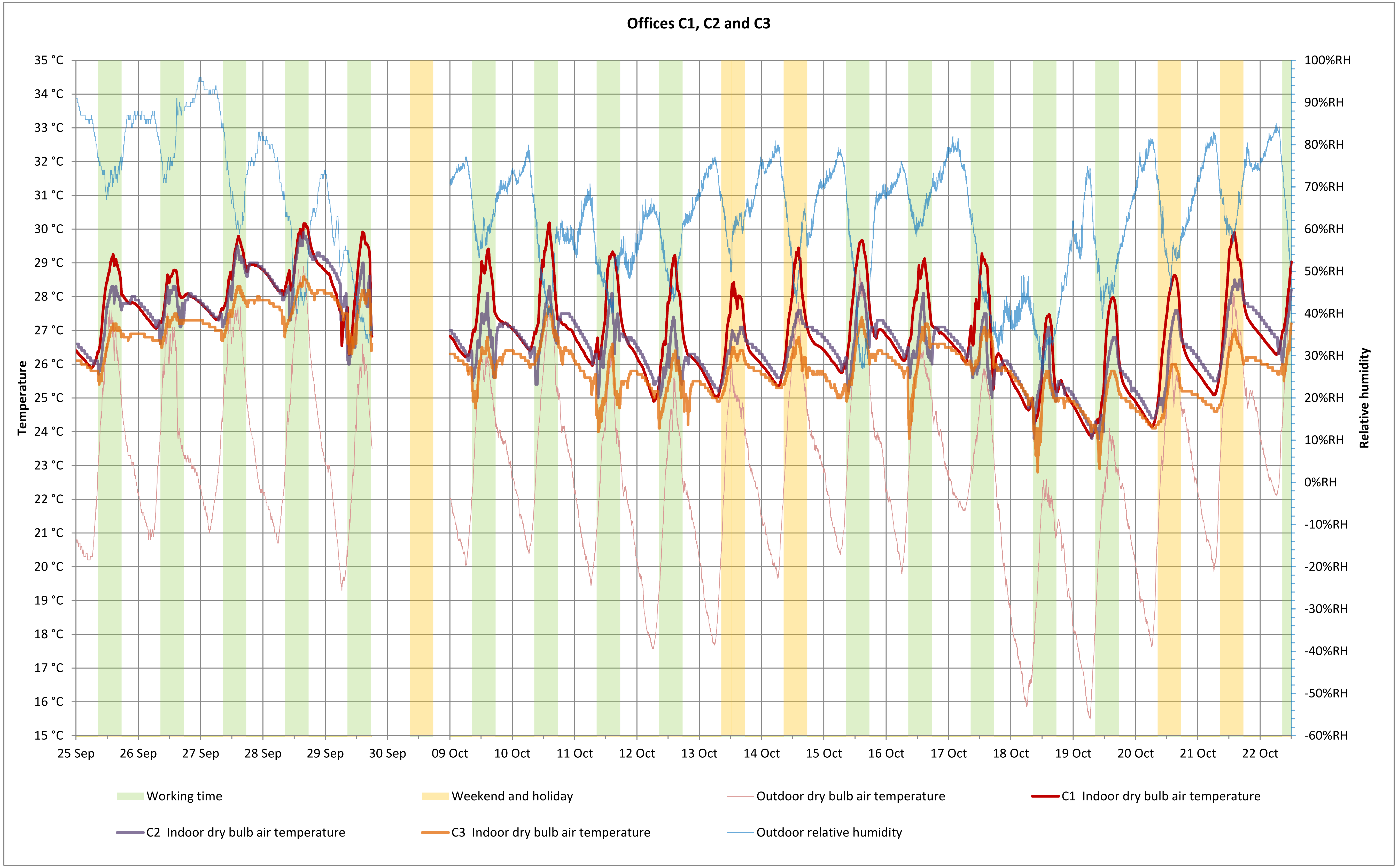


Figure 5.7: Measured indoor dry bulb air temperature and outdoor dry bulb air temperature in office building C.

In office C1 (SSV), except for the effective opening size of the window, the state of the door also influenced the natural ventilation efficiently. If the door was opened, the indoor air temperature drop could still be seen. On 28th and 29th September, there was an indoor air temperature decrease in the office, just after occupants arrived in the office. But on 29th there was an unknown window state change in the early morning at 5:50am, before occupants arrived, and it remained open for about ten minutes. Maybe the cleaner opened the window when they cleaned the office. Besides, at noon time there was a temperature drop as well but not sharp. This was the time occupants finished the noon break and went back into the office (Figure 5.8). It also happened in other offices. Thus, the broken door holder had a significant impact on occupant behaviour and influenced the indoor air temperature in office C1.

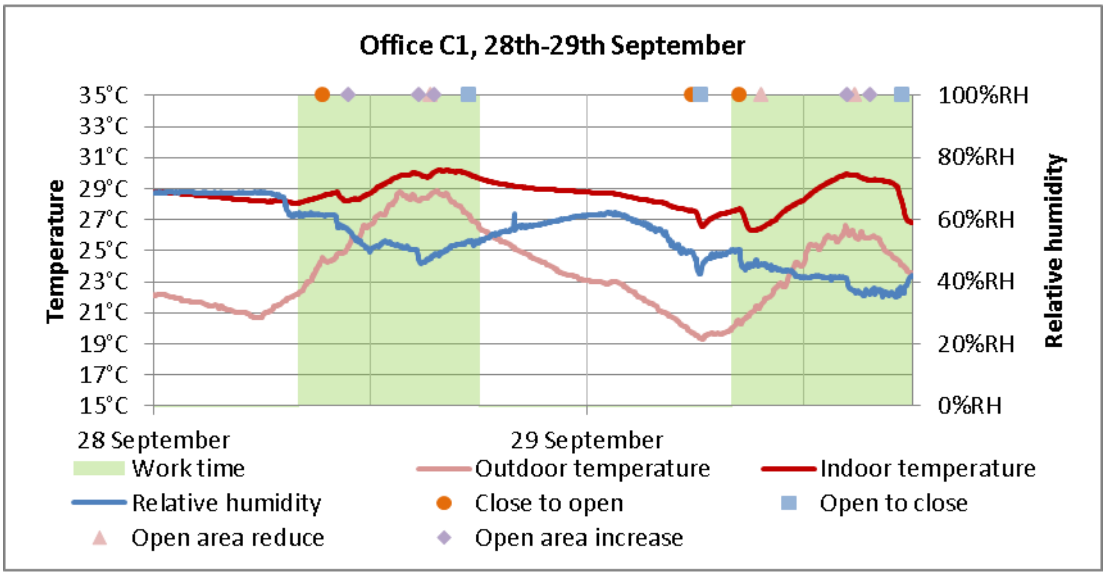


Figure 5.8: Indoor environmental condition in office C1 (SSV) during 28th and 29th of September.

Office C2 was cross-ventilated. The average indoor air temperature was about 1°C lower than C1 and it was more variable. The roller blind was not used quite so often, because there was a cabinet behind the window, so that occupants were sitting in the middle of the office and were some distance from the window. So, controlling the roller blind and window was inconvenient; once the window state had been changed it would last for a long time. Compared with these two cross-ventilated offices, the average air temperature in working hours in office C3 was 0.6°C lower than office

C2. The control of the roller blind and the size of the window's opening may cause the difference.

Although when occupants arrived in the office there was not much difference in the indoor air temperature among these three offices, office C3 controlled its air temperature relatively lower. When the occupants arrived in the office they would first open the window, and then the lower outdoor air temperature would cross the office and take the hot indoor air out of the office, which caused the indoor air temperature to drop. When occupants were disturbed by sunlight, they would low the roller bind and sometimes would make the window opening size smaller. Because the lowered roller blind would cover the opening area, and the incoming air flow would blow up the roller blind; it also influenced the occupant who was sitting near the window. The occupant behaviour in office C3 was quite similar to office B2, and also kept the indoor air temperature in a relatively lower situation. The behaviour of occupants in the office will be discussed in a later chapter. In addition, as for other office buildings, there was a great night-time ventilation potential in office building C.

In office C3, the continuous air flow speed was measured between 16th and 19th of October (Figure 5.9). As for offices A2 and B2, the indoor air temperature dropped with effective air volume flow rate and positive temperature difference. Because the indoor air temperature was much higher than the outdoor, the required air flow rate for cooling was easy to achieve. There was also a small air temperature drop at noon time with a high air volume flow rate, when occupants were back from their break (16th and 17th). Due to the effective opening area changing (from large to small), the air temperature drop trend stopped and continued to rise up.

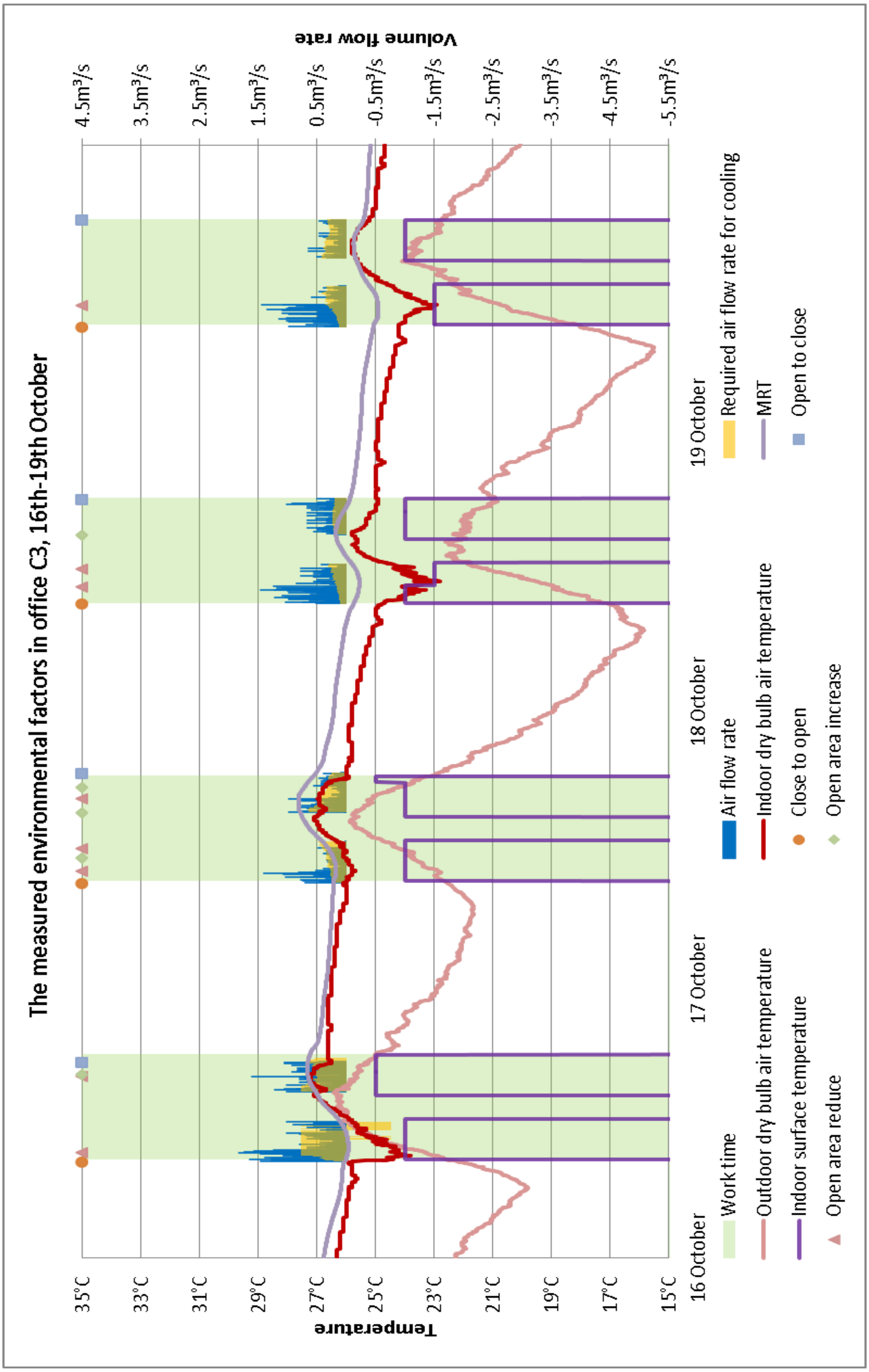


Figure 5.9: Measured indoor temperature and indoor air volume flow rate in office C3 (CV).

However, because of high air flow speed, the small effective opening area would not increase indoor air temperature. In the morning of 18th October, the indoor air temperature dropped 2°C with the air volume flow rate being about 1.5m^3/s, even when the occupants reduced the effective opening size. After the second time reducing the opening size before they left for noon break, the indoor air temperature just started to rise and reached its peak at noon time. When the occupants came back to work in the afternoon and extended the effective opening size, then the indoor air temperature began to decrease. Except for the high air volume flow rate, the lowest outdoor air temperature was 22.5°C, the lowest in these four days, and was 3.3°C lower than the indoor air temperature at noon time. It also boosted the temperature drop in the office. In these four days, the open area reduction was caused by air volume flow rate drops, and most of the time it still achieved a cooling demand, except for 16th. For the remaining three days, the indoor air temperature was still about 2°C higher than the outdoor. So the air flow may have moved into the office through one window and moved out immediately from other windows, and did not pass through the entire room.

The indoor surface temperature on 18th was different from the remaining days. On the other three days, the temperature variations were similar to office B2, stable and the temperature in the afternoon would be higher than the temperature in the morning. But on 18th, the surface temperature in later morning was 1°C lower than early morning and afternoon. This situation may relate to the good natural ventilation condition in the morning, which efficiently cooled down the indoor surface temperature, as for the indoor radian temperature. The mean indoor radiant temperature in working hours was 26.22°C, which was 0.69°C higher than the indoor air temperature. As for office B2, the indoor temperature was difficult to reduce at night, even if the outdoor air temperature had dropped greatly. On the night of 17th, the outdoor air temperature dropped to 7.6°C, but the indoor air temperature was just 1.2°C. Thus, if night time ventilation had been implemented, it could reduce the indoor temperature to a certain extent and provide a cooler indoor environment during the working hours.

5.1.4 Office building D

Office building D had a deep section; three offices were facing different directions. The door on each office remained open during the working hours. According to the building plan, section, and small effective opening area, it seems difficult to achieve cross-ventilation in the office room. However, occasionally the air flow speed around 1m/s could be measured on an opened door; the air flow may come into the measured office and be moved out of the building by one of the behind office rooms or reversed. In addition, the window was never closed in the all three monitored offices during the monitored time, even on the weekend, and the curtain was not used as well. The monitor results are shown in Figure 5.10.

The average indoor dry bulb air temperature during the working hours was 25.1°C in office D1 (SSV), 26.3°C in office D2 (SSV) and 23.9°C in office D3 (SSV). In these three offices, there were no obvious indoor air temperature drops in three weeks, such as when the occupants arrived in the office. This situation only happened in office D1 on the morning of the 29th September. It was continuous until occupants went off duty in the morning. The proper wind direction, inlet and outlet may cause the temperature to reduce. The orientation of the three offices also influenced the indoor air temperature variations and the air flow speed. Office D1 was facing north-East. The indoor air temperature increased faster in the morning, when the sun was rising, then tended to gradually increase and reach the top at noon. Office D2 was facing south-west, so the indoor air temperature reached its peak in the afternoon. The highest air temperature in office D3 was in the afternoon, because the office was facing north-west and would receive direct sunlight in the later afternoon.

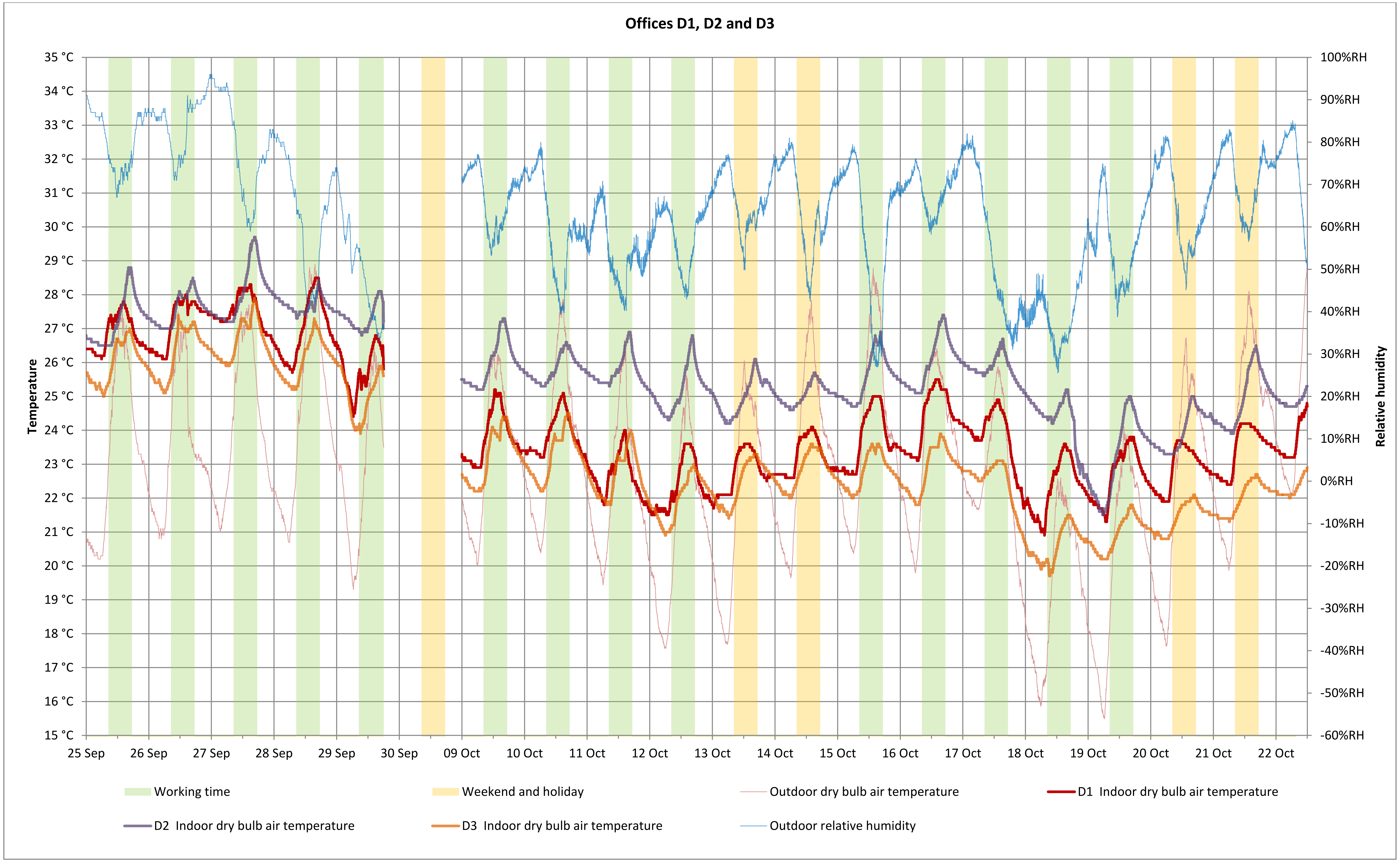


Figure 5.10: Measured indoor dry bulb air temperature and outdoor dry bulb air temperature in office building C.

However, in the first week, the temperatures in the three offices were very close; after a long holiday the temperature in office D2 was much higher than in offices D1 and D3. Office D2 received more heat than two other offices. Because office D1 (facing Southeast) only get direct sunlight in the morning and D3 (facing North-west) only get direct sunlight in the later afternoon. The direct sunlight was effect on office D2 (facing South-west) from later morning to later afternoon. In was clear that the highest daily indoor air temperature in office D2 was occurred just after highest daily outdoor temperature. In the parametric study, it was found that the west-facing office had the hottest indoor temperature. The local building orientation also proved that most of the building was facing south to avoid direct sunlight in the afternoon. Occupants were using curtains to block the direct sunlight and reduce the impact of solar radiation in the afternoon. Because of the large glazing area, closing the curtain has not effect on indoor temperature changing. The closed curtain would block the opening window and may also reduce the indoor air flow rate. During the weekend the door was fully closed; the small opening window could not achieve the cooling purpose, so office D2 was hotter than other offices.

After working hours, the temperature in the three offices gradually decreased, and did not have a temporary indoor air temperature increase. Especially in office D3, it had the lowest indoor air temperature in all monitored office rooms. In the second and third weeks, the indoor air temperature in office D3 was lower than the outdoor air temperature during the working hours, and the maximum indoor and outdoor air temperature was 5.3°C. The indoor air temperature increase was very slow, and the outdoor air temperature had very limited impact on indoor air temperature. It seemed more related to solar radiation. When the outdoor air temperature was dropping in the afternoon, the indoor air temperature was still increasing in offices (e.g. 18th Oct, 19th Oct). In addition, the small effective opening area in an office also restricted the indoor air exchange rate. This situation was similar with offices A1, B2 and C3, which the effective opening area reduced by the occupants. And the indoor air temperature was well controlled.

Compared to the other office buildings, office building D is the only one which had night time ventilation, because the window was kept open in the night. But the impact of night time natural ventilation on indoor air temperature was insignificant in the three offices. On the 18th and the 19th of October, there was a large outdoor air temperature drop in the night; although the indoor air temperature drop rate was higher than other days, the indoor air temperature was still 3.9°C higher than the outdoor air temperature in office D3. The temperature difference rose to 8.9°C in office D2. Thus, the natural ventilation during the night was insufficient in the offices. It may have been due to the thermal inertia of the internal structure which was store a great deal of heat. After the 18th and 19th, the outdoor air temperature was raised which was more than 3℃ higher than 18th and 19th. But the indoor air temperature was just slightly higher than 18th and 19th, especially in office D1 and D3. Besides, the office room had single-side ventilation and the effective opening size was too small, which may be the reason for it being difficult for the indoor air temperature to cool down. And the inertia of the building structure stored great deal of heat and difficult to remove, it also influence indoor air temperature drops. The proper night time natural ventilation strategy was needed to maximise the cooling ability.

The air flow speed on the opening window was measured to assess the impact of natural ventilation on indoor temperature. The measured air volume flow rate and indoor temperature in office D1 from 16th October to 19th October is shown in Figure 5.11. The air flow speed on the opening window in office D1 was the highest in the measured offices. The highest air volume flow rate could reach 2.2m^3/s and the related air flow speed on the open area was 5.5m/s. The average air flow speed was about 2.6m/s. The high air flow speed may be because office building D is a high rise building; when the wind hits the building surface it may move up or down along the building façade, and the open-top hung window was like a wind catcher and would guide the rising air flow to move into the office. The air flow speed measured on the opening window in office D1 was positive, as in most of the time the air volume flow rate could achieve the cooling demand.

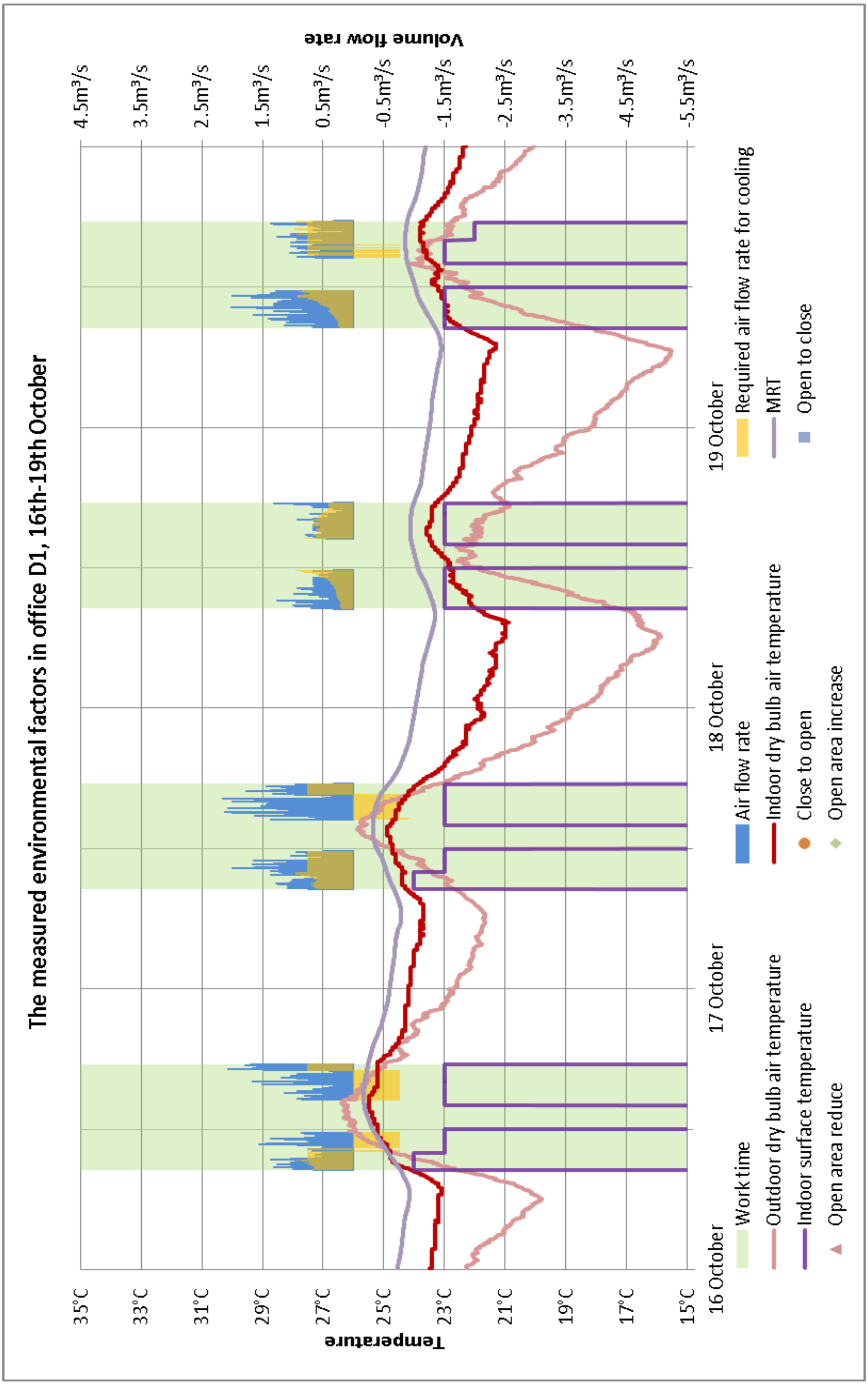


Figure 5.11: Measured indoor temperature and indoor air volume flow rate in office D1 (SSV).

But the high air volume flow rate did not have a significant impact on indoor air temperature. On those four mornings, when the outdoor air temperature was lower than indoor and the air volume flow rate was higher than the required amount, the indoor air temperature was still rising gently. When the indoor air temperature was lower than the outdoor temperature, the high air volume flow rate would move the heat into the office and increase the indoor air temperature. However, the indoor air temperature did not have significant changes, even when the air volume flow rate was much larger than the demand flow rate (e.g., 16th and 17th afternoons). The reason may be that the air flow moving into one opened window was soon driven out, and did not pass through the whole office room, so it only influenced the room near the window. In addition, the temperature of a heavy structure may be quite stable and the temperature was lower than outdoor air temperature in period of day time, and it would cool the incoming warm air and reduce the indoor air temperature increasing rate. According to the indoor air temperature, the rapid increase in the early morning is at the time of sunrise, so solar radiation has more impact on indoor air temperature. The air temperature rapid increase period was close to the time that direct sunlight has influence on the office room.

The indoor surface temperature also showed similar features. The surface temperature in office D1 was unlike the other three offices. The highest temperature was in the morning, especially during the early working hours. For instance, the surface temperature in the early working hours was 1°C higher than the rest of the time on 16th and 17th. On 18th and 19th, the surface temperature was not increasing in the morning; this may relate to the lower indoor air temperature which prevents the surface temperature increasing. Besides, in most of the working hours the surface temperature was quite stable, except for the early morning on 16th and 17th October and later afternoon on 19th, while the rest of the time the temperature was still 23°C. And also, the maximum indoor surface temperature increase and drop was 1°C. The indoor surface temperature seemed to relate to solar radiation. The office would be impacted by direct sunlight in the early morning, which caused surface temperature increase. From noon and during the afternoon the office was opposite to the direct sunlight, and the indoor surface temperature dropped. But the indoor air temperature in the afternoon was higher than the temperature in the morning.

The indoor average mean radiant temperature for these four days during the working hours was 24.3°C and the average indoor air temperature was 23.9°C, the temperatures being close to each other. The daily indoor mean radiant temperature variation was little. The solar radiation in the morning did not have an obvious influence on it. Although the windows were opened at night time, the influence on the indoor air temperature was limited, unless the outdoor air temperature had greatly decreased which may cause the indoor air temperature decrease rate to be higher than other days. For the indoor mean radiant temperature, the impact was even lower.

5.2 Indoor air flow speed and air flow patterns

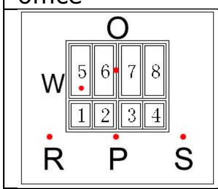
In order to establish the indoor air flow pattern in the office rooms and the effect of window typology on indoor air flow patterns, the results of measured average air flow speed in the offices were analysed. Because the air flow speed on each measurement point was measured at different times and the effective opening area would change, in order to compare each point in an office, the air flow speed on an opening window was assumed as 1, and the internal measured air flow speed was reduced with the same proportion. For example, measured air flow speed on an open window is 2.5m/s and the air flow speed on the desk surface is 1m/s; so, assume the average air flow speed on the open window is 1 and the air flow speed on the desk surface would be 0.4. The results were used to compare the proportion between each point in an office room. About 174,560 data items were recorded in four buildings. The measurement points which are close to the floor and measured air flow speeds are too slow, so they have not been used for analysis.

5.2.1 Office building A

A casement window was used in offices A1 (SSV) and A2 (CV), and the windows were separated into two parts. The big window was on the top and the small window was below the big window. There were more than 14 openable windows in one office. None of the occupants was using the window on the door side. In order to find out the effect on indoor air flow patterns from the door side window, the author suggested using the window on the door side. Also, the door is an important natural ventilation element which could help the office achieve cross-ventilation, but the door might be closed for some reason. In these two offices, occupants only controlled a part of the window, so the window which was opened was recorded.

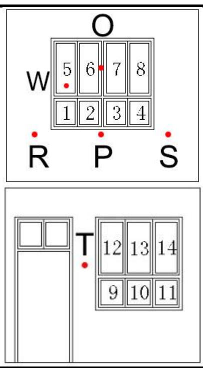
Table 5.1 shows the average indoor air flow speed at different points in offices A1 and A2. The result showed that the indoor average air flow speed in office A1 was too lower and much lower than that in office A2, which could be ignored and will not be used for analysis. The reason was, in most of the monitoring time, office A1 was single-side ventilated as the north-facing door was open but the south-facing window was closed. Occasionally, a gust of wind would raise the indoor air flow speed. And sometimes the occupants would leave the door ajar, so the indoor air flow was still. In office A2, which is cross-ventilated, it had better indoor air flow performance. The average air flow speed on points P, R and S were very close, with point O being the lowest. The better indoor air flow condition can remove internal heat out of the office efficiently, reducing the indoor temperature, and helping occupants achieve thermal comfort.

Table 5.1: The average indoor air flow speed
on different measurement points in offices A1 (SSV) and A2 (CV)
(point W was located at the opened window).

Windows in the office	Office	Point W (m/s)	Point O (m/s)	Point P (m/s)	Point R (m/s)	Point S (m/s)
	A1	0.07	0.05	0.06	0.04	0.04
	A2	1.20	0.48	0.63	0.67	0.69

Occupants would control different windows to satisfy their needs. According to occupant use of window condition, more detailed data are shown in Table 5.2. The measured data at different points on different opening and closing combinations were unified. And the data were compared by proportion; the detailed method was presented in section 4.1.2.

Table 5.2: The proportion of measured internal air flow speed in office A2 (CV) (assume the measuring point W is 1, point W was located at the opened window).

	Windows in the office	Opening window/door	Point W	Point O	Point P	Point R	Point S	Point T Window	Point T Door
Office in building A		1,Door	1	0.11	0.61	0.74	0.19	0	0.58
		4,Door	1	0.13	0.59	0.23	0.72	0	0.57
		1,4,Door	1	0.11	0.64	0.68	0.71	0	0.61
		5,8,Door	1	0.45	0.42	0.48	0.54	0	0.60
		1,8,Door	1	0.18	0.58	0.65	0.58	0	0.58
		1,4,12,13	1	0.14	0.59	0.60	0.63	0.88	0
		5,8,12,13	1	0.50	0.31	0.39	0.37	0.94	0

When window 1 and the door were open at the same time (Figure 5.12), the air flow speed at point R was higher than other points. Point P was slightly lower than point R but much higher than the other measuring points. It showed that the air flow may come in from window 1, pass though point R, and then be moved out of the office from the door. The measuring points O and S were far away from point R, hence the air flow speed at these two points was much lower than that at points R and P. When window 4 and the door were opened, the situation followed the same principle, in that the air flow came in the office from window 4, passed though point S and then moved out from the door. Also, the wind would come in from the door and left from windows 1 and 4.

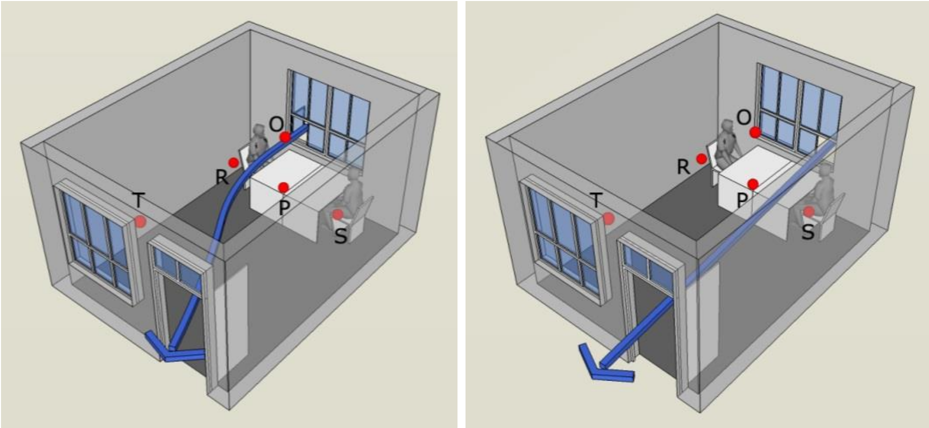


Figure 5.12: Possible air flow path in the office when windows 1 (Left) or 4 (Right) were opened.

When windows 1 and 4 and the door were all opened (Figure 5.13), the air flow speeds measured on points R and S were similar and they were higher than the other points. It showed that when air flow came in from both windows 1 and 4, its path may have moved through points R and S, before moving out of the room from the door. Point P, which is located between points R and S, could be affected by the air flow that passed though points R and S, since the measured speed at point P was slightly lower than points R and S. The air flow speed at measuring point O, which was on the upper part of the room, was very little influenced by opening windows 1 and 4.

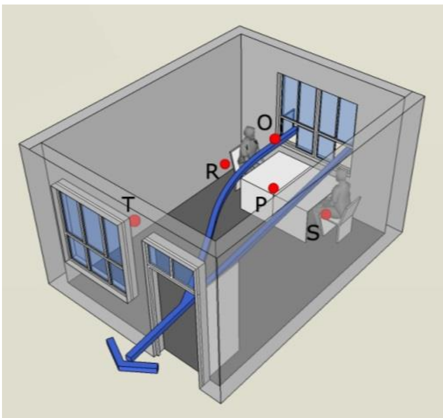


Figure 5.13: Possible air flow path in the office when windows 1 and 4 were opened.

When windows 5 and 8 were opened (Figure 5.14), the air flow speed on each point was close to each other. It was the highest at point S, while point P, which was near the desk surface, was the lowest. However, the air flow speed on point O, which was close to windows 5 and 8, was slightly lower than points R and S. It seemed that most of the air flow went downwards when passing through windows 5 and 8. The possible reason was that the position of the opening door was lower than windows 5 and 8, which caused the air to flow downwards when it came into the office room from windows 5 and 8.

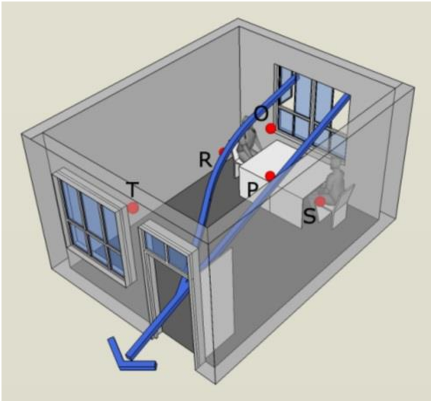


Figure 5.14: Possible air flow path in the office when windows 5 and 8 were opened.

When windows 1 and 8 and the door were opened (Figure 5.15), the air flow speed at point O was the lowest. The average air flow speed at points P and S was close to each other. And point R had the highest air flow speed. It seemed that window 1 had more influence than window 8 on the lower part of the office room near the desk surface level. The behaviour for occupants to control the ambient air flow with window 1 was more efficient than with window 8.

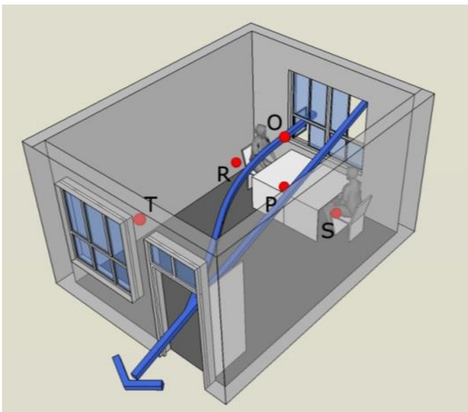


Figure 5.15: Possible air flow path in the office when windows 1 and 8 were opened.

When windows 1, 4, 12 and 13 were all opened (Figure 5.16), and the door was kept closed at the same time, the result showed that the air flow speed measured at points R, P and S was similar, while it was still lower at point O. When windows 1 and 4 were closed, and windows 5 and 8 opened, it can be seen that the air flow speeds at points R and S were still similar, while it was slightly lower than points R and S at point P. However, compared to the result when windows 1 and 4 were opened, the air flow speed was lower than half of the result when windows 1 and 4 were opened. In addition, the air flow speed at point O increased, and was higher than the other three measuring points. Therefore, when windows 5, 8, 12 and 13 were opened, most of the air flow passed through the upper part of the office, and the influence on the lower level of the office was reduced, which caused air flow speed to drop down at points R, P and S.

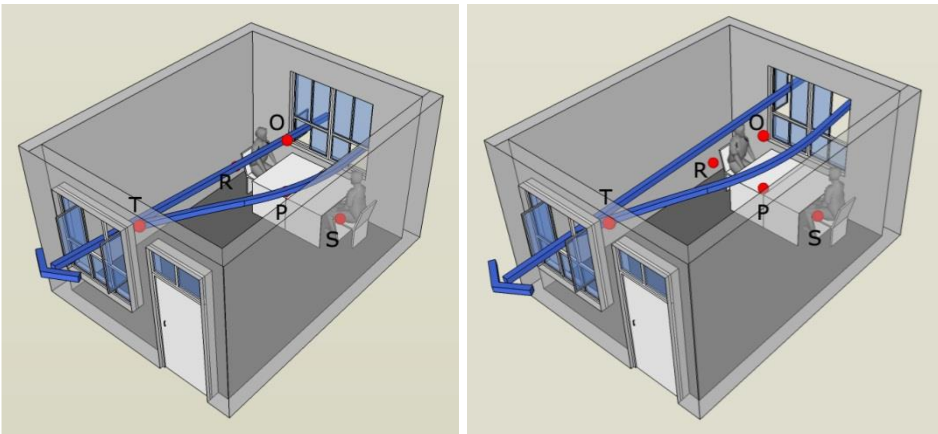


Figure 5.16: Possible air flow path in the office when windows 1, 4, 12 and 13 were opened (Left), and when windows 5, 8, 12 and 13 were opened (Right).

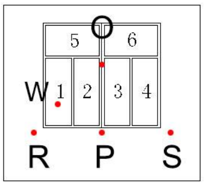
To sum up, when the big top window opened, there was more influence on point O than other measured points. However, the result was opposite when the small window was opened. It is easy to explain that there was more influence when the air flow came from a higher part of the office. And points P, R and S were more active when the small window on the same level was opened. On the other side of the office, when the door was closed while windows 12 and 13 were opened, it would reduce the impact of air flow on points P, R, S. Therefore, in office A2, the separated windows could influence the indoor upper and lower level of air flow pattern. And also, the behaviour of closing/opening windows or doors could change the air flow direction, so that occupants could use windows to control the indoor air flow path. Besides, the window on the upper part was just on the top of the operation level. Opening the big window on the top and closing the small one on the bottom could reduce the impact of air flow on occupants sitting beside the window. Therefore, occupants could use the window to adjust the indoor air flow pattern to achieve comfort.

5.2.2 Office building B

In office building B, casement and top-hanging windows were used. Windows were separated into two parts; the two top-hanging windows were on the top and four casement windows were below them. On the corridor side there was a horizontal pivot window and a top light window which was not used. In offices B1 and B3, the author suggested using the window on the corridor side. The air flow speed measurement was taken in three offices in office building B (B1, B2 and B3).

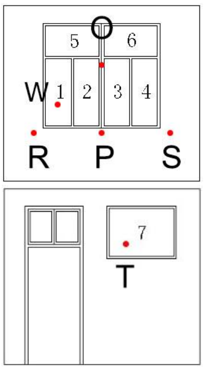
Table 5.3 shows the average indoor air flow speed at different points in offices B1, B2 and B3. The result showed that the indoor average air flow speed in office B2 was lower than that in offices B1 and B3. The reason was, the natural ventilation in office B2 was hybrid; when it was single-side ventilated, the indoor air flow speed was very low and it would influence the average values. In offices B1 and B3, which were cross-ventilated, it had better indoor air flow performance. When the door was closed, the opened pivot window could still make the office room cross-ventilated. But the top light window was never used. The average air flow speed on points P, R and S were very close, point O being the lowest. In office B1, point P had the highest air flow speed, and in office B3 the highest point was S. The difference may be caused by the frequency of occupants using different parts of the window.

Table 5.3: The average indoor air flow speed on different measurement points in offices B1 (CV), B2 (SSV/CV)) and B3 (CV) (point W was located at the opened window).

Windows in the office	Office	Point W (m/s)	Point O (m/s)	Point P (m/s)	Point R (m/s)	Point S (m/s)
	B1	1.10	0.53	0.87	0.80	0.74
	B2	0.59	0.30	0.53	0.45	0.45
	B3	1.12	0.54	0.76	0.82	0.85

In office building B, except for the top light window, the top-hanging window on the south-facing window was not used as well. According to occupant use of window condition, only windows 1 and 4 were used. Detailed data are shown in Table 5.4.

Table 5.4: The proportion of measured internal air flow speed in office building B (point W was located at the opened window).

	Windows in the office	Opening window/door	Point W	Point O	Point P	Point R	Point S	Point T Window	Point T Door
Office in Building B		1,Door	1	0.46	0.73	0.81	0.22	0	0.66
		4,Door	1	0.49	0.71	0.20	0.84	0	0.64
		1,4,Door	1	0.51	0.74	0.79	0.82	0	0.70
		1,4,7,Door	1	0.61	0.77	0.83	0.85	0.80	0.79
		1,7	1	0.59	0.62	0.81	0.19	0.93	0
		4,7	1	0.60	0.63	0.20	0.78	0.90	0
		1,4,7	1	0.63	0.64	0.80	0.78	0.95	0

When window 1 and the door were opened (Figure 5.17), the largest point was R; point P was slightly lower than point R. Point S was the lowest one. Therefore, open window 1 had more impact on points R and P, the air flow mainly passing through points R and P in the office. When window 4 and the door were opened, the situation was the opposite; point S had a larger average air flow speed than point P, while point R was the lowest. In these two conditions, at point O it was very similar. Open windows 1 and 4 had the same influence on indoor air flow at point O. Besides, the figure for point O was lower than point P, which just below point O; the incoming air flow in the office had more impact on the lower part of the room than the upper area.

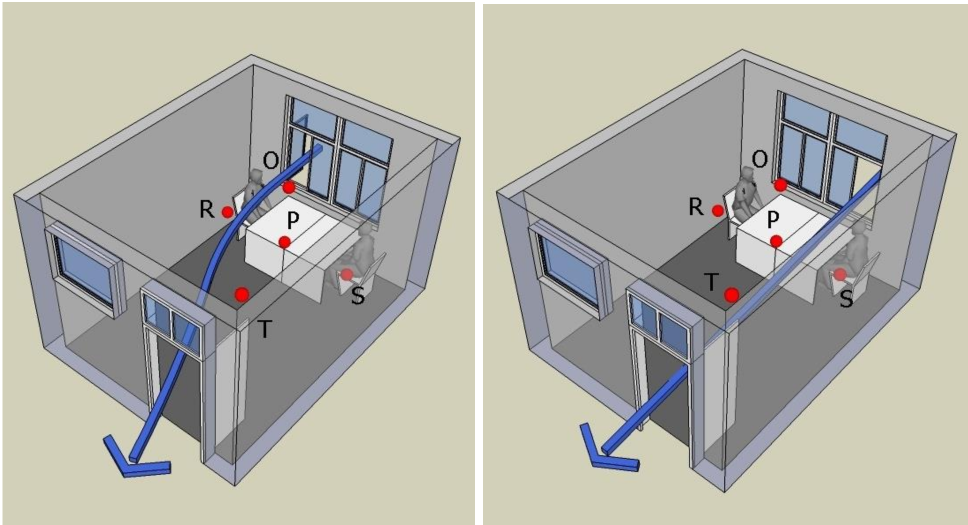


Figure 5.17: Possible air flow path in the office when window 1 and the door were opened (Left), and when window 4 and the door were opened (Right).

When windows 1 and 4 and the door were open together (Figure 5.18), the average air flow speed on points R and S were very close to each other, with the figures at 0.79 and 0.82. Point P was slightly lower than points R and S. Compared to the last two cases, the air flow speeds were very similar. In those situations, the air flow speed at point P was quite steady. When window 7 was open as well, it increased the indoor air flow speed to a certain extent; the air flow speed at each point had slightly increased. Point S had the largest air flow speed, which was 0.85, then point R (0.83), both points reaching their largest average air flow speed compared with other situations, as well as point P.

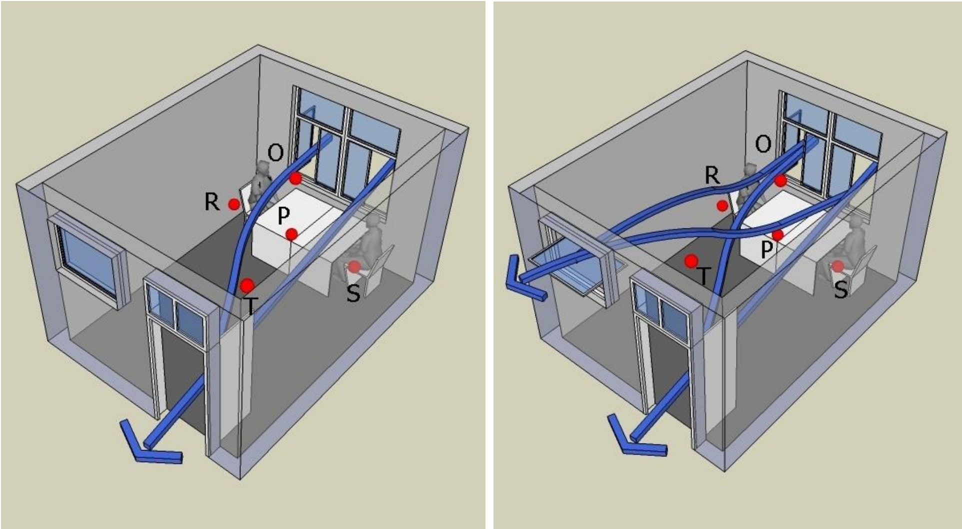


Figure 5.18: Possible air flow path in the office when windows 1 and 4 and the door were opened (Left), and when windows 1, 4, 7 and the door were opened (Right).

Point T (when the door was open) also had the highest air flow speed. The opened window 7 helped to increase the air flow speed on an opened door. It can be understood that when only window 1 or 4 was open, the lower air flow speed on the door side was related to a small opening area between indoor and outdoor which would limit the indoor air flow rate. When both windows 1 and 4 were opened, the air flow speed on an opened door should be higher than that when window 7 was opened, because extending the effective opening area would reduce the air flow speed when the volume flow rate was still. However, the measured result is the opposite. This may be because opening window 7 increased the effective opening areas on the partition wall and the air flow could pass through the office much easier; this could help raise the indoor air volume flow rate and air flow speed. Alternatively, if the air flow was coming from both directions, a stream of air flow would pass through the open door to the other side, and the air flow from the other side of the room would pass through window 7. Although the air flow speed at point O was larger than previous conditions, it was still the lowest air flow speed in the room. As the air flow speed increased at point P was related to open window 7, the air flow would pass through the upper part of the room.

When the door was closed, windows 1 and 7 were opened (Figure 5.19). The air flow speed on window 7 was close to window 1. In the office room, the largest air flow was at point R which was close to opening window 1, and in the middle of the air flow path. The air flow speed at points P and O were close, and point P was slightly higher than point O. The small air flow speed occurs at point S which was far away from a possible air flow path. When windows 4 and 7 were opened the situation was opposite at points R and S. At points P and O, the situation was the same as the previous one but the air flow speed was slightly higher; this may be because opening window 4 has more influence on points P and O. Window 7 was on the diagonally opposite side of window 4; the air flow would pass through the room diagonally.

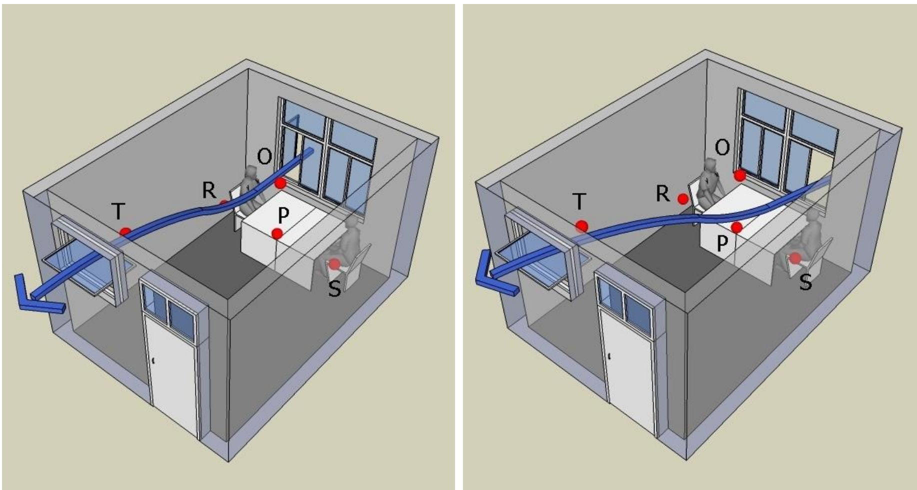


Figure 5.19: Possible air flow path in the office when windows 1 and 7 were opened (Left), and when windows 4 and 7 were opened (Right).

When windows 1, 4 and 7 were opened, point R had the largest air flow speed, and then the second one was at point S. Points P and O were very close, compared to the previous situations when point O had the largest air flow speed. It can be found on Table 5.4 that, when window 7 was opened, the air flow speed at point O was larger than when the window was closed. Changing the opening position could influence the indoor air flow path and the air flow speed at different parts of the room. Opening window 7 raises the indoor air flow path and increases the air flow speed on the upper part of the room. Oppositely, the air flow speed at point P was reduced by closing the door and opening window 7. Because point P was lower than point O, opening window 7 would reduce the impact of air flow on the lower part of the office. Although points R, S and P were at the same height, changing opening height seemed to have a very limited effect on points R and S. The reason probably was that points R and S were close to the opening windows 1 and 4.

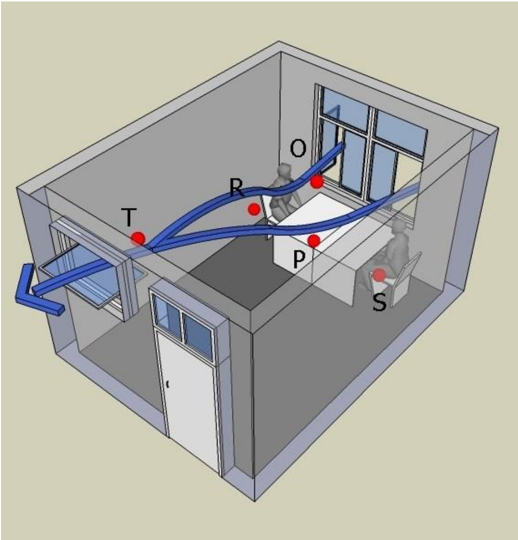


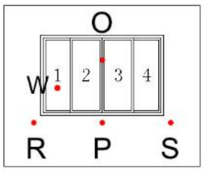
Figure 5.20: Possible air flow path in the office when windows 1, 4 and 7 were opened.

To sum up, in office building B, only windows 1 and 4 were used by occupants on the window side. And points R and S were mainly influenced by those two windows. The air flow speed on points P and O were more related to window 7 and the door on the partition wall. Closing window 7 and opening the door could raise the air flow speed at point P and reduce the air flow speed at point O; if opening window 7 and closing the door, the situation is the opposite. When window 7 and the door were both opened, the indoor measurement point could achieve its largest speed. Opening the door had more influence on points R, P and S. And air flow seemed to go downwards when it moved into the office. In the situation when window 7 and the door were both open, the air flow speed at point P was the largest and the air flow speed at point O was lower than when the door was closed and window 7 was opened. A similar result can be found in office building A. So, changing the location of the opening area can adjust indoor air flow patterns and air flow speed. Also, increasing the opening area on the partition wall and reducing the baffle in the office can raise the indoor air flow speed as well.

5.2.3 Office building C

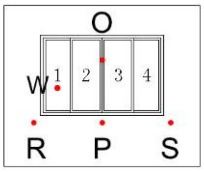
In office building C, there were four sliding windows in the office room, and on the corridor side there was no other openable vent designed, except a door. So, opening the door was the only method to achieve cross-ventilation in the office room, while the opposite office should keep the door and window open. Table 5.5 shows the average indoor air flow speed at different measurement points in three offices. For most of the time, the door in office C1 was closed or ajar, so it was single-side ventilated and the indoor air flow speed was much lower than offices C2 and C3, which were cross-ventilated. The results show the indoor air flow speed at each point were quite close and the average indoor air flow speed in office C3 was slightly larger than office C2. In office C2, point S had the largest average indoor air flow speed and in office C3 it was the point R; this may be because the difference of control of the window in the two offices. In these two offices, point P was larger than point O; the lower part of the office had a higher air flow speed.

Table 5.5: The average indoor air flow speed on different measurement points in offices C1 (SSV), C2 (CV) and C3 (CV) (point W was located at the opened window).

Windows in the office	Office	Point W (m/s)	Point O (m/s)	Point P (m/s)	Point R (m/s)	Point S (m/s)
	C1	0.20	0.09	0.10	0.13	0.13
	C2	1.05	0.51	0.56	0.68	0.72
	C3	1.10	0.52	0.57	0.72	0.72

In office building C, windows 1 and 2 can overlap, as well as windows 3 and 4. Opening windows 2 or 3 were considered as the same condition. There were four window-opening combinations in the office. The detail of window use conditions and the proportion of indoor air flow speeds are shown in Table 5.6.

Table 5.6: The proportion of measured internal air flow speeds in office building C (point W was located at the opened window).

	Windows in the office	Opening window/door	Point W	Point O	Point P	Point R	Point S	Point T Door
Office Building C		1,Door	1	0.58	0.61	0.83	0.26	0.66
		4,Door	1	0.60	0.63	0.28	0.86	0.67
		1,4,Door	1	0.63	0.68	0.81	0.83	0.70
		2,3, 2and3,Door	1	0.87	0.84	0.56	0.49	0.68

When window 1 or window 4 was opened (Figure 5.21), the largest indoor air flow speed was the closest measurement point, which was point R for window 1 and point S for window 4. For each point, the results relative to window 1 or 4 were very close. So, opening window 1 or 4 had a very similar impact on indoor air flow speed, and the air flow speed on points R and S was the opposite. When both windows 1 and 4 were opened (Figure 5.22), the proportion of indoor air flow condition was similar to the previous situation, but the air flow speed was slightly higher. Point S had the largest air flow speed and was very close to point R, but the figure of the air flow speed for these two points was close to the previous situation when window 1 or 4 was open. Opening both windows 1 and 4 could raise the indoor air flow speed at points O, P and T, but would not have much influence on points R and S. In addition, the air flow speed at point P was slightly higher than point O; the air flow seemed to have more impact on the lower point.

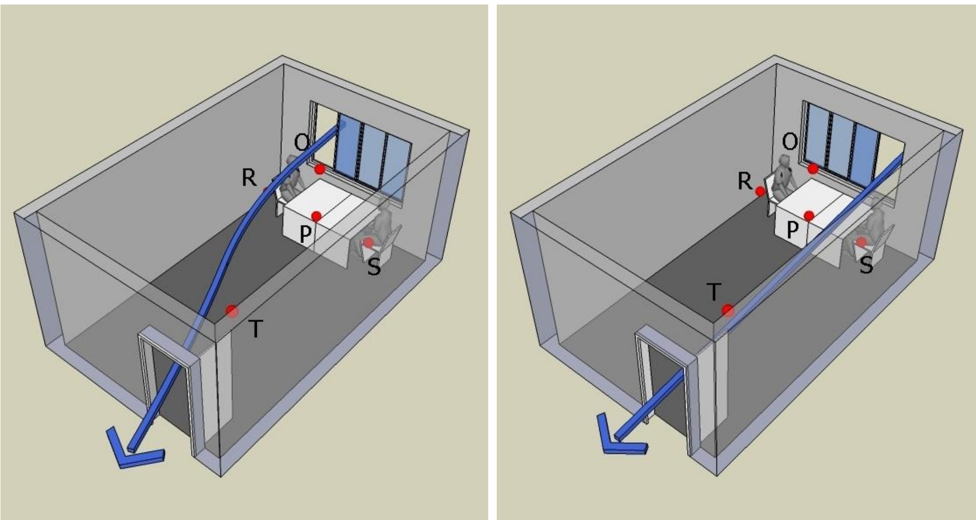


Figure 5.21: Possible air flow path in the office when window 1 and the door were opened (Left), and when window 4 and the door were opened (Right).

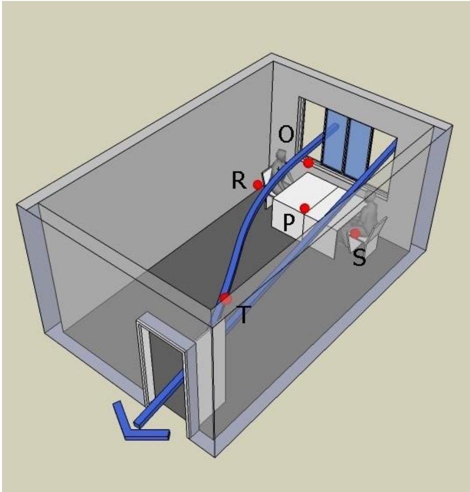


Figure 5.22: Possible air flow path in the office when windows 1 and 4 and the door were opened.

When the middle part of the window was opened (Figure 5.23), the air flow speed at points O and P increased at the middle of the office. At these two points, the air flow speed was very close and point O was slightly larger than point P. Because point O was just behind windows 2 and 3, the air flow speed on points R and S had decreased compared to the previous situation (when windows 1 and 4 were both opened), and point R was larger than point S. The difference between these two points may relate to the direction of incoming air flow or the frequency of opening window 2 being more than window 3 in three offices, which could cause the air flow to pass through point R more frequently and with a relatively higher air flow speed than point S.

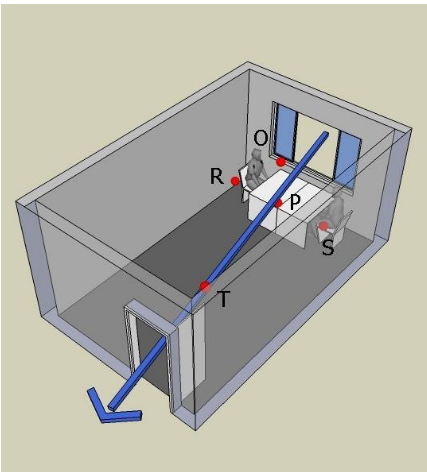


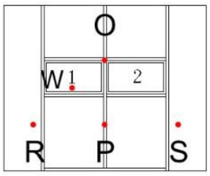
Figure 5.23: Possible air flow path in the office when windows 2 and 3 and the door were opened.

To sum up, in office building C, using window 1 or 4 had a significant impact on air flow speed at points R and S. At this situation the air flow speed at point P was larger than point O. Opening window 2 or 3 would relate to air flow speed increasing at points O and P. And the air flow speed at point O was higher than point P. Synthesising these two situations, the influenced area on the lower part of the air flow was larger than the upper part, and the air flow speed on the upper part was faster than the lower part. The dispersal shape of incoming air flow may be like a trapezium. In addition, when the middle part of the window was open, the incoming air flow direction would influence the air flow speed at points R and S.

5.2.4 Office building D

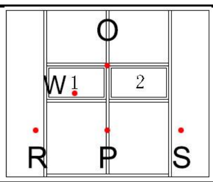
In office building D, each office room had two top-hung windows. Different from other measured office buildings, the desks in these three offices were not close to the window. The measurement points in the office rooms were not changed. The results are shown in Table 5.7. The indoor air flow speeds in offices D1 and D3 were larger than office D2; this may relate to the location of the office room and the wind direction. Because, at the measuring period, the prevailing wind direction was from the north-east (Section 4.3) and offices D1 and D3 were facing north-west and south-east, but office D2 was facing south-west and at the leeward side (Section 4.2). In addition, in office D2, a curtain was used to block the direct sunlight and it covered half of the opening area. In these three offices, the average air flow speed on the window was much larger than the speed in the office. In the office room, the average air flow speed at point O was much larger than the remaining points. And the average air flow speeds at points P, R and S were too slow; none of them was above 0.2m/s, so they can all be ignored.

Table 5.7: The average indoor air flow speed on different measurement points in offices D1 (SSV), D2 (SSV) and D3 (SSV) (point W was located at the opened window).

Windows in the office	Office	Point W (m/s)	Point O (m/s)	Point P (m/s)	Point R (m/s)	Point S (m/s)
	D1	2.63	0.99	0.18	0.18	0.18
	D2	1.31	0.52	0.11	0.11	0.11
	D3	2.47	0.96	0.18	0.16	0.16

The top-hung windows in three offices did not change state during the monitoring time; they were kept open all the time, even at off-duty time (Table 5.8). The window state was simpler than other office buildings. Point O had the largest indoor average air flow speed. It seemed that when the air flow moved into the office room and then rose up, it may be related to the window type (Figure 5.24). The opened top-hung window acted like a wing, and would guide the air flow direction. The same situation was found in the pilot study. The office room with a top-hung window had more effect on the air flow on the upper part of the office rather than the lower part of the office. So, occupants would not be influenced by incoming air flow. Although, based on the building plan, it was difficult for the office room to achieve cross-ventilation, air flow speed could be measured intermittently on opening the door. Sometimes the air flow may also been moved out of the office immediately after it moved into the office. Therefore, a top-hung window had more impact on the upper part of the office. If well designed, it may be able to move the hot air at the upper part of the office more efficiently than other window types.

Table 5.8: The proportion of measured internal air flow speed in office building D (point W was located at the opened window).

	Windows in the office	Opening window/door	Point W	Point O	Point P	Point R	Point S	Point T Door
Office in Building D		1,2,Door	1	0.39	0.07	0.07	0.07	0.19

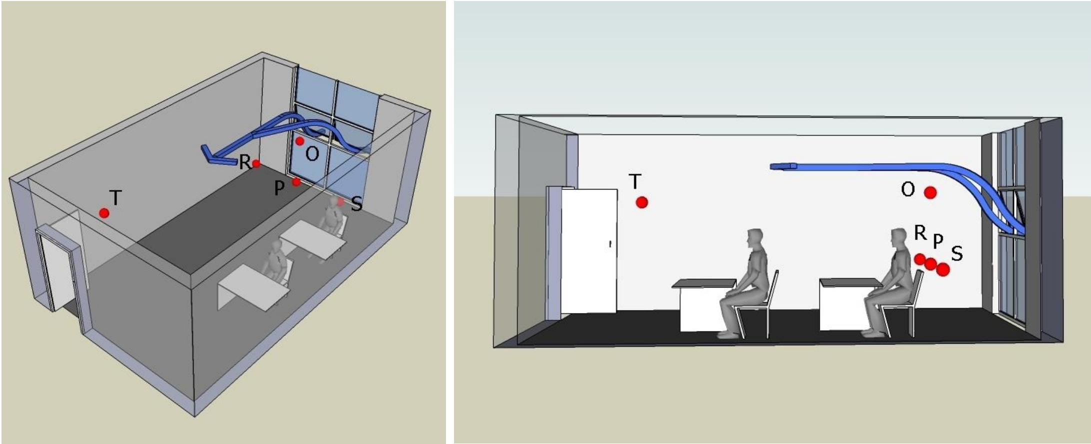


Figure 5.24: Possible air flow path in the office
when windows 1 and 2 and the door were opened.

5.3 Discussion and conclusions

Among these twelve offices, during working hours, there were five cross-ventilated offices, six single-side ventilation offices and one hybrid ventilated. In the cross natural ventilated offices, the indoor air temperature variation was larger than a single-side ventilation office. Office A2 (CV) had the largest indoor air temperature variation than other offices, and during the working hours the indoor air temperature was very close to the outdoor air temperature. It had the best natural ventilation conditions. In the remaining cross-ventilated offices, the indoor air temperature was higher than the outdoor air temperature all day long; the heat could not be moved out of the building as efficiently as office A2. It was related to a small opening area in the office, caused by occupant behaviour. But in the cross-ventilated offices, there were significant indoor air temperature drops at occupant arrival time. The temperature would decrease until it became close to the outdoor air temperature. It proved that cross-ventilation can efficiently reduce the indoor air temperature. The positive indoor air volume flow rate was the main stimulator.

Some offices which controlled the solar radiation and natural ventilation achieved a better indoor air temperature during the working hours. The average indoor air temperature during working hours was lower than a cross-ventilated office. In office A1 (SSV) which was single-side ventilated for the majority of the time, the average indoor air temperature in working hours was just 0.45°C higher than a cross-ventilated office, and in most of the day the highest daily indoor air temperature was lower than the cross-ventilated office. Office B2 (SSV/CV), which had combined cross-ventilation and single ventilation, achieved better indoor air temperature than other offices in the same building. It had the lowest working hours average indoor air temperature in the office building. In office C3 (CV), the situation was similar to office B2 (SSV/CV) compared with the other offices in the building.

All these three offices had very similar characters. First, the roller blind was used quite often; in office A2 it fully covered the window on both windows. In the other two offices, the roller blind was used during the working hours, according to occupant behaviour. It can reduce the solar radiation to a certain extent. Second, the natural ventilation was controlled in the office, especially in offices B2 and C3. The office was cross-ventilated in the early morning when occupants arrived in the office and at the same time the outdoor air temperature was lower than the indoor. Cross-ventilation in the office room can reduce the indoor temperature more efficiently. In the later morning, the roller blind was used; it would block part of the opening area and influence air flow moves in and out of the office. In addition, the in-coming air flow may have blown the roller blind and disturbed the occupant. It would cause occupants to decrease the opening area to reduce the impact of air flow on the roller blind and the air flow itself may also impact the occupant to reduce the opening area as well. Because these three buildings were far away from main road, the opening area reduce would not cause by noise. The reduced opening area would drop the air exchange rate in the office. At the same time, the outdoor air temperature was gradually increasing and becoming higher than the indoor air temperature. The reduced indoor air exchange rate actually reduced the indoor air temperature increasing speed. So, maximum the indoor air exchange rate, when outdoor air temperature was lower than indoor temperature and reduce the air exchange rate when outdoor air temperature was close or higher than indoor air temperature can reduce highest indoor air temperature and control the indoor air temperature relatively low. Also, block solar radiation was necessary.

In all these four office buildings, there was great night time ventilation potential. During the night, when the office was fully closed, the thermal inertia of the building structure influenced the indoor temperature drops. The heat loss in office building A was faster than other office buildings; the indoor air temperatures in the other three offices were quite stable, and the indoor air temperature decrease was about 2°C during the night. Especially in office building C, the office with a relatively lower air temperature would increase after working hours and the air temperature in each office would be very close in the next morning. The thermal performance of the building structure seems to dominate the indoor temperature variations in the night. So, if the building could be night time naturally ventilated, it would help reduce the indoor temperature in the next morning.

Although there was a large temperature gap between indoor and outdoor during the night time, the cooling effect was very limited if the building had not had a proper night time natural ventilation strategy. Office building D was an example. The small opening area restricted the heat moving out of the office room. In office buildings A and B, if the lighting window above the door could be opened at night, it would help the office room to achieve cross-ventilation. All these four office buildings had a security system and a twenty-four hour security guard, so there should not be security issues. In office building B the condition may be more suitable for night time ventilation. Because the upper part of the window on the south-facing window was the top-hung type, it could prevent the rainwater splashing in to the office. Thus, the window typology should be considered for different natural ventilation strategies.

Furthermore, the indoor surface temperature and indoor radiant temperature in the four offices was quite stable. The daily surface temperature variation in office A2 was 2°C and it was 1°C for the other offices. The indoor surface temperature was more close to radiation temperature. In the three south-facing offices, the surface temperature in the afternoon would be higher than the temperature in the morning. In the north-east facing office, the high indoor surface temperature occurs at early morning when the sun rises.

According to occupant controlled different windows, the indoor air flow patterns varied with different influences on different areas of the office. The room area between the inlet and outlet would have more impact by air flow than other areas. In office buildings A and B, the left and right side of the window were mainly used, so the air flow mostly impacted the left and right areas of the office. But the door was on the one side of the office which acted as an air vent in the office; it would impact the indoor air flow directions, especially when the air flow was coming from a diagonal direction.

There were more opening options in office building A; on the south-facing window, opening the lower part of the window could have more impact on the working area than the window on the higher part. Closing the door and opening the higher part of the window on the other side of the office could keep the air flow passing through the upper part of the office and just above the occupants when they were sitting near the table. When the door was open, it would pull the air flow downwards and influence the low part of the office. The situation was the same in office building B. Only two windows were used on the south-facing window. By controlling the window on the corridor side and the door, it could adjust the indoor air flow patterns and speed. When the door was opened, it had more impact on air flow at the low part of the offices, and when opening the corridor side window the situation was the opposite. If both were opened, the air flow was inclined to move downwards. This may because the door's opening area was much larger than the window and less resistance. Perhaps, the door's discharge coefficient may larger than the window's, the air flow can path through the opening door much easier than window. Besides, the position of the door was lower than window, so in the office, opening the door would pull the air flow downwards.

In office building C, the combination of opened windows was less than office buildings A and B. Controlling windows could adjust indoor air flow on the left, middle and right parts of the offices. When the middle of the window was opened, the indoor air flow speed on the left and right sides would be influenced by wind direction. If wind direction was from right to left, then the air flow speed on the left side of the office would be higher than on the right side. In office building D, the incoming air flow had very limited impact on the area where occupants sat. The air flow was moving to the upper part of the office room.

Therefore, the opening location, opening size and window types had great impact on indoor air flow patterns and the air flow speed on different parts of the office. According to different natural ventilation strategies and requirements of indoor air flow patterns, different windows should be selected to achieve the demand and help occupants to adapt to the indoor environment and adjust personal comfort.

According to measured results in these twelve offices, the indoor air temperatures varied in the comfort range in most of working hours. It seemed that the indoor conditions were acceptable. And in the cross-ventilated office, as the indoor air flow speed was positive, occupants used windows to control indoor air flow pattern and air flow speed which may improve their comfort perception. In the next chapter, the occupants' perception results would be presented. It would be found that whether occupants felt comfort or not in these measured offices.

6 Occupants' Perception

This chapter aims to establish the occupants' perception of thermal comfort in the selected four office buildings in a hot summer and cold winter climate condition. Measured value for indoor air temperature and relative humidity results were plotted into a psychrometric chart, where occupants' comfort perception votes were used to identify the thermal comfort zone. This was then compared with Givoni's comfort zone and ASHRAE 55 adaptive comfort zone.

In these buildings, the occupants were mainly doing office work during the monitored time. Their metabolic rate was assumed to be steady, and considered as light activity, and the met rate was adopted as 1.2met. Clothing level was also assumed constant in each season. In summer occupants wear summer clothes (i.e., a short-sleeved shirt and thin trousers for males, and a short-sleeved shirt and a skirt for females), so the clothing level was considered to be 0.39clo. In some occasions, the outdoor air temperature dropped to 15.5℃ and the occupants wore a long-sleeved shirt or light jacket, so that the clothing level was considered to be 0.55clo. According to De Dear's (1997) equation for neutral temperature, if 80% of the votes are feels satisfactory, then the neutral temperature variation was ± 2.5°C. So the comfort temperature in the monitoring place was calculated as between 24.8°C and 29.8°C in September and between 23.4°C and 28.4°C in October.

6.1 Office building A

The measured indoor air temperature in offices A1 (SSV) and A2 (CV) was presented in Chapter 4. The measured average mean indoor radiant temperature was 24.93°C in office A2, which was 0.25°C higher than the average indoor air temperature. But during the working hours the mean indoor radiant temperature was 0.03°C lower than the average indoor air temperature. So it was very close to the indoor air temperature and would not have significant influence on occupant thermal comfort. Consequently, the indoor air temperature will be used for analysis.

According to Givoni's (1998) comfort temperature, whereby dry bulb air temperature was between 20°C and 29°C, the indoor air temperature in working hours in offices A1 and A2 varied in the area (Figure 6.1). Based on the indoor air temperature range, there would not be any discomfort problem in these offices. In order to identify more details of the indoor environment, the data were plotted into a psychrometric chart with Givoni's comfort zone (Figure 6.2 and Figure 6.3).

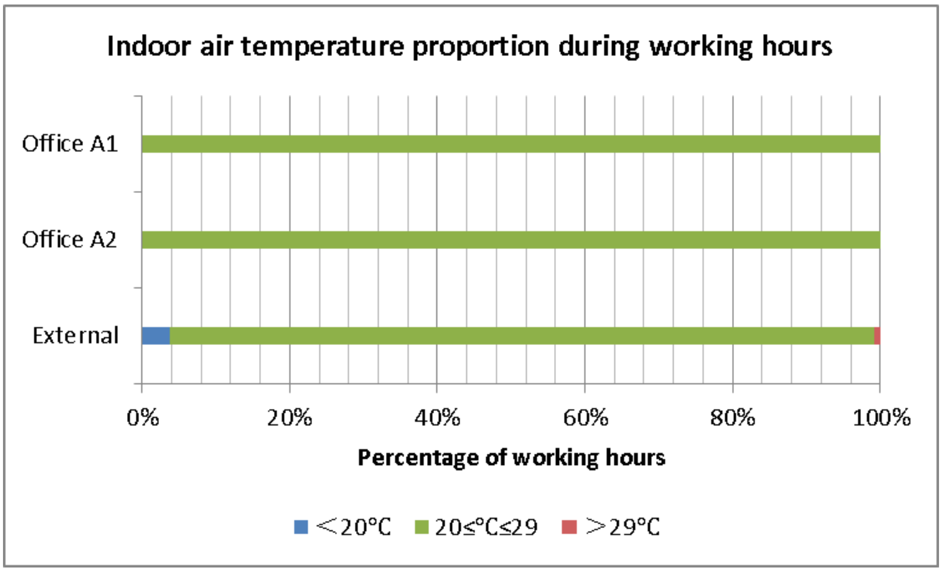


Figure 6.1: The dry bulb air temperature variation in offices A1 (SSV), A2 (CV) and outdoor, during the working hours.

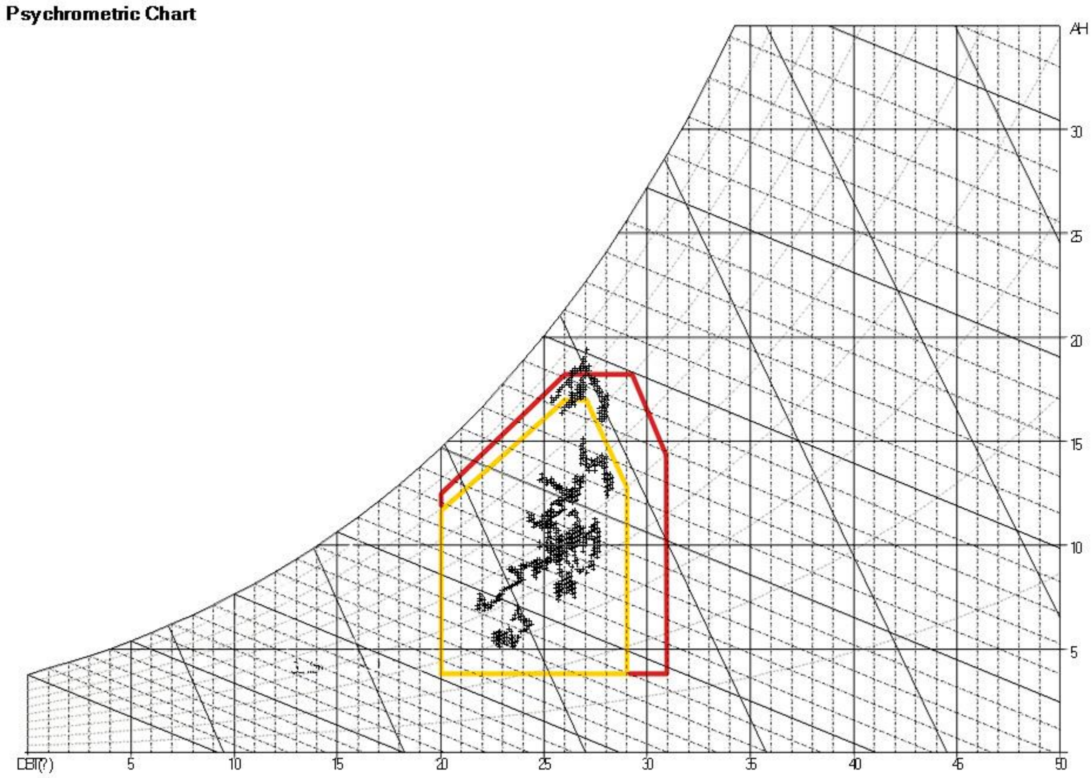


Figure 6.2: The psychrometric chart for office A1 (SSV).
(Yellow: still air condition, red: air flow speed about 1.5m/s).

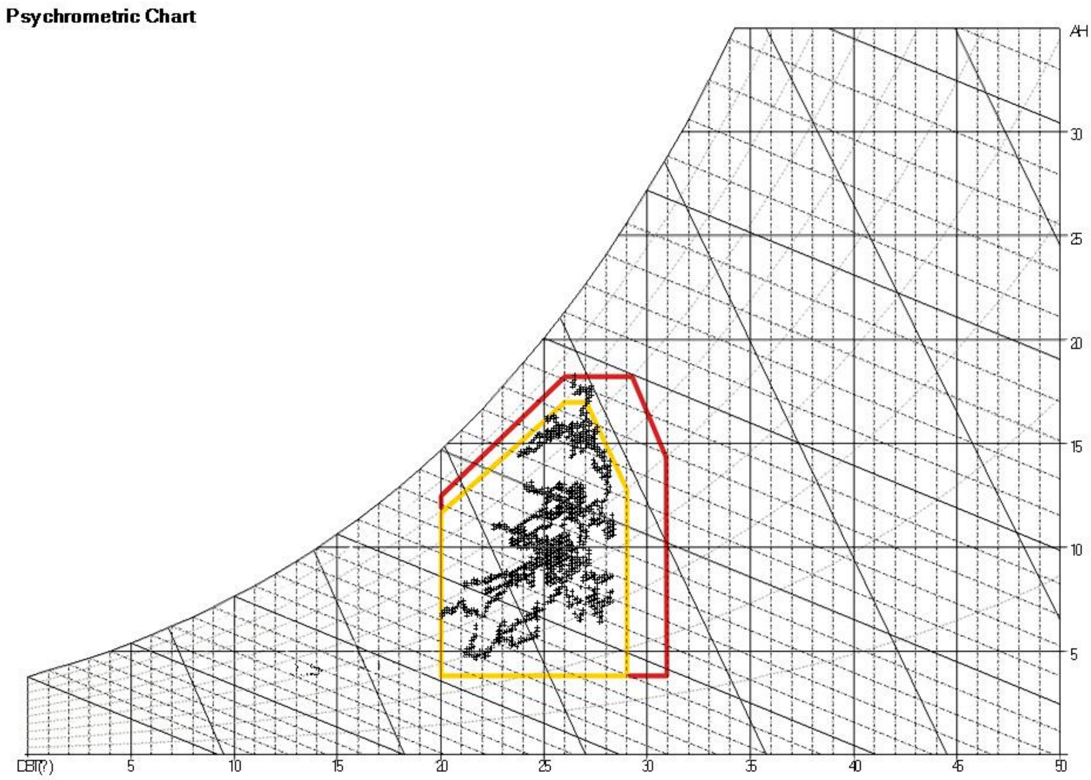


Figure 6.3: The psychrometric chart for office A2 (CV).
(Yellow: still air condition, red: air flow speed about 1.5m/s).

According to the psychrometric chart, the indoor dry bulb air temperature range in office A2 was wider than that in office A1, which was similar to the indoor air temperature curve chart. Although the highest daily indoor air temperature in office A2 was higher than that in office A1, the indoor air temperature was still in the comfort zone. In addition, the indoor relative humidity and absolutely humidity in office A1 was higher than that in office A2, which caused the indoor environmental condition in office A1 to be out of the comfort area in some of the working hours, even out of the extended comfort zone. In the majority of time the occupants in offices A1 and A2 would feel comfortable, even when the indoor air flow speed was nil. The occupants in office A2 would have more comfort time than in office A1. However, whether occupants feel comfortable or not, can only be judged for definite based on occupants' voted perception.

6.1.1 Thermal comfort perceptions in the office A1

The thermal perception vote result in office A1 (SSV) (included 2 voters and 480 votes) is shown in Figure 6.4. It can be seen that, in this offices, all votes were between -1 (Cool) and 1 (Warm), and slightly inclined to 1. As more votes were located on neutral and point 1, occupant thermal sensation varied between cool and warm, which was acceptable in working hours. When the thermal sensation vote was combined with the comfort sensation vote results, which was equal to or larger than 0 (occupant feels neutral or comfortable), the thermal sensation vote result showed that in 88% of working hours occupants felt comfortable to indoor temperature in office A1.

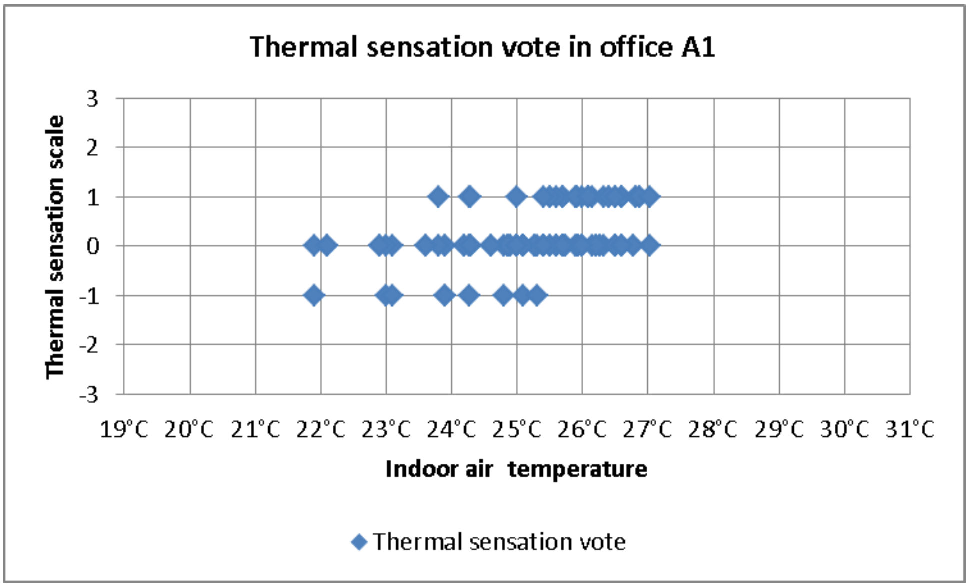


Figure 6.4: Thermal sensation vote in office A1 (SSV) during the working hours in the monitored period.

Relative humidity had a significant impact on occupant thermal comfort. High humidity would restrict the skin's evaporation and reduce heat dissipation from the skin, while low humidity would dry out the skin and cause the discomfort. Nevertheless, the relative humidity would lose its impact when it was between 30% and 70%, then occupants would not feel the difference (Dear et al, 1991., ISO EN 7730, 1994 and Nicol, 2004). Based on relative humidity range and other studies, in majority of time occupants would not feel the difference until the relative humidity level above 70%. According to the measured indoor relative humidity in offices A1, the majority of the humidity sensation votes were located at 0 (Neutral) and -1 (Slightly dry) (Figure 6.5). In office A1, occupants started to vote -2 (Dry) when indoor relative humidity dropped to 50%RH, which may have caused occupant discomfort. The vote appeared as 1 (Slightly humid) when the humidity was over 80%RH, the high relative humidity level did not cause occupant feeling humid. This result was different to findings. The humidity sensation result in office A1 was tend to dry, particularly when the relative humidity was lower than 45% that majority of occupants felt slightly dry or dry. This result was different with results from other studies (Dear et al, 1991., Toftum et al,1998 and Nicol, 2004), but it just presented occupants' perception in the office A1.

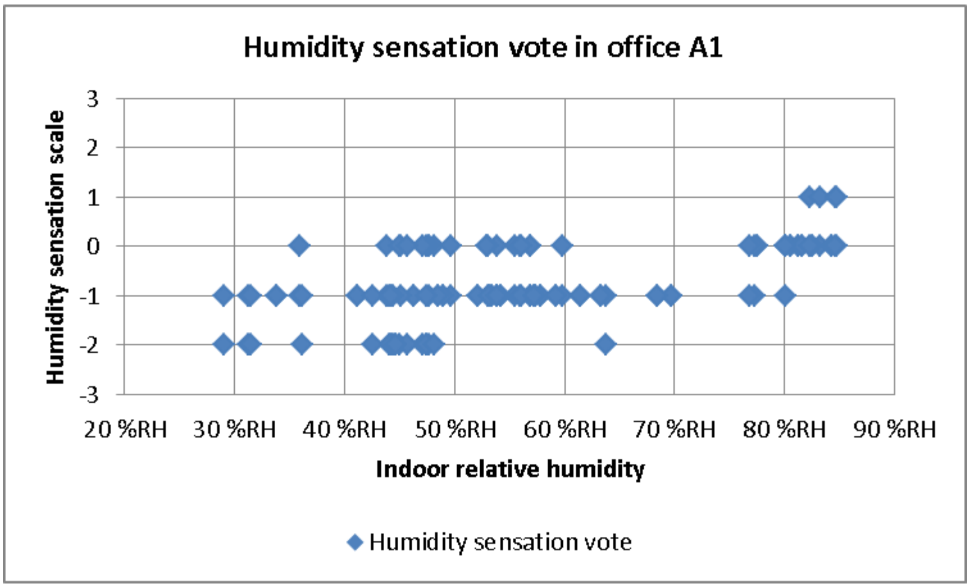


Figure 6.5: Humidity sensation vote in office A1 (SSV) during the working hours in the monitored period.

The indoor temperature and relative humid which cause occupants uncomfortable in office A1 was shown in Figure 6.6, in which hours the indoor air temperature and relative humidity were just located at the top boundary of the extended comfort zone. Office A1 was single-side ventilated, the indoor air speed was much lower than 1.5m/s (presented in section 5.2.1), and the data would be outside the comfort zone which caused occupants to feel uncomfortable. The major relative humidity vote was above 80%RH, which may be the reason for occupant feeling uncomfortable. However, in many hours, the indoor relative humidity level was higher than those points but occupants still felt comfortable. So the main reason which caused discomfort may not be the high humidity level, but some other environmental factors, such as indoor air quality.

Figure 6.6: The psychrometric chart for uncomfortable time (Blue circle) in office A1 (SSV). (Yellow: still air condition, red: air flow speed about 1.5m/s).

The indoor CO_2 level was not measured duo to lack of instrument, thus the indoor air quality was based on occupants' sensation vote results. According to Figure 6.7 and Figure 6.8, the indoor air quality sensation result in office A1 was tended to negative, which the occupants were not satisfy with the indoor air quality. Occupant may feel uncomfortable in the office. In addition, the indoor air quality sensation in the office building did not related to indoor air temperature and related humidity.

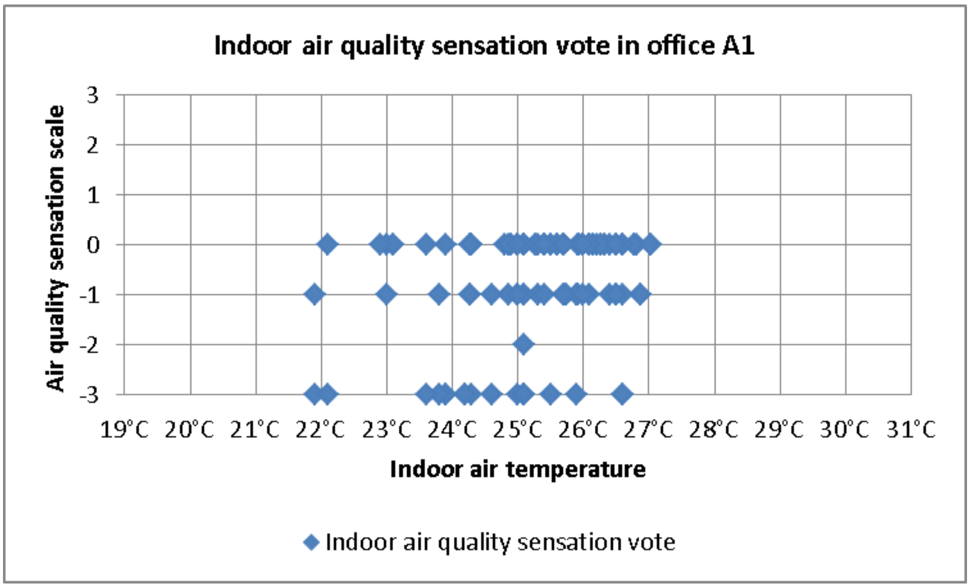


Figure 6.7: Indoor air quality sensation vote in office A1 (SSV) relate to indoor air temperature during the working hours in the monitored period.

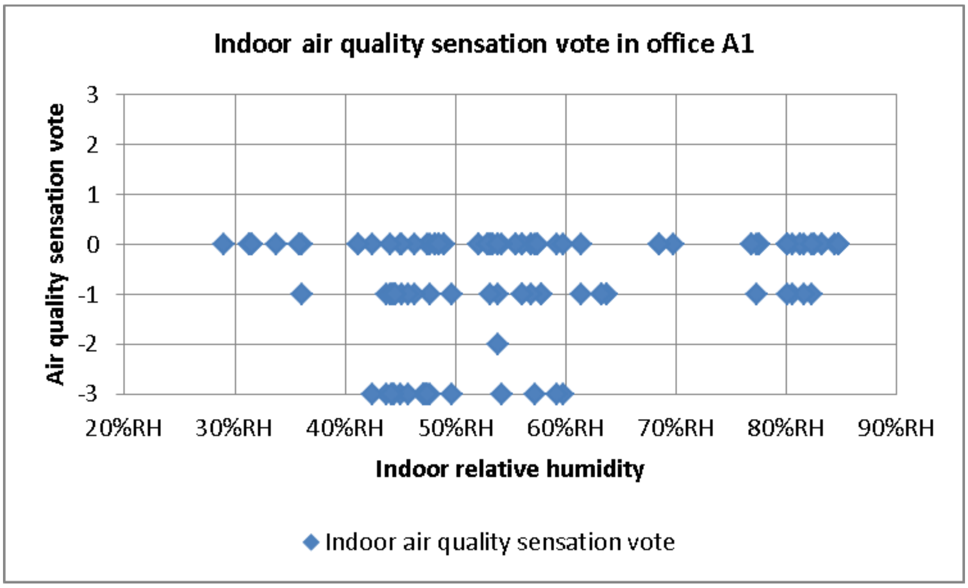


Figure 6.8: Indoor air quality sensation vote in office A1 (SSV) relate to indoor relative humidity during the working hours in the monitored period.

6.1.2 Thermal comfort perceptions in the office A2

In office A2 (CV), the thermal perception vote (included 2 voters and 480 votes) result was shown in Figure 6.9. The thermal sensation result was between -1 (Cool) and 1 (Warm). Most of the votes were selected 0 (Neutral) and 1 (Warm) which was similar to the result in office A1. However, the indoor air temperature variation in office A2 was wider than the temperature in the office A1, which because office A2 was cross ventilated. And in office A2, there were 98% of working hours that occupants felt comfortable.

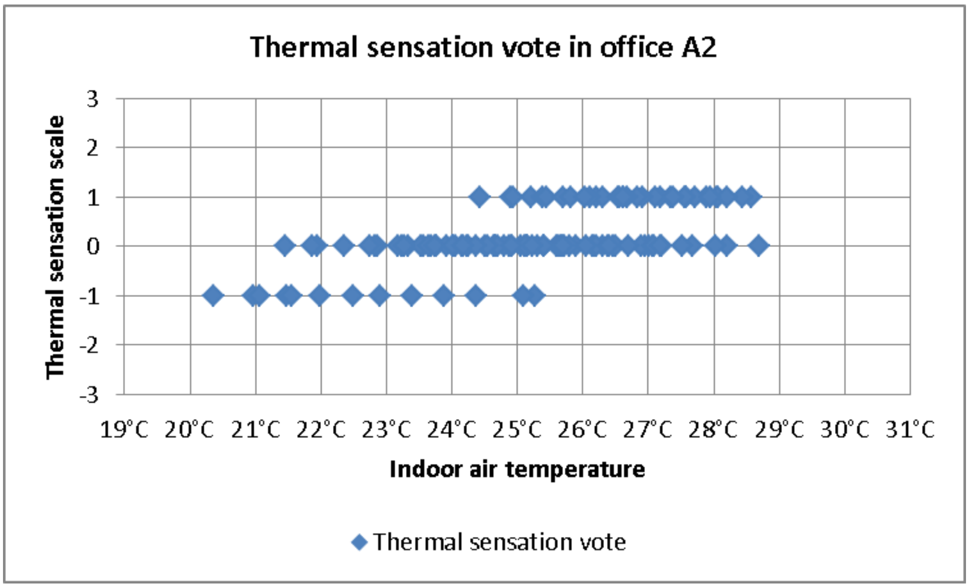


Figure 6.9: Thermal sensation vote in office A2 (CV) during the working hours in the monitored period.

It can be seen that, although the dry bulb air temperature variation in office A2 was greater than that in office A1, occupants in office A2 were more satisfied with the indoor environment than in office A1. This may be because office A2 was cross-ventilated, with a better indoor air flow condition (presented in section 5.1.1 and 5.2.1) that can help occupants extend their comfort sensation range. There was some universality in the thermal sensation vote in these two offices. First, when indoor dry bulb air temperature rose to 24°C, occupants started voting on 1, which means occupants would start feeling warm when the indoor dry bulb air temperature went up to 24°C. Second, occupants started voting on -1 when the temperature was lower than 25.5°C. It can be concluded from the above that occupants would start vote cool when indoor dry bulb air temperature was below 25.5°C, and would start vote warm when the temperature was above 24°C. And, when the temperature was between 24°C and 25.5°C, occupants' thermal sensation became uncertain as the vote varied between -1 (Cool) and 1 (Warm). The vacillation on their thermal sensation vote showed that, in this temperature range, occupants were not so sensitive and the body may be able to adjust to the thermal changes by itself.

Compared to the result calculated by De Dear's equation (Equation 1.7), the measured result of the temperature range in building A was wider, especially on the lower boundary. This may be caused by the clothing level changes. For example, at the end of the third week when a weak cold front arrived, the lowest external dry bulb air temperature dropped to 15°C, and the lowest indoor temperature was about 20°C. Occupants changed their clothing level (from 0.39clo to 0.55clo), such as wearing a long sleeve shirt or even a thin jacket, to adapt to the temperature changing, so that the result of their thermal sensation vote did not change much. Therefore, the changing of clothing level is an important thermal adjustment method that occupants always use to adapt to the temperature changing, which had a significant influence on adaptive comfort model. However, this behaviour was more effective in the condition of cool or cold weather rather than hot, since people need to keep a kind of minimum clothing level according to the venue restriction. For instance, vests were not allowed in the office. Moreover, the weather forecast also played an important role in occupants' adaptive comfort behaviour; this will be discussed later in this work.

The humidity sensation vote result (Figure 6.10) showed that in a couple of hours occupants would feel slightly humid (+1) and humid (+2) when indoor relative humidity was over 70%. There were only a few votes above 0 (Neutral), and many votes appeared the same when the relative humidity value changed, the result was similar in office A1. When the indoor relative humidity level was above 70%, it has not significantly effect on occupants' humidity perception. It can be seen that the relative humidity cannot be accurately perceived by occupants. Hence there is no correlation between the humidity sensation vote and the relative humidity in office building A.

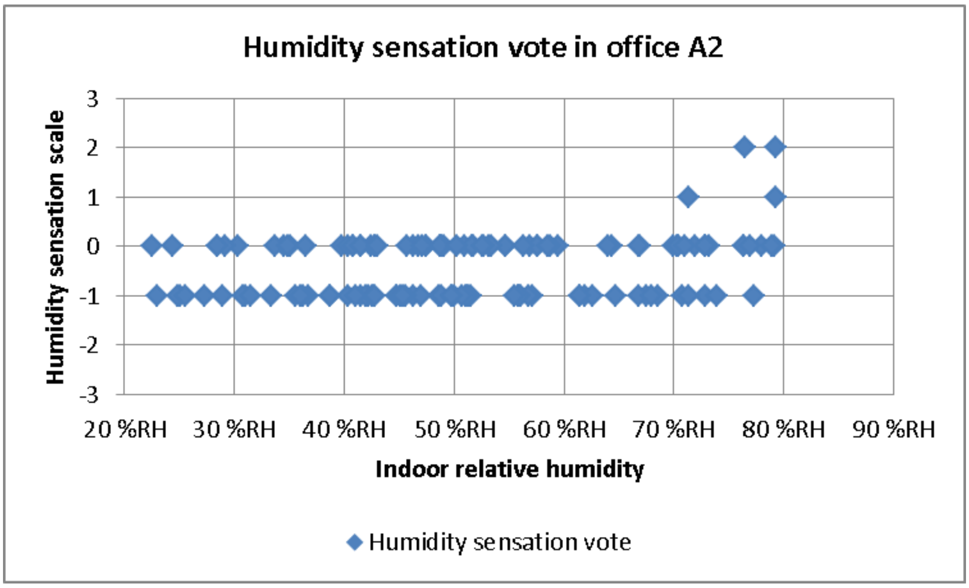


Figure 6.10: Humidity sensation vote in office A2 (CV) during the working hours in the monitored period.

Although the occupants cannot accurately perceive relative humidity, the results showed that the votes were tending towards dry for the indoor humidity sensation. Generally occupants felt slightly dry in the two offices. It also can be observed from occupants' behaviour, such as using balm or lotion to keep the skin/lips moisturised. Thus, the humidity sensation vote can show the occupants' general humidity perception in the office Based on the comfort sensation vote result, it seems it did not cause any comfort to occupants. Thus, it seems that the occupants in office building A could tolerate high indoor relative humidity and they were more sensitive to drier conditions.

The Figure 6.11 and Figure 6.12 showed the indoor air quality sensation in office A2. The result in office A2 was opposite to the result in office A1. The votes were between 0 (Neutral) and 3 (Very fresh). In addition, the indoor air quality sensation in the office A2 was not related to indoor air temperature and related humidity. This result was as same as the result in office A1. However, the results in these two offices showed that the air quality sensation vote in office A2 was better than that in office A1. Thus, occupants felt that the indoor air quality in the cross ventilated office was better than single-side ventilation office in building A. This may be the reason that occupants in office A2 felt more comfortable than in office A1. So in the other offices, figures of indoor air quality sensation result would not be used to correlate with indoor temperature and relative humidity. It would only be used to define the distribution of indoor air sensations result.

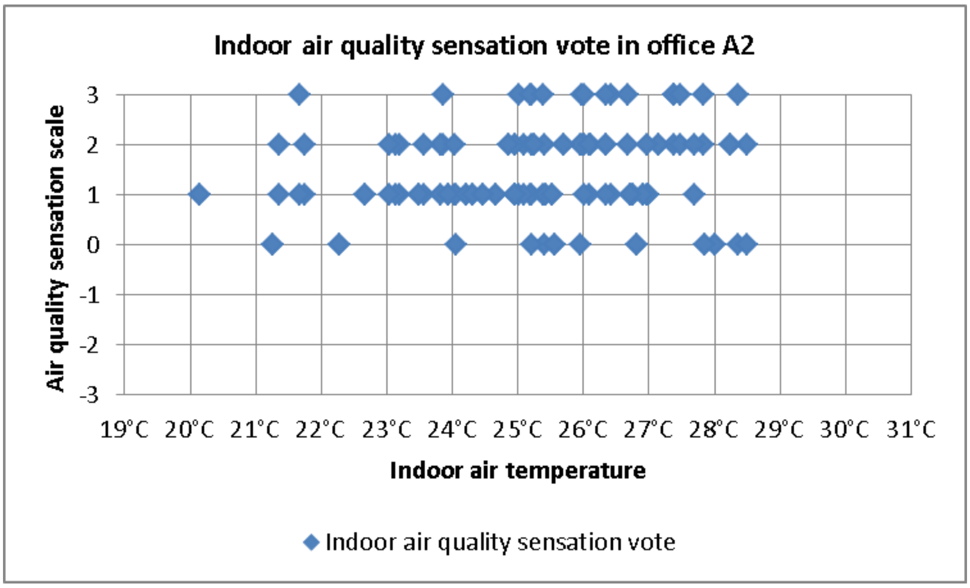


Figure 6.11: Indoor air quality sensation vote in office A2 (CV) relate to indoor air temperature during the working hours in the monitored period.

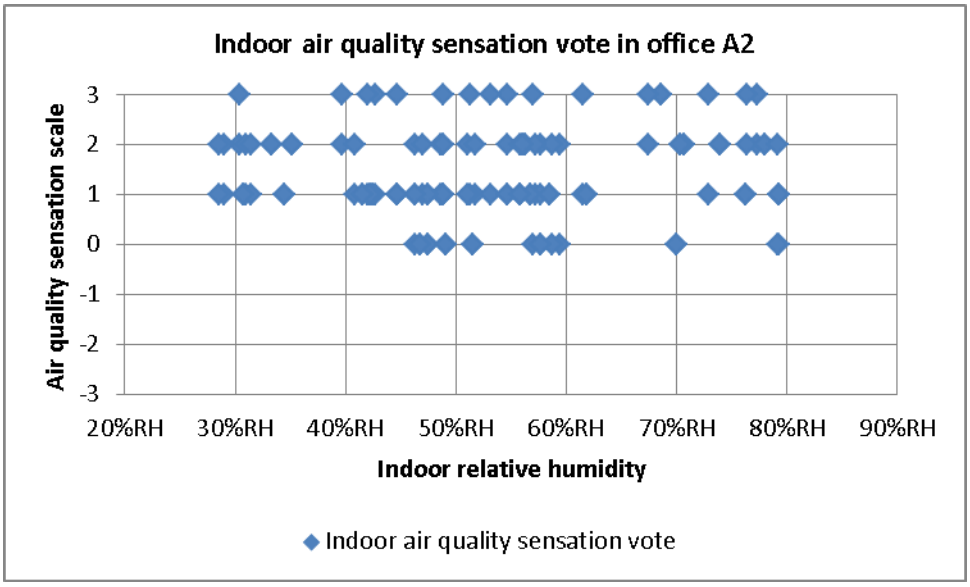


Figure 6.12: Indoor air quality sensation vote in office A1 (CV) relate to indoor relative humidity during the working hours in the monitored period.

6.2 Office building B

In office building B, the indoor mean radiant temperature was measured in office B2 which had the lowest indoor average dry bulb air temperature in building B. The average indoor mean radiant temperature in working hours was 26.23°C which was 0.71°C higher than the average indoor air temperature, considered to be a small temperature difference. The proportion of comfortable indoor air temperature is shown in Figure 6.13. In offices B1 and B3, which were cross-ventilated, the average indoor air temperature in working hours was higher than that in offices B2 and B4. In each office, there were 2 voters and 480 votes.

According to Figure 6.13 the indoor air temperatures in offices B1 and B3 varied within the comfort temperature range, and in 3% and 6% of working hours the air temperature was over 29°C in offices B2 and B4, which was higher than in B1 and B3. Thus, the time occupants in offices B2 and B4 felt uncomfortable was more than the other two offices, though the average indoor air temperature was lower than the other two. In office B2, the natural ventilation type was changing, the proportion of time of indoor air temperature higher than 29°C was lower than office B4, which was single-side ventilated and during about 6% of working hours the air temperature was higher than 29°C. Therefore, if cross-ventilation was applied or could be extended in offices B2 and B4, this situation may be avoided and comfort time could be extended.

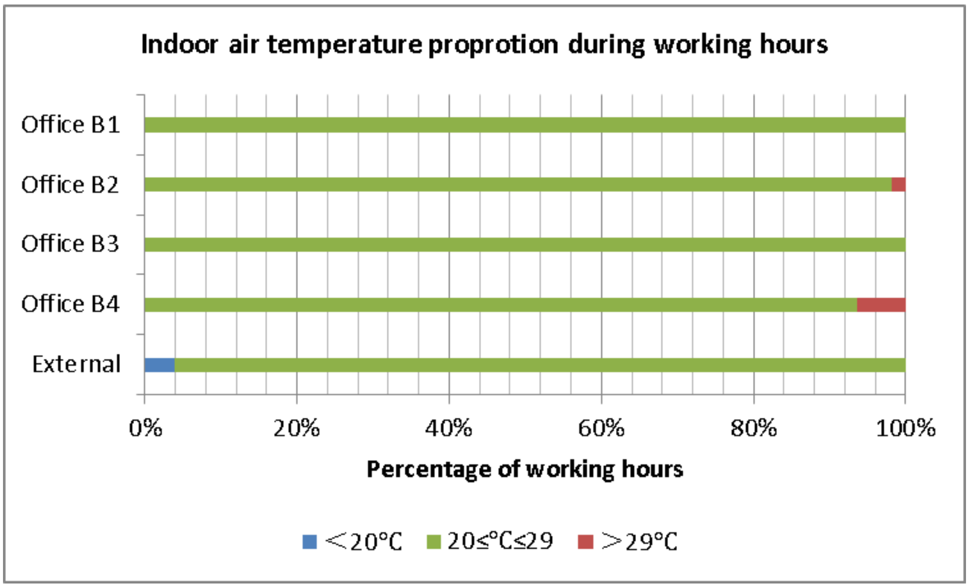


Figure 6.13: The dry bulb air temperature variation in office building B and outdoor, during the working hours.

In order to understand in more detail the indoor air temperature and relative humidity distributions, the data were distributed in psychrometric charts (Figure 6.14, Figure 6.15, Figure 6.16 and Figure 6.17). In these four offices, most of the time the indoor air temperature and relative humidity was located in the still air condition comfort zone; in some of the time the environmental condition could still be covered if positive indoor air flow speed can be achieved. But in office B4, the comfort zone would be difficult to extend by increasing indoor air flow speed, because the room was single-side ventilated. So, there were a number of times that occupants may have felt uncomfortable in office B4. And also, many data points in offices B2 and B4 were located near the edge of the comfort zone (still air condition). Based on the psychrometric chart analysis, the main problem in these offices was caused by high humidity ratio in the offices; some of the data were even outside the extended comfort zone, because the relative humidity was close to 90% and the absolute humidity was about 19g/kg.

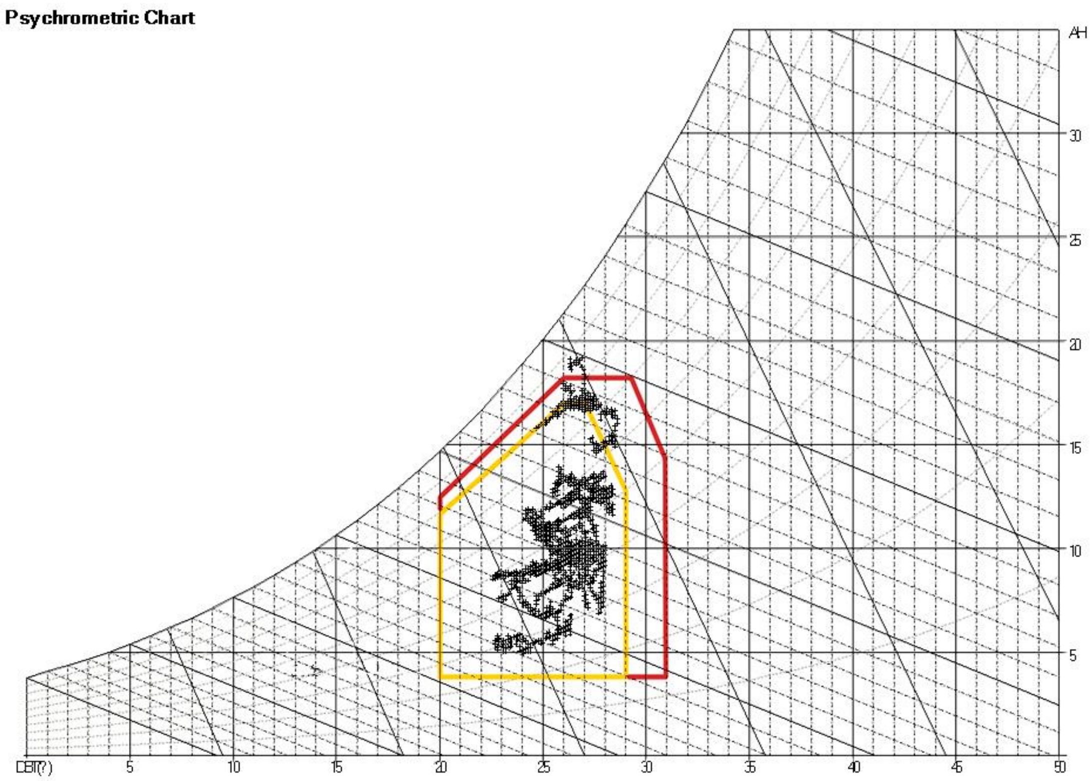


Figure 6.14: The psychrometric chart for office B1 (CV).
(Yellow: still air condition, red: air flow speed about 1.5m/s).

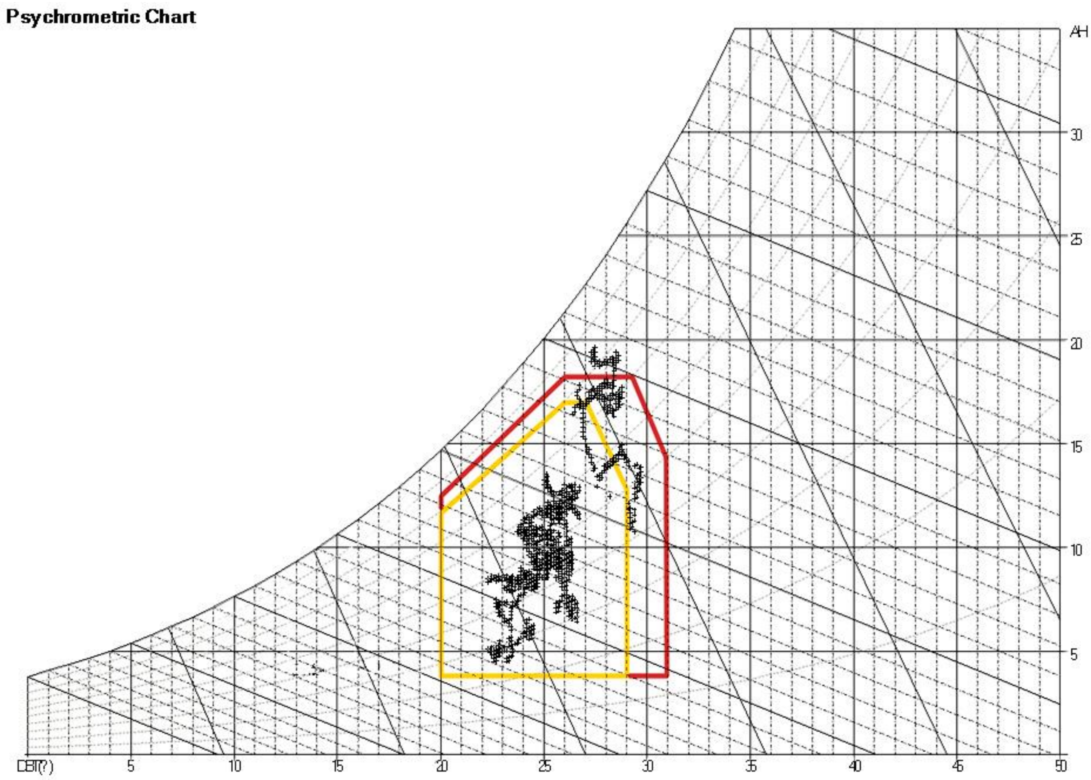


Figure 6.15: The psychrometric chart for office B2 (SSV/CV).
(Yellow: still air condition, red: air flow speed about 1.5m/s).

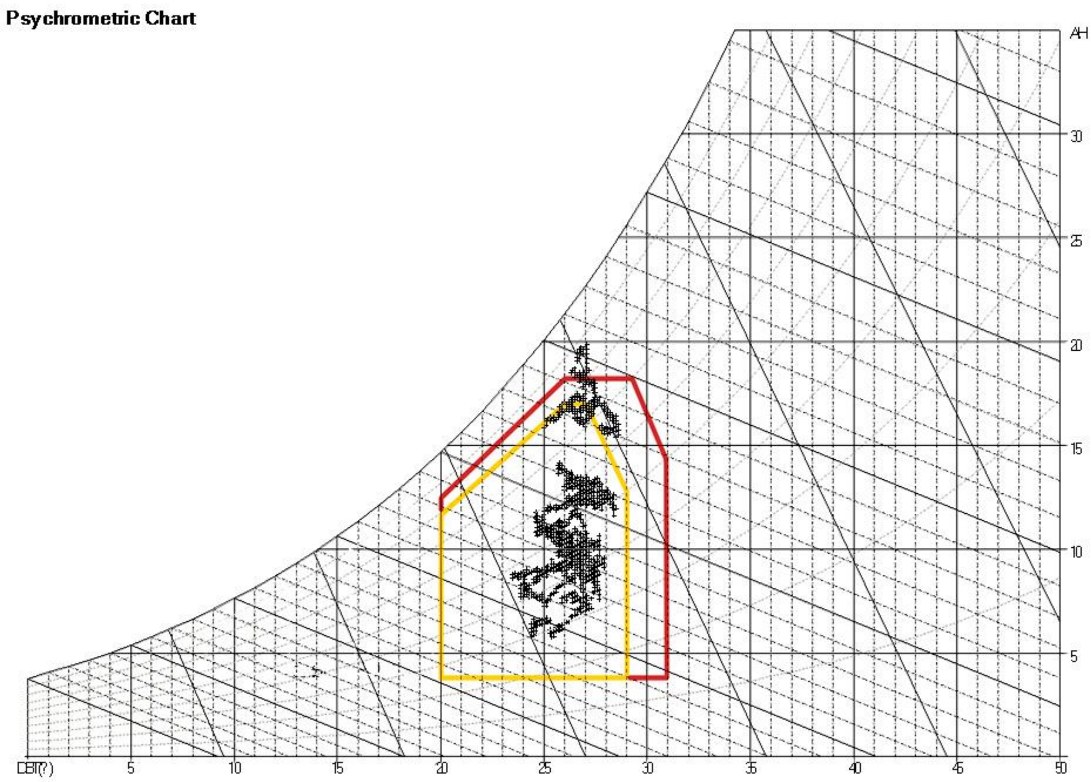


Figure 6.16: The psychrometric chart for office B3 (CV).
(Yellow: still air condition, red: air flow speed about 1.5m/s).

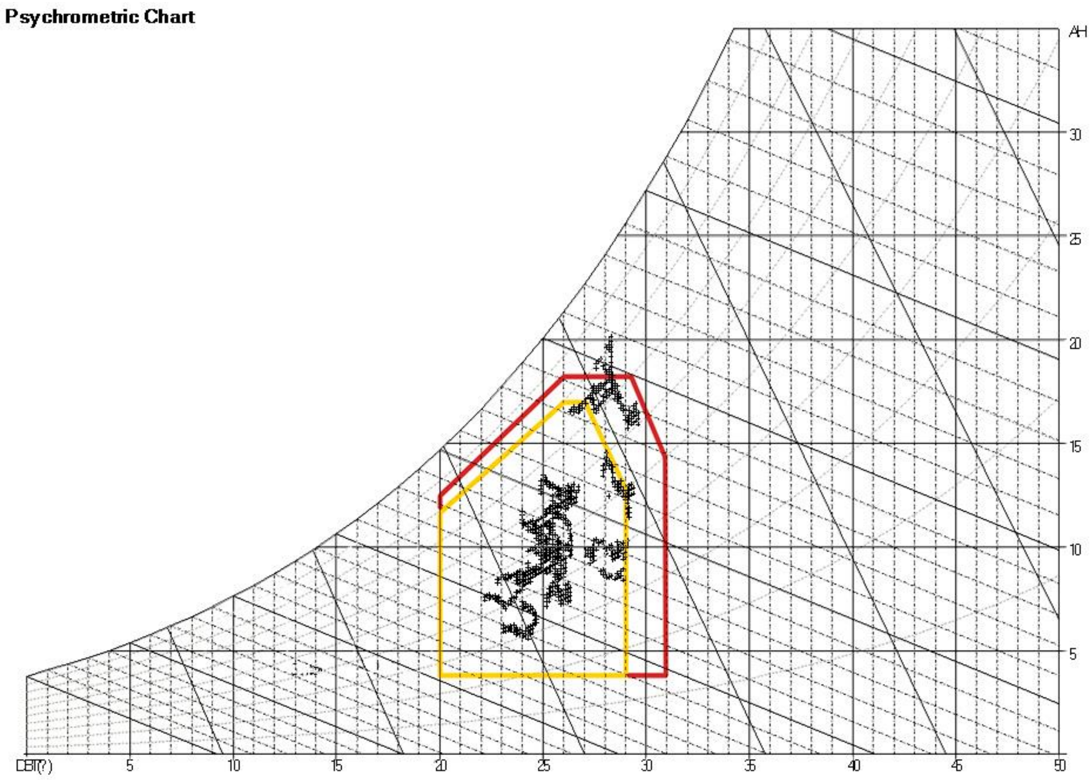


Figure 6.17: The psychrometric chart for office B4 (SSV).
(Yellow: still air condition, red: air flow speed about 1.5m/s).

6.2.1 Thermal comfort perceptions in the office B1

The thermal sensation vote (included 2 voters and 480 votes) in office B1 (CV) (Figure 6.18) varied between -1 (Cool) and 1 (Warm), and the majority vote was on 0 (Neutral) and 1 (Warm). When the indoor air temperature rose over 25°C, occupants started to feel warm in the office. When the temperature dropped below 24°C, some occupants felt cool in the office. Generally, the indoor environment was tending to be warm, but the indoor environmental condition was still acceptable in the working hours. However, according to the psychrometric chart of office B1, some of the working was in the extended comfort zone and in a little of the time it was even out of the extended comfort zone. But, based on the occupant thermal sensation vote result, occupants did not feel too hot or too cold. And according to the occupant comfort vote result, in 99% of working hours occupants felt comfortable. This may be because office B1 was cross-ventilated (presented in section 5.2.2), so that varied indoor air flow could help occupants to achieve personal comfort. It may also prove that using the window on the corridor side and keeping the office cross-ventilated can help occupants to maintain their personal comfort, although the average indoor air temperature in the office was higher than that in the single-side ventilation office.

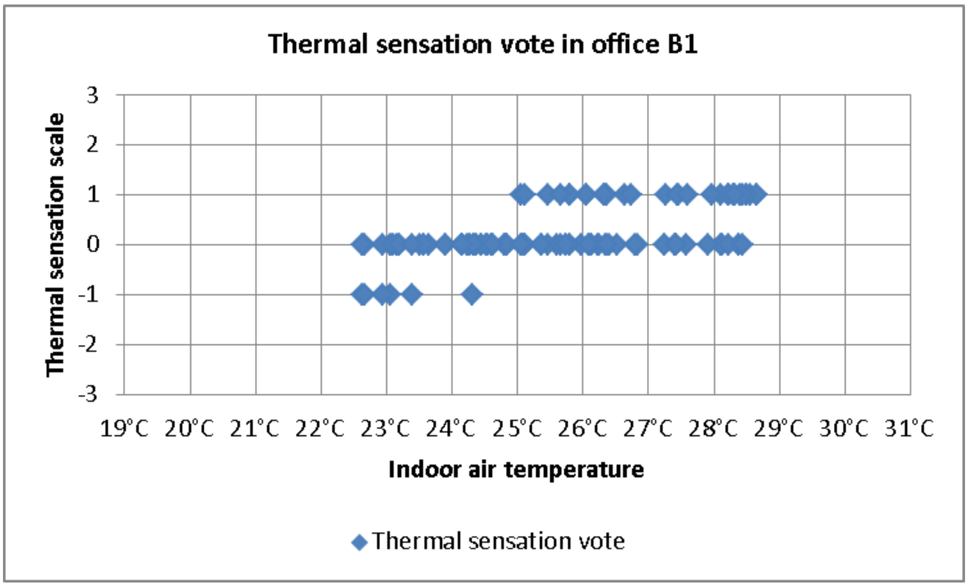


Figure 6.18: Thermal sensation vote in office B1 (CV) during the working hours in the monitored period.

The relative humidity varied between 20% and 90% in office B1 (Figure 6.19). The main vote was on 0 (Neutral) and -1 (Slightly dry), and the office tended to be slightly dry by occupant sensation. When the indoor relative humidity was higher than 80%, the vote was on slightly humid (+1). When the relative humidity was lower 60%, occupants would feel slightly dry (-1). Generally the result was the same as that in office building A, and the occupants in office B1 could not accurately perceive relative humidity. Humidity levels in the office did not impact on occupants' comfort sensation, though some relative humidity values were lower than 30% and higher than 70%.

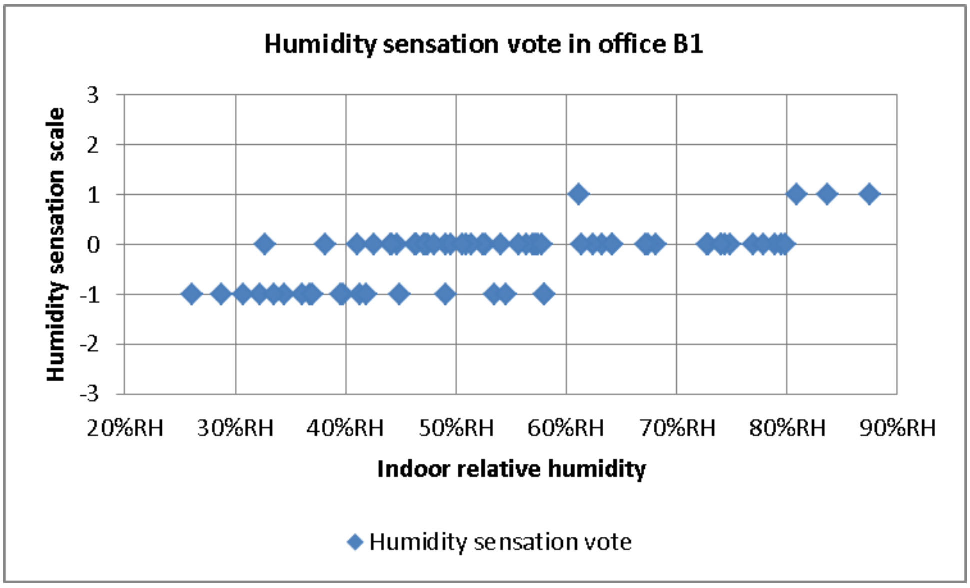


Figure 6.19: Humidity sensation vote in office B1 (CV) during the working hours in the monitored period.

The occupants in the office B1 were satisfied with indoor air quality (Figure 6.20). The votes were between 1 and 3 which all above neutral (0), and most of occupants voted on very fresh (3). In addition, office B1 was cross-ventilated which seemed that the indoor air quality would not cause discomfort.

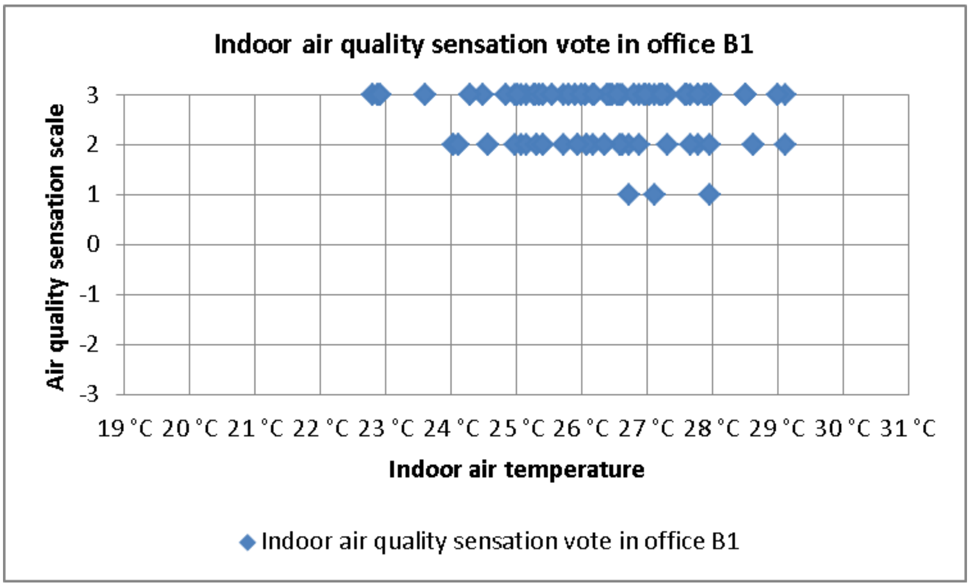


Figure 6.20: Indoor air quality sensation vote in office B1 (CV) relate to indoor air temperature during the working hours in the monitored period.

6.2.2 Thermal comfort perceptions in the office B2

The indoor environmental condition showed more variation in office B2 (SSV/CV), because of the change of natural ventilation type (presented in section 5.1.2). The thermal sensation vote results (Figure 6.21) (included 2 voters and 480 votes) showed that the vote was between -1 (Cool) and +2 (Hot). The vote results between -1 (Cool) and +1 (Warm) were similar to that in office B1. Few votes appeared on -1 (Cool) when the air temperature was lower than 24°C, and the vote started on +1 when the air temperature was over 25°C, and the office was tending to be warm. The difference was that, when the air temperature rose over 27°C, some occupants felt hot (Vote on +2) in the office. When it was applied with the comfort sensation vote (Figure 6.22), the results showed that, when indoor air temperature was higher than 28.5°C, occupants started to vote on -1 (Slightly uncomfortable). For the rest of the time, when occupant thermal sensation vote was on hot, they still felt acceptable.

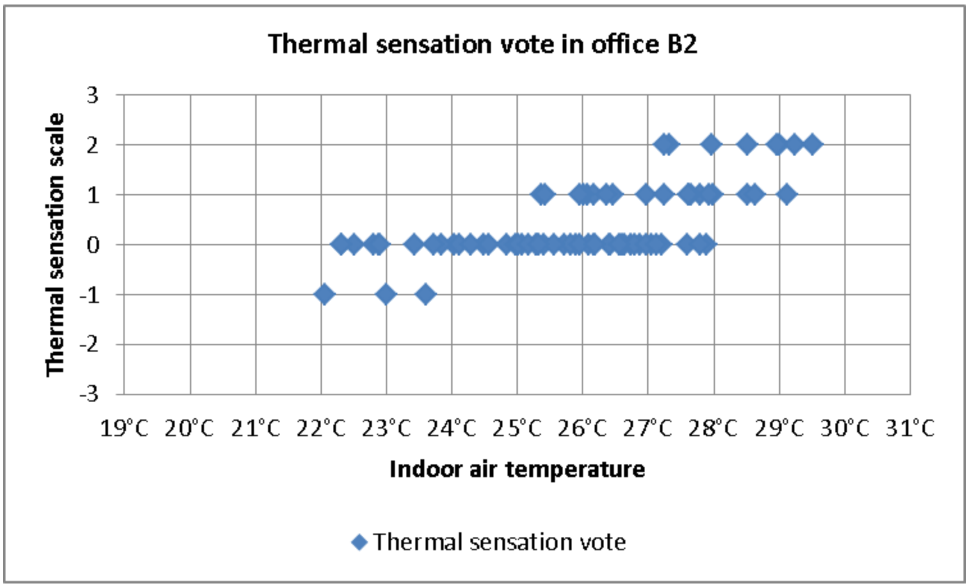


Figure 6.21: Thermal sensation vote in office B2 (SSV/CV) during the working hours in the monitored period.

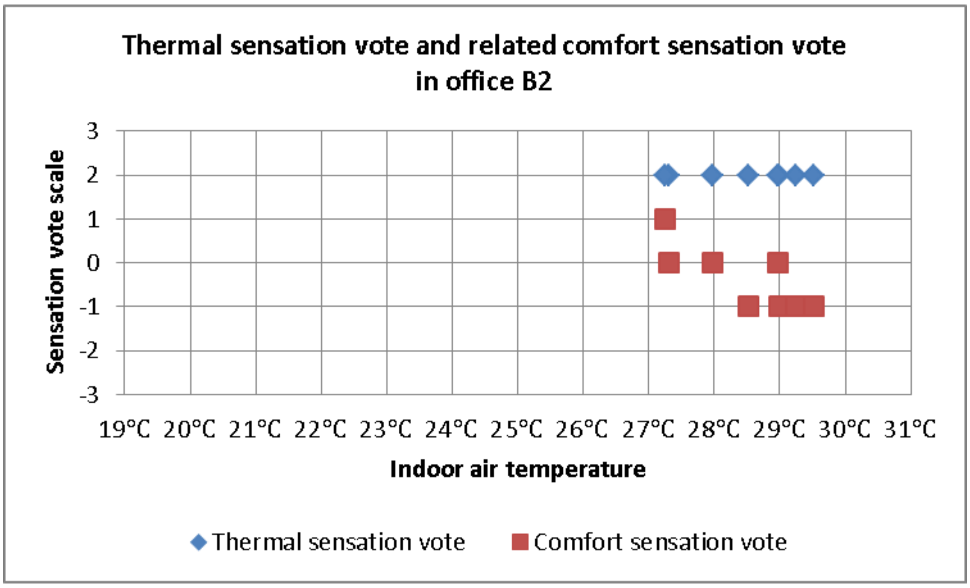


Figure 6.22: Thermal sensation vote and related comfort sensation vote when occupants feel hot and uncomfortable in office B2 (SSV/CV).

Figure 6.23: The psychrometric chart for uncomfortable time (Blue circle) in office B2 (SSV/CV). (Yellow: still air condition, red: air flow speed about 1.5m/s).

Plotting this air temperature and relative humidity which causes occupants to feel uncomfortable into a psychrometric chart (Figure 6.23), the result shows the data were around the boundary of the yellow comfort zone with air temperature between 28°C and 30°C, and the relative humidity was between 40% and 60%. So, on the top of the chart, these data were just near the boundary of the extended comfort zone or outside, and did not cause significant impact on occupant comfort perception in the office. It seems in office B2, occupants' comfort perception was more sensitive to high indoor air temperature rather than high humidity level; and in those times which occupants were feeling hot may be caused by low indoor air flow speed.

The votes on +2 (Hot) were in the first week of measurement (25th, 26th and 27th). Based on the indoor air temperature and window state record (Figure 6.24), on 26th September, the door was closed shortly after occupants arrived in the office and windows were opened. The indoor air temperature gradually increased. In most of the time in the morning, the office was single-side ventilated, until occupants came back to the office after their lunch break. The door was kept open in the afternoon, and the opening area was reduced from about $1m^2$ to $0.5m^2$ when occupants arrived, but the indoor air flow temperature was gradually decreasing. The cross-ventilation seemed to start driving heat out of the office, which may have helped occupants to improve the thermal perception. In the later afternoon the opening area increased (from about $0.5m^2$ to $0.7m^2$), and the indoor air temperature remained unchanged.

In the other two days, the door was open in the morning for a short time, and then closed. The office was single-side ventilated in these two days. The indoor air flow speed had not been measured in office B2 in these three days, and the air flow speed around occupants could not be identified. According to the natural ventilation type in the office (presented in section 5.2.2), the indoor air flow speed would remain low when it was single-side ventilated, and it would not have an important influence on occupant thermal comfort; unless a gust of wind may increasing the indoor air flow speed, but it would not remain long. Thus, the uncomfortable time in office B2 mainly relates to low indoor air flow speed; if the room were cross-ventilated, the comfort time may have been extended in these days.

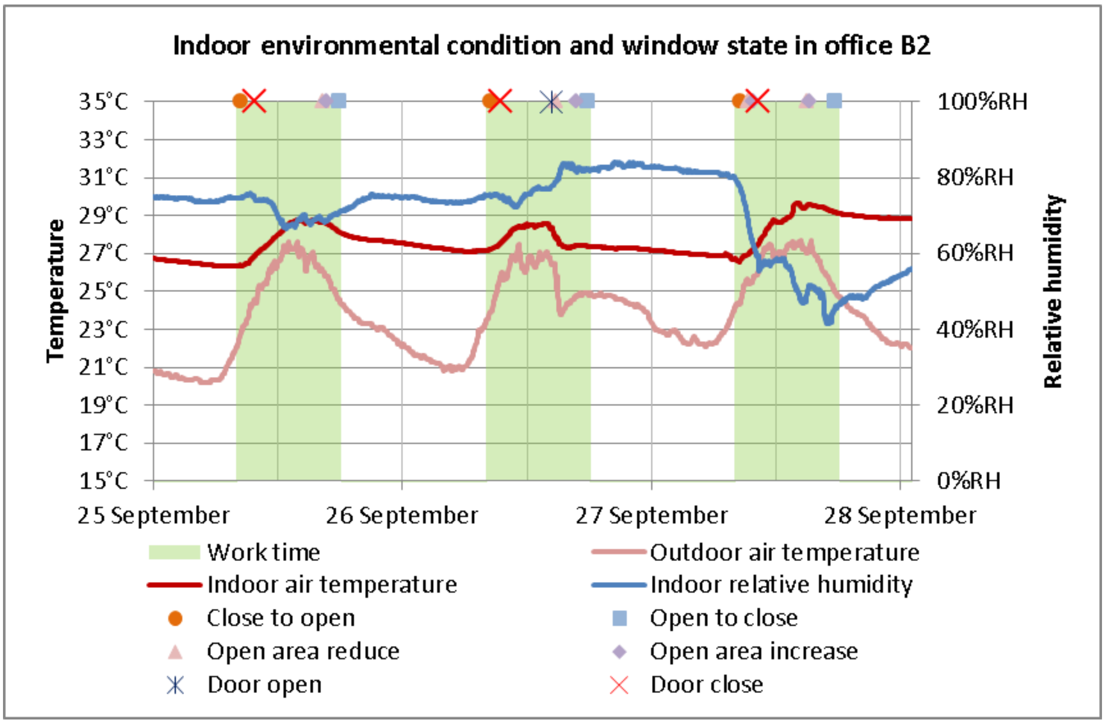


Figure 6.24: Indoor air temperature, relative humidity and widow state in three days in office B2 (SSV/CV).

The humidity sensation vote result in office B2 is shown in Figure 6.25. The result was similar to that in office B1. Most of the votes were between 0 (Neutral) and -1 (Slightly dry), which means the indoor humidity sensation was tending towards slightly dry. When the relative humidity rose over 75%, occupants would feel slightly humid. When the relative humidity dropped below 60%, the votes appeared on the slightly dry level. This result was the same as the result in office B1. All the votes were between -1 (Slightly dry) and +1 (Slightly humid); it would not have a significant impact on occupant comfort sensation.

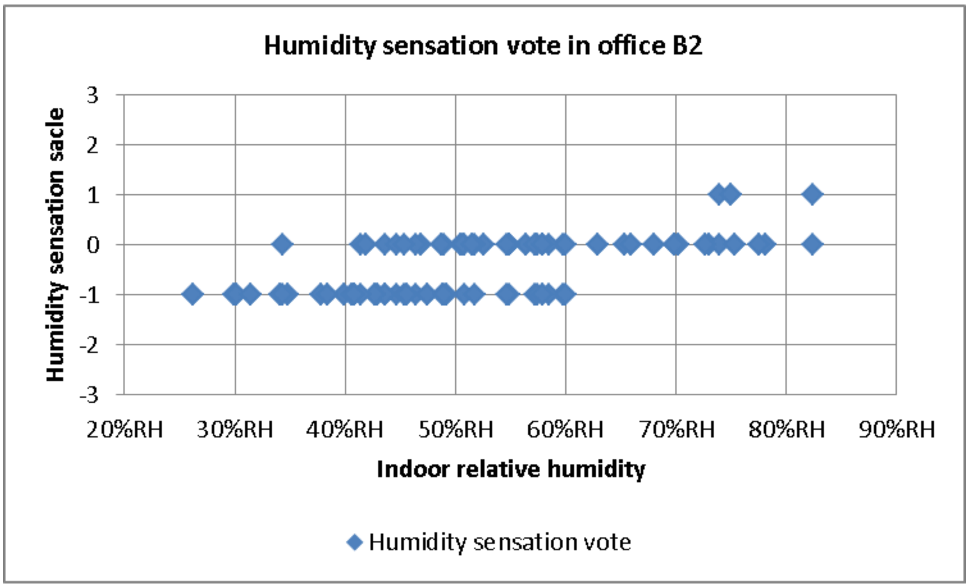


Figure 6.25: Humidity sensation vote in office B2 (SSV/CV) during the working hours in the monitored period.

The indoor air quality perception result (Figure 6.26) in office B2 showed that the votes were between -1(Slightly stuffy) and 2 (Fresh), and most of the votes were on neutral (0) and slightly fresh (1). Thus, the indoor air quality was acceptable that occupants were satisfied with indoor air quality in most of working hours.

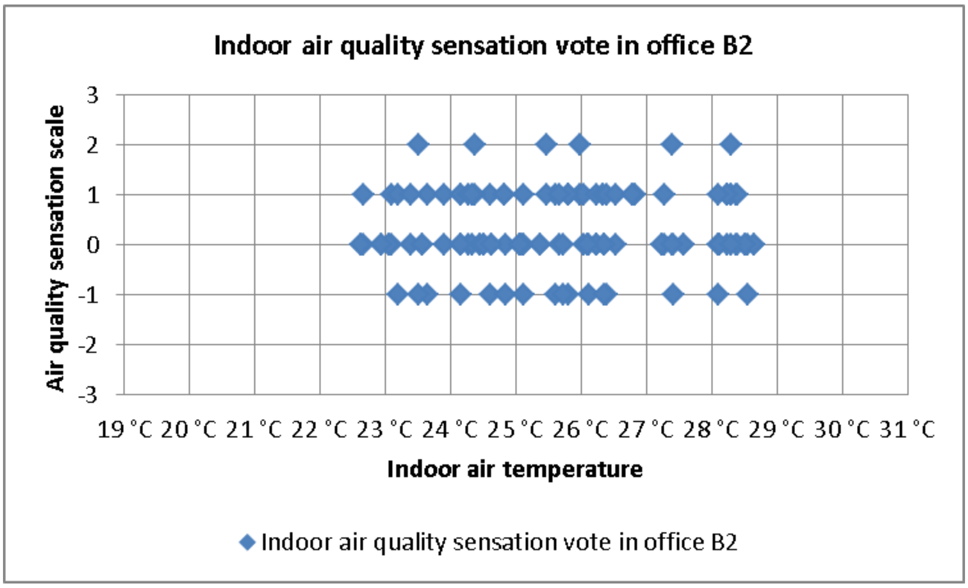


Figure 6.26: Indoor air quality sensation vote in office B2 (SSV/CV) relate to indoor air temperature during the working hours in the monitored period (2 occupants and 120 votes).

6.2.3 Thermal comfort perceptions in the office B3

Office B3 (CV) was cross-ventilated. The indoor air temperature varied between 23°C and 29°C, which was slightly narrower than other offices. The thermal sensation vote (included 2 voters and 480 votes) in office B3 was between 0 (Neutral) and +2 (Hot) (Figure 6.27). The occupants did not feel cool, and the indoor environment was tending towards hot. The vote on +1 was starting on 24.7°C and when the air temperature increased to 27°C occupants would felt hot in the office. Relating thermal sensation vote result with comfort sensation results, the uncomfortable results are shown in Figure 6.28. It can be seen that the uncomfortable sensation vote appeared when the indoor air temperature rose above 27°C. Mainly, the uncomfortable level was on slightly uncomfortable (-1). In a few hours, occupants felt uncomfortable (-2). Compared to the other cross-ventilated office B1, the comfort situation in office B3 was worse.

Figure 6.29 shows the data of uncomfortable time plotted into a psychrometric chart. The data were mainly located at the top part of the comfort zone, within the extended comfort zone. A couple of data were even outside the extended comfort zone and also some data were in the yellow comfort zone. The air temperature varied between 27°C and 29°C, the relative humidity was between 60% and 90%. The high humidity level may be the main reason which caused discomfort. But the office was cross-ventilated and the indoor air flow speed should have been able to reduce occupants’ uncomfortable sensation when air temperature and relative humidity were in the extended comfort zone. The window state and indoor air flow speed would be used to find out the indoor air flow condition.

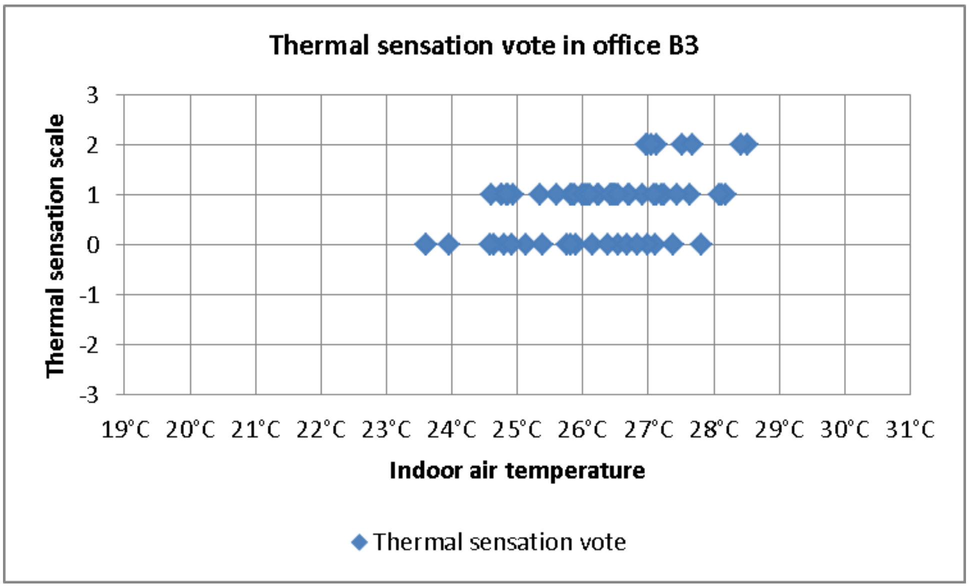


Figure 6.27: Thermal sensation vote in office B3 (CV) during the working hours in the monitored period.

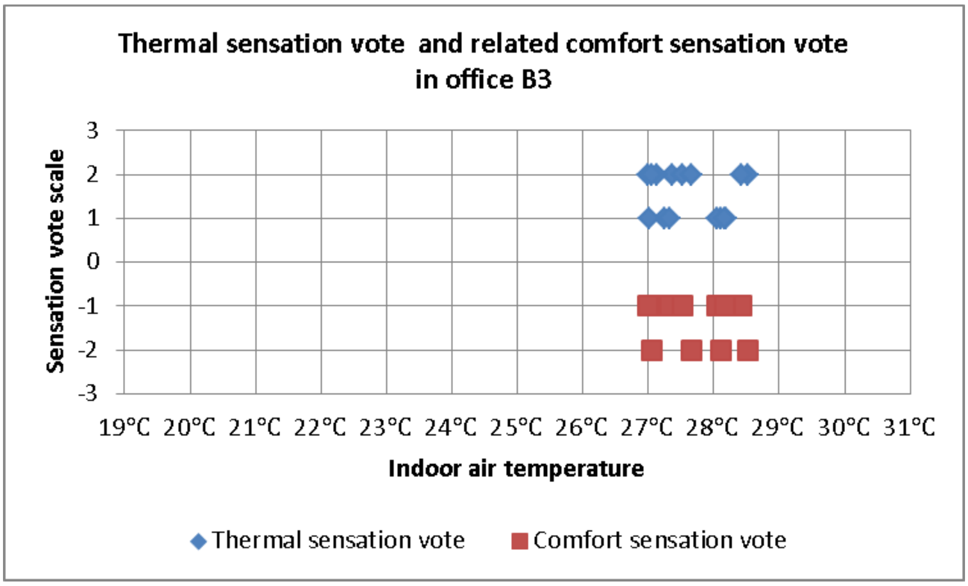


Figure 6.28: Thermal sensation vote and related comfort sensation vote when occupant feels uncomfortable in office B3 (CV).

Figure 6.29: The psychrometric chart for uncomfortable time (Blue circle) in office B3 (CV). (Yellow: still air condition, red: air flow speed about 1.5m/s).

The high relative humidity mainly occurred in the first week, especially in the first three days, during which occupants felt hot and uncomfortable. The occupants changed the window state more frequently in office B3 than in office B2, which may have influenced the indoor air flow speed. The indoor air flow speed was not measured in the first three days, but it was taken on the 28th and the 29th (Figure 6.30). The opening area on 28th varied between 0.3m^2 and 1.1m^2, and the average effective opening area was about 0.65m^2. According to empirical expression for calculating required air volume flow rate for cooling (Equation 2.8), the air flow speed measured on an opening window cannot achieve the cooling purpose because of low indoor and outdoor air temperature difference. In fact, in most of the time the office was well naturally ventilated, which was the reason that the indoor and outdoor air temperatures were close to each other. In addition, the measured average indoor air flow speed was about 0.6m/s, which could extend the comfort zone to a certain extent. For the first three days, the average effective opening area was about 0.9m^2, 0.8m^2 and 0.82m^2, and the indoor air flow speed could be positive in the office. Although the average air flow speed would not be increased to 1.5m/s which could extend occupants' comfort temperature, the intervals of gust wind could reduce uncomfortable sensation in some periods.

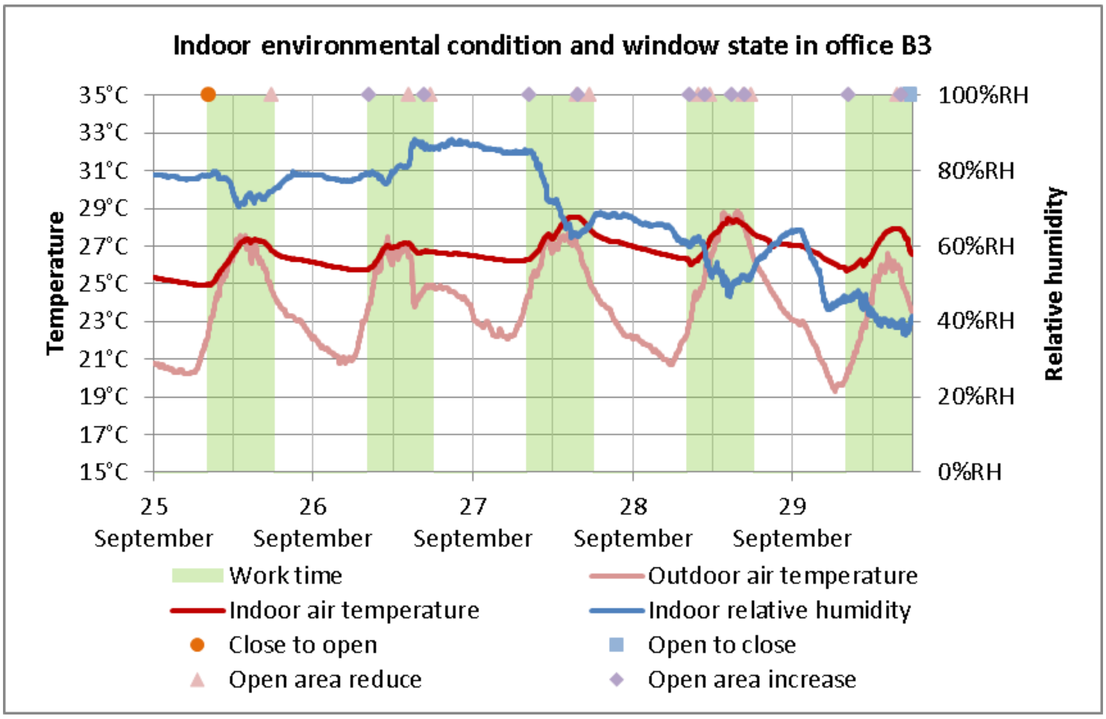


Figure 6.30: Indoor air temperature, relative humidity and widow state in three days in office B3 (CV).

Figure 6.31 shows the humidity sensation vote in office B3 during the working hours. The votes varied between -1 (Slightly dry) and +2 (Humid). However, there were many votes located on -1, but unlike offices B1 and B2 very few votes were on the humid side; the occupants in office B3 seemed more sensitive to the humidity level. When indoor relative humidity increased to 50%, occupants would start to feel slightly humid (+1). When then relative humidity increased to over 75%, all occupants would feel moist in the office. The vote was located on humid (+2) when the relative humidity was over 80%, as this may cause occupants to feel uncomfortable.

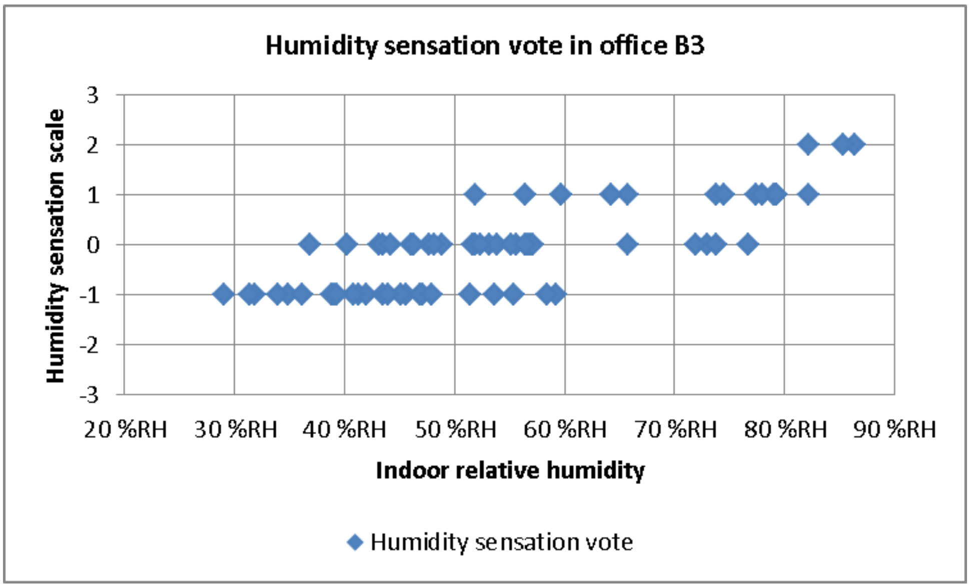


Figure 6.31: Humidity sensation vote in office B3 (CV) during the working hours in the monitored period.

According to the psychrometric chart for uncomfortable time in the office (Figure 6.29), in these uncomfortable times, the relative humidity was between 60% and 90%. The primary uncomfortable time was located above 70% relative humidity (Figure 6.32). When the indoor relative humidity was above 75%, it would start to cause an uncomfortable sensation (-2) in office B3. The related indoor air temperature was between 27°C and 28°C, at least one degree lower than the comfort temperature threshold. Therefore, the high humidity level was the main reason for impact on occupant comfort sensation in office B3. For the slightly dry vote (-1) in the office, the result was similar to offices B1 and B2, the occupant dry sensation appeared when the indoor relative humidity dropped below 60%.

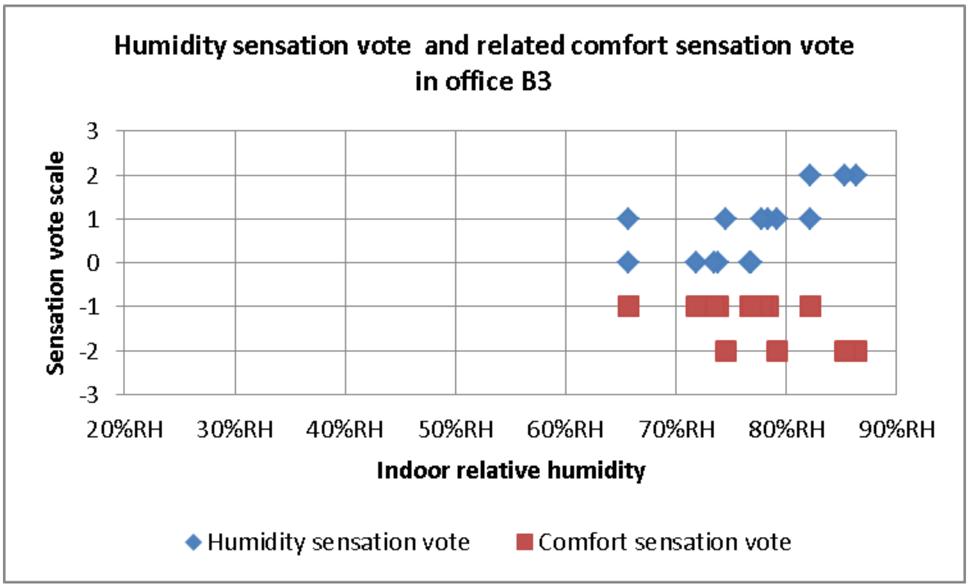


Figure 6.32: Humidity sensation vote and related comfort sensation vote when occupant feels uncomfortable in office B3 (CV).

Office B3 was cross ventilated, according to indoor air quality perception result (Figure 6.33). The vote was between 0 (Neutral) and 2 (Fresh), and most of the votes were on neutral. Like in other cross-ventilation offices, occupants were satisfied with the indoor air quality.

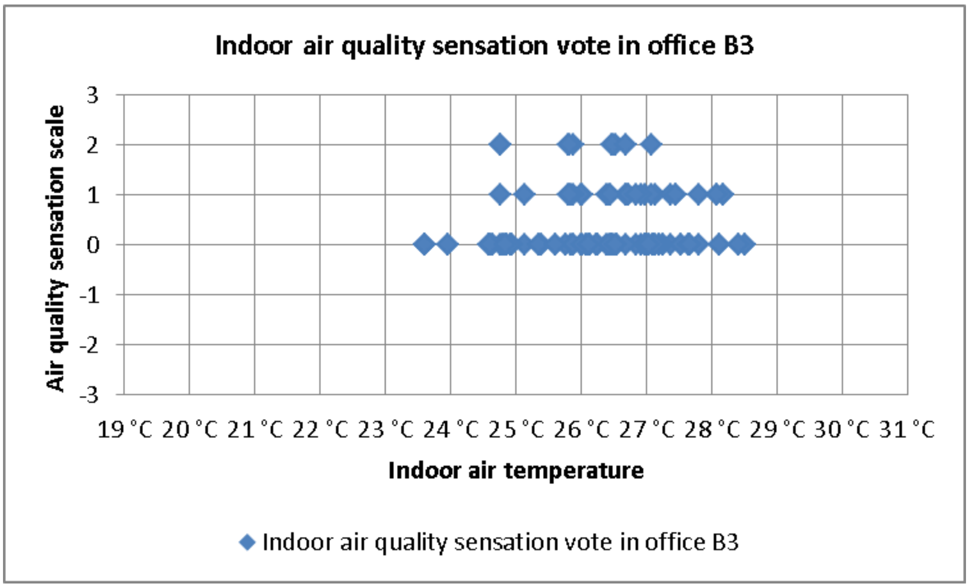


Figure 6.33: Indoor air quality sensation vote in office B3 (CV) relate to indoor air temperature during the working hours in the monitored period .

6.2.4 Thermal comfort perceptions in the office B4

Office B4 (SSV) was single-side ventilation dominated during the working hours. The thermal sensation vote (included 2 voters and 480 votes) was between 0 (Neutral) and +2 (Hot), such that none of the votes was on the cold sensation (Figure 6.34). The indoor environment was tending towards hot. When the indoor air temperature rose over 25°C, occupants would feel warm (+1) and when the temperature was over 29°C, the thermal sensation was on hot (+2). Compared with the comfort sensation vote, only in a little time did occupants feel slightly uncomfortable (+1) when the air temperature was over 29°C (Figure 6.35). After plotting the data into a psychrometric chart, the indoor air temperature and related relative humidity which caused occupants slight discomfort were in the extended comfort zone (Figure 6.36). A group of data was close to the yellow comfort zone with relative humidity under 50%. Another group had relatively higher humidity, which was between 60% and 70%, near the boundary of the extended comfort zone. Thus, the uncomfortable sensation was more related to indoor air temperature, rather than humidity level. Cross-ventilating the office and increasing indoor air flow speed could reduce occupants' hot sensation when the indoor air temperature was about 29°C. Generally, it seemed that when the air temperature was between 29°C and 30°C, there was no serious influence on comfort sensation in office B4, that occupants still could tolerate the indoor environmental condition, slightly uncomfortable but still acceptable.

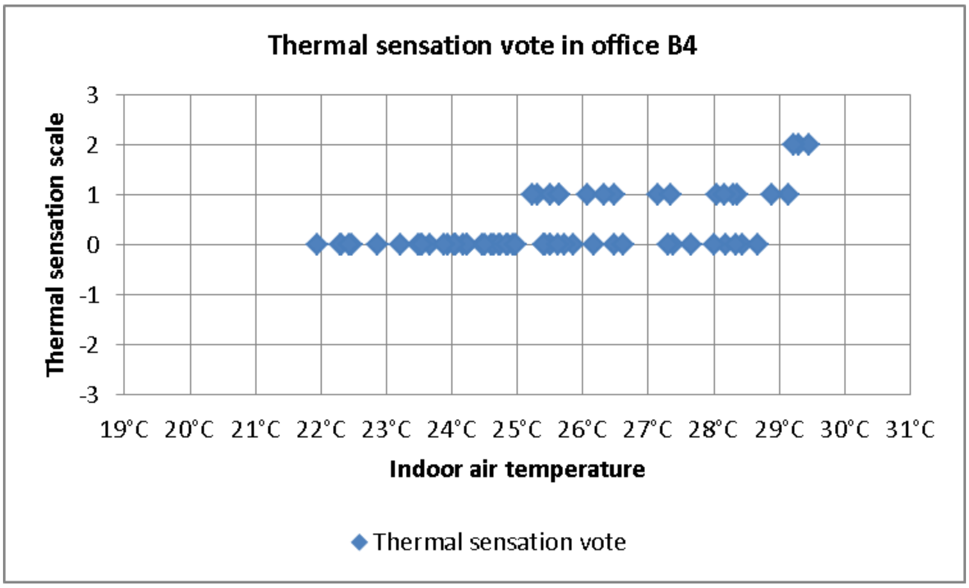


Figure 6.34: Thermal sensation vote in office B4 (SSV) during the working hours in the monitored period.

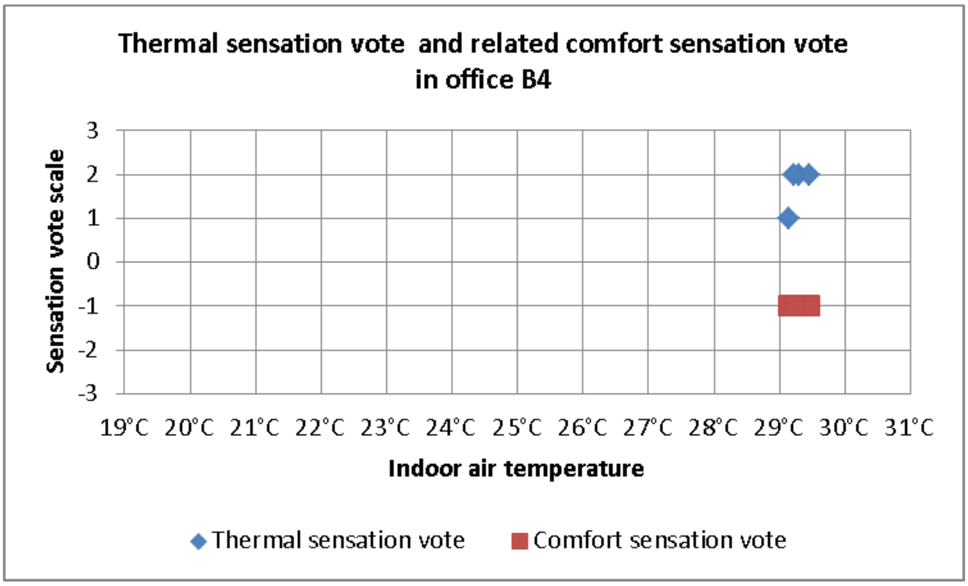


Figure 6.35: Thermal sensation vote and related comfort sensation vote when occupant feels uncomfortable in office B4 (SSV).

Figure 6.36: The psychrometric chart for uncomfortable time (Blue circle) in office B4 (SSV). (Yellow: still air condition, red: air flow speed about 1.5m/s).

The humidity sensation vote result showed the relative humidity varying between 30% and 80% in the office, but occupants did not have any humid sensation during the entire monitored period (Figure 6.37). The votes were mainly on 0 (Neutral) and -1 (Slight dry). The result was similar to that in offices B1 and B2. And also, the slightly humid (-1) vote appeared when the relative humidity dropped below 60%. This result was the same as in four rooms in office building B.

Therefore, the related environment data of the slightly humid sensation vote was addressed in the psychrometric chart to identify whether it related to absolute humidity in the office or not (Figure 6.38). The figure showed that all the data were located within the yellow comfort zone, which was the reason that the low relative humidity value and slightly dry sensation did not cause any uncomfortable sensation vote in the office. The data distribution was random, and absolute humidity value was between 4g/kg and 14g/kg which would not cause any arid problem in the office. The reason that the slightly dry sensation started when the indoor relative humidity dropped below 60% may need further study.

Occupants in office building B, except for those in office B3 who felt the indoor environment was tending towards dry, may relate to personal adaptability to the environment. They can adapt to the relatively high humidity and are more sensitive when the relative humidity was decreased in the office. The situation was similar to that in office building A.

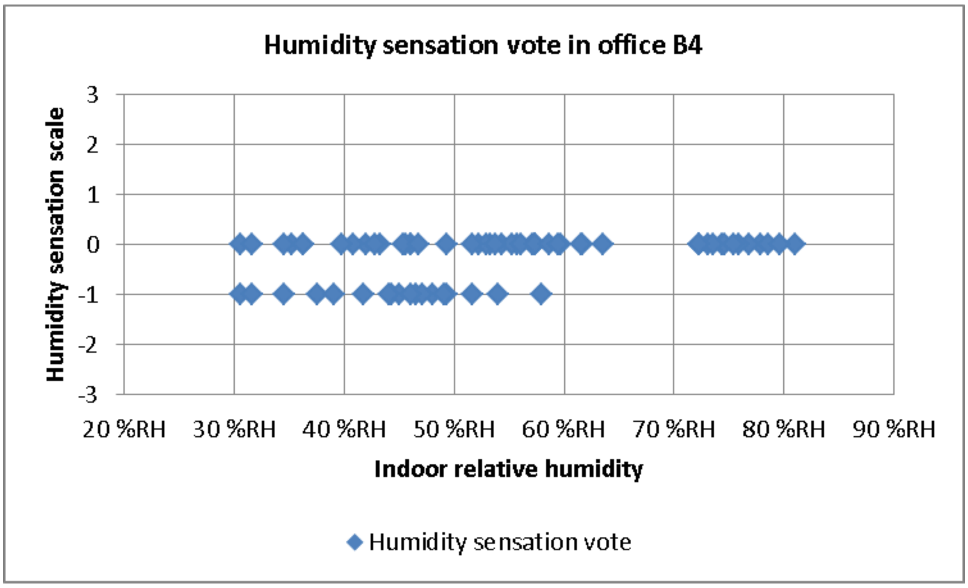


Figure 6.37: Humidity sensation vote in office B4 (SSV) during the working hours in the monitored period.

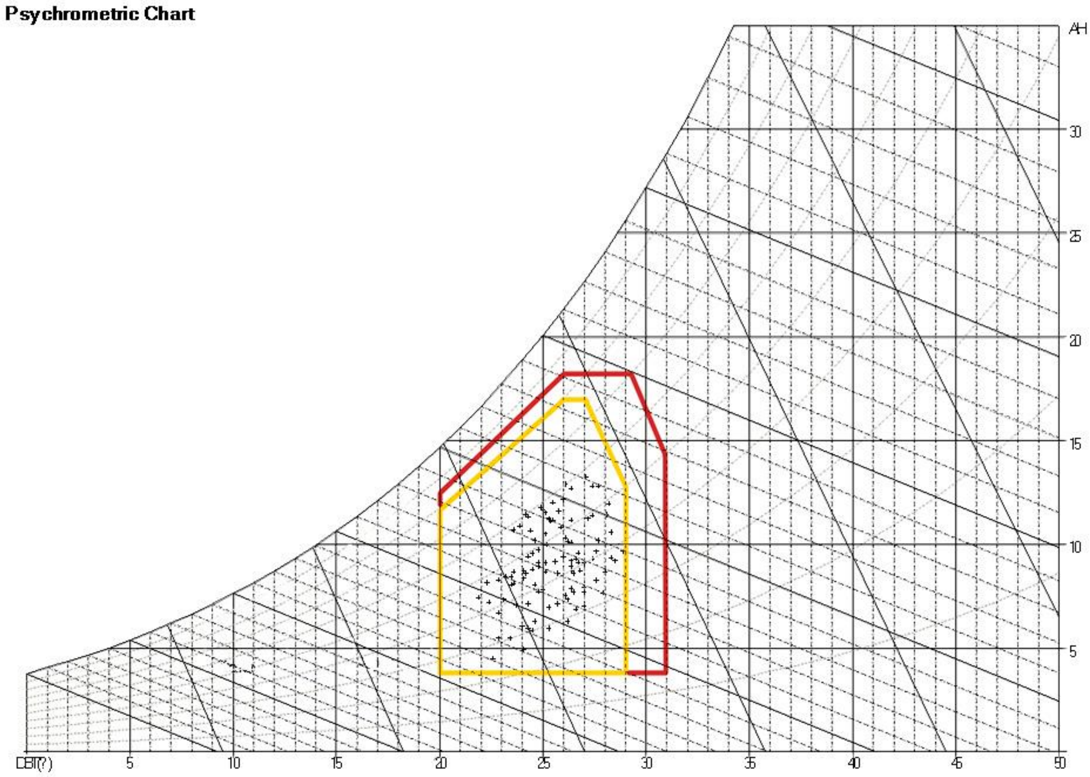


Figure 6.38: The psychrometric chart for humidity sensation vote on -1 (Slightly dry) in office building B. (Yellow: still air condition, red: air flow speed about 1.5m/s).

The indoor air quality perception result was shown on Figure 6.39. The vote was between -1 (Slightly stuffy) and 1 (Slightly fresh), and most of the votes were on neutral (0). According to the result, the indoor air quality was acceptable. However, the vote on -1 was more than that on 1. The indoor air quality perception was tending to slightly stuff, which may because office B4 was single-side ventilated during the working hours. Compared with cross-ventilated office, occupant felt slightly stuff in this office.

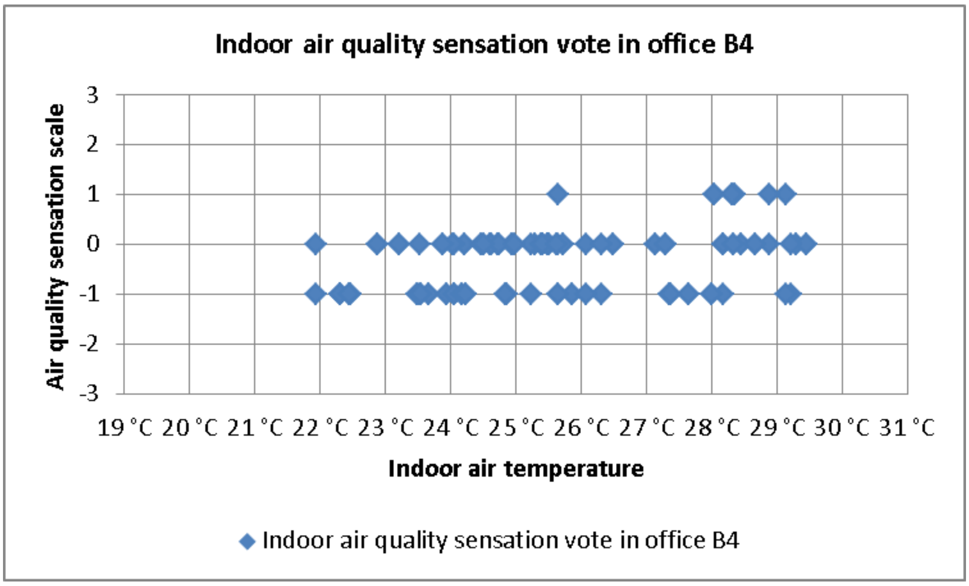


Figure 6.39: Indoor air quality sensation vote in office B4 (SSV) relate to indoor air temperature during the working hours in the monitored period.

To sum up, as office B1 was cross-ventilated, the occupants did not have an uncomfortable sensation in the office during the working hours, even though some of the data were out of Givoni's (1998) comfort zone with high relative humidity. Office B2 had the lowest average indoor air temperature during the working hours, but the time when occupants felt uncomfortable was more than that in other offices of the building. The reason was that the indoor air temperature was slightly higher than 29°C, which was just out of the boundary of the yellow comfort zone (still air condition). The closed door was another reason which caused the indoor air flow speed to reduce. If an office room could be cross-ventilated, the uncomfortable time could be reduced. Office B3 was cross-ventilated and the indoor air temperature was in the comfort range. The high humidity level was the reason leading to occupant uncomfortable sensation, though the indoor environment was well naturally ventilated. In office B4, the result was similar to that in office B2, and the high indoor air temperature was the reason which caused occupants to feel uncomfortable. Changing the natural ventilation type from single-side ventilation to cross-ventilation would improve the situation.

Besides, based on the thermal sensation vote result in these four offices, it can be seen that the warm sensation vote (+1) started at 24°C or 25°C, the same as the result in office A. And the cool sensation vote (-1) started around this temperature as well. It seemed the air temperature between 24°C and 25°C was the neutral point in the offices during the monitored period. Based on De Dear's equation (Equation 1.7), it was 27.3°C for September, 25.9°C for October, and ±2.5°C for 80% acceptability. The air temperature in these offices was lower than this point, but the acceptable air temperature range was much wider than ±2.5°C. The lowest indoor air temperature was 20°C, occupants feeling cool but still comfortable. For the upper threshold, if the indoor air temperature was below 29°C, 84% of occupants felt comfortable; and if the temperature was lower than 27°C, all the occupants in the office were satisfied. If the office could be cross-ventilated with positive indoor air flow speed, the comfort temperature could be extended. The comfort thresholds for occupants in office building B and office building A were very close to Givoni's (1998) comfort zone. It will be further identified in the next two offices.

In addition, in these four offices, the humidity sensation vote cannot precisely perceive the indoor humidity level, but it gives occupants a general humidity sensation in the office. And a small number of occupants felt slightly humid when the relative humidity rose over 70%. But, mainly, most occupants felt slightly dry in the room, so they used different ways to moisturise the skin. Occupants could adapt more to the humid situation than the dry condition. However, the situation was different in office B3, where occupants were more sensitive to the high humidity level compared to the other offices when the relative humidity rose over 75%. But if the relative humidity was below 60%, they also would feel slightly dry as well. The reason for the relative humidity at 60% to become a threshold for the slightly dry sensation in the office cannot be identified by a psychrometric chart.

The indoor air quality perception result was similar with building A that indoor air quality perception result in cross-ventilated office was better than single-side ventilated office. But in the single-side ventilated office in building B, occupant felt slightly stuff in the office which was better than the result in single-side ventilated office in building A.

6.3 Office building C

In office building C, office C1 (SSV) was single-side ventilated, the average indoor air temperature was higher than the other two offices in the building. During more than 20% of working hours, the indoor air temperature was higher than 29°C (Figure 6.40). This number was about 6% in office C2 (CV), which was cross-ventilated. Office C3 (CV) was cross-ventilated as well. It has the lowest average indoor air temperature and the mean radiant temperature in the office. The average indoor mean radiant temperature was 26.27°C during the working hours, which was 0.04°C lower than the average indoor air temperature. Besides, in the working hours, the indoor air temperature was within Givoni's comfort temperature range.

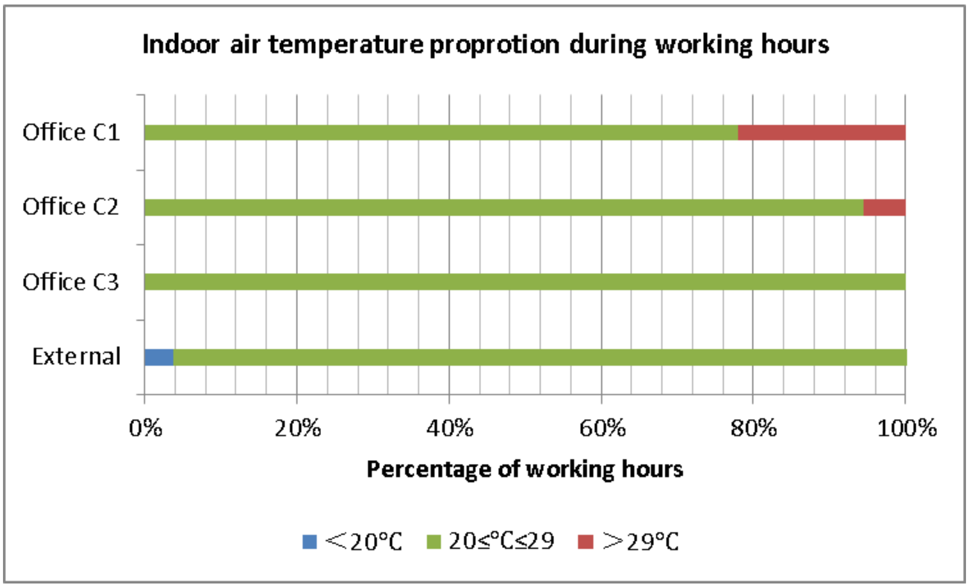


Figure 6.40: The dry bulb air temperature proportion in office building C and outdoor, during the working hours.

The detailed indoor air temperature and relative humidity are shown on the psychrometric chart (Figure 6.41), which also shows the environmental data distribution in office C1. In lots of the time the data were located in the extended comfort zone, varying from 30% to 80%. Some data were even outside of the comfort zone which is related to high relative humidity. Therefore, in office C1, during the time in the extended comfort zone it was difficult for occupants to achieve comfort because of the natural ventilation type in the office (presented in section 5.2.3). In office C2 (Figure 6.42), the data in the extended comfort zone were on the top of the comfort zone, mainly related to high relative humidity. Because the office was cross-ventilated, thermal comfort may still have been achieved in the office. There were also few times outside of the comfort zone. In office C3 (Figure 6.43), the situation was much better compared to other offices. In most of the time, the indoor air temperature and relative humidity were within the yellow comfort zone, while only a few times were in the extended comfort zone.

Figure 6.41: The psychrometric chart for office C1 (SSV).
(Yellow: still air condition, red: air flow speed about 1.5m/s).

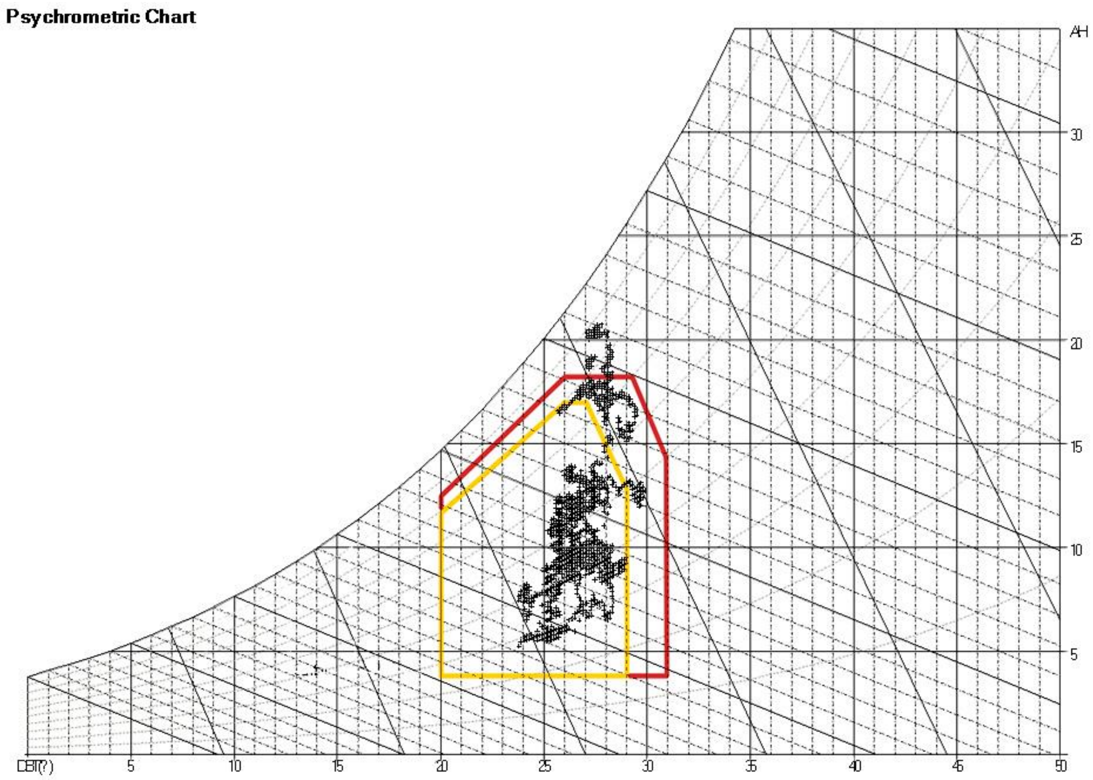


Figure 6.42: The psychrometric chart for office C2 (CV).
(Yellow: still air condition, red: air flow speed about 1.5m/s).

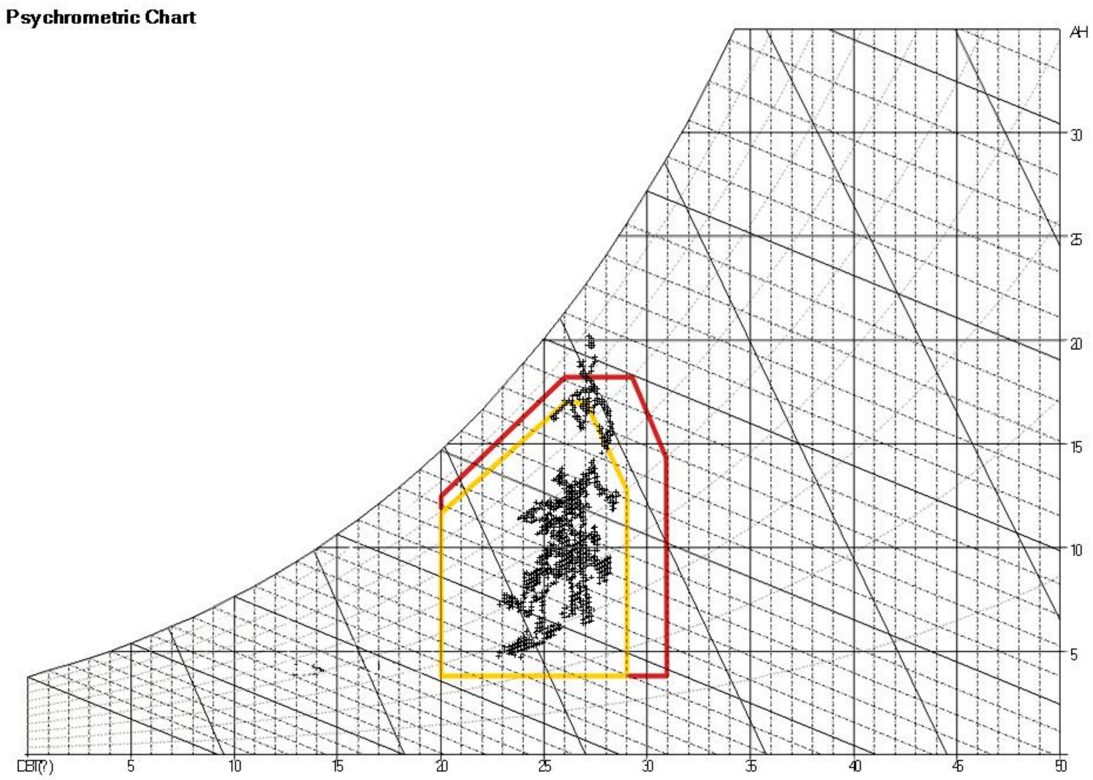


Figure 6.43: The psychrometric chart for office C3 (CV).
(Yellow: still air condition, red: air flow speed about 1.5m/s).

6.3.1 Thermal comfort perceptions in the office C1

Office C1 (SSV) had the worst indoor environmental condition when compared to the other offices. Figure 6.44 shows the thermal sensation vote (included 2 voters and 480 votes) in office C1. The vote was from 0 (Neutral) to 3 (Very hot) and the indoor environmental condition was tending towards hot. The indoor air temperature varied between 24°C and 30°C. When the indoor air temperature rose above 24.9°C, occupants would feel warm in the office and the votes were mainly between 27.6°C and 29.3°C. When the indoor air temperature exceeded 26.4°C, the occupants were voting on hot (+2) and the vote was primarily above 29°C. And the vote was on very hot (+3) when the air temperature was around 30°C. Thus, the occupants would feel hot in the office when the indoor air temperature rose over 29°C, which would probably cause occupants to feel uncomfortable in the single-side ventilated office.

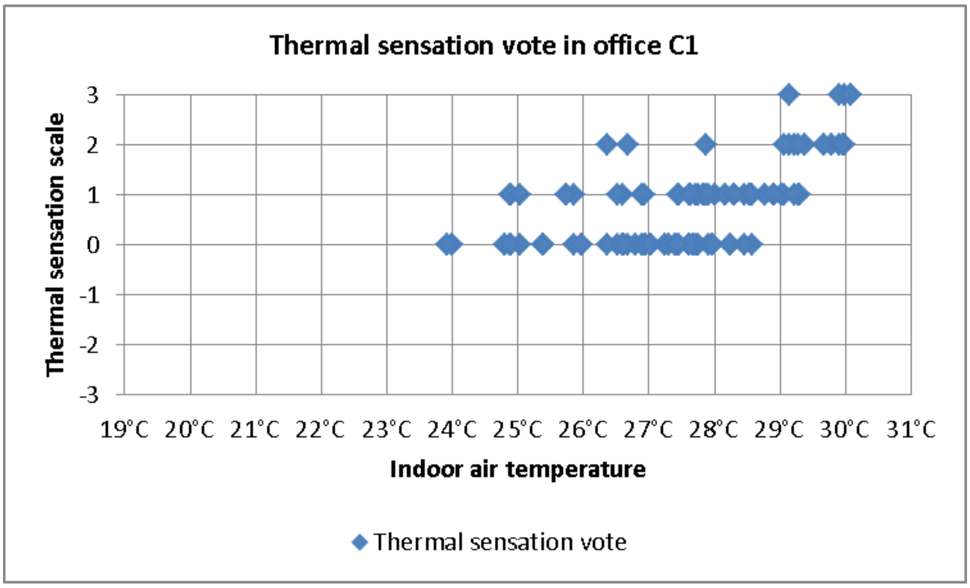


Figure 6.44: Thermal sensation vote in office C1 (SSV) during the working hours in the monitored period.

Correlating the thermal sensation vote with occupant uncomfortable sensation vote, the results show (Figure 6.45) that during 27% of working hours occupants felt uncomfortable (the comfort sensation vote was negative). When indoor air temperature rose over 27°C, the occupants were beginning to vote on slightly uncomfortable (-1), and most of the uncomfortable vote (-2) started when indoor air temperature exceeded 29°C. So, when indoor air temperature was higher than 29°C, all the occupants felt uncomfortable in the office, and only the thermal perception degree was different. Although occupants were feeling very hot (+3) in the office, none of them voted on very uncomfortable (-3), so it seems in some situations when the indoor air temperature was around 29°C the occupants could still tolerate the indoor environment. For a couple of hours the occupant thermal sensation vote was on neutral (0), but they did feel slightly uncomfortable. The indoor air temperature was under 28°C and relative humidity was around 40%. Based on these environmental factors which were in the comfort zone, occupants should be satisfied with the indoor environment, and other reasons may cause discomfort. Those data of uncomfortable time were plotted into a psychrometric chart to identify whether it was outside the comfort zone or not.

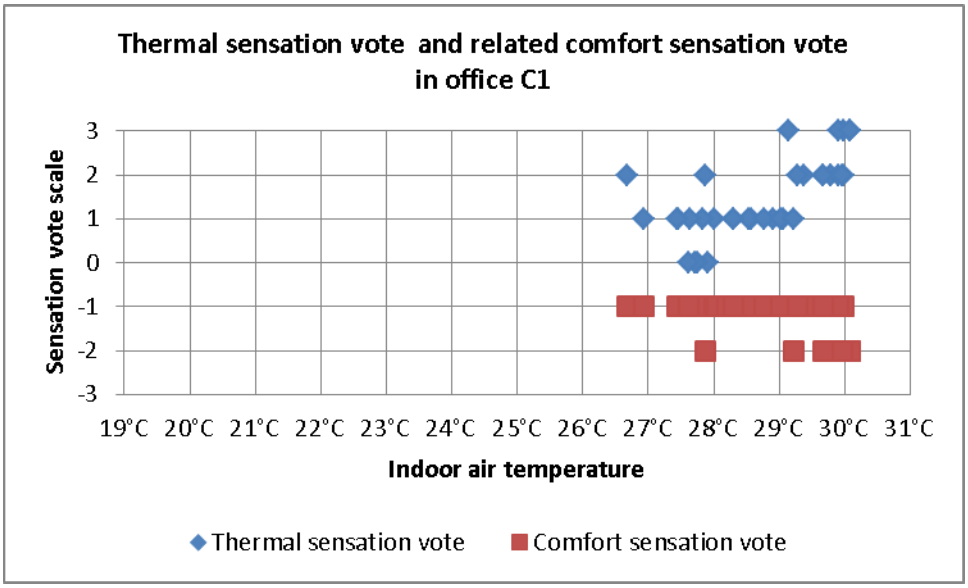


Figure 6.45: Thermal sensation vote and related comfort sensation vote when occupant feels uncomfortable in office C1 (SSV).

The indoor air temperature and relative humidity which causes occupants to feel uncomfortable are shown in Figure 6.46. The indoor uncomfortable time was mainly in the red comfort zone; some data were also located in the yellow comfort zone; and the data were above 27°C. According to Figure 6.45, when indoor air temperature was below 29°C, occupants felt slightly uncomfortable, which means those data in the yellow comfort zone were endurable, even some points being in the extended comfort zone area. The uncomfortable data were entirely located in the extended comfort zone, although one datum was around 28°C but with 74% relative humidity, which was just located outside the yellow comfort zone. Thus, the indoor air temperature was the main issue to the occupant thermal comfort, and increasing indoor air flow speed was an efficient way to reduce the uncomfortable time. Repairing the door holder and allowing the office to be cross-ventilated was an easy way to keep office cross ventilated.

Figure 6.46: The psychrometric chart for uncomfortable time (Blue circle) in office C1 (SSV). (Yellow: still air condition, red: air flow speed about 1.5m/s).

The humidity sensation vote results showed that most of the votes were on 0 (Neutral) and -1 (Slightly dry) (Figure 6.47). When the indoor relative humidity was lower than 63.7%RH, some occupants would feel slightly dry (-1). Only in a little time did occupants feel slightly humid (+1) or humid (+2) when the indoor relative humidity was above 70%RH. The situation was quite similar with that in office buildings A and B, that occupants felt the indoor environment to be slightly dry.

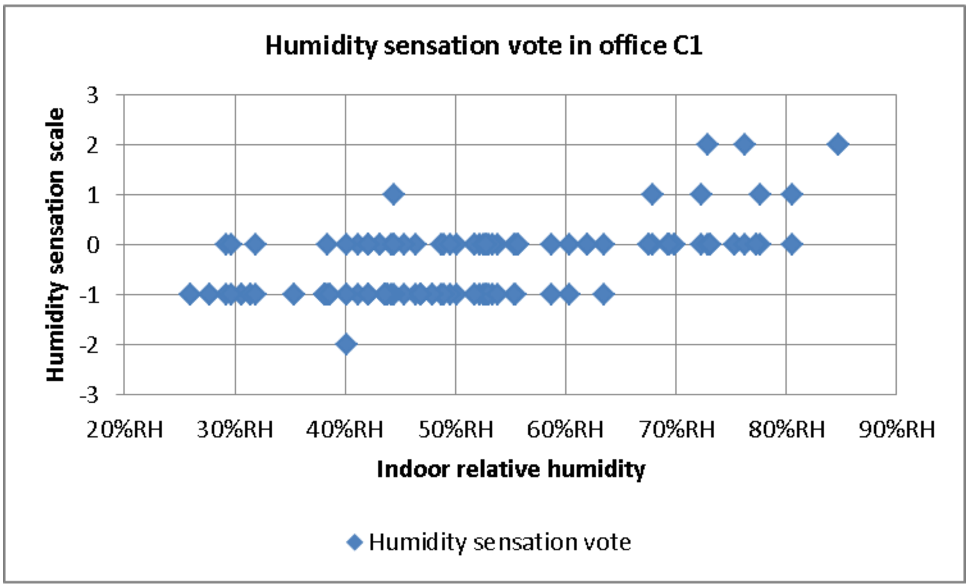


Figure 6.47: Humidity sensation vote in office C1 (SSV) during the working hours in the monitored period.

Office C1 was single-side ventilated, and the indoor air quality perception result (Figure 6.48) was similar to the single-side ventilated office in building B. According to the result, the vote was between -1 (Slightly stuffy) and 2 (Fresh), and most of votes were between 0 (Neutral) and 2 (Fresh). So the indoor air quality was acceptable during the working hours. In addition, in most of working hours that occupant was satisfied with the indoor air quality.

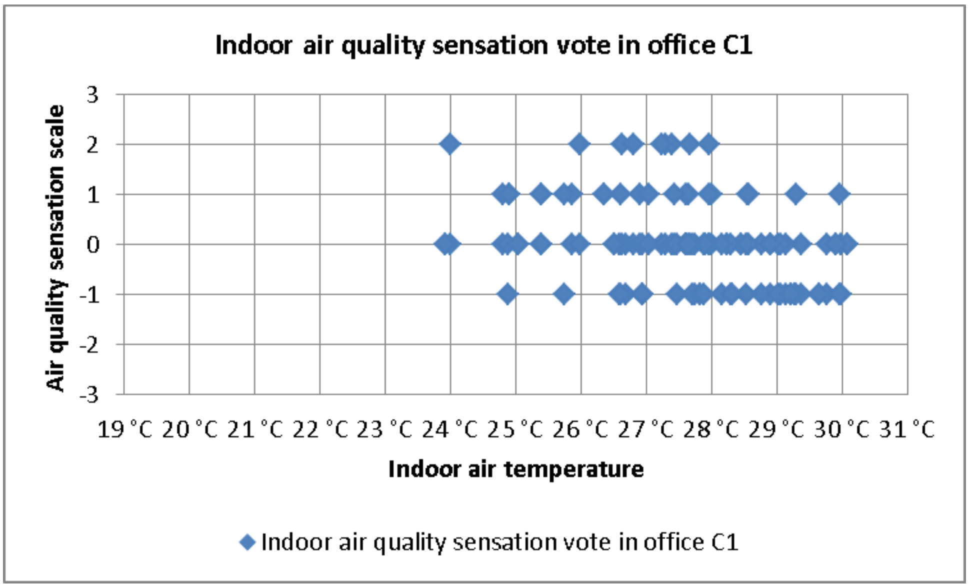


Figure 6.48: Indoor air quality sensation vote in office C1 (SSV) relate to indoor air temperature during the working hours in the monitored period.

6.3.2 Thermal comfort perceptions in the office C2

In office C2 the thermal sensation vote (included 2 voters and 480 votes) was from -1 (Cool) to +2 (Hot). In the little time that occupants felt cool was when the indoor air temperature was below 25°C, when the main vote was tending towards hot in the office (Figure 6.49). The warm sensation vote (+1) started at 24.8°C, which was quite close to the offices in buildings A and B. When the indoor air temperature was over 26.6°C, occupants would feel hot (+2) in the office. When the air temperature was over 29°C, it would cause occupants to feel hot in the office, but some votes were still on warm (-1), which means the indoor air temperature was still acceptable. And the number of votes on warm (+1) and hot (+2) was close, so the difference was related to an occupant's thermal acceptability – some occupants feel hot, while some feel warm in the same temperature.

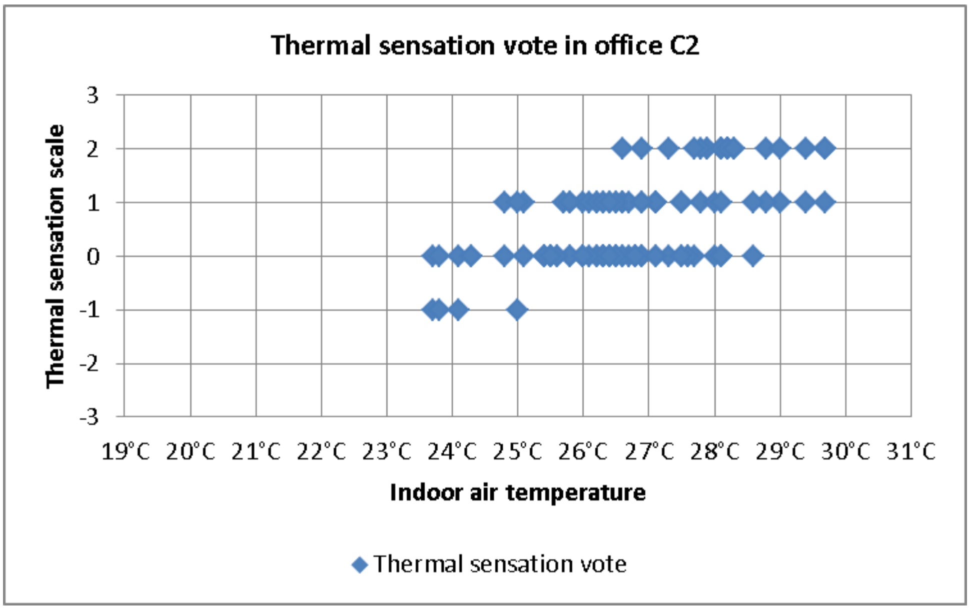


Figure 6.49: Thermal sensation vote in office C2 (CV) during the working hours in the monitored period.

The occupants felt slightly uncomfortable (-1) when the indoor air temperature rose over 26.6°C, and even when it was 29.4°C some occupants still had the same thermal sensation vote, which means they still can accept the indoor temperature (Figure 6.50). But for some occupants the situation was different. The lower threshold for slightly uncomfortable was closer to the result in office C1 but lower than the offices in buildings A and B. In 5% of working hours occupants felt uncomfortable (-2) in the office, and in 20% of working hours occupants voted on hot (+2). Some occupants voted on hot (+2), but the hot perception did not cause an uncomfortable sensation. Thus, during most of the time, occupant comfort sensation still voted on neutral or comfortable, and the main environmental conditions were still acceptable. According to the psychrometric chart (Figure 6.51), the uncomfortable related data were on the top part of the comfort zone, mainly located in the extended comfort zone. It seemed that the uncomfortable sensation vote was caused by high relative humidity, though when the occupant vote was on -2 (Uncomfortable), the related data were in the extended comfort area and the relative humidity was lower than 70%. The vote on -2 (Uncomfortable) was mainly related to the indoor air temperature. The high relative humidity was the reason that caused occupants to vote on -1 (Slightly uncomfortable) and this situation was still tolerant.

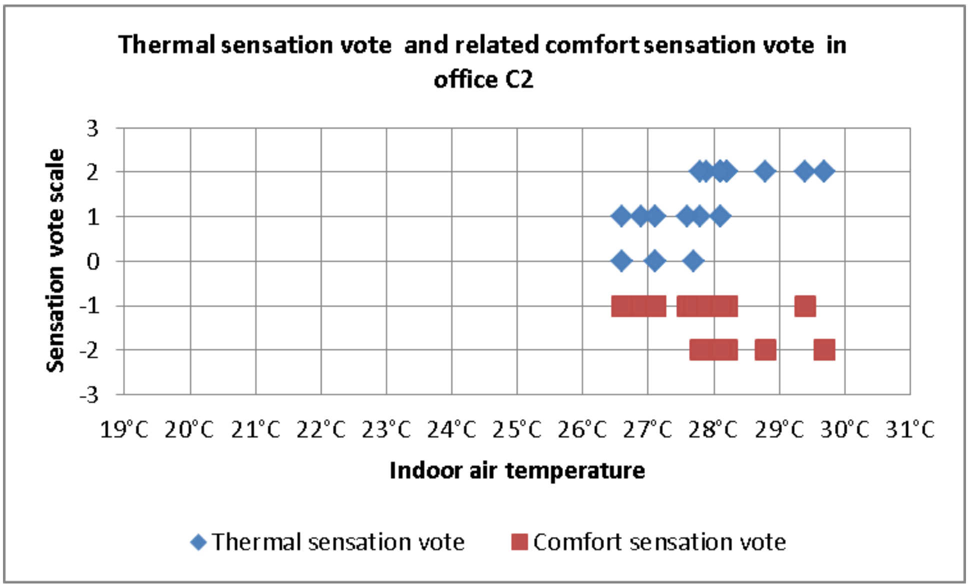


Figure 6.50: Thermal sensation vote and related comfort sensation vote when occupant feels uncomfortable in office C2 (CV).

Figure 6.51: The psychrometric chart for uncomfortable time (Blue circle) in office C2 (CV). (Yellow: still air condition, red: air flow speed about 1.5m/s).

The humidity sensation vote in office C2 was from -2 (Dry) to 2 (Humid) (Figure 6.52). The time that occupants felt humid was more than that in other offices. The slightly humid vote (+1) began at 40.0%RH and ended at 87.1%RH. Few humid (+2) sensation votes occurred when the relative humidity was above 70%, but some occupants still felt humid. The slightly dry (-1) sensation vote varied between 27.0%RH and 61.9%RH. This result was close to that in office building B. According to the psychrometric chart and humidity sensation vote result, the occupants in office C2 were more sensitive to humidity than other offices, and high relative humidity would cause an uncomfortable sensation but most of the situation seemed acceptable. More votes were located on slightly dry (-1) and neutral (0), in most of the working hours; occupants still felt the indoor environmental condition to be slightly dry.

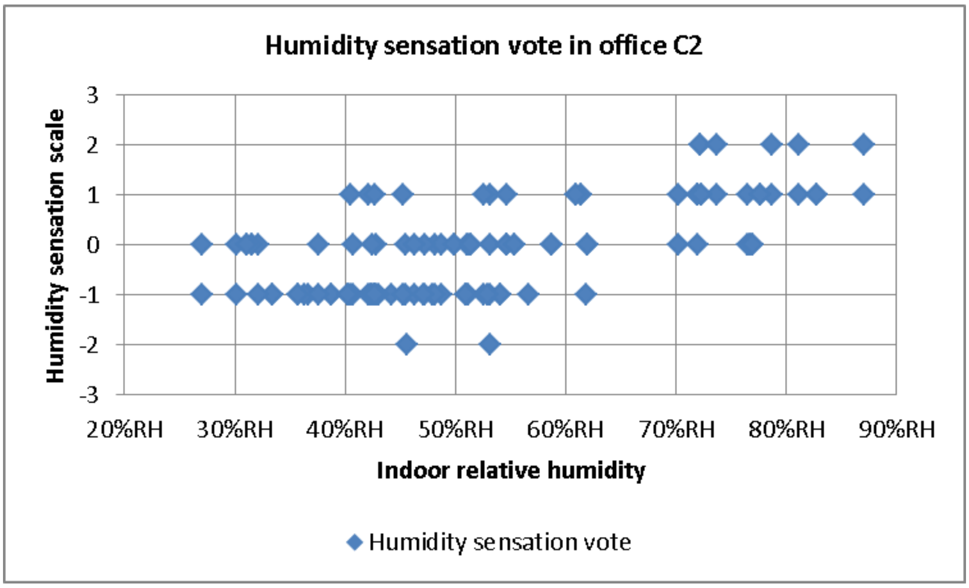


Figure 6.52: Humidity sensation vote in office C2 (CV) during the working hours in the monitored period.

In office C2, the air quality perception result (Figure 6.53) varied between -1 (Slightly stuffy) and 3 (Very fresh). Most of the votes were between 0 (Neutral) and 2 (Fresh). Occupant felt slightly stuff in the office in a very short period. As same as in other cross-ventilated offices, the indoor air quality was acceptable in the office and occupants were satisfied in most of working hours.

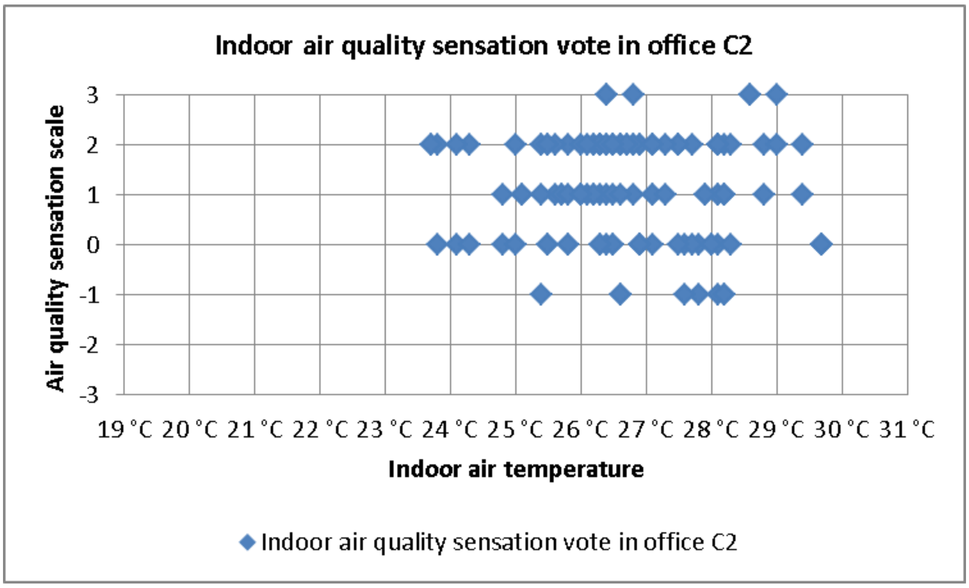


Figure 6.53: Indoor air quality sensation vote in office C2 (CV) relate to indoor air temperature during the working hours in the monitored period.

6.3.3 Thermal comfort perceptions in the office C3

Office C3 (CV) had the lowest average indoor air temperature in office building C. The result of thermal sensation vote (included 2 voters and 480 votes) distribution was similar to office C2 (Figure 6.54). The vote was mainly between 0 (Neutral) and 2 (Hot), and the indoor environment was tending towards hot. The warm sensation vote started when the indoor air temperature rose over 25°C. This result was similar to the other offices in office buildings A and B. The hot sensation vote occurred when the indoor air temperature was over 26°C. This was similar to the other two offices in the building and this temperature was 1°C lower than the result in office building B. This may be related to indoor air flow speed, based on Table 5.3and Table 5.5, the average indoor air flow in office B being slightly higher than that in office C, especially on points R and S which were close to the occupant. In addition, because the indoor air temperature was not over 29°C during the working hours, it was estimated that the vote on hot would be limited. But there was still 11% of working hours that occupants felt hot in the office. Because in office C3 the roller blind was used quite often, that would influence the air flow passing through the open window when it was lowered. It may be the reason that caused occupants to feel hot in the office.

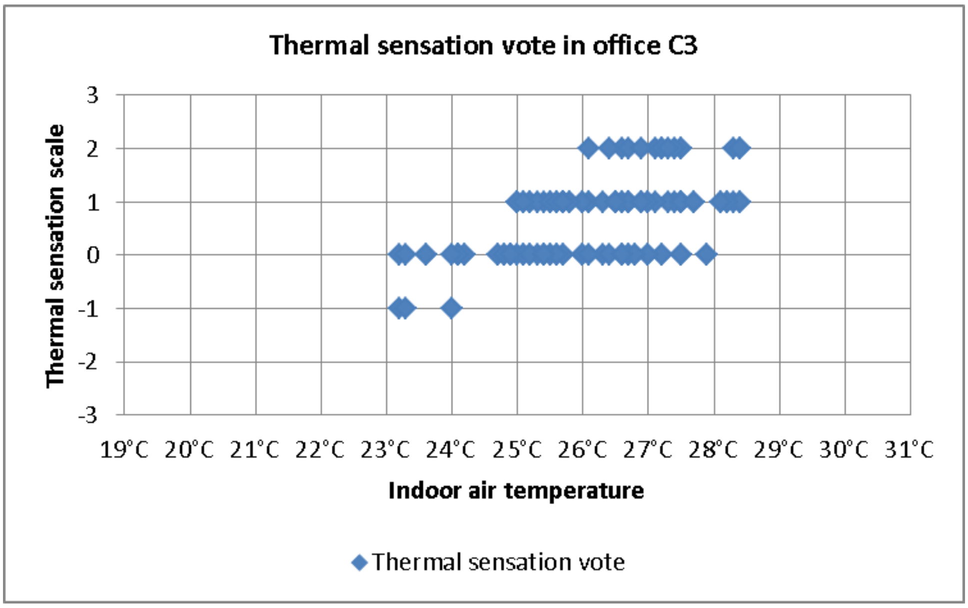


Figure 6.54: Thermal sensation vote in office C3 (CV) during the working hours in the monitored period.

Figure 6.55 showed the uncomfortable sensation vote related to the thermal sensation vote. None of the occupants felt uncomfortable (-2) in the office, the vote was only on the slightly uncomfortable (-1), which was better than other offices in the building (presented in Figure 6.45and Figure 6.50). Although some occupants felt hot in the office, it did not cause occupants to felt uncomfortable (-2) in the office, and the indoor environmental condition seemed still to be acceptable by the occupants in office C3.

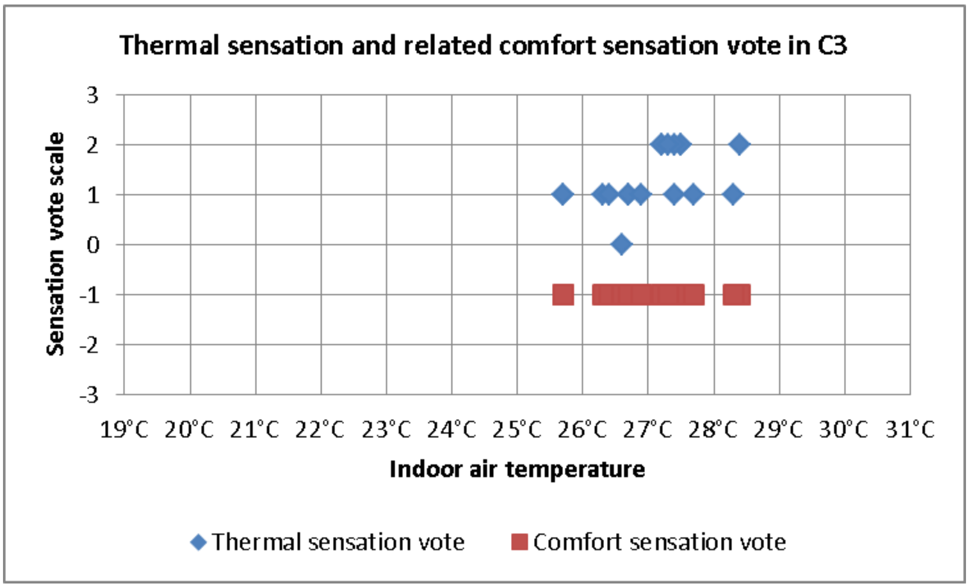


Figure 6.55: Thermal sensation vote and related comfort sensation vote when occupant feels uncomfortable in office C3 (CV).

The slightly uncomfortable vote mainly occurred in the first week of monitoring time. Because the indoor air flow speed was not measured in office building C in the first week, the indoor air flow condition could not be identified. The opening state and effective opening size of the window can be used to estimate the possible indoor air flow condition. According to Figure 6.56, during the working hours the indoor air temperature was very close to the outdoor air temperature. Windows were opened in the working hours, so the office was cross-ventilated. But in the morning and afternoon, the outdoor air temperature was lower than the indoor. The indoor air temperature drop was limited when the window was opened widely. Especially on 28th and 29th, there was a large temperature difference. The daily indoor air temperature difference was 2°C, which means the indoor air temperature was very stable. Based on the open record, the average effective opening area on 28th varied between $0.5m^2$ and $1.2m^2$, while this value was between $0.3m^2$ and $1.3m^2$ on 29th. In addition, the measured average indoor air flow speed around occupants was about 0.7m/s, which was positive for occupant thermal comfort. This may be the reason that occupants felt hot but felt just slightly uncomfortable.

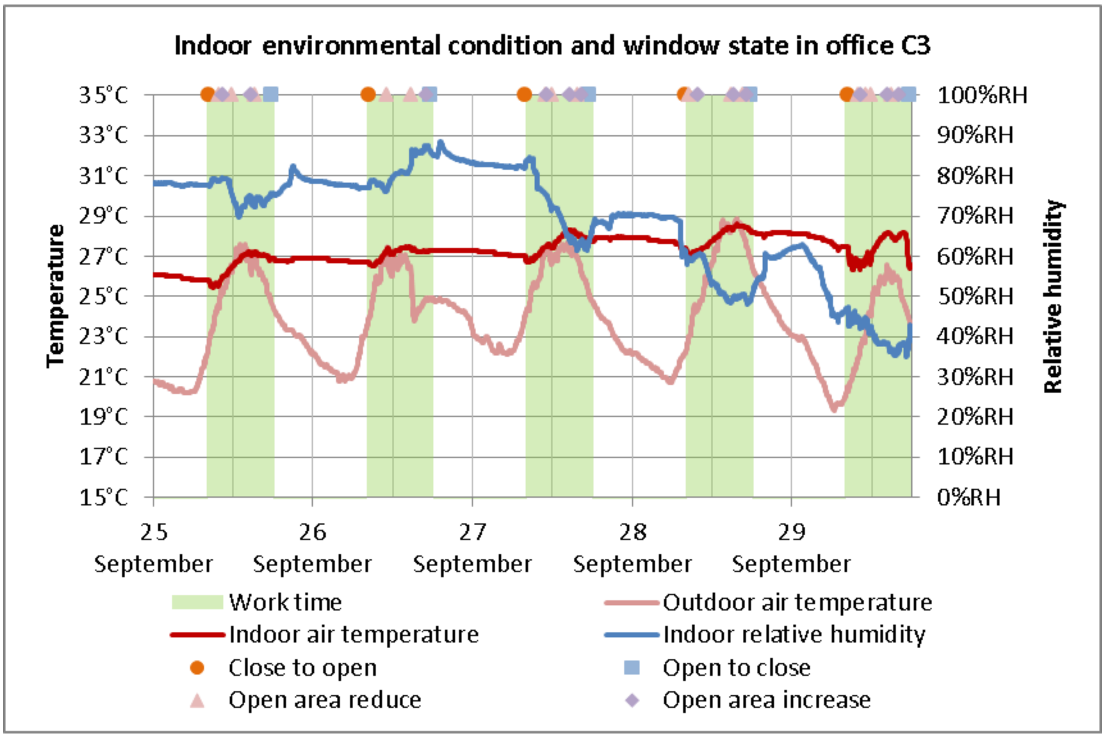


Figure 6.56: Indoor air temperature, relative humidity and widow state in three days in office C3 (CV).

The humidity sensation vote in office C3 was between -2 and 2 (Figure 6.57). The occupant humidity sensation was more varied than in the other two offices, occupants could not perceive the humidity level, and the result was close to office building A. Only when indoor relative humidity rose over 80%RH did occupants feel humid (+2) in the office. Generally, the same as that in other offices, more votes were inclined to the dry condition.

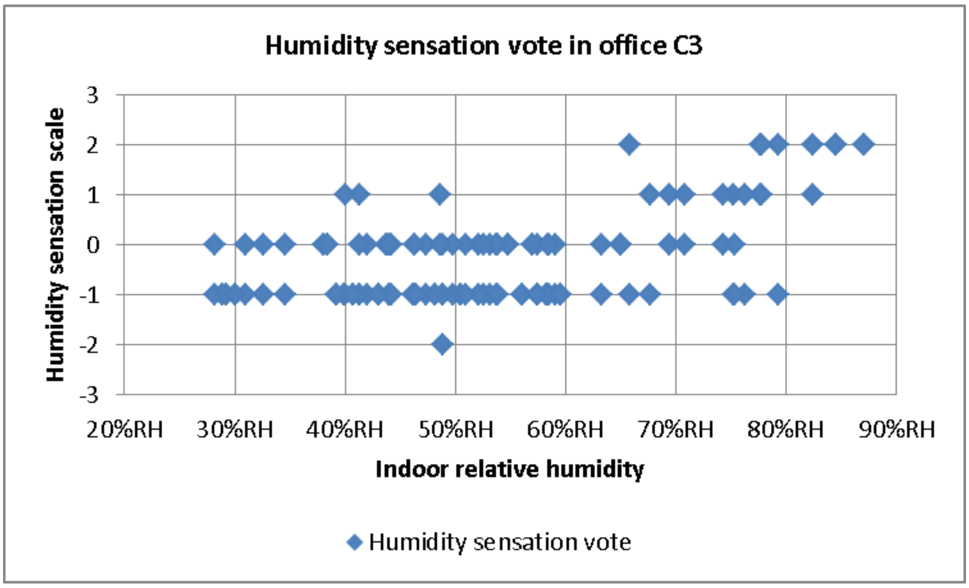


Figure 6.57: Thermal sensation vote in office C3 (CV) during the working hours in the monitored period.

The indoor air quality perception result in office C3 (Figure 6.58) was between -1 (Slightly stuff) and 2 (Fresh), and few votes were on 2. In generally, the air quality in office C3 was still acceptable.

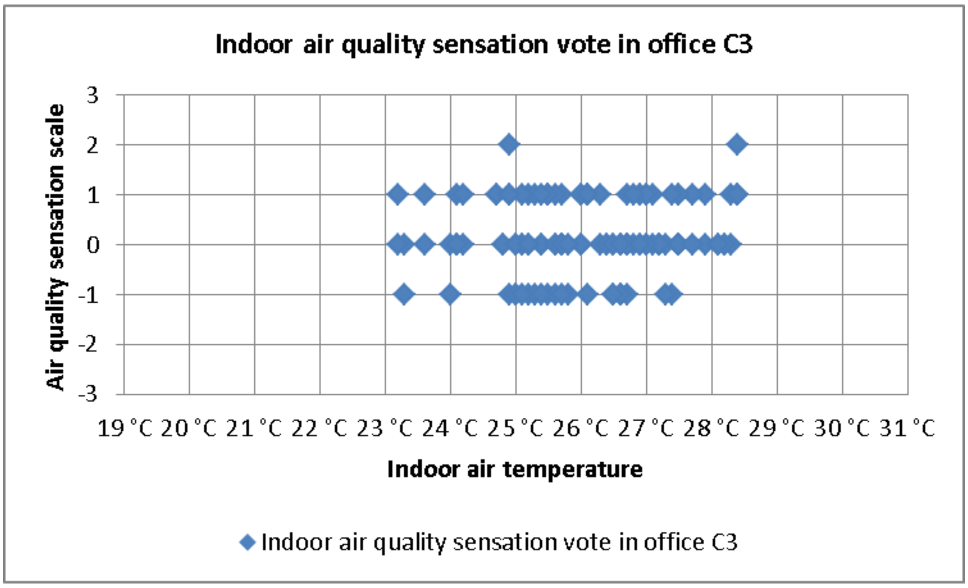


Figure 6.58: Indoor air quality sensation vote in office C3 (CV) relate to indoor air temperature during the working hours in the monitored period.

To sum up, in office building C, the indoor environmental condition was tending towards hot in three offices, which was similar to the situation in office buildings A and B. Many occupants voted on hot when the indoor air temperature rose over 26°C, but based on occupants' comfort sensation vote the indoor situation was still acceptable when the indoor air temperature was below 28°C. In office C1, this air temperature was 29°C, though the office was single-side ventilated with the worst thermal sensation vote results. If cross-ventilation could be achieved, this situation could be improved. In office C2, the vote on uncomfortable (-2) was related to indoor air temperature which was higher than 28°C. And the vote on -1 (slightly uncomfortable) was related to the higher humidity level. Occupants could still tolerant this situation. In office C3, none of the occupants voted on uncomfortable (-2) and they voted on slightly uncomfortable when the indoor air temperature rose above 25°C, and the indoor thermal situation was still acceptable. The lower threshold of warm vote was between 24°C and 25°C, the same as the other office buildings.

Generally, the occupants in office building C felt neutral or slightly dry, as most of the humidity sensation vote was on 0 (Neutral) and -1 (Slightly dry). But when the indoor relative humidity was over 80%RH, some of the occupants felt humid in the office. Compared to the other offices in the building, occupants in office C2 were more sensitive to the humidity, as the vote on humid was more than other offices, which caused occupants to feel slightly uncomfortable in the office. And indoor air quality was acceptable by occupants.

6.4 Office building D

In office building D, the three offices have different orientations. According to Figure 6.59, the indoor air temperature in office D1 (SSV) (facing north-east) during the working hours was within the comfort zone. The indoor air temperature was higher than 29°C in office D2 (SSV) (facing south-west) in 3% of working hours, which was mainly because of the direct sunlight in the afternoon that caused discomfort. In office D3 (SSV) (facing north-west), there was 1% of working hours that the indoor air temperature was below 20°C. Based on the indoor air temperature proportion, only in 4% of the time may occupants have felt uncomfortable. The indoor mean radiant temperature was measured in office D1 where the average value was 24.3°C in working hours, and it was 0.8°C lower than the average indoor air temperature. According to the psychrometric chart for the three offices (Figure 6.60, Figure 6.61 and Figure 6.62), there were still many data located in or even outside the extended comfort zone, because of the high humidity level. Therefore, increasing indoor air flow speed near the occupant was needed to achieve thermal comfort when the air temperature and relative humidity was in the extended comfort area.

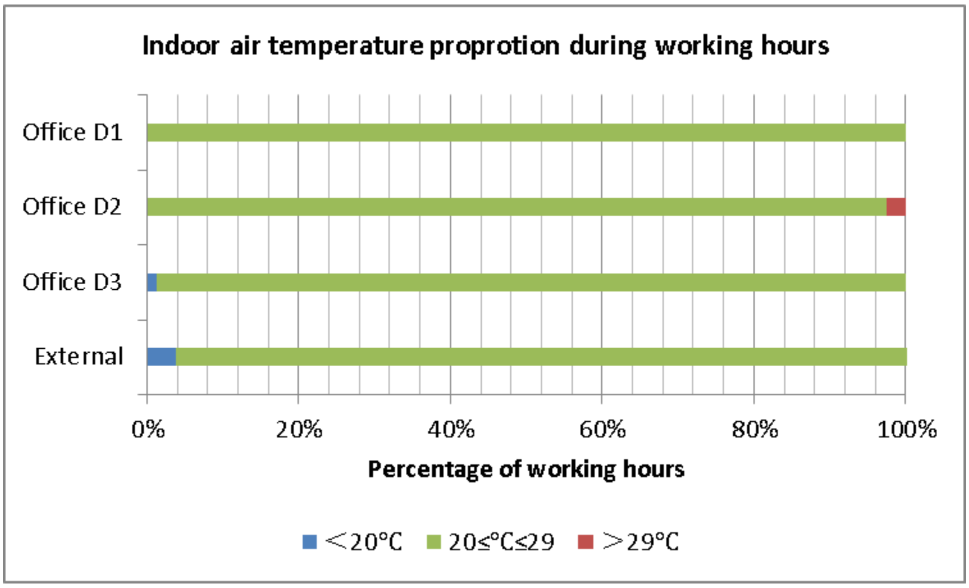


Figure 6.59: The dry bulb air temperature proportion in office building D and outdoor, during the working hours.

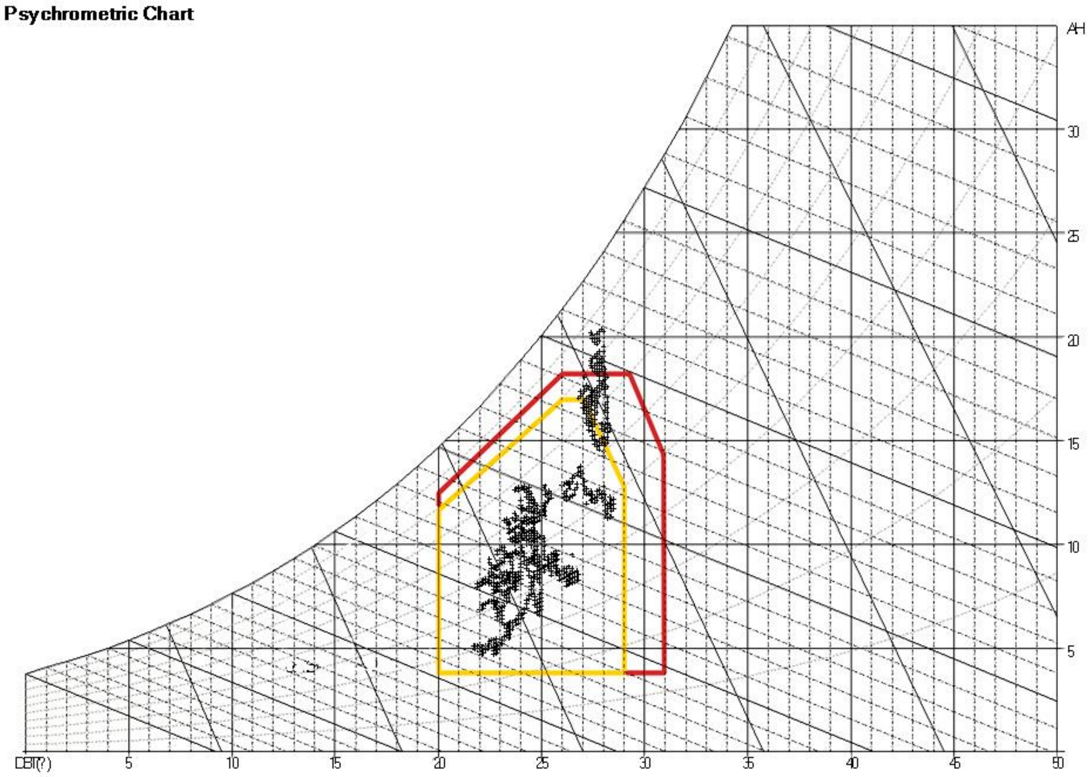


Figure 6.60: The psychrometric chart for office D1 (SSV).
(Yellow: still air condition, red: air flow speed about 1.5m/s).

Figure 6.61: The psychrometric chart for office D2 (SSV).
(Yellow: still air condition, red: air flow speed about 1.5m/s).

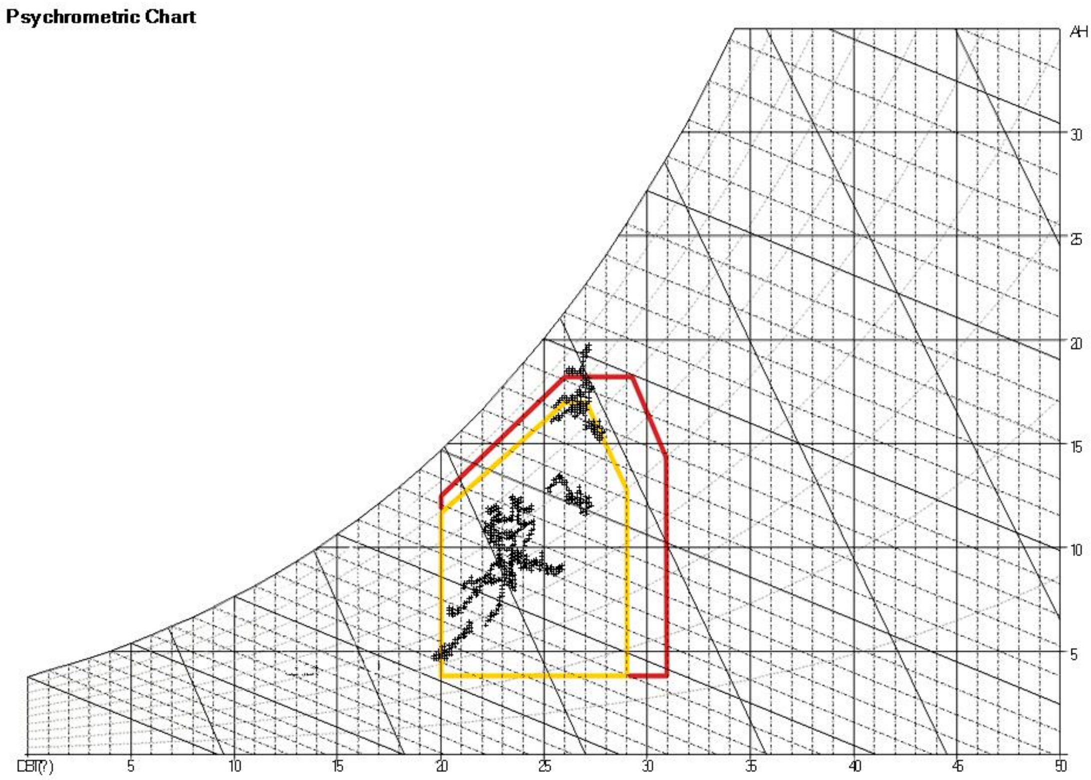


Figure 6.62: The psychrometric chart for office D3 (SSV).
(Yellow: still air condition, red: air flow speed about 1.5m/s).

6.4.1 Thermal comfort perceptions in the office D1

The thermal sensation vote (included 2 voters and 480 votes) in office D1 was between Cool (-1) and Warm (+1) (Figure 6.63). When the indoor air temperature rose over 24.7°C occupants started feeling warm (+1), and when the indoor air temperature was below 25.7°C the cool sensation occurred. The same as in other offices, the cool and warm sensation developed around 24°C and 25°C. The major vote was on 0 (Neutral) and -1 (Cool), the occupant sensation was inclined towards cool in the office. Based on occupants' votes, the indoor environment was acceptable during the working hours.

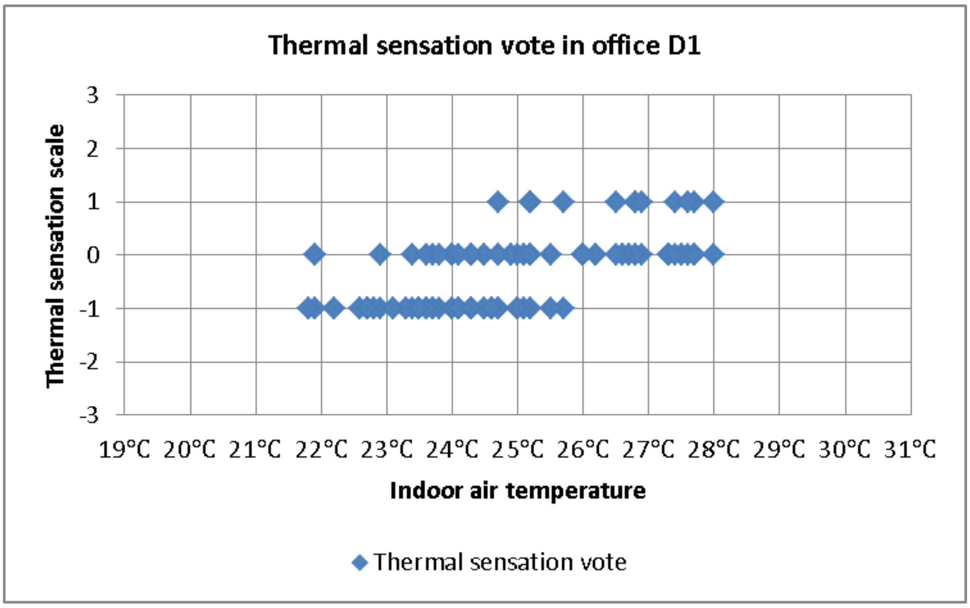


Figure 6.63: Thermal sensation vote in office D1 (SSV) during the working hours in the monitored period.

According to the comfort sensation vote results (Figure 6.64), the occupants were satisfied with the indoor environmental condition, none of them feeling uncomfortable during the working hours. More votes were on 2 (Comfortable) and 3 (Very comfortable) when the indoor air temperature was lower than 26°C, and the vote was inclined to 1 (Slightly comfortable) and 0 (Neutral) when indoor air temperature was over 24°C. Occupants preferred a cool indoor environment condition in the office in the monitoring time. Based on psychrometric chart, some of the data were located in or even outside of the extended comfort zone, because of the high relative humidity. Although it has been proved that the indoor air flow speed near the occupant would not have an important influence on occupant comfort, the occupants' comfort sensation seems not to have been influenced by high relative humidity in office D1.

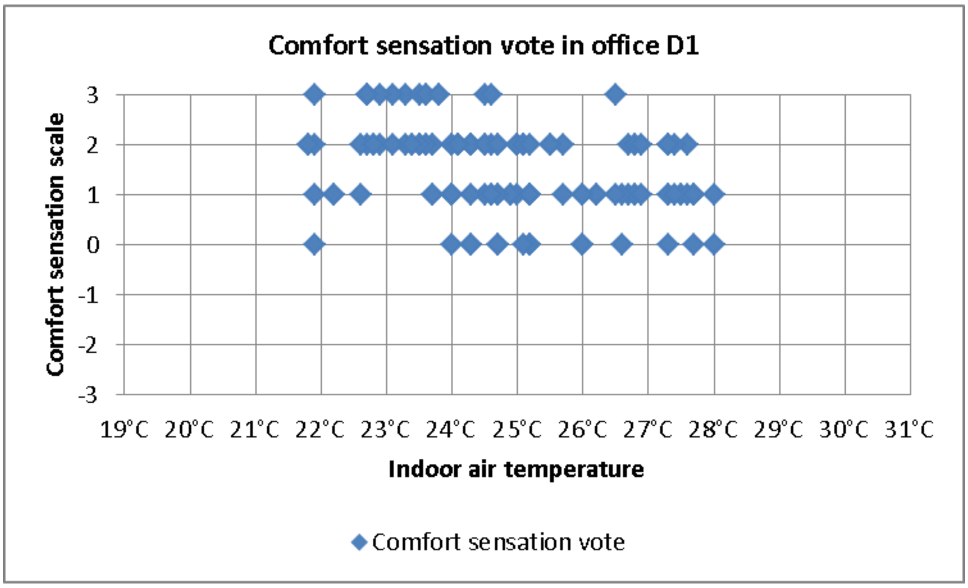


Figure 6.64: Comfort sensation vote in office D1 (SSV)
during the working hours in the monitored period.

Figure 6.65 shows the humidity sensation vote result. The votes were mainly on 0 (Neutral) and -1 (Slightly dry). And the votes on -1 (Slightly dry) were more than the votes on 0 (Neutral), while there were very few votes on 1 (Slightly humid). The occupants felt slightly dry in the office, even when the indoor relative humidity was over 80%RH. As seen in the comfort sensation vote result and psychrometric chart result, the humidity level in office D1 did not impact on occupants' thermal comfort in the office.

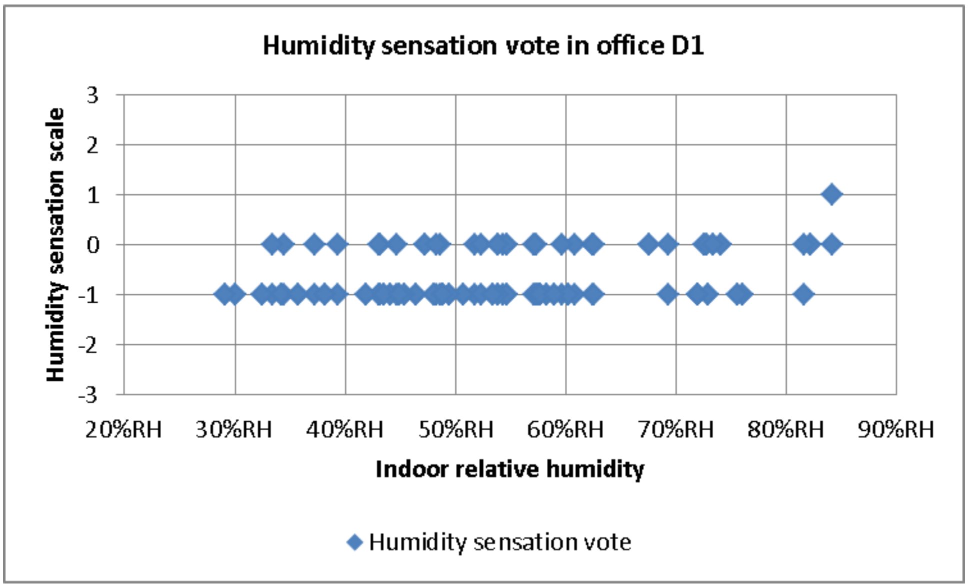


Figure 6.65: Humidity sensation vote in office D1 (SSV)
during the working hours in the monitored period.

In office D1, although the room was single-side ventilated, the indoor air quality perception result (Figure 6.66) was positive which was between -1 (Slightly stuffy) and 3 (Very fresh). Occupants were satisfied with indoor quality during the working hours, this result was better than in other single-side ventilated offices. This may benefit from the building type (high rise building), in which the air speed on opening area was large and much better than other single-side ventilated office. Due to the window typology and small opening size (presented in 5.2.4), the indoor air speed on upper part of the office was higher than occupant working area. But it cannot effect on achieving the fresh air. This may be the reason that occupant in office D1 was satisfied with indoor air quality.

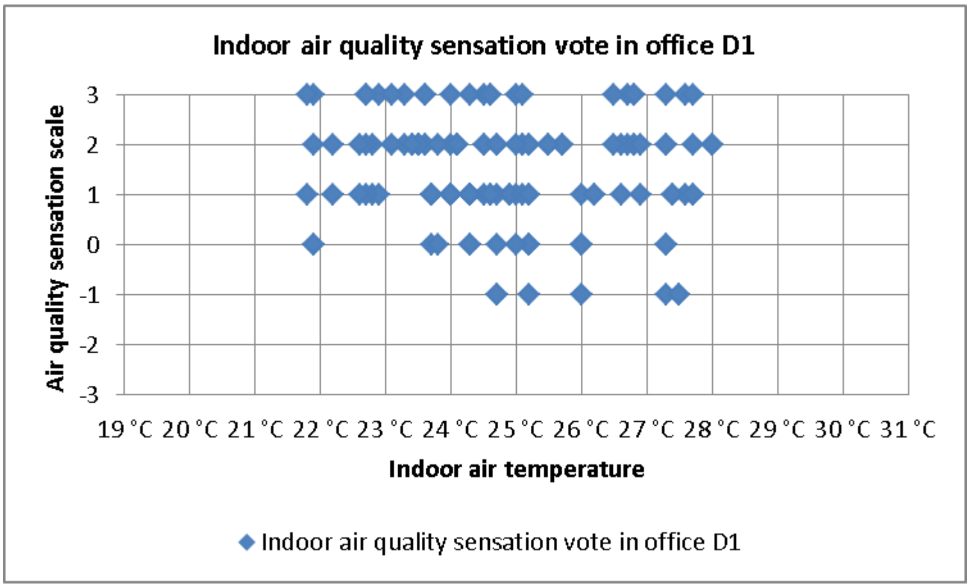


Figure 6.66: Indoor air quality sensation vote in office D1 (SSV) relate to indoor air temperature during the working hours in the monitored period.

6.4.2 Thermal comfort perceptions in the office D2

Based on indoor air temperature proportion and office orientation, the occupants in office D2 may have felt uncomfortable in the afternoon. The occupants' thermal sensation vote (included 2 voters and 480 votes) result showed that the majority of votes were located between 0 (Neutral) and 1 (Warm). Some occupants voted on +2 (Hot) when the indoor air temperature was over 27.9°C (Figure 6.67). The occupants' sensation was tending towards hot in the office; the direct sunlight in the afternoon may have been the main reason. According to Figure 6.68, all votes on the uncomfortable side were on -1 (Slightly uncomfortable), but the indoor air temperature varied between 25.1°C and 29.6°C. Although the vote on slightly uncomfortable seems occupants could still accept the indoor air temperature, the starting temperature was lower than that in other offices. Most of these votes were in the afternoon; the indoor air temperature was decreased, but direct solar radiation entering the room would make occupants uncomfortable. Because the curtain was used to block the direct sunlight, the influence of solar radiation on occupants could have been reduced. Figure 6.69 shows that a group of slightly uncomfortable data was in the yellow comfort zone; the occupant normally would feel comfortable in this area. Solar radiation may be the reason for the uncomfortable sensation. Another group was near the edge of the extended comfort area with high relative humidity; for this group of data, except for the solar radiation influence, the high humidity level may also be the reason.

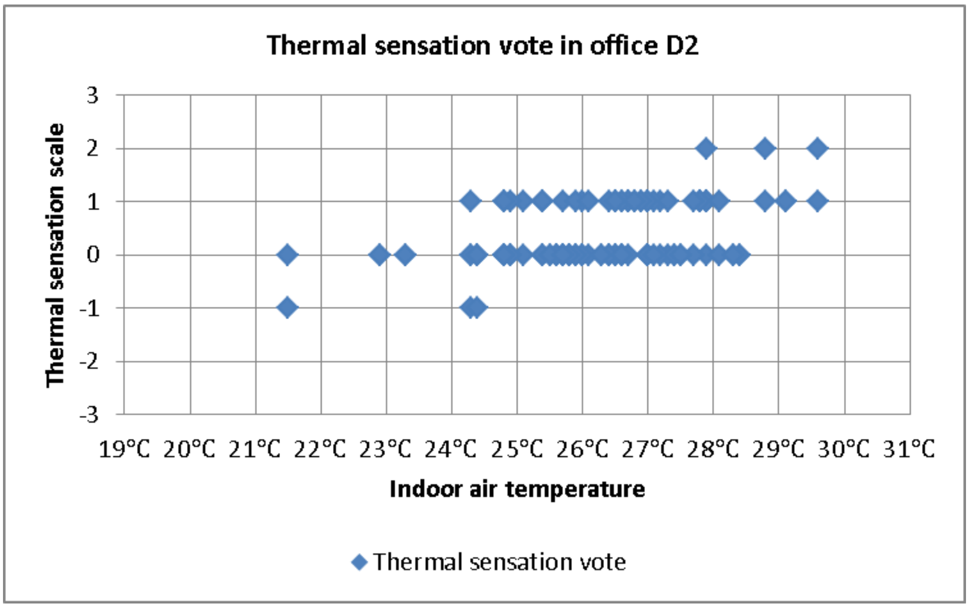


Figure 6.67: Thermal sensation vote in office D2 (SSV)
during the working hours in the monitored period.

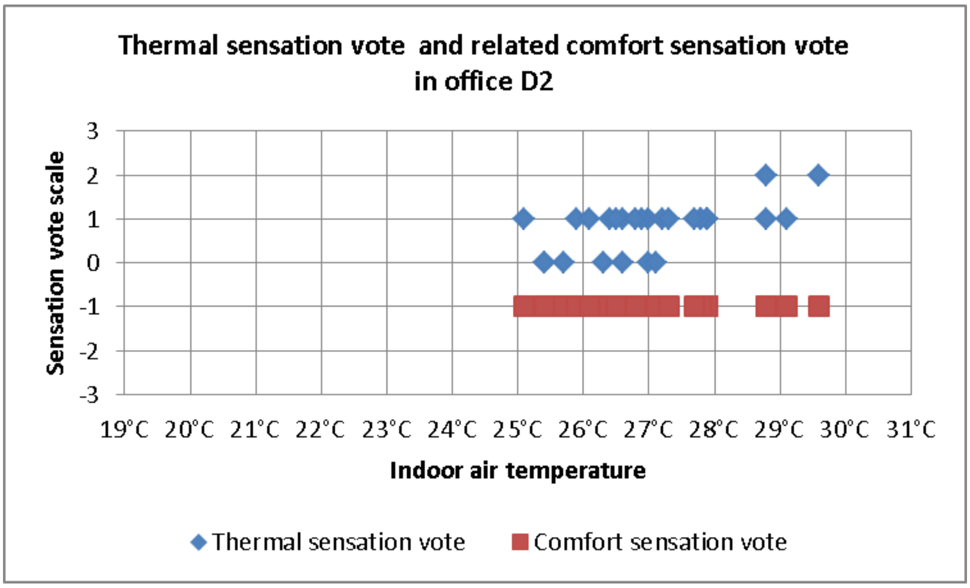


Figure 6.68: Thermal sensation vote and related comfort sensation vote when occupant feels uncomfortable in office D2 (SSV).

Figure 6.69: The psychrometric chart for uncomfortable time (Blue circle) in office D2 (SSV). (Yellow: still air condition, red: air flow speed about 1.5m/s).

The result of the humidity sensation vote in the office was similar to that in office D1. Most of the votes were on 0 (Neutral) and -1 (Slightly dry), while very few votes were on 1 (Slightly humid) when the indoor relative humidity rose over 76% (Figure 6.70). The occupants in office D2 also felt slightly dry during the working hours. Based on the psychrometric chart for uncomfortable time, those data outside the yellow comfort zone with high relative humidity would still be acceptable for occupants. The indoor relative humidity did not have a significant impact on occupant thermal comfort in office D2.

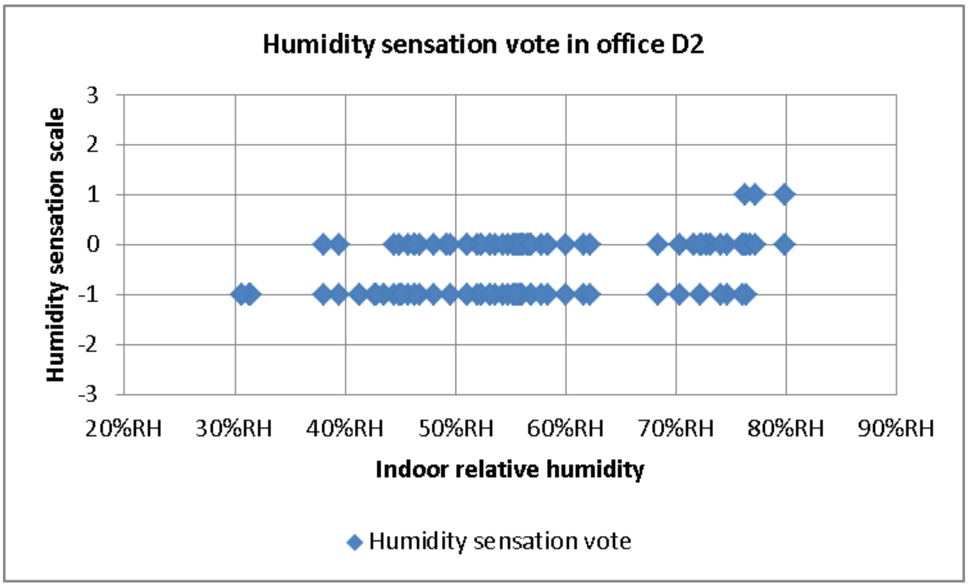


Figure 6.70: Humidity sensation vote in office D2 (SSV) during the working hours in the monitored period.

In office D2, the indoor air quality perception vote result (Figure 6.71) was between -1 (Slightly stuffy) and 3 (Fresh) which was similar to the result in office D1. Although the vote on slightly stuffy was much more than the result in office D1, the indoor air quality was still acceptable in office D2.

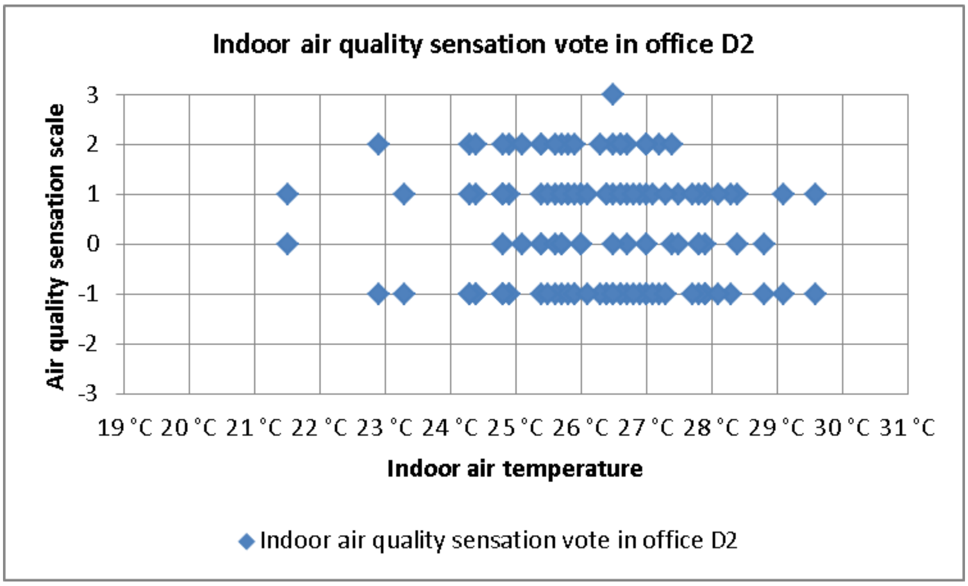


Figure 6.71: Indoor air quality sensation vote in office D2 (SSV) relate to indoor air temperature during the working hours in the monitored period.

6.4.3 Thermal comfort perceptions in the office D3

Office D3 (SSV) had the lowest average indoor air temperature in working hours. The thermal sensation vote (included 2 voters and 480 votes) was between -1 (Cool) and 1 (Warm), and most of the votes were on 0 (Neutral) and -1 (Cool) (Figure 6.72). In addition, the warm sensation started on 24.5°C. Occupants felt cool in the office during the working hours. These results were similar to office D1. There was very little time that occupants felt slightly uncomfortable (-1) in the office, and the related thermal sensation vote was on -1 (Cool) (Figure 6.73). Therefore, as the indoor air temperature proportion result, in 1% of working hours the indoor air temperature was lower than 20°C and it may have caused occupants to feel uncomfortable in the office because of the low temperature. Generally, occupants felt comfortable in office D3. And in the last two days, when the lowest outdoor air temperature dropped to 15.5°C, additional clothes were added by occupants, such as a thin jacket. Occupants had more opportunity in the office to adjust their comfort and it could extend their comfort range.

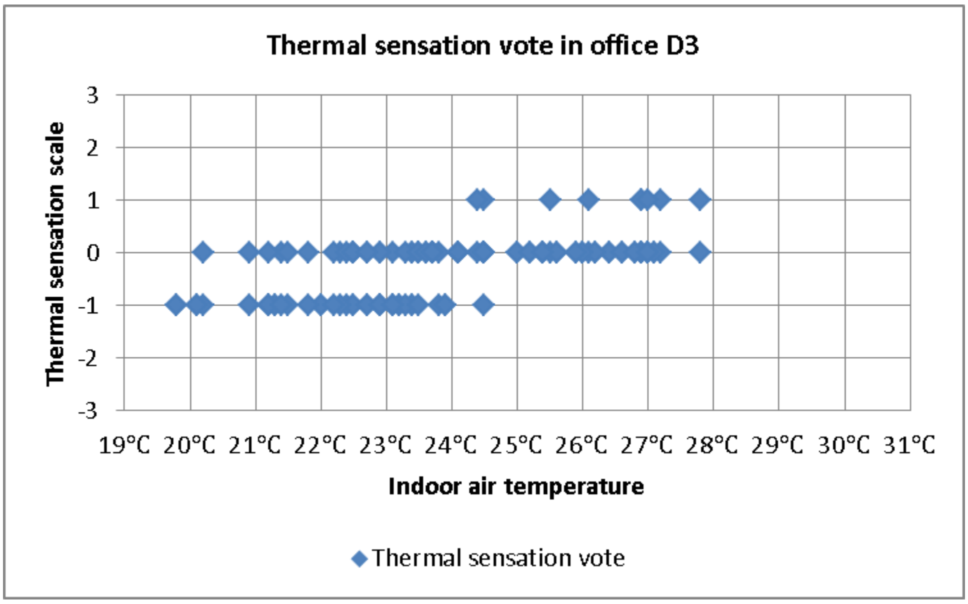


Figure 6.72: Thermal sensation vote in office D3 (SSV)
during the working hours in the monitored period.

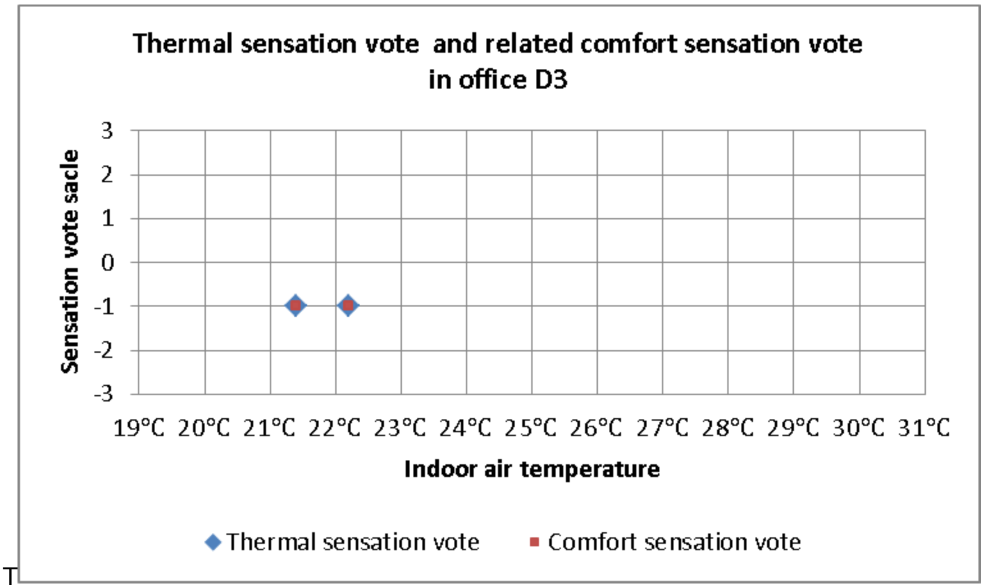


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Figure 6.73: Thermal sensation vote and related comfort sensation vote
when occupant feels uncomfortable in office D3 (SSV).

As shown in Figure 6.74, the result was the same as that in other offices in the building. The votes were on 0 (Neutral) and -1 (Slightly dry). When occupants voted on -1, the relative humidity varied between 33.9% and 64.1%, which would not cause significant impact on occupant thermal comfort. When the indoor relative humidity increased to above 70%, or even over 80%, occupants still felt neutral (0) in the office. Some occupants felt slightly dry in the office as well.

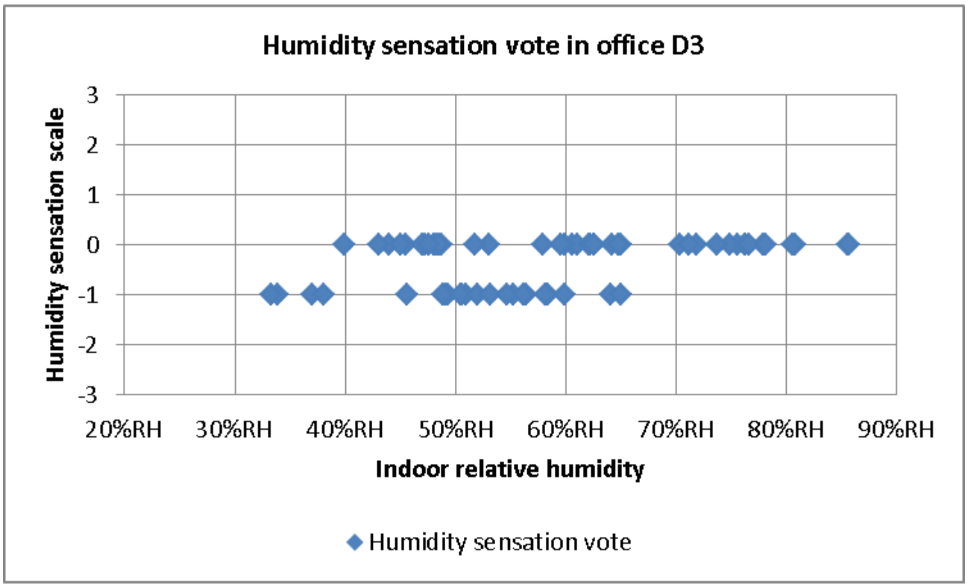

Figure 6.74: Humidity sensation vote in office D3 (SSV) during the working hours in the monitored period.

In office D3, the indoor air quality perception result is shown in Figure 6.75. The vote result was between -2 (Stuffy) and 3 (Very fresh), which was wider than other offices. Besides, the votes were accumulated -2 and 2, and the neutral (0) point was less selected. The result was tending opposite poles; it may because occupants in the office had different perception of indoor air quality. This situation can be further investigated in the future with proper indoor air quality monitor instrument.

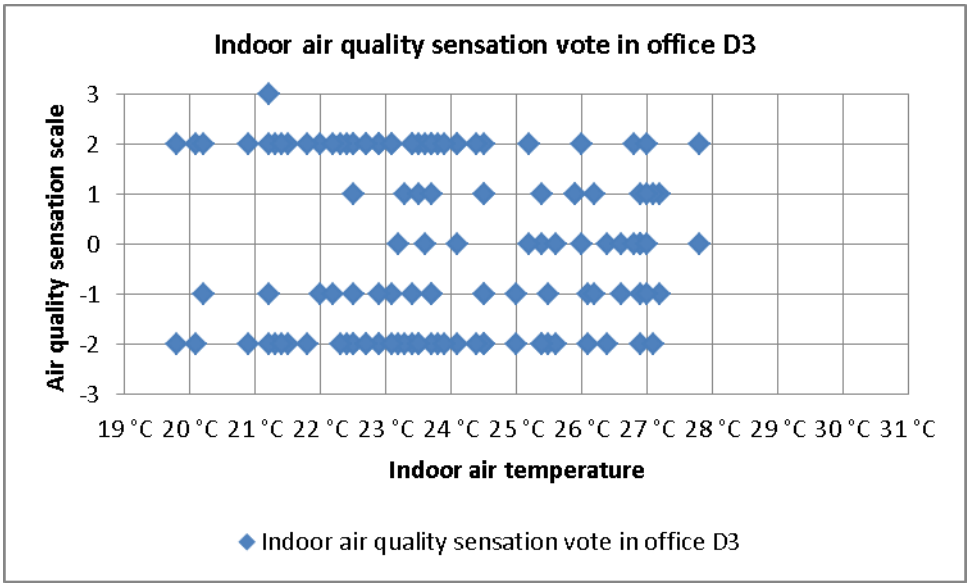

Figure 6.75: Indoor air quality sensation vote in office D3 (SSV) relate to indoor air temperature during the working hours in the monitored period.

To sum up, in office building D, the indoor air temperature in offices D1 and D3 was lower than 29°C, and occupants were satisfied with their indoor air temperature, although a few votes were on slightly uncomfortable in office D3, because of the low indoor air temperature. The indoor environmental condition in office D2 was worse, because of the direct sunlight in the afternoon. Occupants felt hot when indoor air temperature rose over 28°C. In addition, related to solar radiation in the afternoon, the occupants felt slightly uncomfortable when the indoor air temperature increased above 25.5°C. However, the uncomfortable sensation level did not increase with air temperature rises. Occupant uncomfortable sensation was still on -1 (Slightly uncomfortable), thus, for most of the time, the indoor air temperature was still acceptable.

For the indoor humidity sensation vote, the results were similar to other office buildings. Occupants felt slightly dry in the office and most votes were on 0 (Neutral) and -1 (Slightly dry), the same as the relative humidity value, which was above 70%. Based on the psychrometric chart in the three offices, the relative high humidity level caused some of the data to be in the extended comfort zone and even outside it. And the indoor air flow speed around occupants was proved not to have influenced occupants' comfort. Therefore, the occupants could accept higher indoor relative humidity in office D. And most of occupants can accept indoor air quality, except one occupant in the office D3 which had different indoor air quality perception than others.

6.5 Discussion and conclusions

Based on the sensation vote results in these office buildings, two common results were found. The starting air temperature that occupants would vote on warm or cool was between 24°C and 25°C, which was probably the neutral temperature for those offices, though it was slightly lower than the predicted result based on De Dear's equation (Equation 1.7). Occupants could not precisely perceive the indoor relative humidity, but occupants felt slightly dry in the office, the majority of the slightly dry

(-1) vote being under 60%RH. In addition, occupants were more tolerant of humid conditions than the predicted result by Givoni's comfort zone (1998).

6.5.1 Thermal sensation and humidity sensation vote

According to the measured result (Figure 6.76), the data showed that occupant thermal sensation vote on 0 (Neutral) varied in the office between 20°C and 29°C. In 56% of working hours occupants would feel neither hot nor cold in the office. This temperature range was the same as Givoni's comfort temperature range (1998) with still air condition. When the indoor temperature rose up, the votes on the hot aspect were gradually increased. When indoor air temperature rose over 26°C, occupants felt hot in the office and none of occupants felt cool in the office. When the temperature was over 29°C, some occupants felt very hot (+3) in the office, and it may have caused occupants to feel uncomfortable, but most of the votes were still on 2 (Hot) and some of the votes were on 1 (Warm) when the indoor air temperature was over 29°C. This may be because most of the offices were cross ventilated, then the indoor air flow could help occupants extend their comfort threshold. This temperature threshold was lower than the temperature found in other studies which were 30.5^{O}C (Zhang et al, 2010), 31^{O}C (Dear et al, 1991 and Busch, 1992) and 31.5^{O}C (Jitkhajornwanich et al, 1998). When the indoor air temperature dropped below 23.8°C, none of occupants would feel warm in the office; the thermal sensation was tending towards cool. Occupants' votes seemed more varied, when the indoor air temperature was between 23.8°C and 25.7°C, as found before, in most offices this temperature was between 24°C and 25°C. So, other environmental factors may have more affected occupants' vote.

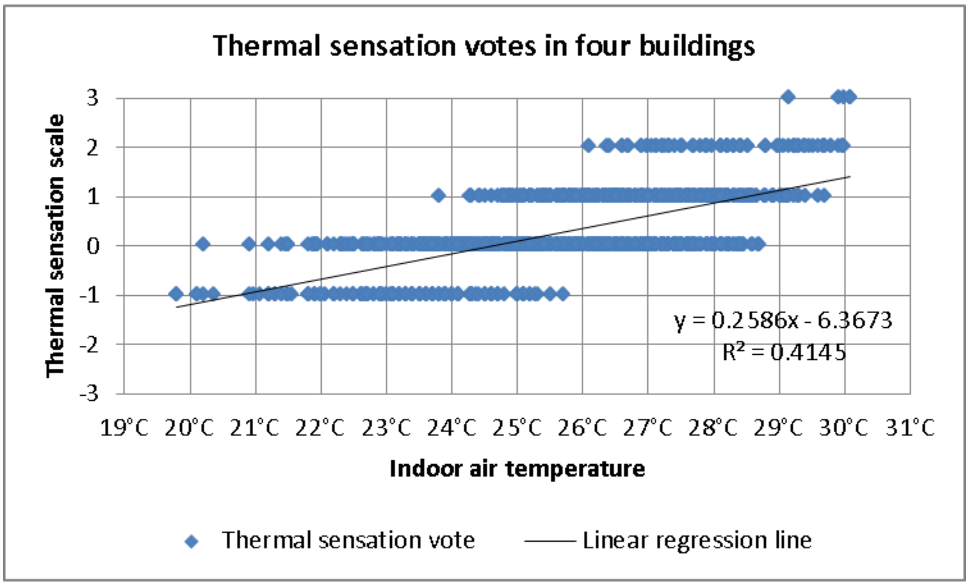

Figure 6.76: Thermal sensation vote with measured indoor air temperature for all buildings studied (included 24 voters and 1440 votes).

Comparing single-side ventilation offices with cross-ventilated offices, the average indoor air temperature in the cross-ventilated office (25.6°C) was 0.5°C lower than the single-side ventilation office (26.1°C) (Figure 6.77, Figure 6.78). In the cross-ventilated office, the vote on hot (+2) was more than the single-side ventilation office, but the upper boundary of comfort temperature was higher than that in the single-side ventilation office which means occupants in cross ventilated office can adapt slightly higher indoor temperature. In the cross-ventilated office there was 9.3% of working hours that occupants felt uncomfortable in the office and in the single-side ventilation office the number was 10.1%, slightly higher than the cross-ventilated office. The uncomfortable percentage between single-side ventilated office and cross ventilated office was small. This may be because, in some single-side ventilation offices, the daily indoor air temperature was lower than the cross-ventilation ones, which could reduce the time in which occupants may have felt uncomfortable. In addition, there was 13.8% of comfort time that occupants voted on slightly cool in the cross-ventilated office, and this number was 3.4% in the single-side ventilation office. The possible reason is that the indoor airflow speed in the cross-ventilated offices was positive that the average air speeds near occupants varied between 0.67m/s and 0.82m/s. The measured indoor average air speed was higher than the suggested air speed (0.25m/s) in CIBSE AM10 (2005) for sufficient maintaining occupant thermal comfort in summer. The indoor air speed in monitored cross ventilation offices has great benefits to occupants' comfort. The indoor air flow speeds were higher than single-side ventilated office. The air flow speeds in the cross-ventilated offices can reduce the indoor temperature and increase heat loss from the occupants, and improve occupants' thermal comfort. Therefore, in the cross-ventilated office, occupants felt comfortable than in the single-side ventilation office.

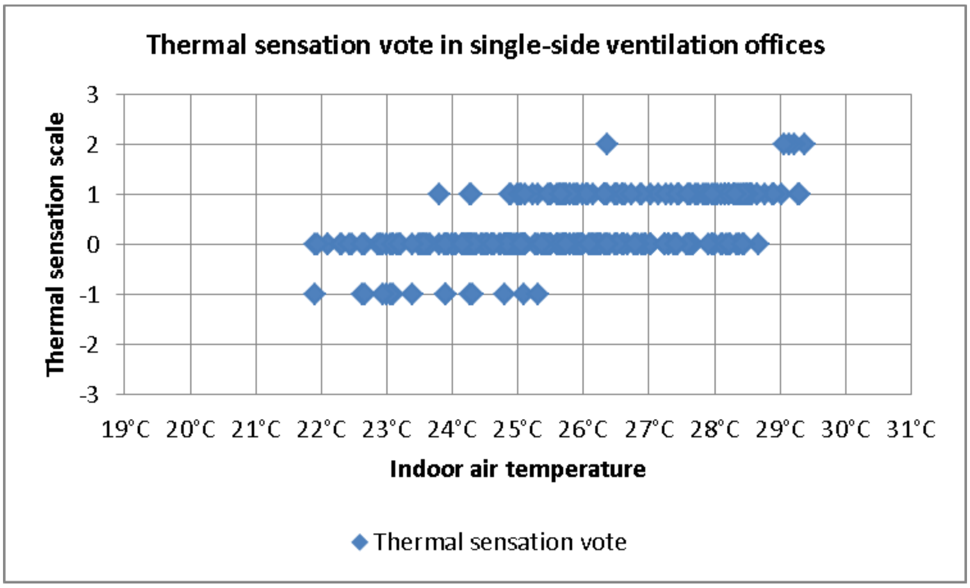

Figure 6.77: Thermal sensation vote with comfort sensation vote on neutral and comfort in single-side ventilation offices (included 14 voters and 840 votes).

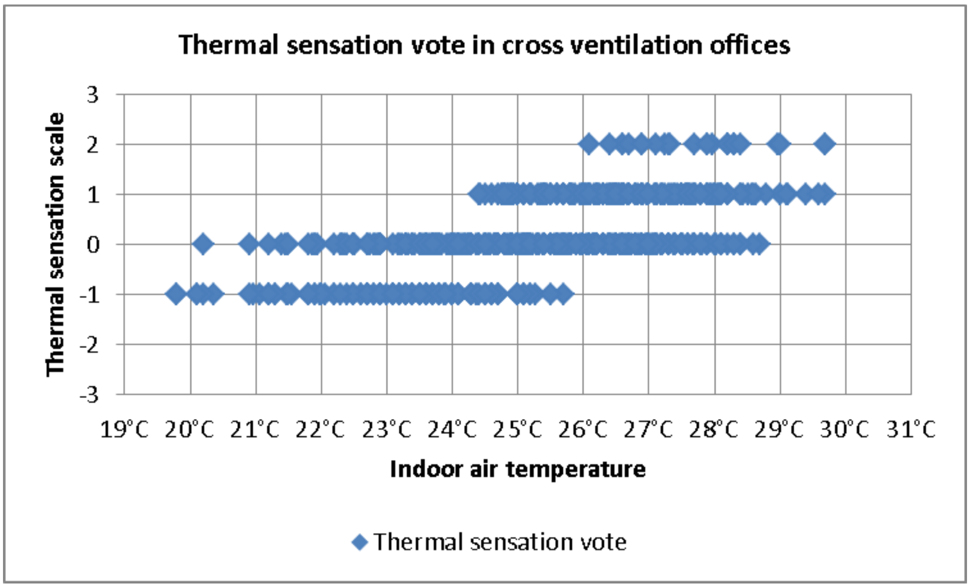

Figure 6.78: Thermal sensation vote with comfort sensation vote on neutral and comfort in cross-ventilated offices (included 10 voters and 600 votes).

For the thermal sensation vote, it could be considered that 90% of occupants would feel satisfactory when the vote was between -1 (Cool) and 1 (Warm). This number was 93.7% in the measured data, which was slightly higher than 90%. If the thermal sensation vote compounded with the comfort sensation vote (the vote of thermal sensation) was between -1 (Cool) and 1 (Warm), and the comfort sensation greater than or equal to 0 (Neutral) was chosen, the percentage at satisfactory decreased to 87.7%. This means that, when the indoor air temperature was between 19.8°C and 29.6°C, 87.7% of occupants felt comfort for the indoor environmental condition. If the slightly uncomfortable vote were included, the result was 93.7%, which means when occupants voted between -1 (Cool) to 1 (Warm), the indoor environmental condition was acceptable.

In addition, occupants would still accept the indoor environment when they felt hot. So, in the working hours, there was 90% of time that occupants felt comfort in the office and this number can increase to 98.6% when votes on slightly uncomfortable (-1) are included. In most of the working hours, the indoor environmental condition was acceptable. In addition, the sensitivity of thermal sensation to indoor air temperature was examined by the linear regression model. The result shows the R^2 value was 0.41, which means the relationship between thermal sensation vote and indoor air temperature during the monitored time was hardly significant. It indicated that the occupants in these offices were better acclimatised to the indoor thermal environmental conditions during the monitoring time. The enhanced acclimatisation of occupants to the indoor environment could be a result of the occupants' thermal sensation change being compensated by the impact of window state change, roller blind control and clothing adaptation, which subsequently affected the low R^2 value. It also proves most of the occupants would feel comfortable in the offices with the indoor air temperature varying between 19.8°C and 29.7°C. This comfort indoor air temperature range was consistent with Givoni's comfort zone (1998).

Compared to the result calculated by De Dear's (1998) equation (September: 24.8°C-29.8°C and October: 23.4°C-28.4°C), the measured temperature range was much wider than this, especially on the lower boundary. This may be because of the clothing level changes; a cold front arrived at the end of the third week, and some occupants changed to a long-sleeved shirt or added a thin jacket. This was an important thermal adjustment method that occupants used to adapt to temperature changes, and it had a significant influence on the adaptive comfort model.

Normally, the relative humidity would have a significant impact on occupant thermal comfort. High humidity could restrict the skin's evaporation and reduce heat dissipation from the skin, whilst low humidity would dry out the skin and cause discomfort. Nevertheless, when relative humidity was between 30%RH and 70%RH, it did not have an important influence on the results of the survey.

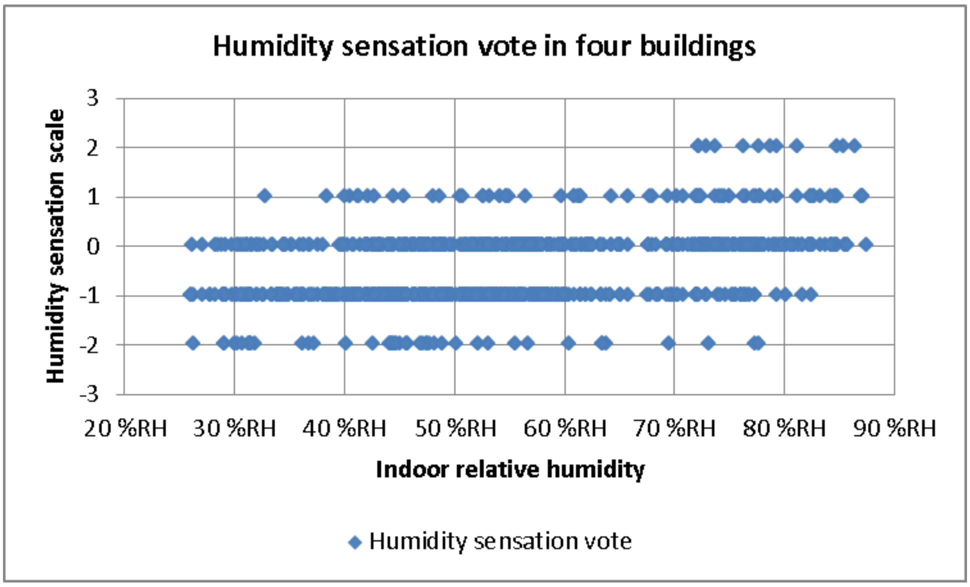

Figure 6.79 Humidity sensation vote with measured relative humidity for all offices studied (included 24 voters and 1440 votes).

According to measured relative humidity (Figure 6.79), 90% of the votes were located on 0 (neutral) and -1 (Slightly dry), while 50% of the votes were under the neutral point. There were a small number of votes that were above +1 (Slightly humid) when the relative humidity was over 70%RH. None of the occupants felt too dry or too humid. However, the vote of the humid sensation did not increase with increasing relative humidity. It seemed that relative humidity could not be accurately perceived by occupants. It only presented occupants' general humidity sensation in the office. There was no correlation between the humid sensation vote and the relative humidity.

Occupants' humidity sensation votes were tending towards slightly dry. During the monitored period, some of the occupants used lip balm to keep lips moist. In order to establish the threshold for indoor relative humidity which caused occupants to have a slightly dry perception, the vote below neutral (0) and compounded with the comfort sensation vote which was lower than 0 (neutral) were plotted into a psychrometric chart (Figure 6.80). The figure shows that a large number of votes was between 30%RH and 60%RH, which means when the relative humidity dropped below 60%RH, the majority of occupants would feel dry and started to keep or restore the body's moisture.

Figure 6.80: Humidity sensation vote at -1 (Slightly dry) and -2 (Dry), with comfort sensation vote below 0 (Neutral). (Yellow: still air condition, red: air flow speed about 1.5m/s).

In the ASHRAE adaptive standard (2004), the absolutely humidity was also considered. When the absolutely humidity was between 4g/kg and 12g/kg, there was not a significant impact on thermal comfort. Givoni

(1992) suggested that the upper threshold could rise up to 17g/kg in still air condition, and this number could be extended to 19g/kg if the indoor air movement could be achieved. In Figure 6.80, the majority of humidity votes were between 5g/kg and 15g/kg, which were slightly wider than ASHRA's range, and 3g/kg over its upper threshold. But during the measuring period occupants still felt dry and prevented their moisture from being lost. Compared to Givoni's (1998) humidity threshold, the measured results were still in the range. The votes and compound with comfort sensation vote which was greater than and equal to 0 (Neutral) were addressed on the psychrometric chart (Figure 6.81). Compared to the slightly dry (-1) condition, the vote on relative humidity between 70% and 90% was increased, and the absolute humidity range was between 15g/kg and 20g/kg. When the humidity level rose, there was not a significant influence on occupant humidity sensation. However, the main data was still under 70%RH. When occupants felt comfort the vote on humidity sensation was randomly distributed. The humidity cannot be presented by occupant humidity sensation vote and the occupant humidity perception may be correlated with other factors. Beside, occupants can tolerant high humidity level in this climate condition. This result was consistent with many other field works in hot and humid climate (Busch, 1992., Jitkhajornwanich et al, 1998 and Zhang et al, 2010). In hot and humid climate, occupant was continuous and consistent expose in the humid climate and they can acclimatize the local climate condition.

Figure 6.81: Humidity sensation vote on 0 (Neutral), with comfort sensation vote on 0 (Neutral) and above. (Yellow: still air condition, red: air flow speed about 1.5m/s).

6.5.2 Psychrometric chart

The comfort sensation vote which was greater than and equal to neutral (mean occupants felt comfortable) was selected and plotted into a psychrometric chart with the Givoni comfort zone (1998) (Figure 6.82). The measured comfort indoor air temperature range which was discussed above was between 19.8°C and 29.7°C. The lower temperature threshold could be decreased to 19°C. This is because none of an occupant was vote below -1(Cool) when temperature rapidly drops and occupants could add thin clothes to adapt to temperature drops as they benefitted from weather forecasts and new technology. The smart phone is one of the important things for people's daily life; the weather app can be used to check weather at any place and time, even in places far away from you, also including several days' weather forecast. It provides temperature, relative humidity, probability of rainfall, dominant wind direction and speed, air pollution level, whether suitable for outdoor exercise or not, and so on. In the monitored offices, 96% of occupants were using smart phones and checked weather conditions daily. In additional, a free text message about the weather condition, including today and tomorrow, would be sent by the weather station. Excepting weather conditions, the message content also gives the suggestion about suitable clothes, food, other concerns (i.e., need to drink water, need shading to avoid ultraviolet rays) and so on. In some office buildings, an electronic information board was installed near the main entrance; the weather information was displayed at intervals. All this information could help occupants predict future weather conditions and prepare them to adapt to the weather. Occupants can adjust their clothing level according to the weather forecast and their experience. And this advantage was verified in the field measurement when the outdoor air temperature rapidly dropped to 15°C. Thus, the low threshold for comfort temperature can be set at 19°C.

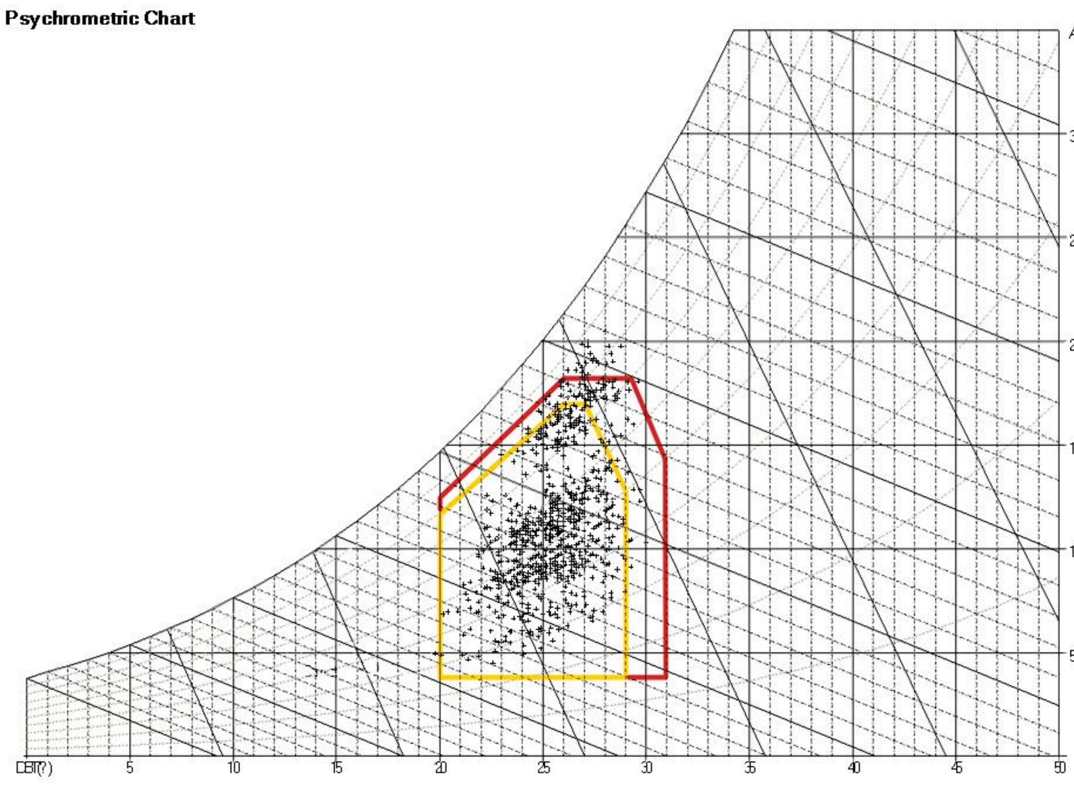

Figure 6.82: Comfort sensation vote was equal to or larger than 0 (Neutral) in the psychrometric chart with Givoni's comfort zone. (Yellow: still air condition, red: air flow speed about 1.5m/s)

Furthermore, some of the data were in the extended comfort zone and even outside. In the monitored period, some of the offices were cross-ventilated and the indoor air flow condition was variable. When the indoor air flow speed near the occupant was positive for the occupant's thermal comfort, the comfort threshold in the office could extend to the red boundary. In addition, there was a small number of data located outside the red comfort zone, because of high relative humidity. In these data, the majority of the comfort votes were neutral. This means when the indoor air temperature was around 28°C and the indoor relative humidity was over 80% and under 90%RH, the indoor environmental condition was still accepted by occupants. It seems that in the monitored office buildings, occupants were more tolerant of the high humidity condition. The occupants living in a hot and humid climate zone can acclimatise to the locale climate conditions. Thus, the extended comfort zone for the natural ventilation office can be considered for the occupants living in this environmental condition (Figure 6.83), which is when the upper threshold for absolute humidity can increase to 20g/kg when the temperature is lower than 29°C and the upper indoor relative humidity threshold can be set at 85%. Besides, the occupants were more tolerant of a high humidity level rather than a high temperature. Although most of the office was cross-ventilated, very few data were above 29°C. And 29% of the vote was on comfort when the indoor air temperature was over 29°C and most of the vote was on neutral (0). The occupants were more sensitive to increasing indoor temperature.

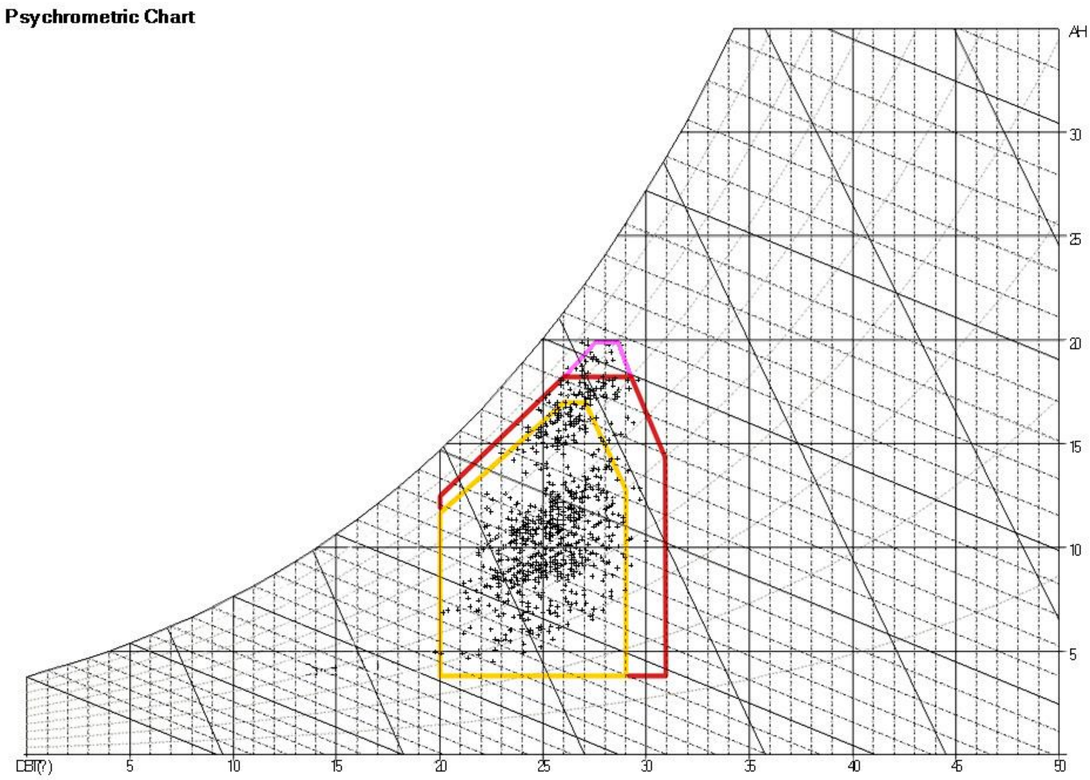

Figure 6.83: Comfort sensation vote was equal to or larger than 0 (Neutral) in the psychrometric chart with suggest extended comfort zone (Pink area). (Yellow: still air condition, red: air flow speed about 1.5m/s)

6.5.3 Comparing Givoni's comfort zone and ASHRAE55 adaptive comfort zone

Givoni's psychrometric chart and comfort zone was designed to evaluate the thermal comfort in the hot and humid climate. According to the measured results, it was found that the comfort indoor temperature range in the measured climate which has the hot summer and cold winter condition was close to Givoni's comfort temperature range. Although most of those free-running offices were cross-ventilated, the temperature threshold was slightly higher than 29°C but lower than 30°C. It was much closer to the yellow comfort zone (still air condition) than to the extended comfort zone (Figure 6.83). It seemed that the effect of rising indoor air flow speed was less than the predicted result. This may be caused by the average indoor air flow speed near the occupant, which was lower than the predicated speed (1.5m/s). The measured average air flow speed was 0.61m/s in these offices. Therefore, further extending the upper threshold for comfort temperature was still achievable by increasing indoor air flow speed.

The comfort humidity ratio in Givoni's comfort zone was between 4g/kg and 19g/kg when the indoor air flow speed can achieve 2m/s. The measured comfort humidity ratio result was matching the lower threshold but 1g/kg higher than the upper threshold. The measured average indoor air flow speed was lower than Givoni's limit (2m/s), so the occupants' humidity acceptability in these measured offices was higher than that in Givoni's result. Generally, the measured results were close to Givoni's comfort zone for a hot and humid climate. The suggested comfort zone can be used to predict occupant thermal comfort in a hot summer and cold winter climate zone.

The ASHRAE adaptive comfort zone was based on occupants doing sedentary activity (1.2met) with a light clothing level (0.5clo). It was close to the occupant activity level and clothing level during the measurement time. The comfort zone on the psychrometric chart can be moved left or right according to an occupant's activity and clothing level. Also, increasing air flow speed can extend the comfort zone on the upper threshold. The measured comfort result data were plotted into a psychrometric chart with the ASHRAE adaptive comfort zone (Figure 6.84). The result showed that nearly half of the time the data were located outside the comfort zone, which was for October. Based on the ASHRAE comfort zone occupants would consider as uncomfortable with related indoor temperature and humidity, so the air condition or other method was needed to restore occupants' comfort.

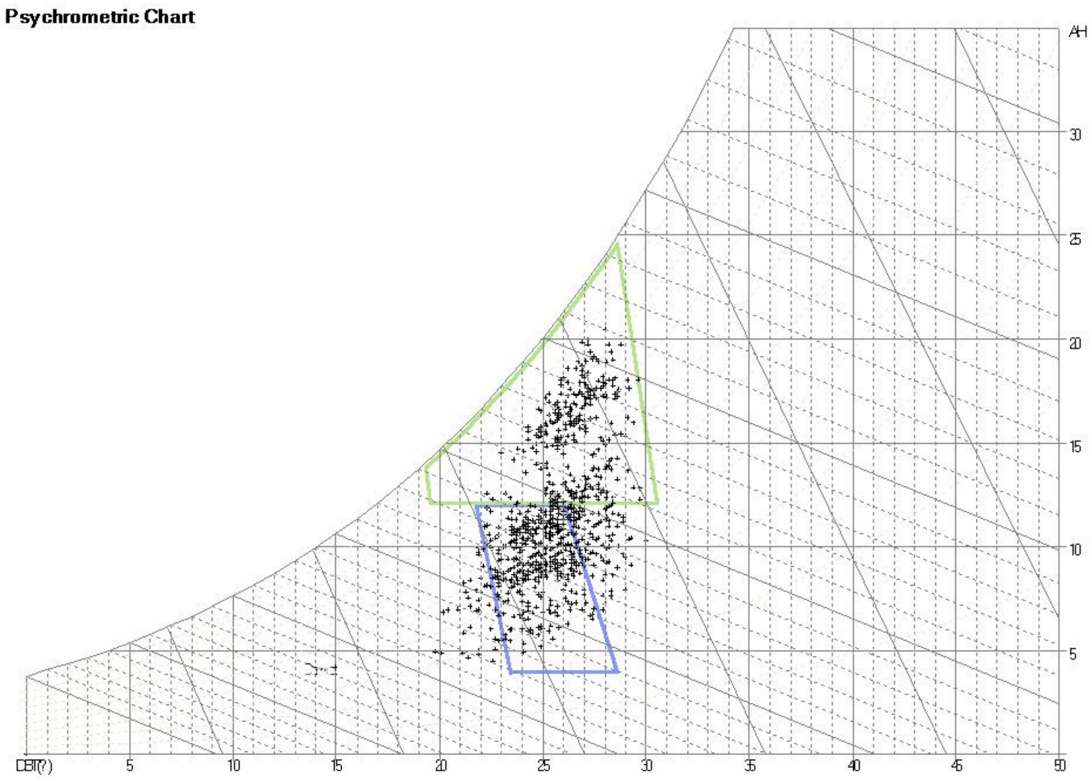

Figure 6.84: The comfort data and ASHRAE adaptive comfort zone (Blue) for measurement period (raise air flow speed can be used when the data point is in the green area, but air flow speed may not higher than 0.8m/s) (ASHRAE, 2010).

However, the measured comfort range was broader than the predicted comfort zone by the ASHRAE adaptive comfort zone. The measured indoor temperature range was wider because, during the working hours, occupants were stimulated by indoor temperature, and the measured data were presented in terms of indoor air temperature and the temperature in different buildings would vary according to the buildings' characters. In some of the offices the indoor temperature range between morning and afternoon was more than 5°C. Occupants have to adapt to these changes and restore their comfort. So the temperature was more variable than the ASHRAE chart which was based on the monthly mean outdoor air temperature.

The main reason for the data to be out of the comfort zone was the humidity ratio. The humidity threshold for the ASHRAE adaptive comfort standard was between 4g/kg and 12g/kg. Increasing indoor air flow speed enabled the comfort zone to be extended and cover the high humidity area, but on the still air condition the absolute humidity threshold was much lower than Givoni's humidity threshold and also the measured result. This result indicated that the occupant who lives under a humid climate was more tolerant of a high humidity condition than others. They could physiologically and psychologically acclimatise to the climate in which they live.

The ASHRAE (2010) adaptive comfort zone seemed not to consider occupants' acclimatisation on the humid climate. This may be because the data used for the ASHRAE adaptive standard were based on de Dear's (1998) field experiments, in which the data were taken worldwide, and the humid region was just a part of it and a significant result was not found on humidity acceptability. So the latest humid threshold followed the standard in 1981 (presented in section 1.4.2). But Givoni's comfort zone was focused on the hot and humid climate, so it was more fitting for the humid climate than for the ASHRAE (2010) adaptive comfort zone. Therefore, there was an air flow speed limit of 0.8m/s for occupants with light clothing and primary sedentary activity. Givoni (1992) pointed out that, based on his measurement, in the cross-ventilated office the indoor air flow speed was often around 2m/s and occupants in the office could accept this air flow speed. The air flow speed limit in the ASHRAE standard was too restrictive than in Givoni's for the natural ventilation buildings. Also, according to the author's field measurement, in the cross-ventilated office the limit of 0.8m/s was easy to exceed. The relatively low indoor air flow speed would restrict occupants' comfort to a certain extent in a high humidity environment. Thus, Givoni's comfort zone was more directly applicable to the hot and humid climate than to the ASHRAE adaptive comfort zone. And the comfort zone for the hot and humid climate in China was consistent with Givoni's comfort zone.

The indoor air flow speed would relate to occupant window control behaviours which can adjust indoor air flow pattern and air speed in naturally ventilated office. Occupants can improve their comfort through window control. In the next chapter, occupant window control behaviour would be established and the impact on indoor air flow speed and occupant comfort perception would be identified.

7 Occupant Window Control Behaviour

In these 12 monitored offices, most of the occupants sat near the window. Controlling the window was a way to control the indoor air flow and help occupants to adjust their personal comfort. The work in this chapter aimed to establish the occupant window control pattern in naturally ventilated offices by analysing the occupants' window control frequency at their arrival, working hours and leave times. The correlation between occupant window control behaviour and indoor air temperature and air flow speed has also been investigated. The window state records and indoor environmental factors were used for analysis. Furthermore, the control behaviour related to different window types was explored. This was particularly interesting in the offices in the buildings A and B where the windows were designed to boost natural ventilation.

7.1 Occupant window control patterns

The recorded window control patterns illustrated the occupants' window control frequency during the monitored period. The monitoring was divided into three stages: arrival, working and leave. In each stage, four window states were included: from closed to open, from open to closed, no change, and opening area change. The opening area change means the effective opening area had been reduced or extended when the window was in an opened state. It was not possible to record exactly effective opening area, so the general measured open area were used for analysis. This is a limitation of the work.

7.1.1 Office building A

The recorded occupant window control patterns are shown in Figure 7.1. In office building A, the main window state change happened when occupants arrived in the office and when they left the office; also, during the working hours, changes in the effective open area were the major part of the window state change. At the arrival period, in two offices, the majority of window state change was from closed to open, and no-one closed the window when they arrived at the office. In office A2 (CV), in more than 90% of the working hours, occupants would change the effective opening area; this percentage is much more than that in office A1. Although the effective opening area change was still the highest frequency in office A1 (SSV), for about 30% of the time the occupants did not change the window state. In office A2, occupants always closed the window when they left the office. In office A1, it was found that, in 10% of time, the window stayed open, which was because occupants did not fully close the window.

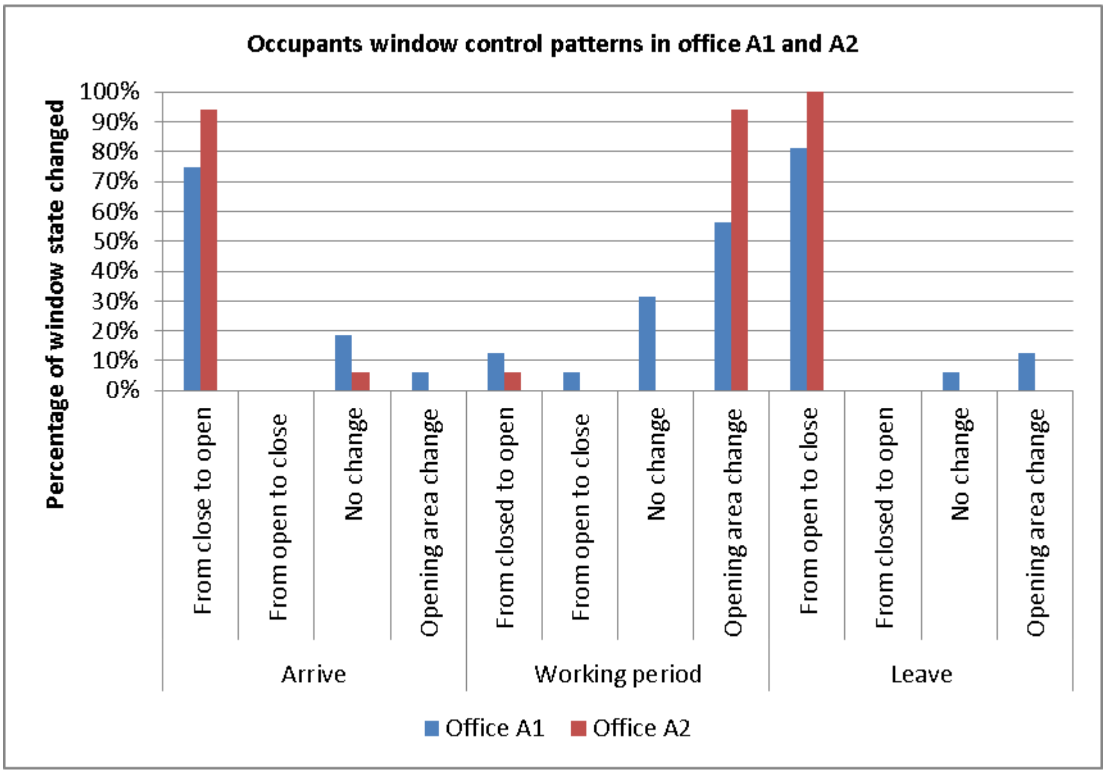

Figure 7.1: The percentage of occupants' window state control during the monitored period in offices A1 and A2.

7.1.2 Office building B

In office building B (Figure 7.2), the main window state change at arrival was from closed to open in offices B2 (SSV/CV) and B4 (CV). But in offices B1 (CV) and B3 (CV), the main state change was the opening area change. This means the window was not closed when occupants left the office the day before. This result was shown at the leave section that 55% of time in office B1 and 80% of time in office B3 the window state was a change of the opening area when occupants left the office. But, according to the assistants' record, the window was closed when occupants left the office. The reason was that the window lock had an E shape and the window could be locked on a different level. So the window would leave a gap if the window was locked on one of the grooves. In offices B1 and B3, the occupants did not fully close the window, so the window state monitor considered the window as still open. In fact, the occupants in offices B1 and B3 closed the window when they left. During the working period, the opening area changes were also the highest in those four offices. The data in offices B1 and B3 which were cross-ventilated were higher than those in offices B2 and B4. It seems that occupants in a cross-ventilated office could adjust the window more than those in a single-side ventilation office.

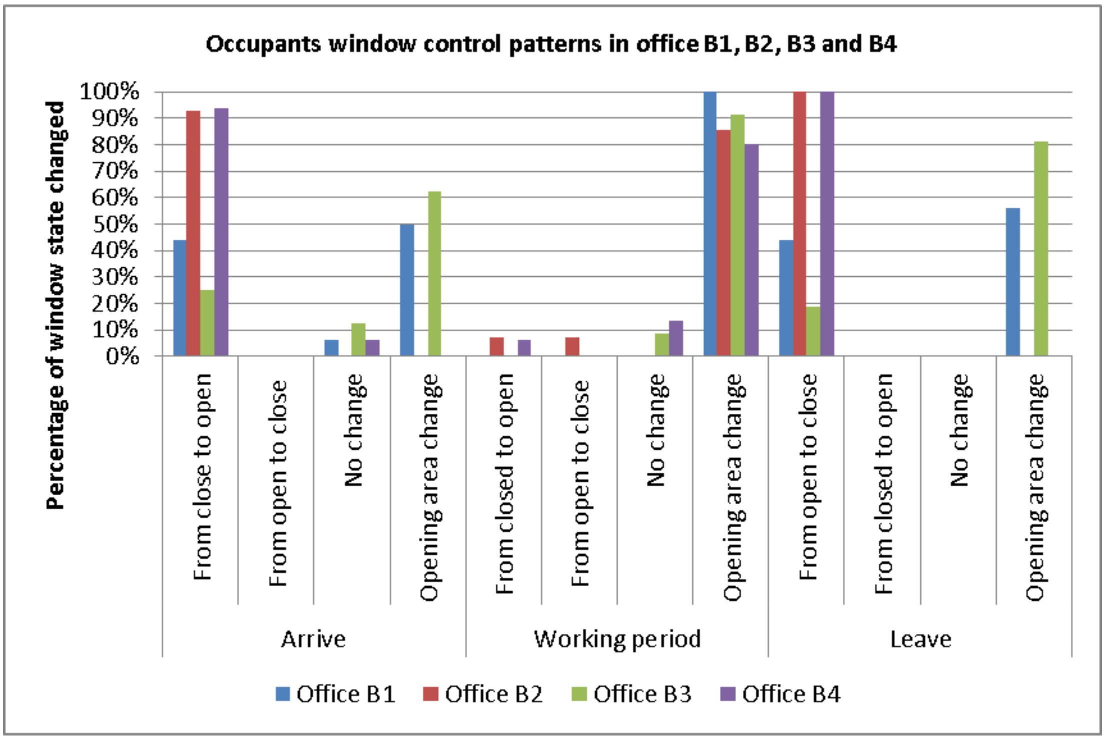

Figure 7.2: The percentage of occupants' window state control during the monitored period in offices B1, B2, B3 and B4.

7.1.3 Office building C

In office building C (Figure 7.3), as for the other offices, when the occupants arrived, most of the window states were changed from closed to opened. When the occupants left, most of the window states were changed from opened to closed. During the working hours, the window open area changed quite often. In office C1 (SSV), the window state change in the working period was much lower than in the other two offices. And the ‘no change’ window state was the second highest. So in office C1 (SSV) the window was not frequently changed. Therefore, in office building C, the opening area change rate in the cross-ventilated offices C2 (CV) and C3 (CV) was higher than in office C1 (SSV) which was single-side ventilated. This result was the same as the result in other offices.

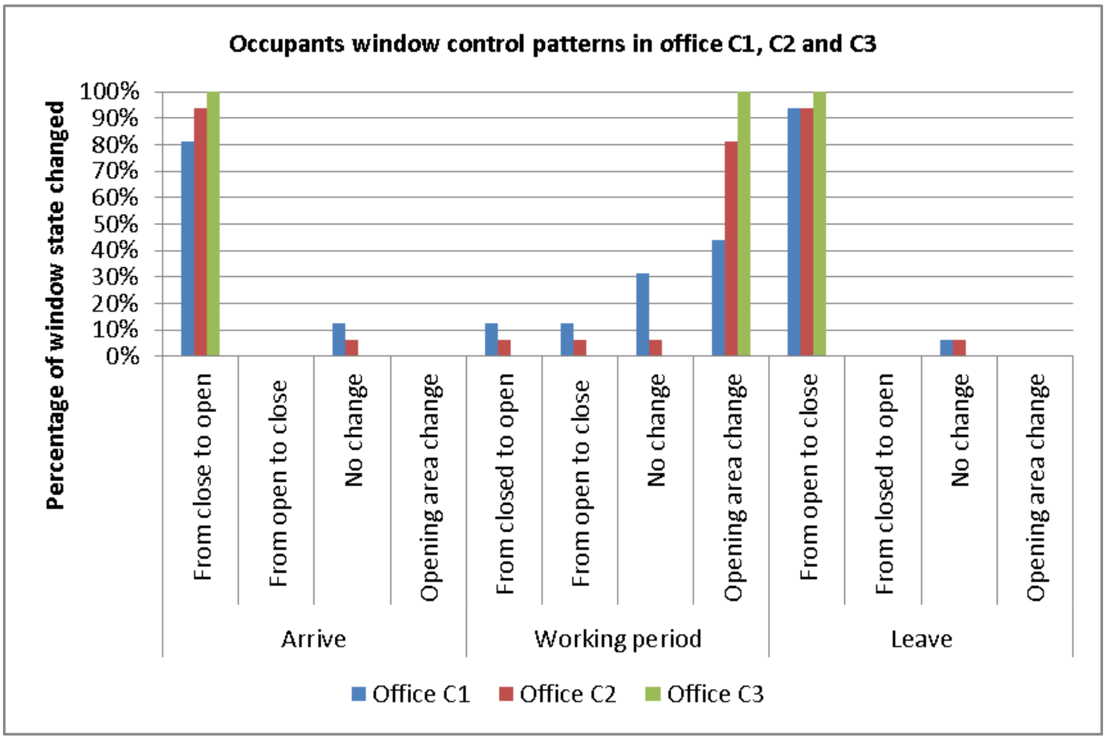

Figure 7.3: The percentage of occupants’ window state control during the monitored period in offices C1, C2 and C3.

7.1.4 Office building D

In office building D, none of windows changed state in the monitored time. All the windows were kept opened at all times, so the results are not presented here.

7.1.5 Analysis of buildings A, B C and D

A summary of the window control pattern in all buildings is shown in Figure 7.4. At the arrival period, the majority window state was from closed to open; none of the windows were closed at arrival time in the office. In office building B, the percentage of window state change from closed to opened was much lower than in other office buildings and about 30% of occupants changed the opening area when they arrived at the office. This was caused by the way occupants used the window lock, which kept the window on a small open state rather than fully closed. Although the window was not fully closed, the effective opening area was too small to have impact on indoor air temperature during the night time. When occupants left the other offices, they tended to close the windows in order to prevent rainfall and gusty wind.

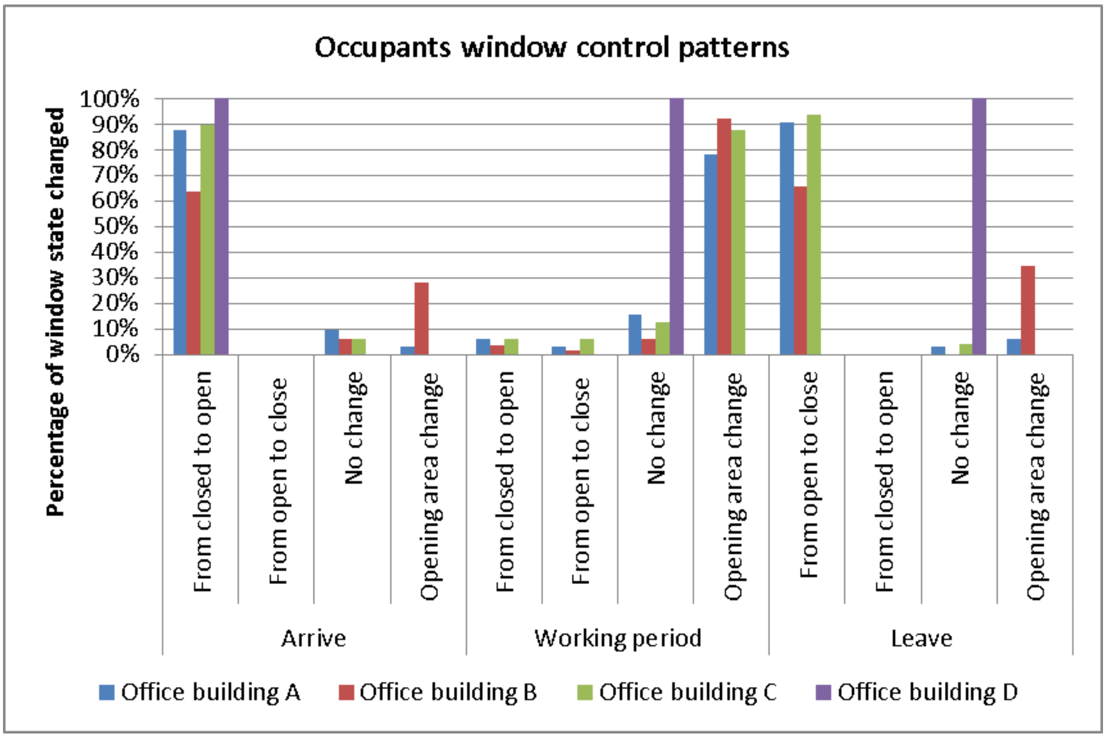

Figure 7.4: The percentage of occupants' window state control during the monitored period.

During the working hours, a small number of occupants would close the windows. According to the records, this was mainly because of rainfall. Most of the windows were closed and rarely there was a small open area left when it was raining. The effective opening size change accounted for the highest proportion during the working period. The percentage in office building B was higher than in the other two office buildings. This was mainly related to the window control frequency in the single-side ventilation office in the building; because in office buildings A and C the opening area change percentage in a single-side ventilation office was much lower than the percentage in single-side ventilation offices in building B. In cross ventilated offices in each building the opening area change was the main behaviour in window control frequency in working hours which was around 90%. When the window control frequency between the single-side ventilation office and the cross ventilated office was compared (Figure 7.5), the result showed that in the cross ventilated offices the window control frequency was 27% higher than that in single-side ventilated offices. Thus, the occupants in the cross ventilated offices adjusted the window opening area more frequently than in single-side ventilated offices. The windows seem to be an important factor often used by the occupants in the cross ventilated offices to control the indoor environment.

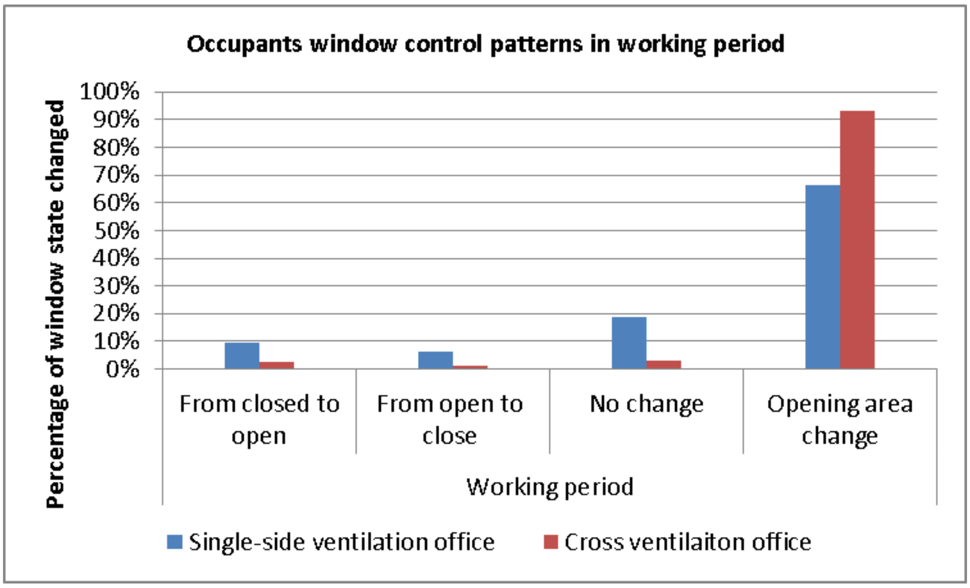

Figure 7.5: Occupant window control patterns in working hours between single-side ventilation office and cross-ventilated office.

The occupants in office building D had a different window control pattern, when compared to the other offices. The window state was not changed once the windows were open. The same result was found in the pilot study with the same window typology (top-hung window). The only difference was that, in the pilot study, the occupants would close the window when they left the office. Occupants seemed to not like to control this type of window during the working period. It was probably because the opening area was restricted and the effective opening area was small. The result of adjusting a small opening area meant little to the occupants.

In summary, the window state changing from closed to opened mainly occurred at the occupant arrival time. When occupants left the office, the window state was mainly from opened to close. These results were consistent with many field study results (Herkel et al, 2008; Yun et al, 2008; Haldi and Robinson, 2009). In working hours, the change of window opening area in the cross-ventilated office was more than that in the single-side ventilation office. However, in Fritsch et al (1990) and Yun and Steemerss' (2008) field work, the window state remained during most of the working time, relatively few was changed. They concluded that occupants have adapted to the indoor environmental condition, so, changing window was not important to occupants' comfort sensation. In the field study, the office with a top-hung window and small opening area meant that the window opening area was rarely changed during the working hours. In other monitored offices, some other environmental factors influenced occupant window control behaviour during the working hours.

7.2 Effective opening areas versus indoor air temperature and air flow speed

The windows were quite often used in the naturally ventilated office during the working hours during the measured period. The windows were important for occupants to control their indoor environment condition and adjust their comfort. The change in the effective opening area may be correlated with indoor environmental factors. The relationship between effective opening size with air temperature and indoor air velocity is set out in this chapter.

7.2.1 Effective opening area as a function of indoor air temperature

Indoor temperature has significant influence on occupant window control behaviour and related opening size (Raja et al, 2001., Yun and Steemers, 2008 and Robinson, 2006). Changes in the effective opening area dominated the occupants' window control behaviour during the working hours. The recorded window state and related indoor air temperature in office A2 (CV) in the first week is shown in Figure 7.6. The geometrical figure on the top of the chart marks the time when occupants changed the window state. It was found that there was an indoor air temperature drop when the occupants arrived in the office and opened the windows. In these conditions the indoor air temperature was higher than the outdoor air temperature and the indoor air flow speed was positive.

However, during working hours there was no obvious temperature variation related to the change in effective opening size. Figure 7.7 shows the indoor environmental condition and window state record on the 25th and the 26th of September. It is clear that increasing or reducing the effective opening area would not cause significant indoor air temperature variations. The result was the same in the other offices.

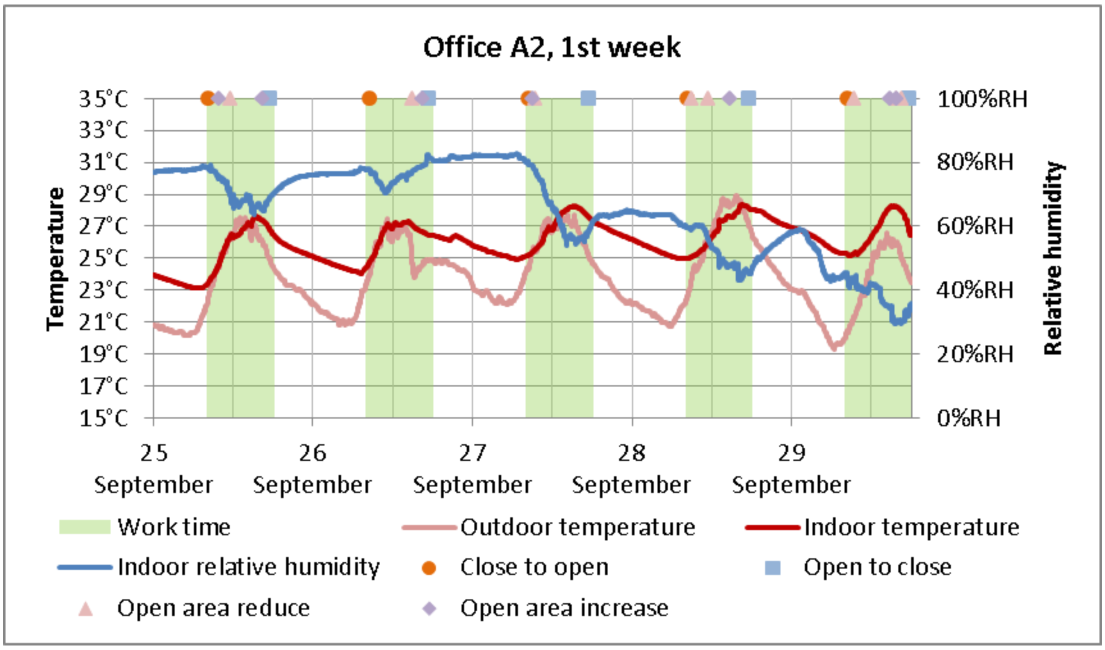

Figure 7.6: First week indoor environmental condition and window state change record in office A2 (CV).

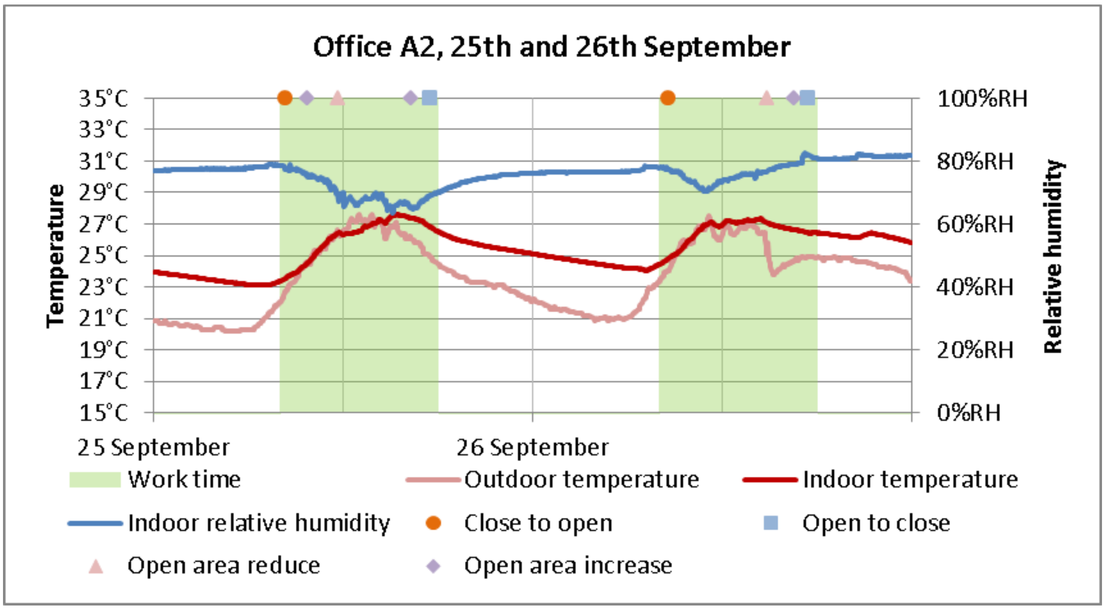

Figure 7.7: Indoor environmental condition and window state change record in office A2 (CV) on 25th and 26th September.

In order to present a clearer relationship between the window opening percentage and the indoor air temperature, all the data points are shown in Figure 7.8. The window opening percentage was not increased with indoor air temperature rose. But it is shown that, when the indoor air temperature increased from 20°C to 25°C, the largest opening percentage gradually increased and the largest opening area was about 50% of the window area. When the indoor air temperature rose over 25°C, the window opening percentage was randomly distributed. The maximum effective opening area started reducing when indoor temperature was below 25°C, which may be related to occupant thermal sensation. Some occupants would start feeling cool in the office when the indoor air temperature dropped below 26°C, which was presented in section 6.5.1.

Reducing the effective opening area can decrease the air flow rate. It can reduce the heat loss from the office and also the heat loss from occupants. When indoor air temperature was higher than 28℃, no window would be closed. When occupants feel hot in the office, keeping windows opened can maintain the office to be naturally ventilated. According to Haldi and Robinsons' (2008) field measurement result, the effective opening area was increased with the rise of indoor temperature. The possible reason is that this result was based on long term field measurement and the data was much more comprehensive than this field measurement. More studies can be carried out in this climate condition in the future.

A large accumulation of data points was between 0% and 20% of the window opening area. This was because in office buildings A and B the window can be fully opened, but in fact the occupants only control the window closest to them. For instance, there were six openable windows in an office in building B but occupants only used two of them. In office building A, there were fourteen openable windows in an office, but only four of them were frequently used. Therefore, even when these used windows were fully open, compared to the entire window area the opening area was still small. This was the reason that the data point was accumulated under 20% and the maximum opening size was around 50% of the window area.

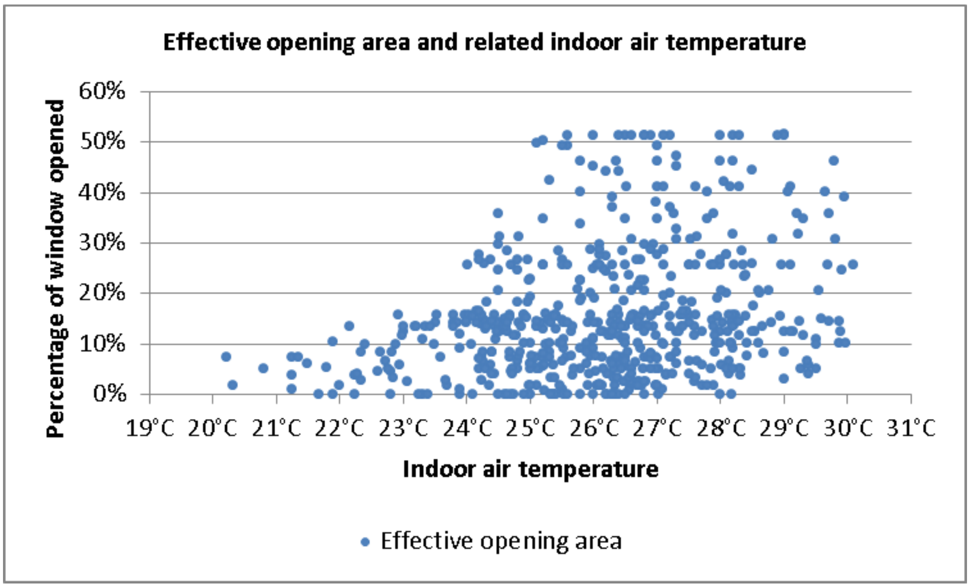

Figure 7.8: The relationship between the window open percentage and indoor air temperature.

If only considering the occupant-controlled window during the working hours, the open percentage would increase. For instance, in an office, an occupant was only controlling two windows, so if two windows were fully opened that would be considered as 100% open. The results using this method are shown in Figure 7.9. The data points' distribution was similar to Figure 7.8 and only the window opening area was extended. The maximum effective opening area was extended to 90%, which can be considered as fully open. And in most of the time the window effective opening area was between 0% and 50%.

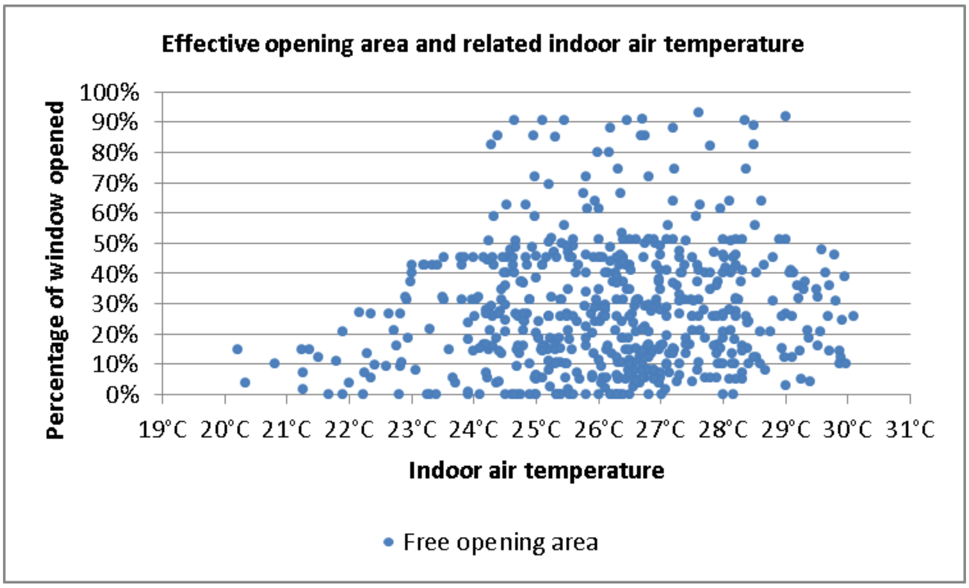

Figure 7.9: The relationship between the window open percentage and indoor air temperature (only considering the occupant-controlled window panel).

In these offices, there was a lack of time that the effective opening area was above 50%; this may be because there were two occupants in an office and they controlled different windows. Only when both controlled windows were fully opened would it be considered as 90%. The occupant would base on personal comfort demand and behaviour to control the opening area, so both windows having a large opening area did not frequently happen.

Therefore, occupant changing opening area behaviour was like a reflex action. They would push or pull the window when they sat. The distance between the occupant and the window also limited the opening area, because occupants had to stand up if they needed a large opening area. This was also the reason that only the window near the occupant had been used, because it was easier to reach and control. During the working hours, occupants were focused on their work, so it was important to control the window conveniently. Therefore, in an office such as the one in building B, the light window on the top of the door, the window on the partition wall and the top-hung window on the top part of the window could be designed as automatically controlled, because these windows were very difficult to control, but have great benefit to cross-ventilation and indoor temperature. For instance, at the end of the day, after occupants had left the office, opening these windows could cross-ventilate the office during the night time. The top-hung window can prevent rainfall from drenching the room, and the position of the window can keep the air flow at the top of the office, avoiding air flow blowing away papers.

The correlation between indoor air temperatures and percentage of windows usage was also analysed (Figure 7.10). The figure shows in three weeks, in all four buildings, all the monitored and frequently-used windows were opened in the working hours and the indoor air temperature varied between 19.5°C and 30.3°C. According to the results, the effective opening area was reduced with decreased indoor air temperature when indoor air temperature was below 25°C. And occupants still kept the windows open. So the occupants in these offices still could accept the indoor environment, and the indoor air flow did not cause occupants to feel uncomfortable. This may be because clothes were added by some occupants to adapt to the temperature drop and reduce the influence of air flow on occupants' comfort. No correlation was found between indoor air temperature and percentage of opened windows when indoor air temperature was between 25℃ and 28℃. The percentage of opened windows would not increase with rising indoor air temperature, the data points were randomly distributed. This is because most of the occupants felt comfortable when the indoor air temperature was between 25°C and 28°C. Controlling the window may be related to indoor air flow speed rather than adjusting indoor air temperature. Further study can be carried out in the future to investigate this correlation when indoor air temperature was lower than 20°C or higher than 28°C.

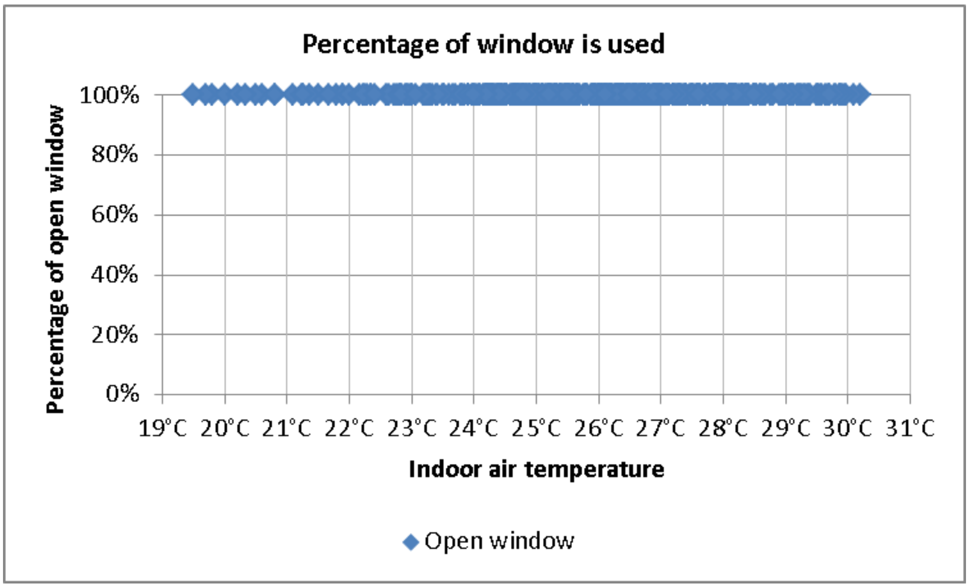

Figure 7.10: Probability of the opening of windows in four office buildings in the monitored period (the monitored and frequently-used windows were opened in the working hours).

7.2.2 Effective opening area as a function of indoor air flow speed

The effective opening area change may be related to indoor air flow speed. Continuous measurement was used to measure the air flow speed around the occupants in all four buildings. The results in offices A2 (CV), B2 (SSV/CV), C3 (CV) and D1 (SSV) are presented in this section.

Indoor air flow speed was measured on points R, P and S (presented in section 4.1.2), which were near the occupants. The measurement collected in office A2 are shown in Figure 7.11, Figure 7.12 and Figure 7.13. The measured average indoor air flow speed on points R (0.57m/s) and S (0.53m/s) were higher than that on point P (0.31m/s). Due to gusty wind, the indoor air flow speed would rise over 1m/s, and near the points were this was most noticeable, this would be followed by a window state change. The air flow speed increase on point P meant that the occupants started to close the windows to reduce the opening area, and the air flow speed increase on points R and S were related to different window states in the office. In the afternoon of 11th and 12th, the air flow speed on points R and S were around 1.8m/s, but the window state did not change. It seemed that the air flow speed increase on point P may have caused the reduction of the open area. This may be because point P was close to the desk surface. Increasing the air flow speed would cause paper to move on the desk and disturb the occupants' work. Points R and S were behind the occupants, and the increased air flow speed would cause the occupants to reduce the opening area. But sometimes increased air flow speed would not cause any window state change.

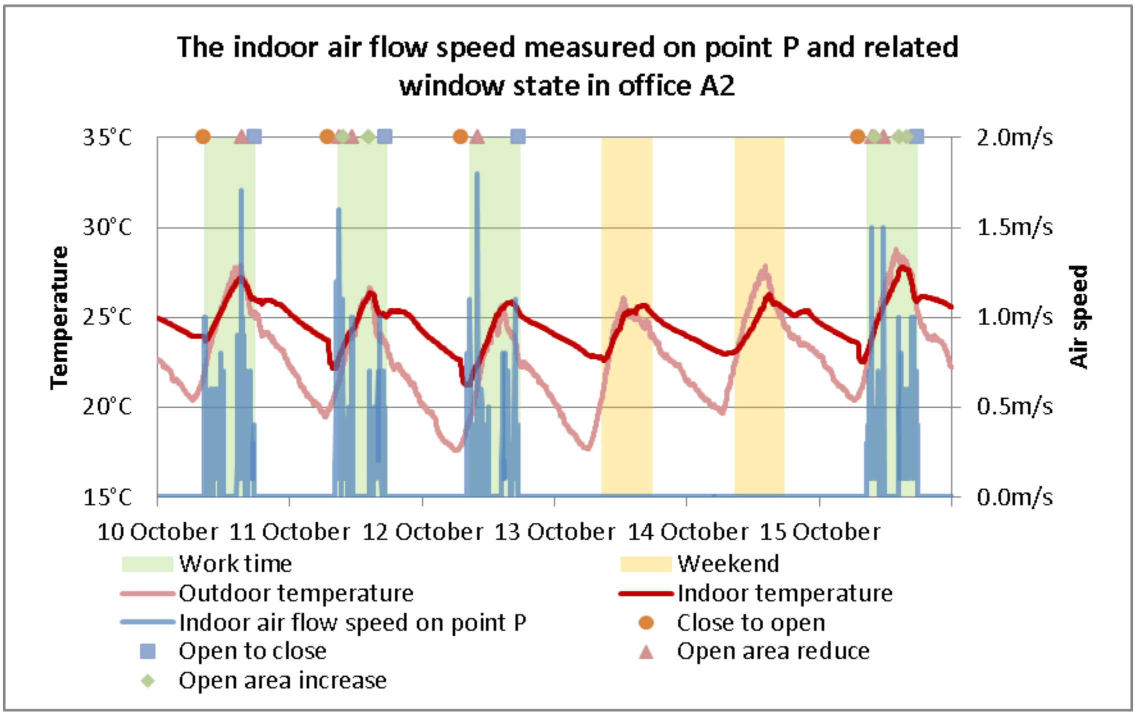

Figure 7.11: The indoor air flow speed measured on point P and related window state in office A2 (CV).

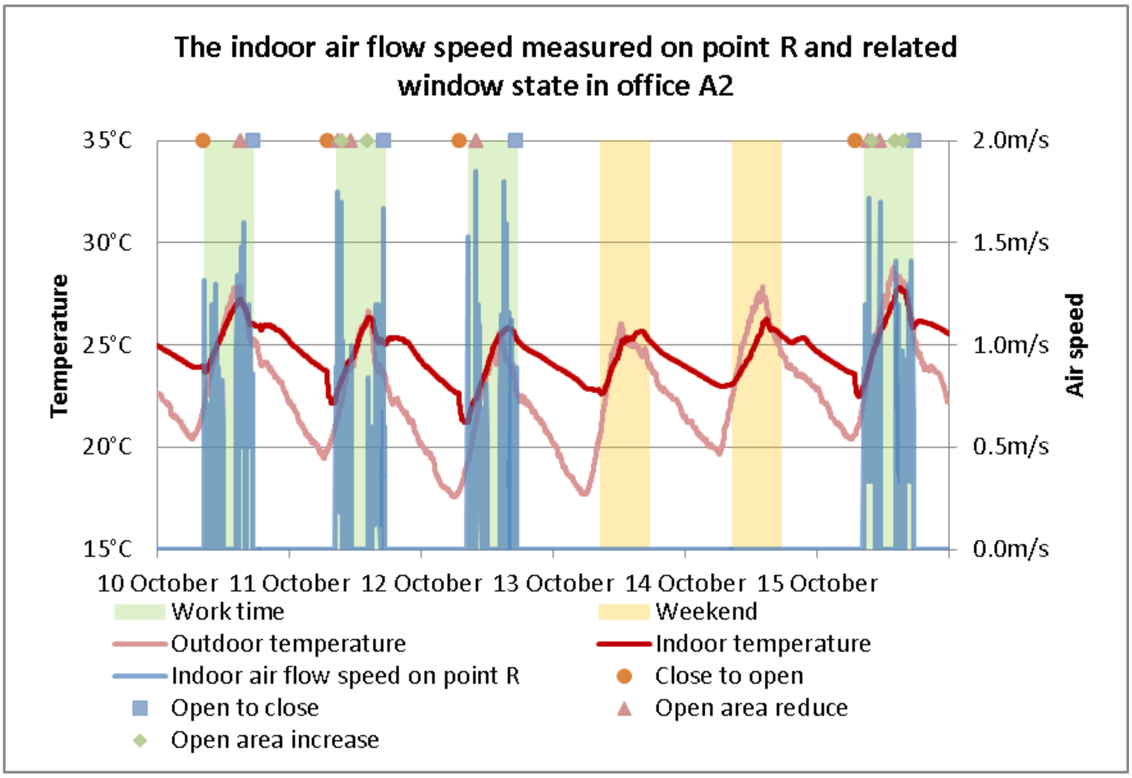

Figure 7.12: The indoor air flow speed measured on point R and related window state in office A2 (CV).

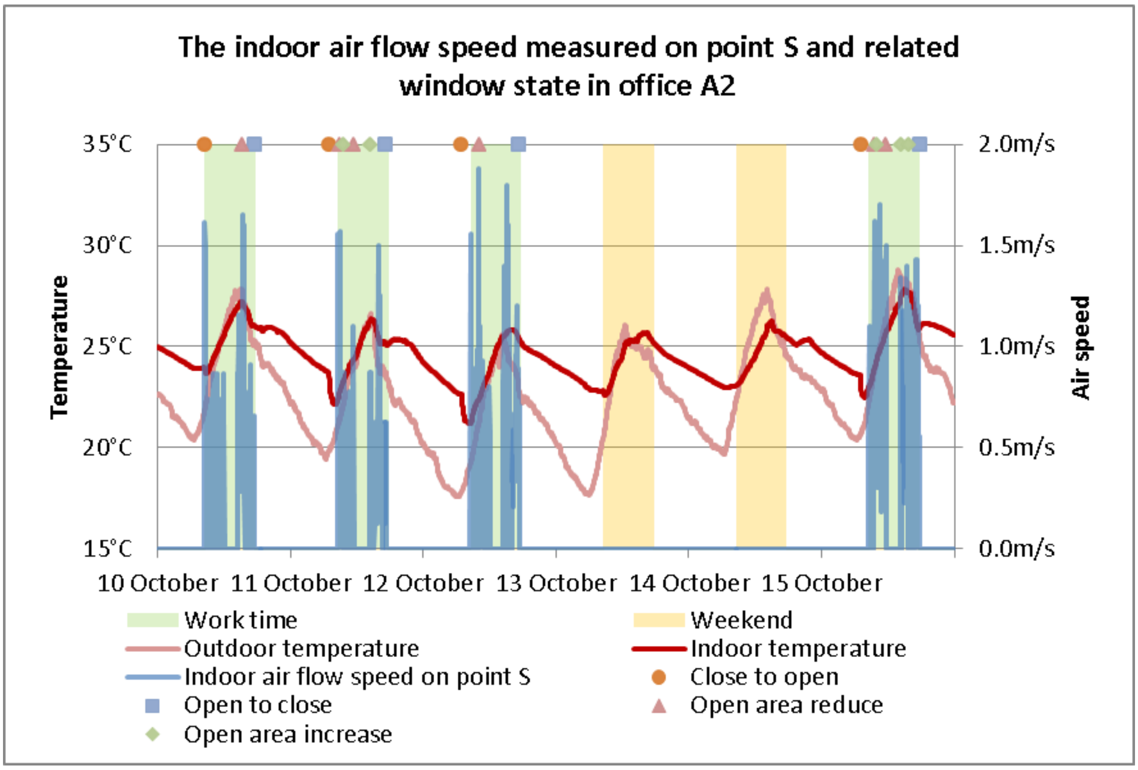

Figure 7.13: The indoor air flow speed measured on point S and related window state in office A2 (CV).

The window state changes during the working hours and the related indoor air flow speed on points R, P and S are shown in Figure 7.14 and

Figure 7.15. Figure 7.14 shows measurements just before the occupant reduced the open area. The indoor air flow speed on three monitoring points was mainly above 1.5m/s. Only in one group of data was the indoor air flow speed around 1m/s, which may have been caused by an occupant closing the window or reducing the open area when they left the office in the morning. This behaviour was not related to indoor air flow speed, but probably a habitual action. In office A2, the opening percentage was below 10% after occupants reduced the opening area. So decreasing the opening area aimed to reduce the indoor air flow speed. In office A2, the threshold for reducing the opening area was 1.5m/s. When the window opening area increased, the related indoor air flow speed varied from 0m/s to 1.2m/s. The indoor air flow speed was random. Increasing the window opening percentage was not related to indoor air flow speed.

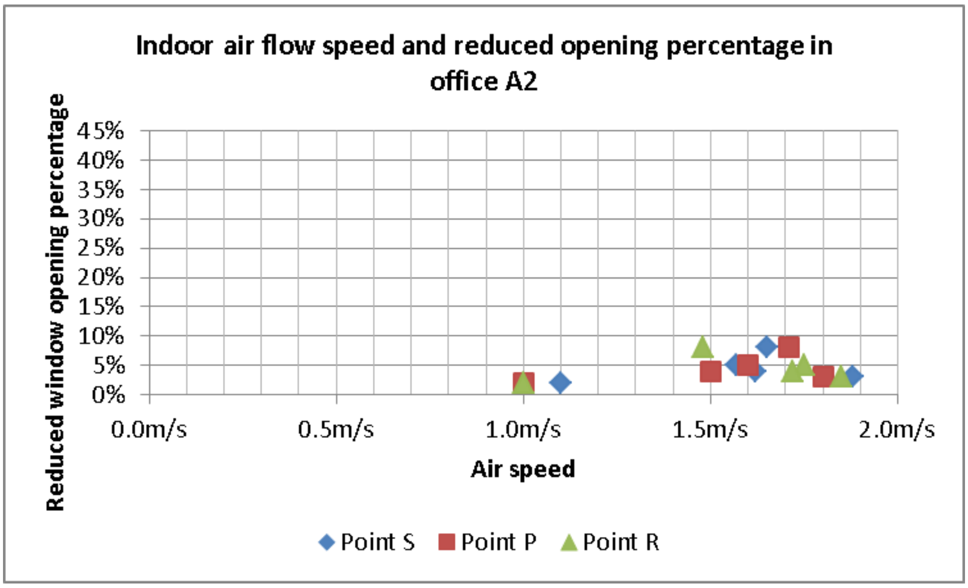

Figure 7.14: The indoor air flow speed in three monitor points when occupant reduces the opening area and the reduced opening percentage in office A2 (CV).

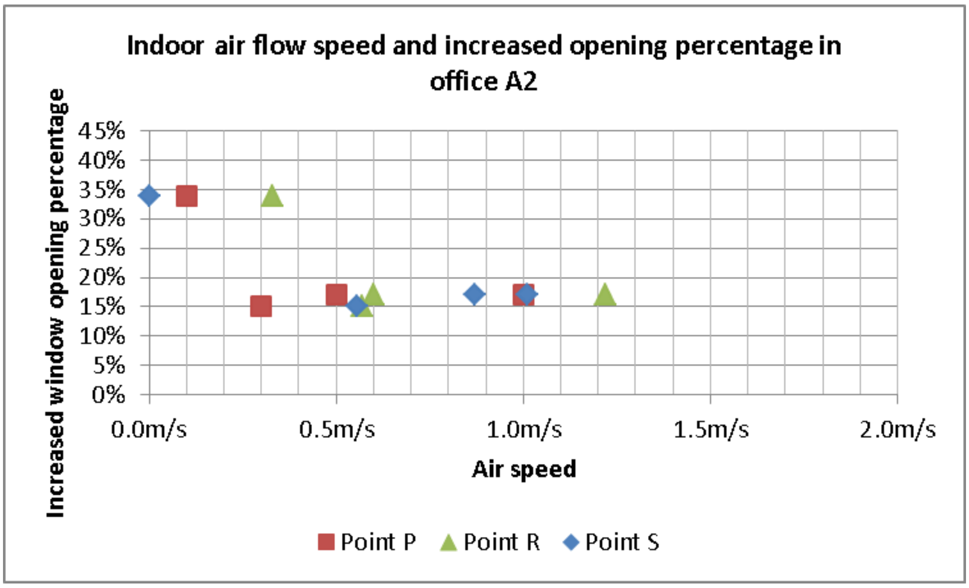

Figure 7.15: The indoor air flow speed in three monitor points when occupant increases the opening area and the increased opening percentage in office A2 (CV).

The result in office B2 was similar to that in office A2. The increased indoor air flow speed would cause the reduction of the opening area. Figure 7.16 showed the indoor air flow speed when occupants reduced the opening area. The indoor air flow speeds on three monitor points were over 1.3m/s, which was slightly lower than that in office A2. The reduced open area was between 5% and 22%. The open area was larger than that in office A2. The occupants in office B2 reduced the opening area randomly; as long as the opening area was reduced, the indoor air flow speed was decreased. Some reduced opening area was larger than the increased opening area. As shown in Figure 7.17, the indoor air flow speed at three points varied between 0.5m/s and 1.2m/s just before occupants extended the opening area. Also, the extended opening area was below 20% and only one group of data was at 31%. This may be because 20% of the glazing area was the largest opening area that occupants could open when they sat near the desk. If they needed a larger opening area, they had to stand up and push the window further. So when an occupant was working, they would not stand and extend or reduce the opening area frequently.

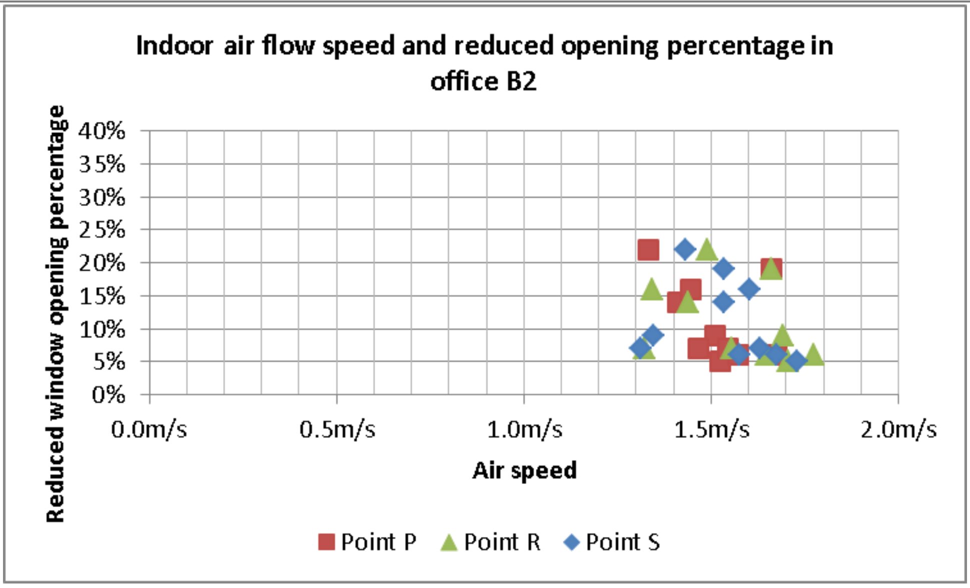

Figure 7.16: The indoor air flow speed in three monitor points when occupant reduces the opening area and the reduced opening percentage in office B2 (SSV/CV).

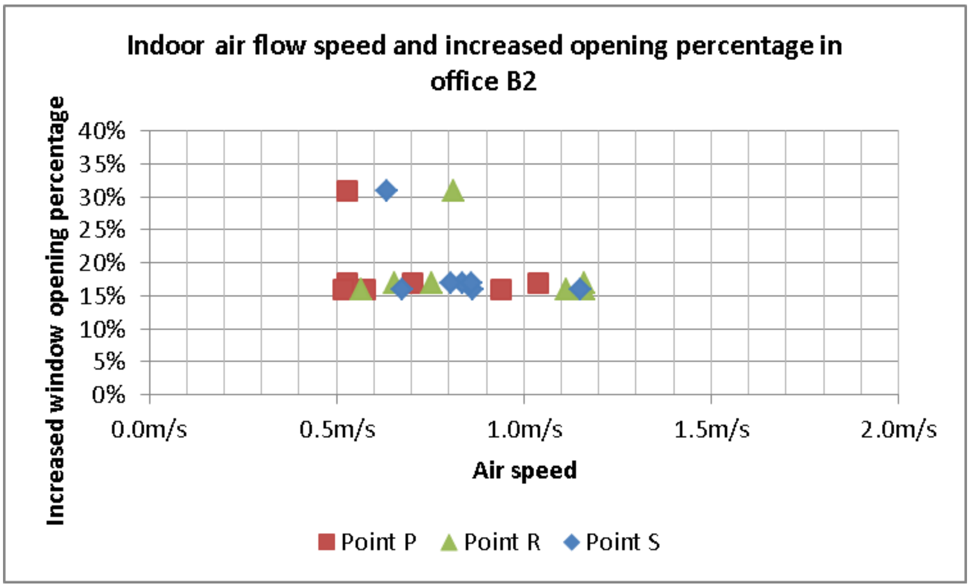

Figure 7.17: The indoor air flow speed in three monitor points when occupant increases the opening area and the increased opening percentage in office B2 (SSV/CV).

In office C3, the indoor air flow speed caused the reduction of the opening area to be mainly above 1.3m/s, and among these data most of them were over 1.5m/s (Figure 7.18). This result was close to that in the other two offices. The reduced opening area was mainly around 25% of the glazing area. The reduced opening area in office C3 was larger than the other two offices. This may be related to window type and window usage condition. Two sliding windows close to the occupants were more frequently used than the window in the middle. When the opening area was reduced, at same time the window moved the air flow path as well

(Figure 7.19). Compared to the fully-opened window, reducing the opening area can move the air flow path away from the desk and decrease the impact of air flow on desk surface/ occupant. So the occupant does not have to reduce the opening area to a small size. When the opening area increased, the related indoor air flow result was the same as that in other offices (Figure 7.20).

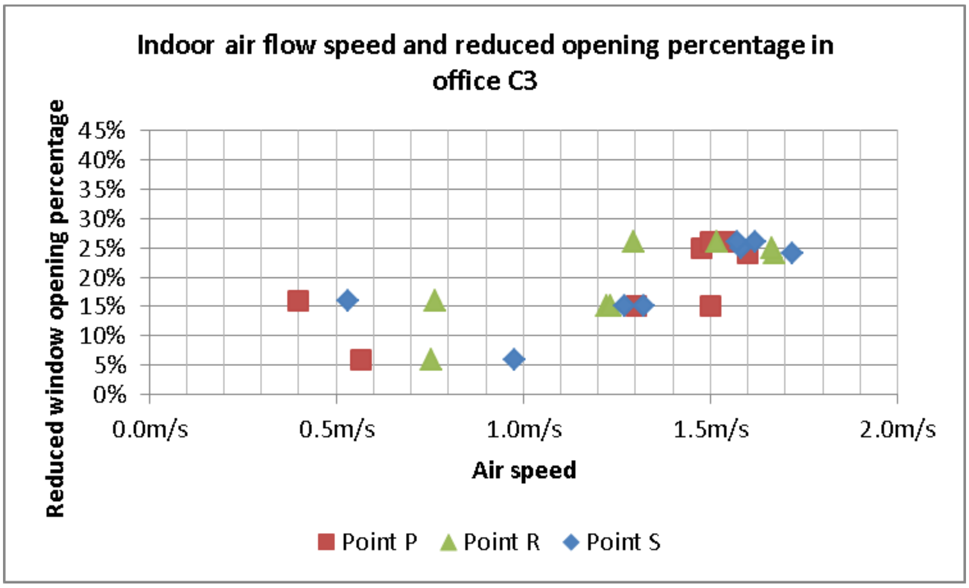

Figure 7.18: The indoor air flow speed in three monitor points when occupant reduces the opening area and the reduced opening percentage in office C3 (CV).

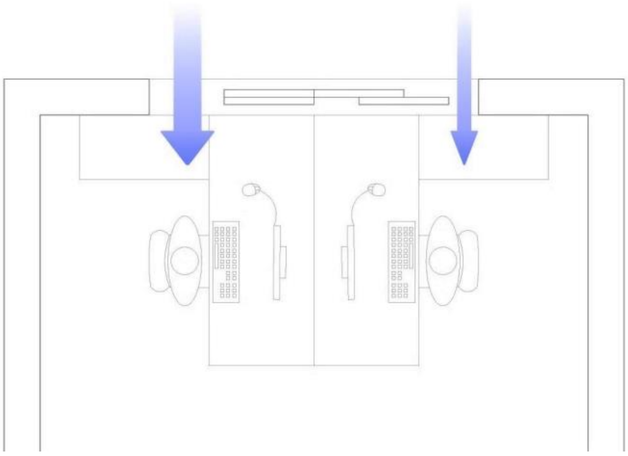

Figure 7.19: Air flow path on the window when the window was fully opened and half-closed.

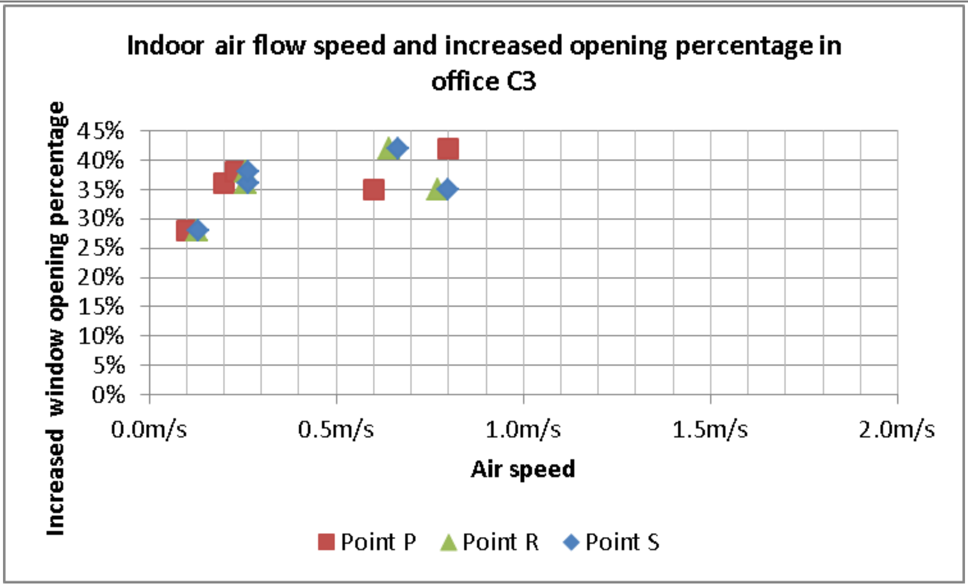

Figure 7.20: The indoor air flow speed in three monitor points when occupant increases the opening area and the increased opening percentage in office C3 (CV).

In office D1, the window was not changed during the entire measurement period. Because of the window type and opening area, the indoor air flow near the occupant and desk was very low, which has been presented in Chapter 4. But it was also proved that the high air flow speed was the main reason causing occupants to reduce the opening area.

In general, the indoor air flow speed causing occupants to reduce the open area was mainly over 1.2m/s (Figure 7.21). So, when the indoor air flow was above 1.2m/s it may have caused occupant discomfort. The indoor air speed was suggested not over 1m/s in office building, which may causes occupant feel uncomfortable (ASHRAE 55, 2010). But, as shown in office A2, sometimes when the air flow speed on points R and S was much higher than 1.2m/s, say around 1.8m/s, the window state was not changed. This also can be measured in offices B2 and C3. Except at the time occupants leave the office, most of the opening area reductions were related to air flow rise on point P which was close to the desk surface. Thus, the window change behaviour in the monitored period was more related to the air flow speed on the desk surface. And the air flow speed on point P causing the open area reduction was mainly over 1.3m/s (Figure 7.22). Thus, preventing air flow from moving the paper on the desk was the main reason for the occupants to decrease the window opening area and reduce the air flow speed. In order to reduce the influence of air flow on the paper, occupants always put some heavier book or stationery on the paper to avoid them moving. When air flow was above 1.3m/s, some paper also started flapping. The measured air speed was slightly lower than the speed suggested by EN ISO 7730 standard (1994) which was 1.5m/s in office buildings. The relatively higher airflow speed near occupants would not cause the open area to be reduced when it is 1.8 m/s. Therefore, as suggested by Givoni (1998), the indoor airflow speed up to 2 m/s would not cause occupants discomfort in naturally ventilated office, and it could help to extend occupants' comfort threshold. The measured result was much higher than the speed suggested by ASHRAE 55 (2010) which was 1m/s. The indoor air flow needs to be away from the desk surface to avoid disturbing occupants' work.

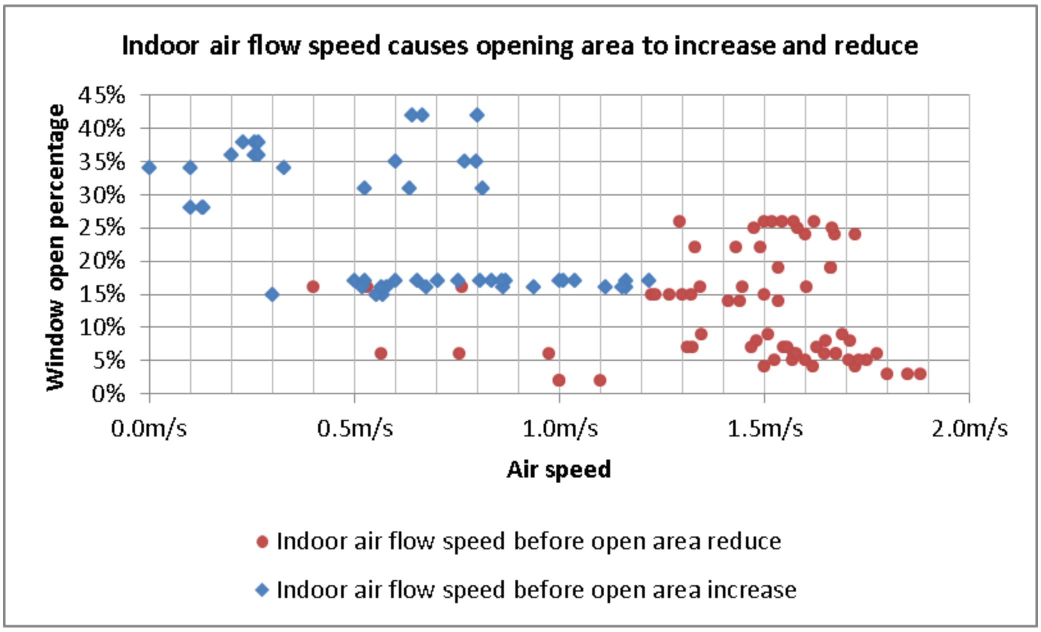

Figure 7.21: The indoor air flow speed causes occupant increase and reduces the opening area.

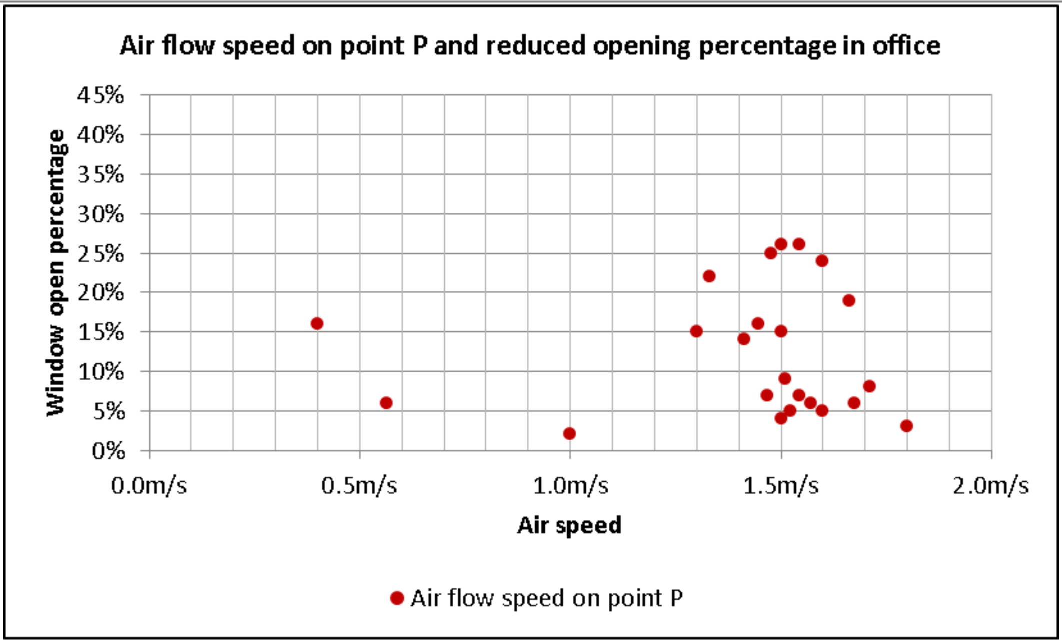

Figure 7.22: The air flow speed on point P, which causes open area reduction.

In summary, during the monitored period, when the indoor air temperature was lower than 25, the effective opening area reduced with decreased indoor air temperature. When the indoor air temperature was above 25°C, the effective open area showed more variety than the air temperature below 25°C. Changing the effective opening area did not correlate with indoor air temperature when indoor air temperature was between 25℃ and 28℃, and the effective opening area was randomly changed. Furthermore, the occupants would not change the opening area because of the indoor air flow speed. But when the air flow speed on the desk surface was over 1.3m/s, it would result in the occupants reducing the effective opening area. In field measurement, the high air flow speed was caused by a gust of wind. The paper on the desk would be moved by the air flow, disturbing occupants' work. If air flow could avoid the desk surface, higher air flow speed could be accepted by occupants, which could help to extend occupants' comfort threshold. The reason for these results was that, in the measurement period, most occupants were satisfied with the indoor environment. Adjusting the effective opening area was not important to indoor air temperature when the indoor air temperature was between 25 ℃ and 28 ℃. Thus, in the comfort temperature range, the effective opening area change was more influenced by indoor air flow speed than indoor air temperature.

In the measurement period, the window control behaviour was mostly caused by whether the indoor air flow would disturb occupants' work, rather than the indoor air temperature. This can explain why occupants closed the window and kept the door open, or had a small effective open area in the office; because, in most of time, the indoor air temperature was still in the comfort range and would not cause an extremely uncomfortable sensation. Furthermore, in some of the single-side ventilation offices, the average indoor air temperature was higher than in the cross-ventilated offices, but the highest daily indoor air temperature was lower than for cross-ventilation. A roller blind was often used in these offices to block the open area and reduce the air flow speed, but it would also block the solar radiation and reduce the heat gain. So, in these offices, the indoor air temperature could still be in the comfort range and also the low indoor air flow speed would not cause any disturbance to occupants' work. This was the reason for the window to be rarely used in the office. Occupants may consider that a variety of indoor air flow speed was more unacceptable than a slightly higher indoor air temperature.

7.3 Window typology and occupants behaviour

Indoor air flow speed has impact on occupant window control behaviour during the measured period. And indoor air flow path and speed were changed according to window typology and opening position in the offices. The occupants were controlling the windows in the offices to adjust the indoor air flow path and speed, and to satisfy their demanding. The windows in building A and B were used to analysis.

7.3.1 Office building A

In the cross-ventilated office, the window was frequently used by occupants. But not all windows were used in the office, as controlling these windows was inconvenient, and also opening some windows would cause unnecessary indoor air flow rise, which would influence occupants' work.

In office building A, there were 14 openable windows in the offices. Occupants had more window control feasibility here than in other offices. But only four windows near occupants were highly used. Occupants only used the nearest window which could be easily controlled. Occupants would not spend too much time on controlling the windows in the office. If they opened 14 windows when they arrived, they would have to close them all when they left. So more openable windows in the office could be of benefit to interior furnishing, enabling enough flexibility to choose where to put a table in the office with the closest window being openable. Although in office building A most of the windows were not used, the window type could help occupants to reduce the impact of air flow on the desk surface.

The window in office building A was segmented, the upper part window being bigger than the lower part. The detail was shown in section 4.4.2. The middle part of the window was never used, because opening the lower middle part of the window may have caused the air flow to rise on the desk surface and influence occupants' work, and the upper middle part of the window was inconvenient to control. However, this design could help occupants to control the indoor air flow and to avoid disturbance of air flow on office work.

The height of the upper part of the window was just above the occupants when they were sitting (Figure 7.23). Opening the upper window could keep the indoor air flow in the upper part of the office; even when the air flow speed rose by gusty wind, the indoor air flow would not have much influence on the desk surface. Occupants could focus on their work and did not have to change the opening area frequently. The position of the window was not suitable for frequent adjustment when occupants were sitting. But opening the upper part of the window would reduce the indoor air flow speed near the occupants, which could help occupants to extend their comfort temperature range when the indoor air temperature was higher than the comfort threshold. In addition, when it rained, the large opening area would bring the rainfall into the office and influence occupants' work.

In these conditions, closing the large window on top and opening the small one may help. The small window was at desk surface level and occupants could control it very easily when they were sitting. The incoming air flow had more influence on the desk surface level and occupants than the upper part window. Because the middle part was closed and only two small side windows were open, the influence on the desk surface was limited. And the air flow had more impact on occupants, but occupants could control the air flow by adjusting the small window. Thus, in office building A, occupants could use the segmentation window to adjust the indoor air flow to fit their demands. It was used quite well in office A2, which may be the reason that the window open area reducing frequency in office building A was the lowest in the four office buildings. In addition, the door was used more often instead of opening the window on the corridor side; this was because of convenience. Another reason was that opening the corridor side window would narrow the corridor area and influence the pedestrians on the corridor.

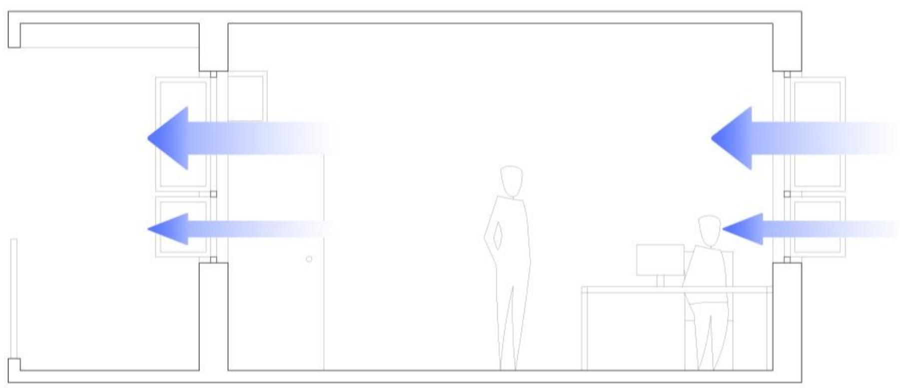

Figure 7.23: The possible air flow path with open window in an office in office building A.

7.3.2 Office building B

In office building B, the window was also segmented: two top-hung windows on the top and four casement windows on the bottom, the detail being shown in section 4.4.3. As for office building A, only two casement windows near the occupants were used. Two casement windows in the middle were not used because the air flow would blow away the paper on the desk. The two top-hung windows were not used, mainly because the window position was difficult to reach, the same as the window on the corridor side. Some occupants pointed out that there used to be a stick which was used to open or close the window on the corridor side, but the window was rarely used because it was inconvenient.

Those two inconvenient windows had a great advantage for cross-ventilation in the double banking office buildings, such as office building B (Figure 7.24). The window on the corridor side could provide daylight in the corridor and keep the office cross-ventilated if the door was closed. In the field measurement, in two offices the corridor windows were opened during the measurement period as the author suggested. Although the average indoor air temperature was slightly higher than other offices, the occupants' comfort vote results in these two offices were better than others in the building (presented in section 6.2). The higher indoor air flow speed near the occupant may maintain occupant comfort sensation.

Opening the top-hung window could guide the indoor air flow along the top of the office room and reduce the impact of air flow on the occupants. On a rainy day, the opening area of the large casement window would be reduced and prevent the influence of rainfall. The top-hung window could have a large opening and keep the office cross-ventilated. Furthermore, there was great potential for night time natural ventilation in the office. By opening the top-hung window and the window on the corridor side at night, the office could be cross-ventilated, which may reduce the indoor temperature and extend the comfort time in the next working day.

The office was designed to promote cross-ventilation and maximise the natural ventilation opportunity. However, because the window was difficult to control, it was rarely used. Thus, the practicability and accessibility are important issues to consider for window design in offices. An automatic control system could be considered.

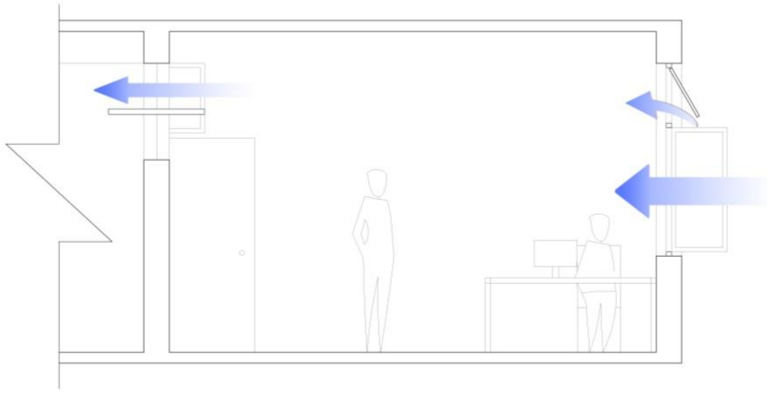

Figure 7.24: The possible air flow path with open window in an office in office building B.

In office building C there were four sliding windows in an office room. The sliding window cannot control the air flow direction when it flows into the office indiscriminately. However, the opening position of the sliding window can be changed which to control the indoor air flow path along a horizontal direction, it giving the occupants more opportunity to control the indoor air flow path in order to achieve their thermal comfort. According to occupants' sitting place, the only two closest windows were highly used. Because open the window in the middle part would led indoor air flow across over working surface which may disturb occupants' work. This result was the same as occupant window control behaviour in office buildings A and B. In office building D, as presented in section 5.2.4, the two top-hung windows were never closed in the monitoring time. Because the incoming air flow would be directed to the upper part of the office; as such the air flow speed in the upper part of the office was much higher than at the occupant working level. Thus, the air flow passing though the top-hung window had very limited impact on occupants' window control behaviour.

Comparing these two office buildings with office buildings A and B, the natural ventilation opportunity was less considered in the offices. This may be because office buildings C and D were designed after the late-90s, when the air-conditioning system was highly applied in office buildings. The architect relied on the performance of air-conditioning to content occupant comfort rather than considering design. So there was no particular design to encourage occupants to use natural ventilation in the office. Conversely, office buildings A and B were designed before the 1990s. Air-conditioning was not used in China; thus, the architects tried to maximise the natural ventilation opportunity in the office in order to provide a more comfortable indoor environment. These windows were particularly designed to achieve this purpose. However, due to the inconvenience of using some of the windows in the office and occupant window control habit, some of the offices in office buildings A and B lost these advantages for natural ventilation, making no difference with office buildings C and D. Therefore, the accessibility was a significant point for windows in the office.

7.4 Applying measured data into a dynamic analyses model

The results of this field survey were applied into a simulation model (showed in Chapter 2), to define the impact of window control behaviour on indoor temperature. The south and north orientation single-side ventilation office and cross-ventilated office were used for the analysis. The glazing ratio was 30%. In the field survey, most of the buildings were south and north facing. In addition, the hourly data analysis (Chapter 3) identified that the thermal performance in a 30% glazing ratio office was better than the larger glazing ratio office in both natural ventilation offices. In the cross-ventilated office, the north and south orientations had the best indoor thermal performance and the largest comfort temperature percentages. Night-time ventilation was considered in the simulation, as well as the segmentation window (Appendix 1) in office buildings A and B.

7.4.1 Investigating night-time ventilation

Based on the model characteristics in Chapter 2, some parameters were changed. The open window temperature was revised from 22°C to 19.5°C and the effective opening area would be increased to maximum when the indoor air temperature reached 25°C. For the indoor temperature percentage result analysis, the low indoor comfort temperature threshold was reduced to 19°C. The result showed that the comfort temperature percentages in the single-side ventilation office were the same as the result in Chapter 2, so the reduced window open temperature and comfort threshold did not have an influence on the single-side ventilation office. In the cross-ventilated office, the comfort temperature percentage was increased, but was very limited. The maximum increase was 0.8% in May and 3% in October when the glazing area was 100% opened (Figure 7.25). The increased percentage on different opening areas was similar. No change was found in July and September. The increase was mainly on the low temperature boundary, because the comfort temperature threshold and open window temperature were extended on the low boundary, and in May and October in 10.5% and 18.5% of working hours the external temperature was below 19°C. But in June and September, the percentages were 1.4% and 0%. Thus, the lower window open temperature would not have a significant impact on indoor air temperature.

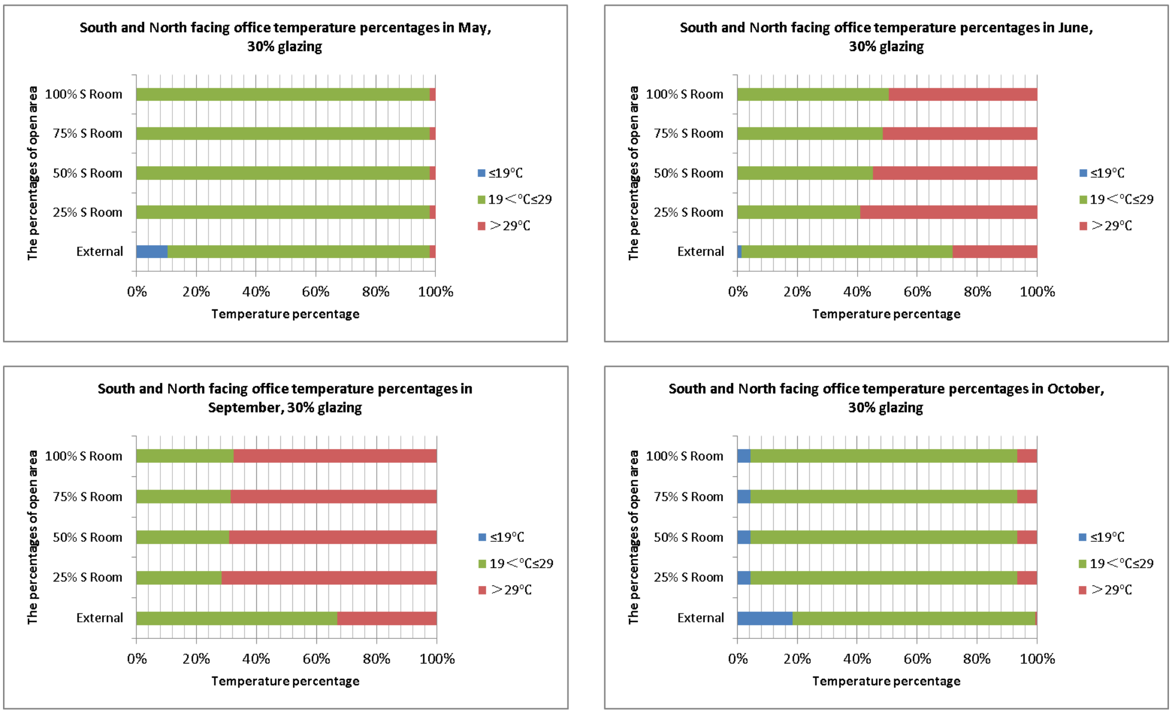

Figure 7.25: The temperature percentage in cross-ventilated office with applied new threshold.

In addition, there was large indoor and outdoor air temperature difference during the night. Opening the window at night may be able to reduce the indoor temperature and extend comfort temperature percentages: 25% of the glazing area was set to open at off working hours, because in the cross-ventilated office the comfort temperature percentage was very close when the effective opening area was above the 25% glazing ratio. The same opening area was employed in the single-side natural ventilation office. The result is shown in Figure 7.26. In the single-side ventilation office, the change was very limited. In May, on the comfort temperature, the percentage increase was about 2% and the results on 50%, 75% and 100% open cases were the same. On the 25% open case the increase was small: 1.2%. The results in June and September were similar, the increase being only about 1.1% on each open case. In October, the result was slightly better than that in other months, the increase was 3.6% on each opening case. This may be because in October the night-time outdoor air temperature was lower than the other three months, which can slightly cool the indoor environment. But the effect of night-time natural ventilation was very limited in a single-side ventilation office.

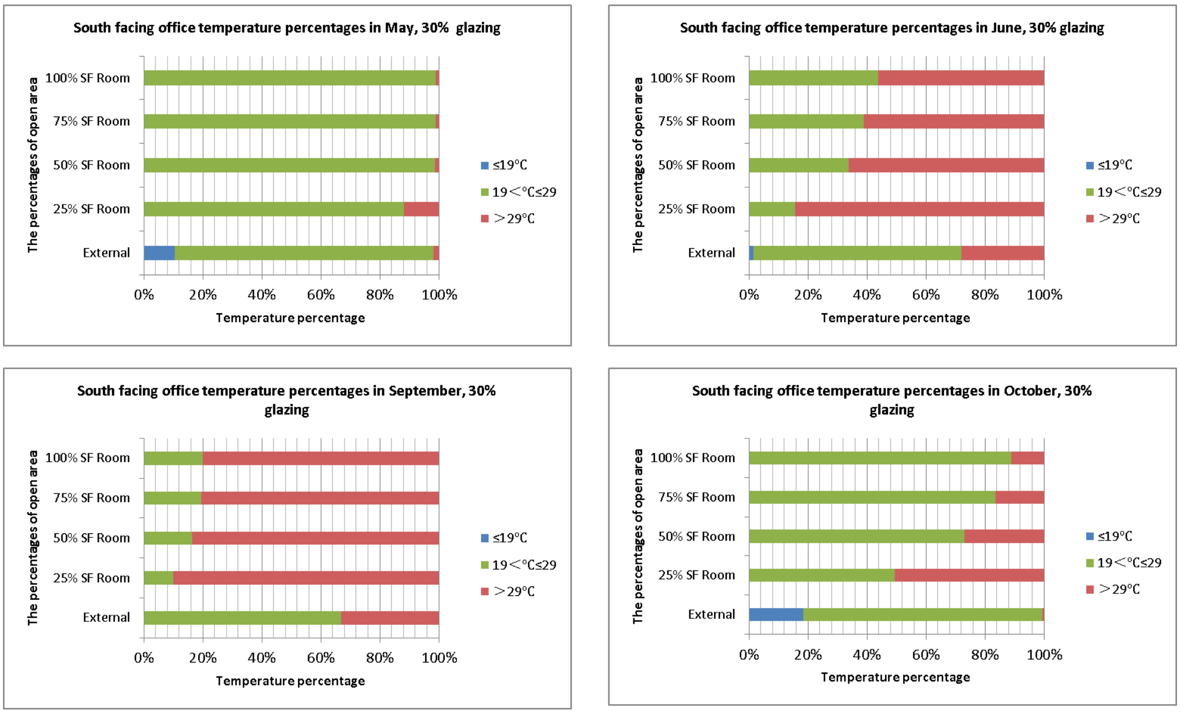

Figure 7.26: Temperature percentage in 30% glazing south- and north-facing single-sided ventilation office and with night-time ventilation in four months.

In the cross-ventilated office, the night-time ventilation result is shown in Figure 7.27. In May, the comfort temperature percentage increased 2% and none of the temperatures were outside the comfort temperature range during the working hours. But in June and September, the results were similar to that in single-side ventilation, the comfort temperature percentage increase being very little, about 3% in June and 1.5% in September when the open area was 50%, 75% and 100% of the glazing area. The increase on the 25% open case was even lower in each month. The comfort temperature percentage ascent in October was 4% in each open case, the result was better than that in other months. However, the increased amount was still limited in the cross-ventilated office in four months and just slightly better than the single-side ventilation office. Thus, according to the simulated results, the night-time ventilation did not have a significant impact on office indoor air temperature in both single-side ventilation and cross-ventilated offices.

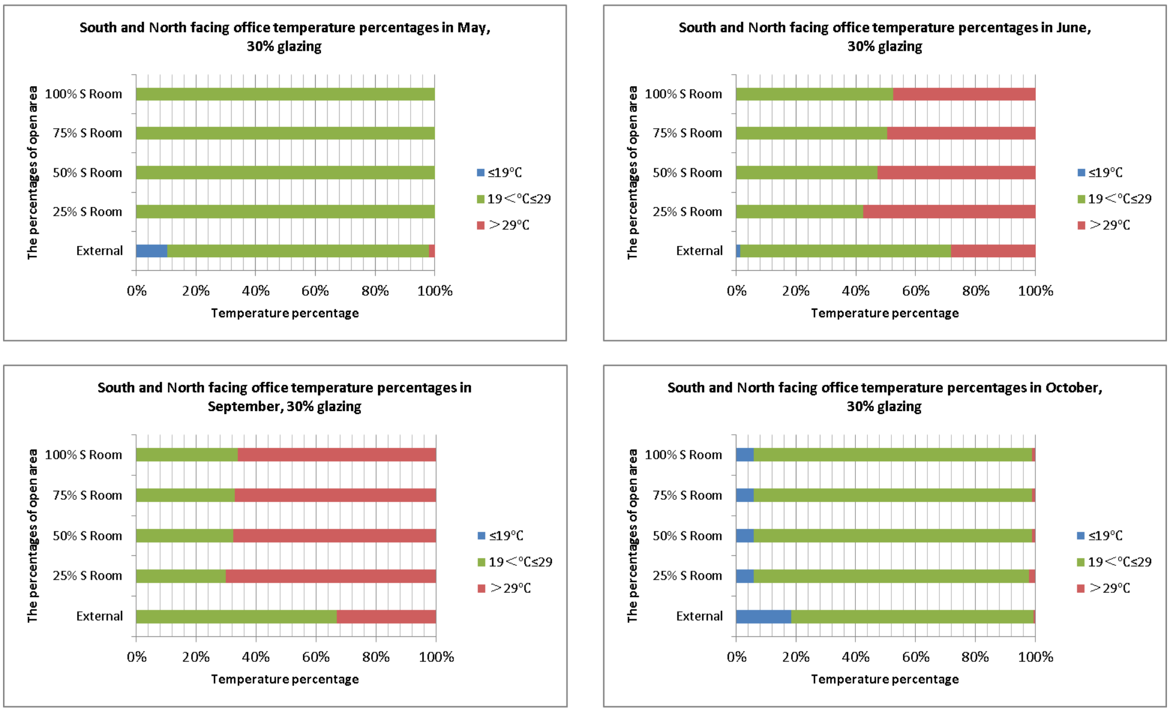

Figure 7.27: Temperature percentage in 30% glazing south/north-facing cross-ventilated office and with night-time ventilation in four months.

In May and October, the night-time ventilation was not important in the office because, if the office could be cross-ventilated or have a large open area in a single-side ventilation office, the indoor comfort temperature percentage was even larger than the outdoor comfort temperature percentage. Reducing the indoor temperature in June and September was more significant on extending the comfort temperature, because the outdoor comfort temperature percentage was more than 20% higher than the indoor. However, the night-time ventilation could not help in extending the comfort temperature in the office, the main reason being the higher indoor radiant temperature. Figure 7.28 shows the temperature variations in five days in September in a cross-ventilated office. The indoor air temperature was close to the outdoor air temperature, which means the office was well ventilated. The rise of indoor air temperature may be related to the reduction of air flow speed and heat accumulated. The indoor radiant temperature was about 4°C higher than the outdoor and the temperature drop was 2°C during the night. The building structure could not be cooled at night and be heated in the day time, which would cause occupants to be uncomfortable. It was also the reason for the indoor comfort temperature percentage to be much lower than the outdoor in June and September.

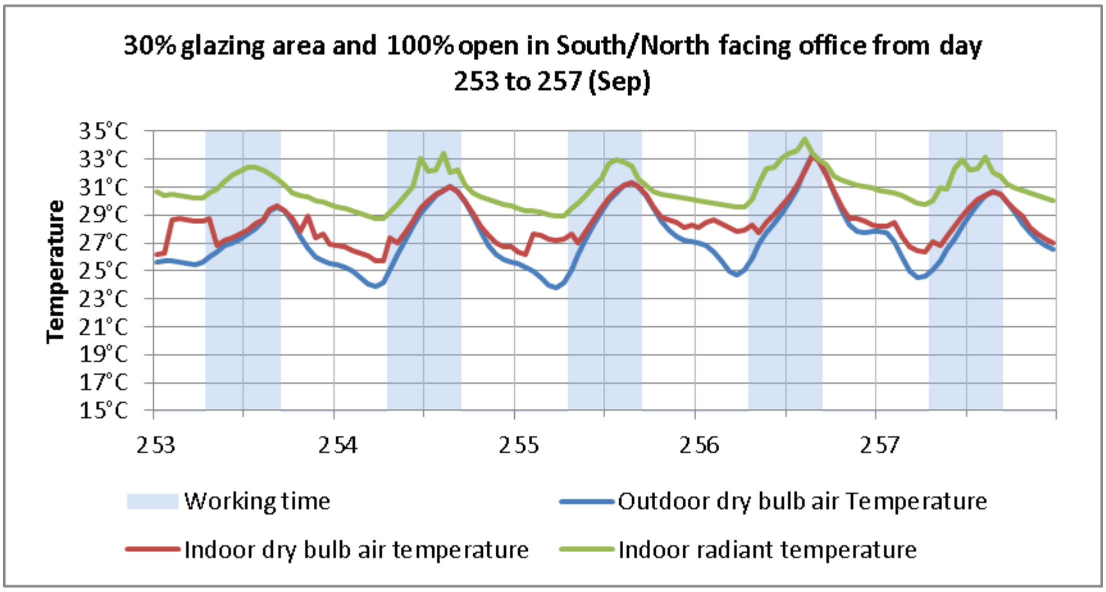

Figure 7.28: Indoor and outdoor temperature in south/north-facing office with night-time ventilation in September.

7.4.2 Investigating windows segmentation

The window in the simulation model was changed to the window type in office building A and office building B, which was segmented. The other parameters were kept the same in the simulation. And the window open temperature and open percentage were the same for segmentation windows. The day time only natural ventilation was first analysed. Figure 7.29 shows the result in a single-side ventilation office with the window type in office building A. In May and October, the indoor temperature was in the comfort temperature during the entire working hours. The comfort percentage had great improvement compared with the previous simulation result. Especially for the small opening case (25% glazing area open), it increased 16% in May and 52% in October.

In June and September, the comfort temperature percentage also had a great rise. The comfort temperature percentage results were the same at 50%, 75% and 100% open cases. As for the feature in May and October, the percentage increase was larger in the smaller opening case than in the larger opening case. The comfort temperature percentage in the 25% opening case was even larger than the other opening cases. The comfort temperature percentage increased 46% in June and 22% in September. A single-opening window with a segmentation had a significant impact on indoor temperature. The office was simulated as having single-side ventilation with two openings at different levels, so the comfort temperature result was better than the previous one.

In the simulation model the opening type cannot be chosen, and the open area may start from the bottom of the window. The height difference between two open in a small open area would be higher than a large open. This may cause the comfort temperature percentage in a 25% glazing area open case to be larger than 50%, 75% and 100% cases. But, in fact, in office building A the window was a casement type. Changing the opening area would not cause a height difference change; thus, the comfort temperature percentage would be lower than the simulation results. Although the comfort temperature percentage result would be lower than the predicted, the comfort temperature percentage was much higher than the single-opening model, such as in office building C. The model with the window type in office building B performed slightly better than the window type in office building A, which was about 2% in June and 1.4% in September. The large open area below the small open area would perform better than the large open area on the top of the small open area.

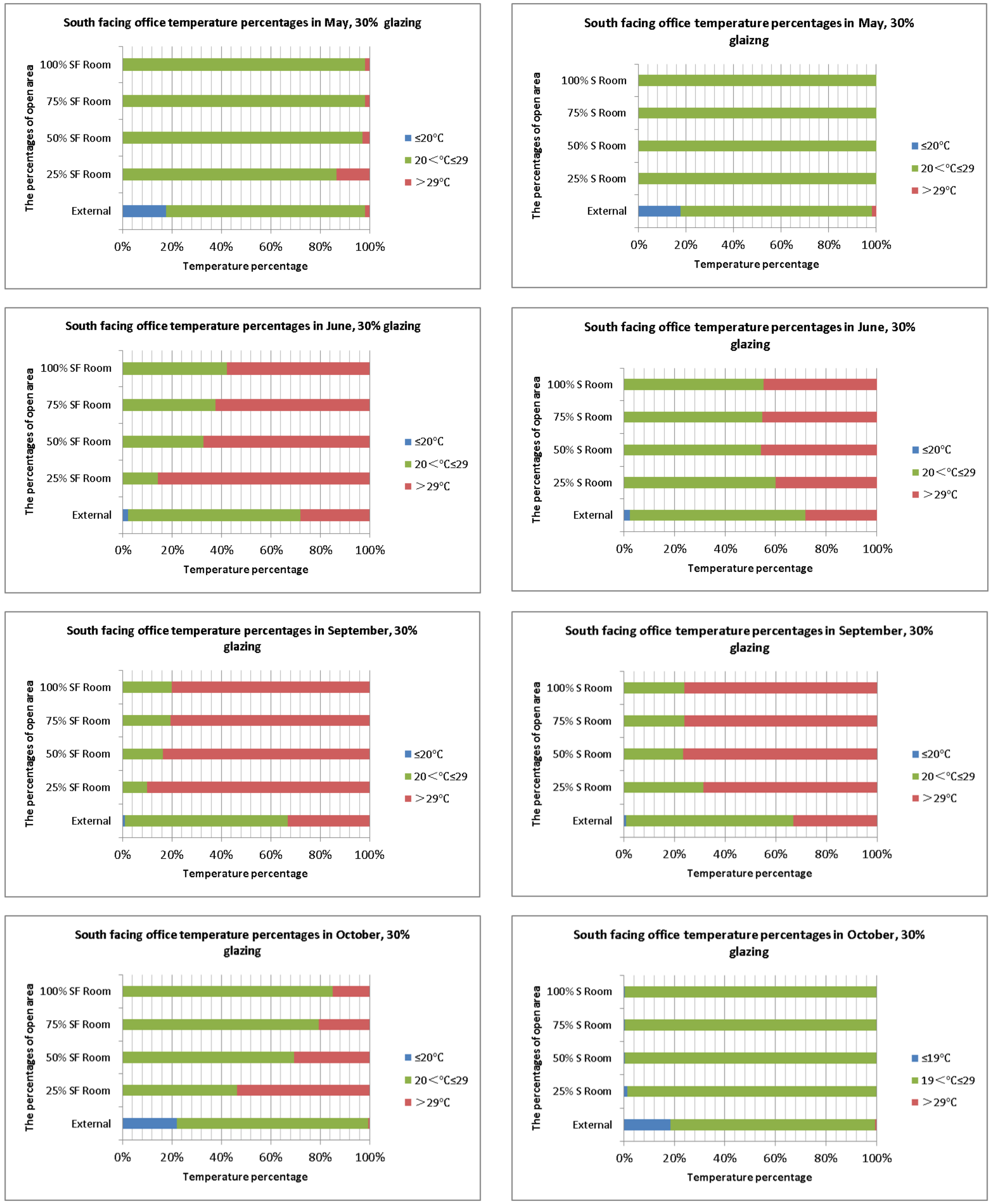

Figure 7.29: Temperature percentage results in single-side ventilation south-facing office with single-opening window (Left) and segmentation window (Right).

However, in the actual usage this advantage did not present because, in office building A, the single-side ventilation office used the door as a main vent rather than controlling the window. In office building B, the top window was never used because it was difficult to control. Although two windows at different heights can be more efficient for ventilating the office than a single-opening window, the accessibility of the window and the occupant window control behaviour would influence the performance of the window.

In the cross-ventilation model, both the windows were changed to segmentation type. The result showed that the indoor temperature in May was the same as the single-opening window result (Figure 7.30). In October, the comfort temperature percentage in each open case was similar and there was 4% of working hours that the indoor temperature was lower than 19°C. Compared to the single-opening window result, the comfort temperature percentage was extended and the indoor temperature was below 29°C. The indoor temperature reduction may be because of a non-windy condition, and the buoyancy drive could efficiently move the heat out of the office with a segmented window.

In June and September, the indoor comfort temperature percentage in the cross-ventilated office with a segmentation window was no different than a single-opening window. The only increase was in June: with the 25% and 50% open cases, the comfort temperature percentage was raised by 4% and 8%. In the cross-ventilated office, the effect of the segmentation window on indoor temperature was lower than that in the single-side ventilation office. It had been discussed in section 3.6 that, in a cross-ventilated office, the effect of the wind drive on indoor air flow rate was more than the buoyancy drive. Thus, the segmentation window in the cross-ventilated office would not have as much influence on indoor temperature as in the single-side ventilation office.

To sum up, the segmentation window type had a significant impact on indoor temperature in a single-side ventilation office because it could increase the indoor air flow rate by enlarging the buoyancy-driven force.

In the cross-ventilated office the wind-driven force had more influence than the buoyancy-driven force, and the impact of the segmentation window type on indoor temperature was limited. However, the accessibility of the window and occupant window control behaviour would influence the window's performance. If the window was difficult to control, the advantage and the impact on indoor air flow rate would be lost. However, this parametric study was limited, because the correlation between effective opening area and indoor air temperature can not be set in the software. In addition, the impact of night-time natural ventilation potential on indoor thermal performance and occupants' comfort needs further study to identify in the future.

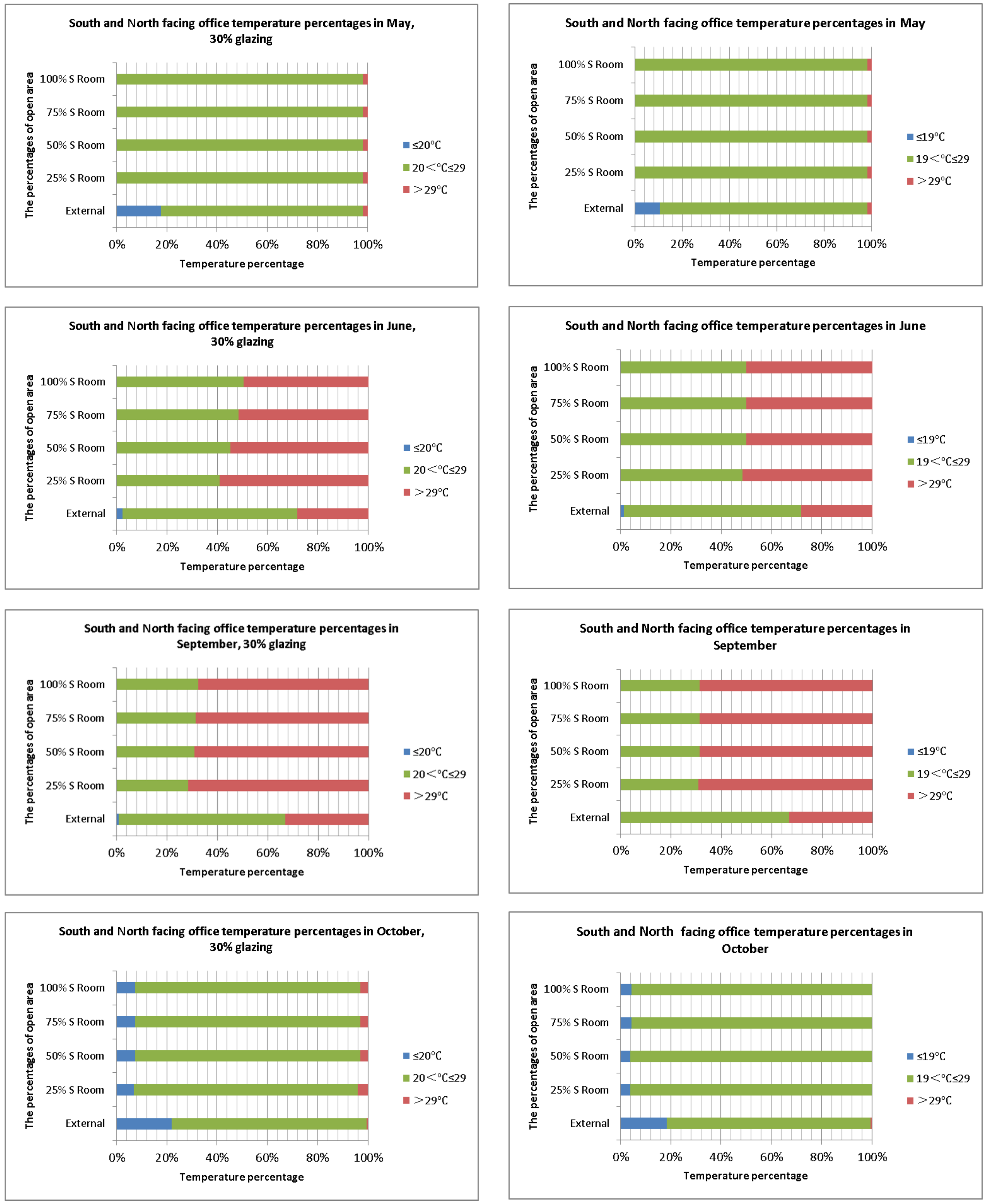

Figure 7.30: Temperature percentage results in cross-ventilated office with single-opening window (Left) and segmentation window (Right).

7.5 Discussion and conclusions

In this chapter, occupants' window control patterns in naturally ventilated offices have been presented. The data were divided into three time slot for analysis: occupant first arrival time, working hours, and leaving the office. The results showed that, at arrival time, more than 87% of time occupants would change the window state from closed to open. But, in office building B, the percentage was much lower while the window state changes from small to large were higher compared with other office buildings. This was related to occupant window control behaviour at leave time on the day before. And, also, it was related to the window locker which could lock the window on a different level. It would leave a small gap if the window was not fully locked, so when occupants left the office they may not fully lock the windows and the window state recorder was not recorded as closed. Actually, occupants in office B were intent on closing the window when they left the office. The result was the same in office buildings A and C, that occupants would close the window when they left the office. In the working hours, only in a few cases was the window closed during the working hours, the reason for which was rainfall. In most of the time, occupants controlled the window opening size. And in the cross-ventilated office the occupants adjusted the opening size more frequently than in the single-side ventilation office.

In order to find the reason for window opening size to change during the working hours, the correlation between occupant window control behaviour and indoor air temperature and air flow speed was investigated. The results showed that, when the indoor air temperature dropped below 25°C, the effective opening size started to decrease as well. With a related comfort sensation vote, occupants felt cool when the indoor air temperature dropped to 26°C or below. Thus, occupants reduced the opening area to drop the indoor air flow speed, which may have caused occupants to have an extra cooling sensation and feel uncomfortable. The results also showed that there was no correlation between indoor air temperature and window open percentages when indoor air temperature was between 25℃ and 28℃, the opening percentage data points were randomly distributed. This was because the occupant was satisfied with the indoor air temperature during the working hours, so they would not aim to adjust indoor air temperature by changing the opening area. In addition, when the indoor air temperature was higher than 28℃, none of windows was closed, occupants would feel hot and tried to increase the heat loss from the body, and keeping the window open can maintain the indoor air flow speed and improve their thermal comfort.

Furthermore, the window state change was not correlated with the indoor air flow speed. But the open area reduction was mainly related to indoor air flow speed on the desk surface. When the air flow speed was above 1.3m/s it would cause the reduction of the open area, and the reason was that the air flow would blow the paper on the desk and annoy occupants while working. Although heavy stationery was put on the paper, when the air flow speed was over 1.3m/s, it would still disturb the paper. In the office, occupants could tolerate higher indoor air flow speed. The maximum air flow speed measured near the occupant was 1.8m/s, which did not cause the reduction of the window area. Therefore, if a higher indoor air flow speed could avoid the desk surface, the open area would keep still and the high air flow speed had advantages on occupant thermal comfort when the indoor temperature was over the upper comfort threshold.

The window typologies and their usages in office buildings were also discussed. The window type in office buildings A and B had great benefit on natural ventilation and occupants' thermal comfort. For casement windows, the opened window is like a wind wall which can slightly direct the air flow in the office. On the other hand, when opened, the sliding windows cannot control the air flow direction as it tends to flow into the office indiscriminately. Nonetheless, the opening position of the sliding window can be changed which to control the indoor air flow path along a horizontal direction thereby giving the occupants more opportunity to adjust indoor air flow path in order to achieve their comfort. In office building D, the situation was different. The incoming air flow would be directed to the upper part of the office, the air flow speed in the upper part of the office was much higher than at the occupant working level. Whereas this can prevent high air flow speed from negatively impacting on occupants in high-rise building, but it reduced the opportunity of air flow effect on extending occupants' thermal comfort in office. This may be the reason that the window in office building D was not been used during the measured period.

The segmentation window can be used to adjust the indoor air flow, which can maintain the office cross-ventilation, but also help occupants to achieve their comfort without disturbing their work. In the actual usage situation, the middle part of the window was kept closed in the monitoring time to avoid air flow from blowing the paper away. Besides, the window on the high level of the office was rarely used, because it was difficult to control by occupants. So the characteristic of a window would lose its advantage on controlling the indoor air flow. The accessibility had a significant impact on window performance, which would result in indoor air flow and temperature. It is also an important element for window design and this should be considered by designer during the design process. Auto system can be considered for windows in the office, which should be easy for the occupant to understand and operate.

The hourly result showed that significant impact of the segmentation window on indoor temperature in a single-side ventilation office and indoor comfort temperature could be extended. Especially for the small-opening size, compared with a single-opening window, the comfort temperature percentage increased much more than for a large-opening size. The window was considered as two windows at different heights, the buoyancy drive being more efficient than a single-opening window. So two windows at different heights would be suitable for the office with a small-opening window.

In the cross-ventilated office, the impact of a segmentation window on indoor comfort temperature was limited. Because the wind drive was dominating the natural ventilation in the office, the effect of the buoyancy drive was little. Furthermore, the new indoor air temperature threshold for an open window was implicated in the simulation and analysed with a new comfort temperature range. The comfort temperature percentage had slightly increased on the lower boundary. The night-time ventilation was also considered in the model, but the result showed that the impact on indoor comfort temperature was limited. The reason may because of the thermal inertia of the building structure which stored a great deal of heat and difficult to cool down. This simulation was limited, further study is needed to be carried out to identify the influence of night-time ventilation on indoor thermal performance and occupants' thermal comfort.

In summary, the window control behaviour was mainly caused by the indoor air flow speed on the desk surface when the indoor temperature was in the comfort temperature range. And window opening percentage was reduced with decreased indoor air temperature when the temperature was lower than 25℃. In addition, the segmentation window had some advantages on adjusting the indoor air flow and reducing the indoor temperature, which could extend the occupant thermal comfort range if occupants were flexible in controlling it.

8 Conclusions

8.1 Summary of the work

This work has explored the occupants' adaptive behaviour related to natural ventilation, thermal comfort and their implications for the thermal performance of the office buildings. Natural ventilation is an efficient passive cooling method which can contribute to occupants' thermal comfort and building thermal performance. However, the lack of understanding of the relationship between occupant window control behaviour and window design can result in restricted natural ventilation resulting in occupant discomfort. The aim of this study has been to investigate the natural ventilation patterns, as well as the impact of indoor air flow pattern on occupants' thermal comfort and window control behaviour, in generic office buildings in South-east China with the climate of hot summer and cold winter.

This thesis started with a critical review of existing literature on occupant thermal comfort, particularly on window control behaviour in the office building (Chapter 1). The occupant thermal comfort threshold in a hot and humid climate has been identified as the related parameter to occupant window behaviour in the office building. The impact of indoor air flow speed and the opening configurations on indoor environmental conditions were also reviewed.

A parametric study was introduced in Chapter 2, to investigate the effective indoor air flow rate in single-side ventilation and cross-ventilated offices with different glazing areas, opening sizes and orientations in South-east China between April and October. The objectives of this study were to identify the impact of solar radiation and air flow rate on indoor temperatures within this climate zone. The optimum orientation and effective opening area were defined as well. Thus, this process generated results that could then be used in a subsequent field study exercise to predict thermal performance of offices and inform whether the identified effective opening areas in the offices could be used to meet its cooling and occupant comfort requirements.

The results show that solar radiation has more impact on indoor temperature than increasing air flow rate. In the single-side ventilated office, the north-east orientation achieved the highest indoor comfort temperature percentage, while the south-west performed the worst. The best orientation for a cross-ventilated office was south/north, while the worst was east/west. Reducing the glazing area from 70% to 30% could increase comfort working hours by a maximum of 144 hours in offices in four months which was about 17.5% of total working hours. Besides, in the cross-ventilated office, when the opening area was larger than 25% of the glazing area, the effective air flow rate for cooling can be achieved. A further increasing opening area does not increase the indoor comfort temperature percentage. However, the influence of occupants' behaviour on office thermal performance and their comfort perceptions is difficult to predict by parametric studies. These factors were derived from the field study data.

In Chapter 3 the study methodology was explained and examined in the pilot study, which was carried out in an office building in South-east China in April and May 2011. In the pilot study investigation, the researcher monitored indoor and outdoor environmental conditions, occupant window control behaviour and indoor air flow patterns. For purposes of this study, the upper threshold for occupant thermal comfort has been defined by Givoni's (1998) comfort zone for a hot and humid climate, the upper threshold of which was about 30°C in measured offices. Analysis of the study results indicated that the indoor air flow pattern was influenced by the top-hung window which would guide the air flow to the upper part of the office. Consequently, the air flow speed near occupants was much lower than that at the open area.

The control of windows was suggested to be related more to the requirement for fresh air. During the pilot study, it was found that occupants would keep windows open - even when the air-conditioning units were still running. However, a heat wave that occurred during the study period caused a rise in indoor air temperature and occupants continued to use air-conditioning in the monitoring period. This being the case, it was not possible to find a correlation between occupant window control behaviour and indoor environmental factors. Although the pilot study proved inconclusive, it was deemed useful as some problems were identified from it. For instance, the windows were used very rarely during the working hours. This may relate to window type as all the windows in the selected offices were of the top-hung type. The indoor air flow speed measurement was not comprehensive. Further, the survey questionnaire had a vote scale ranging from 1 to 7, in which 4 was the neutral point. For instance, the thermal sensation vote was from too cold (1) to too hot (7), while comfort sensation vote was from very uncomfortable (1) to very comfortable (7) (Appendix 5). The description of the vote scale was confusing for respondents which resulting in ambiguity in the comfort perception results and the correlations be can not be found between occupants' comfort survey and indoor temperature or air speed.

As a build up from the work conducted during the pilot study, the revised methodology was presented and four new case study buildings (with twelve offices which were used for field measurement) were described in Chapter 4. Additionally, three more window types were selected to find out the impact of window typology on indoor environmental conditions and occupants' comfort. More areas in the office were measured which can identify more specific indoor air flow speed and air flow patterns, which are related to different openings. Besides, continuous measurements have been taken in the office, in order to identify the impact of indoor air flow speed on occupant thermal comfort and window control behaviour. The occupants' perception vote scale was replaced by -3 to +3, according to occupants responded and perception result in the pilot study. For instance, the thermal sensation vote was from too cold (-3) to too hot (+3), and 0 was the neutral point of the scale. In addition, the ambiguity bar chart was replaced by scatter diagram which was more clearly shows occupant perception result.

Based on the field study results, the thermal performance of offices has been identified in Chapter 5. The indoor air flow speed, air flow path and air flow pattern have been identified based on different types of opening. The occupants' perception survey results were shown in Chapter 6, and their thermal perceptions, humidity perceptions and air quality perceptions were defined. Besides, the comfort perception results were compared with Givoni's comfort standard and ASHRAE adaptive comfort standard by psychrometric chart. A wider band of comfort zone for South-east China was presented based on Givoni's comfort standard. In Chapter 7, occupants' window control patterns have been defined and occupants' window control behaviour which is related to indoor air temperature, air flow speed and window typology was identified. These three chapters form the main part of this work, more conclusions and discussions are presented in the following section.

8.2 Discussions

The main conclusions were based on field work results. The conclusions related to the objectives of this thesis are summarised in the following sections.

8.2.1 Thermal comfort in the offices

The field survey described in Chapter 4 was carried out in twelve offices in four office buildings in South-east China during September and October in 2012. The results showed that the average indoor air temperature in a single-side ventilated office was close to that of the cross-ventilated office. In cross-ventilated offices, the indoor air temperature variation was larger than that in single-side ventilated offices and close to the outdoor air temperature. The cross ventilated offices were well naturally ventilated and moved internal heat efficiently out of the office. Besides, the highest daily indoor air temperature in some single-side ventilated offices where the roller blind was frequently used was lower than that in a cross-ventilated office, and the daily indoor air temperature variation was lower than 2°C. As indicated in the parametric study, blocking solar radiation was more effective in controlling the indoor air temperature than extending the open area. According to the thermal performance of these twelve offices, the indoor environmental conditions were acceptable in both single-side ventilated offices and cross-ventilated offices during the working hours. Occupants were likely to feel comfortable in the offices.

Based on the occupant thermal comfort survey results, in 87.7% of working hours occupants felt comfortable in the offices. So, most of time, the indoor environmental conditions were acceptable which supports the predicted results. Controlling solar radiation and reducing air flow during the midday proved to be effective methods to avoid rise in indoor temperatures. Thus, applying a proper external shading device can reduce the impact of solar radiation on indoor temperatures, and the curtain which would block air flow path through the opened window could be used less. Therefore, keeping the office cross ventilated in the morning and later afternoon, and reducing indoor air flow rate around midday can reduce the indoor temperature and help to improve the comfort of occupants.

The occupants' survey results suggested that the occupants' comfort zone was consistent with Givoni's (1998) comfort zone for developing countries in a hot and humid climate. Thus, the comfort zone was defined for a hot summer and cold winter climate zone in South-east China. The comfort temperature range was from 19°C to 29°C and the extended comfort zone, by increasing air flow speed, was the same as Givoni's (1998) comfort threshold. The occupant adaptive comfort threshold on low temperature can be further extended, because no one voted on cold (-2) in the comfort survey. The humidity threshold was defined by an absolute humidity level, which was between 4g/kg and 20g/kg when the indoor air flow speed was not still, and the relative humidity value was 85%.

The occupants can actually tolerate a slightly higher indoor humidity level (20g/kg) than Givoni's high humidity threshold (19g/kg), because in the monitored period the indoor air flow speed varied and most of time the air flow speed was lower than 1.5m/s. Besides, occupants felt dry in the office and tried to reduce loss of moisture from the body. Thus, the occupants could acclimatise to the local humid climate conditions. This finding was consistent with some previous work that found the occupants who live in a hot and humid climate can acclimatise to the local environment. They can tolerate a higher temperature and humidity level than people from other climate conditions (Busch, 1992; Jitkhajornwanich et al., 1998; Hwang et al., 2009; Zhang et al., 2010; Liang et al., 2012).

These results indicated a higher upper comfort threshold than the ASHRAE 55 adaptive comfort standard (2004), particularly on the humidity band. The humidity threshold for the ASHRAE adaptive comfort standard was between 4g/kg and 12g/kg at still air conditions. Increasing air flow speed can extend the upper threshold of humidity but air flow speed should be below 1m/s (0.8m/s in the ASHRAE 55-2010 comfort standard) which were lower than the air flow speed suggested by Givoni. It seems the ASHRAE adaptive comfort zone may not consider occupants' acclimatisation to the humid climate. This may relate to the data used for ASHRAE's adaptive standard which were taken from a worldwide database in comparison to Givoni's comfort standard that was focused on a hot and humid climate. Therefore, compared with Givoni's comfort standard (1998), the ASHRAE adaptive comfort standard was not applicable in a hot and humid climate. This is the reason that the defined comfort zone for the hot and humid climate zone in South-east China is consistent with Givoni's standard.

8.2.2 Thermal comfort and indoor air flow speed

It was clear that increasing air flow speed can extend occupants' comfort zone. Although, the average indoor air temperature in the single-side ventilated office and the cross-ventilated office were very close to each other in the measured offices, the survey results for occupants' perceptions show that the occupants in the cross ventilated office were more satisfied with the indoor environmental conditions than the occupants in the single-side ventilated office were, which the number was 0.8% of measured working hours. Besides, the comfort votes on cool (-1) and hot (2) in cross ventilated offices were much higher than in single-side ventilated offices which the votes were mainly on neutral (0) and warm (1). And, the indoor air quality perceptions in the cross-ventilated office were more positive than those expressed in the case of the single-side ventilated office. These results in cross-ventilated offices have benefited from indoor air flow. The relatively higher indoor air flow speed in the cross-ventilated office can extend occupants' comfort threshold on the high temperature boundary and also can improve indoor air quality. This was the reason that occupants in the cross-ventilated office voted on hot but still accepted the indoor conditions.

As the air flow speeds in single-side ventilated offices were too low to be recorded, the air flow speed was only measured in the cross-ventilated offices. The measured indoor air flow speeds in different areas of the office have been used to demonstrate indoor air flow paths in these offices related to different opening position and opening size. Therefore, if occupants can understand controlling opening position and opening size to adjust the indoor air flow path, it can help them to improve their comfort perceptions and also the potential for convective cooling.

1. Opening positions.

It has been found that changing the opening position of the window had significant impact on indoor air flow path and air flow speed around occupants. For instance, in building A, occupants kept large windows that are set at high positions open during the working hours. Subsequently, the air flow path was mainly on the upper part of the office. The air flow speed through the upper part of the office was higher than in the occupant working level. Although this opening position would reduce the air flow speed around the occupant, it can keep the office cross-ventilated without disturbing the occupant’s work. It was suitable when indoor air flow speed was high. When the lower part of the window was open, it had direct impact on the air flow speed around the occupant. Even if the opening position was located on the opposite side of the office, the impact on the air flow speed around the occupant was limited. Controlling the opening size on the lower part of the window has a significant impact on occupants’ thermal comfort in building A.

The window on the corridor side in building B was an important design for natural ventilation. In building B, offices were located on both sides of the corridor. In the current office design in China, it was difficult to find instances where the windows would be designed on the corridor side, such as the case in building C and D. Office rooms can be cross ventilated, only when the doors on both sides of the corridor were opened. Thus, windows on the corridor side can give opportunity to cross-ventilate the office when the door is closed.

The window on the corridor side also has a great benefit for occupants’ thermal comfort. When the window on the corridor side was open and the door was open as well, the air flow speed through the occupants’ working area was higher than in the upper part of the office. Even when the window on the corridor side was the only open area, the air flow speed through the occupant working area was still slightly higher than that in the upper part of the office. Thus, these windows offer the potential to maintain the indoor air flow speed and environmental comfort. In addition, the lighting windows above the doors play the same role as the windows on corridor side, they not only encourage natural ventilation in the office but also serve to illuminate the corridor and reduce the need for artificial lighting during the day time.

Other windows at the top area of the facade side have not been used. The reason for this is discussed in a later section. If these windows were used, the result would be a similar effect to the window at a high position in office building A which can retain the air flow through the upper area of the office.

2. Window typologies

The indoor air flow patterns and air flow speed in different parts of the office were related to the window type and the way they opened. In these three office buildings (A, B and C), with casement and sliding windows, the air flow speed though the lower part of the office was higher than the air flow speed through the up part of the office. The air flow went downwards when it flowed into the office and had more influence on the lower part of the office which can impact occupants comfort and work. Besides, for casement windows, the opened window is like a 'wing' wall which can slightly direct the air flow in the office. While for the sliding windows, the opened window can not control the air flow direction as it just flows into the office. However, the opening position of the sliding window can be changed which can control the indoor air flow path along a horizontal direction. Therefore, the occupants have more opportunity to adjust indoor air flow path in order to achieve their comfort.

The situation, however, was different in office building D, because of the window type being a top-hung window. The incoming air flow would be led to the upper part of the office, so the air flow speed in the upper part of the office was much higher than at the occupant working level. This can prevent high air flow speed from negatively impacting on occupants in high-rise building, while it reduced the opportunity of air flow effect on extending occupants' thermal comfort in office. In addition, the effective opening area of the top-hung window was quite small, because it was normally restricted for safety purposes, but it would also restrict the indoor air flow rate. The pilot study was a good example that showed the internal heat can not be removed efficiently; even when the external air temperature was much lower than the indoor air temperature. So, it is suggested that a top-hung window should not be used on their own in low rise buildings which would restrict the potential for convective cooling and occupants comfort threshold, unless it can be fully opened.

On the other hand, when compared with the casement window and sliding window, an advantage of the top-hung window is that it can be kept open on rainy days as the rainfall can not get into the office, while for the other two types of window, occupants had to close the windows or reduce the opening area to avoid the rainfall drenching the office. This would then reduce the indoor air flow speed which may cause discomfort for the occupants. Because of its rain proof characteristic, the top-hung window can also be used as a night-time ventilation window. This characteristic was also one of the reasons that occupants kept the window open during the night and at the weekend. This has been proved in office building D. Thus, in the design process, selecting an adequate window type which accords with the natural ventilation strategy according to the window's character can benefit the indoor air conditions and occupants' thermal comfort. The window designs in buildings A and B reflected designers' natural ventilation strategies. These two buildings were built before the 1990s when air-conditioning was not used in office buildings in that time period, and reflects how designers may maximise the natural ventilation opportunity in order to enhance comfort indoor conditions.

The segmentation windows in offices A and B also had the potential to boost the buoyancy driven force when the office was single-side ventilated. The window was divided by two parts, the higher one and the lower one. Under still air conditions, it showed better indoor air flow performance rates than single opening window did. But this result was based on parametric study and dynamic simulation which has not been measured through the field work, so, it can be considered in future work.

In general, window opening position and typology have a significant impact on indoor air flow speed and air flow path, and also influence the potential for convective cooling and occupant thermal comfort. However, these essential window designs have not been considered in the current office design, such as buildings C and D. This because they would impact on indoor air flow speed and result in higher indoor temperature, which makes occupants feel uncomfortable. It has been proved that the indoor temperatures in buildings A and B were better than that in building C, as reflected by the occupant comfort perception results. The indoor temperatures in two offices of building D were lower than some of the offices in buildings B and C, because these two accessible offices were facing North-east and North-west, which means they can only get direct sunlight in the morning and later afternoon. And also, thermal inertia of the massive building structure meant it was difficult to heat. But the average indoor air temperature in another office in building D which faced South-west was about 2℃ higher than in other offices in the building, because the office can get direct sunlight from later morning to later afternoon. Therefore, when the indoor building structure was heated by solar radiation, the temperature was difficult to decrease which also influence the indoor air temperature. Even, when windows were kept open throughout the whole measured period. Therefore, understanding indoor air flow speed and air flow path that relate to window opening type and location is important for architects to design energy efficient office buildings, and to help occupants improve their thermal comfort in the office.

8.2.3 Window control behaviour and indoor environmental condition

Irrespective of the role of personal occupant acclimatisation, the control of windows can help occupants adapt to the indoor environment. In the field work, the occupants mainly opened the window when they first arrived in the office, and they closed the window just before they left which is because of the security issue and the weather influence. During the working hours, except on rainy days, only a few windows were closed which were mainly in the single-side ventilated office. Changing the window opening size was the main behaviour that the occupant would do during the working hours. The opening size change is a method whereby the occupants adjust their thermal comfort in the office. However, the situation was different in the office with the top-hung window. The window was very rarely used during working hours in the building in both the pilot study and building D. In building D, the windows were not closed during the monitored period. It seems that controlling the top-hung window does not have an impact on indoor environment or occupants' thermal comfort.

Herkel et al. (2008) and Yun and Steemers (2008) indicated that the manual control of windows was mainly correlated with outdoor temperature and occupant patterns. Rijal et al. (2007, 2008) pointed out that the windows opening percentage was related to both indoor and outdoor air temperature. It depends on which environmental factor was considered as stimulus. The wind speed also had a significant impact on window control (Zhang and Barrett, 2012) and indoor air quality (Yin, 2006).

1. Indoor air temperature

In the study, the indoor air temperature was considered as the main stimulus in the office, because in the cross-ventilated office the indoor air temperature was close to the outdoor air temperature during the working hours. The window opening area was reduced with decreased indoor air temperature when the indoor air temperature was below 25℃. When the indoor air temperature drops below 25℃, the occupant felt cool in the office and tried to reduce the heat loss from the body (in the study, the occupants start selected on 'cool' when the indoor air temperature dropped below 26℃). Reducing opening area can decrease the indoor air flow speed and reduce the convective cooling effect on body and indoor temperatures. No significant correlation was found between the occupant window control and the indoor air temperature when the indoor air temperature was between 24℃ and 28℃. Because in this temperature range, most of the occupants were satisfied with the indoor environmental conditions during working hours, adjusting the window would not have much impact on personal comfort. Thus, the indoor air temperature as an environmental stimulus lost its function on occupant window control behaviour and window opening size was random. Other environmental stimuli may have more impact on window control behaviour than indoor air temperature, such as indoor air velocity.

In addition, when the indoor air temperature rose over 28℃, no windows were closed. Occupants would feel hot and tried to increase the heat loss from the body, and keeping the window open can maintain the indoor air flow speed and improve their thermal comfort. Because of the limited measuring time, the window control behaviour could not be identified when the indoor air temperature was lower than 19℃ or higher than 31℃. Further study is needed to be undertaken in this climactic condition.

2. Indoor air velocity

In this study, the air velocity had a significant impact on window control behaviour. The indoor air flow speed would cause changes to the window opening area, particularly on reducing the opening area. The main reason was that the air flow would disturb occupants' work by moving paper on the desks. The indoor air flow speed causing the opening area to be reduced was 1.3m/s across the desk surface. The reason was that the top-hung window in office building D was never used, because the air flow was limited on the occupant's working surface, due to the window typology. However, the high air flow speed which directly passed by the occupant would not cause occupant reduce the window opening area. The maximum air flow speed of 1.5m/s was suggested by standard EN15251 (2007) and 1m/s for sedentary activity in the ASHRAE55 adaptive standard (2004). When the indoor air flow rose above these thresholds, it would cause occupants discomfort.

The measured maximum air flow speed near the occupant was 1.8m/s at which they would not feel uncomfortable. The air flow speed of 2.0m/s was pointed out by Givoni (1998) for the hot and humid climate. Thus, occupants in a hot and humid climate could accept a higher indoor air velocity, if the air flow could be controlled to avoid the working surface. It also meant that the occupant thermal comfort threshold at a higher temperature can be further extended so that architects have more flexibility to design energy efficient buildings and also achieve a comfortable indoor environment.

3. Accessibility

Accessibility was an important factor for window control. The window would not be used if it was difficult to control, subsequently, occupants would lose their opportunity to control the indoor air flow to suit their demands. It would also result in increased indoor air temperature and lost design characteristics, such as cross-ventilation and night-time natural ventilation. It has been proved that the offices which use these windows, such as, lighting window, window on the corridor side, have better indoor environmental condition than the office without these windows. The simulation also proved that if the entire window was controllable by occupants, then the segmentation window would have a significant impact on indoor temperature in a single-side ventilated office, particularly with the small opening percentage, the indoor comfort temperature percentage could rise more than 20%.

These windows, however, were rarely used which is because they were positioned too high for the occupants to control them conveniently. In addition, the number of windows in the office can provide the occupants with more opportunities to adjust indoor air flow speed and path to improve their comfort. However, occupant just like to control the window which is near them or easy to reach. They do not want to spend much time opening or closing windows when they arrive at or leave the office. Thus, accessibility is an important element for window design and this should be considered by designer during the design process. Auto system can be considered for windows in the office, which should be easy for the occupant to understand and operate.

In summary, the indoor air temperature had a significant impact on occupant window control behaviour when the indoor air temperature was below 25℃ or higher than 28℃ during the measured period. When the indoor air temperature was between 25℃ and 28℃, it had no relationship with window control behaviour. The indoor air velocity was the main reason which caused the opening area change during the working hours. It was high air velocity on desk surface which disturbed occupants' work, but, if the air flow can be directed away from the desk surface, occupants can accept higher indoor air velocity which can help extend their comfort threshold. Besides, the accessibility of window was an important fact which can affect occupant windows' control behaviour. It also affected the potential of convective cooling and occupant thermal comfort. Thus, understanding occupant window control behaviour is important for architects to design energy efficient buildings.

8.2.4 Possible solutions for designers

According to the field measurement results and findings, there were some possible solutions pointed out as below:

- Window on the corridor side was suggested in office buildings. This design character was missing in recent office buildings in China. For the office building that has offices on both sides of the corridor, this design character can bring daylight into the corridor and create cross ventilation opportunity in the offices. But the problem caused by noisy from the corridor should be considered during the design process.
- The segmented window has great benefit on reducing the air speed on desk level without influence the indoor air flow rate, such as in office building A. Occupants will have more chance to adjust their comfort by controlling the window at different level.
- The top hung window can prevent the rainfall drop into the office and keep the office naturally ventilated. It is a useful typology for night ventilation cooling strategy. Under the premise of safety, large opening area should be given. Large air vent can be considered in the office near the occupant but away from the desk area. The advantages of the air vent were that they could be made

secure, weather proof but still functional satisfactorily. It has potential to be as the night natural ventilation vent.

- The most important thing was the accessibility of windows. Occupant will only control the windows that were easy to reach and use. For the windows that were outside of occupants' activity sphere, especially at the high level, the automatic window control system was suggested. For example, the window with opening area at different levels has great potential for natural ventilation at low wind speed conditions. A control system was needed for the windows at high level.

8.3 Summary of main findings

The findings of this study will help architects and engineers to design for the natural ventilation of office buildings in South-east China. The main findings were:

- As a result of this work, the comfort zone has been defined for the hot summer and cold winter climate zone in South-east China. The result was consistent with Givoni's (1998) comfort zone for hot and humid climates. And from the study, the high humidity threshold is slightly higher than Givoni's humidity range. The occupant who lives in a hot and humid climate can adapt to higher humidity levels. The defined comfort zone can be used to predict occupant comfort in naturally ventilated offices under this climate condition.
- The measurement of the indoor air flow speed in different parts of the selected offices has identified the indoor air flow path and related it to different opening combinations. It has also identified the impact of window opening type on indoor air flow patterns.
- Window opening type and location has a profound influence on air flow pattern, and internal air velocity. This clearly also affects the potential for convective cooling and occupant thermal comfort. Segmented windows, as well as the lighting window and the window on the corridor side benefited the indoor air flow and the

occupants' thermal comfort. These essential designs are often neglected in modern office design.

- This study found that in many cases, window control was more related to the indoor air flow speed across the occupants' working surface rather than on the occupants themselves. Disturbing the work was not acceptable in the offices. It is clear that the air flow must be controlled at the working surface level.
- Occupant can accept higher indoor air velocity than the speed across the working surface level, which has great benefit on extending occupant thermal comfort in this climate. The indoor air temperature has an impact on occupant behaviour when the indoor air temperature is lower than 25℃ or higher than 28℃.
- The accessibility of windows is important for window control behaviour. Poor accessibility would result in lost designed natural ventilation characteristic, and may lead to a rise in indoor temperature that makes occupants feel uncomfortable.

8.4 Limitations of the study

The limitations of this study were the period during which the measurement was carried out and the subjects sample size. Three weeks of measurements in twelve cellular offices was limiting, and the range of the monitored environmental factors' was also limited, such as the indoor dry-bulb air temperature range being between 19°C and 31°C. Besides, in this study, occupant window control behaviour only represented the reaction to certain environmental factors, such as indoor and outdoor air temperatures, and indoor air velocity. The indoor air quality had not been measured during the field work, because of the shortage of appropriate instruments. The indoor air quality may cause the occupant to feel uncomfortable in single-side ventilated offices and result in changes to the opening area of the window. In addition, because of the limitations of equipment, there were only six measurement points in the office, to prove that general indoor air flow path is related to different window opening combinations. If more measurement points had set in the office, a more detailed indoor air flow path can be mapped. The access permission was another challenge for field measurement. South-east facing offices in building D can not be used for measurement, therefore it was difficult to compare the results of the indoor environmental conditions with those of south facing offices in other buildings. In addition, the impact of height of the office building on indoor air speed, window typology and occupant window control behaviour were not considered in the study, as well as the impact of solar control.

8.5 Originality and contributions

This study is based on field measurement and occupant survey in a hot and humid climate in South-east China, in order to identify the impact of indoor air flow speed and air flow patterns on occupants' thermal comfort, and the impact of window control behaviour on thermal comfort and natural ventilation in office buildings. The originality of the work has been summarised in the points below:

- The measurement collected 14400 sets of temperature and relative humidity data, 174560 pieces of indoor air velocity data and 1344 questionnaires in four office buildings over a period of three weeks. All the results and conclusions are based on these data. The measurement methods are presented in Chapter 4.
- The method used to identify the indoor air flow path by the measurement of the indoor air flow speed in different parts of the office has been developed. It identified the indoor air flow path which is related to different window opening combinations and types in the cross-ventilated office. And it also identified the impact of indoor air velocity on occupants' window control behaviour and occupant thermal comfort. The limitation of indoor air velocity which would influence occupant window control behaviour has been defined.
- The comfort zone for a hot and humid climate in South-east China is suggested which is consistent with Givoni's comfort zone for a

hot and humid climate. Besides, the occupants' high humidity threshold is slightly higher than Givoni's humidity threshold. Occupants who live in a hot and humid climate can acclimatise to local climate condition which means they can tolerate higher humidity level.

- The window control behaviour in offices which correlate with indoor air temperature and air flow speed has been defined. Furthermore, some design suggestions in terms of window typology and control behaviour are pointed out for naturally ventilated office buildings.

The contributions of this study to knowledge are outlined as follows:

- The field measurement result and occupant comfort survey result can be used as reference for designers and researchers. Further research in the fields of the naturally ventilated office, occupant thermal comfort and occupant behaviour in a hot and humid climate in China will enable more comprehensive understanding of their correlations and environmental implications.
- Based on the measured data, the adaptive comfort zone for this climate condition is identified with a psychrometric chart. Designers and researchers can use this comfort zone to predict other environmental condition by applying their environmental data into psychrometric chart.
- The method used to identify indoor air flow path can be applied to research on other indoor air flow conditions, such as the air flow path in open plan offices and residential buildings. It can also be used to identify the effect of other window typologies on indoor air velocity and air flow path.
- The typology and opening position of the window have a significant impact on indoor air velocity and air flow pattern. They would also influence the potential for convective cooling and occupant thermal comfort. In addition, occupant window control behaviour is related to indoor air velocity and indoor air temperature. Understanding these principles is helpful for architects to design a practical naturally ventilated office building which can be easily operated by

the occupant, so that occupants can improve their thermal comfort by controlling these windows themselves.

8.6 Further work

As a suggestion for further study, long-term field measurement should be considered, and more monitoring data can benefit a more comprehensive understanding of occupant thermal comfort and window control behaviour. Particularly on occupant adaptive comfort and window control behaviour when the indoor air temperature is lower than 19°C. Because in the comfort survey no one selected the cold (-2) option during the measured period, the lower temperature threshold could be further extended. Besides, because no heating system is set in office buildings in this climate zone, occupants' adaptive behaviour would become important to occupants' comfort, particularly when the indoor air temperature rises over 31℃.

Furthermore, the occupant thermal comfort and window control behaviour in open plan offices can be taken into account and more window types can be investigated, as well as, the correlation between indoor air quality and window control behaviour. In addition, in the field work, according to indoor and outdoor temperatures and building design characteristics, there was night-time natural ventilation potential in the buildings which can be investigated.

Another suggestion for future work is the impact of new-technology on occupants' thermal comfort. The weather forecasts and adaptive suggestions on the smart phone can help occupants to predict the weather change in the future which can assist occupants in adapting to weather change in order to achieve personal comfort.

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Appendices

1. Images of Tas model geometry and material properties

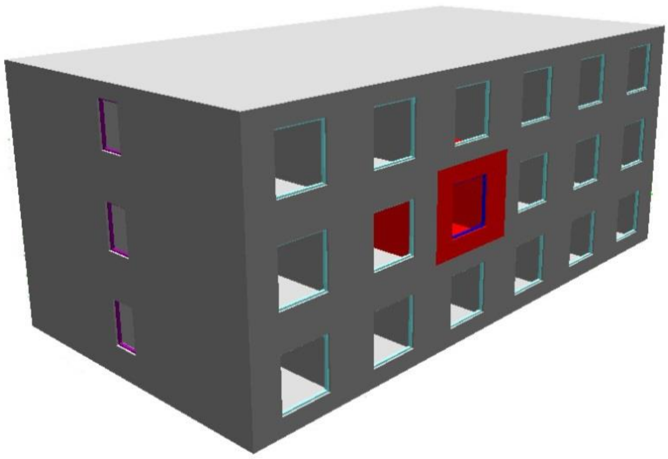


Figure 9.1: Tas model of the single-side ventilated office.

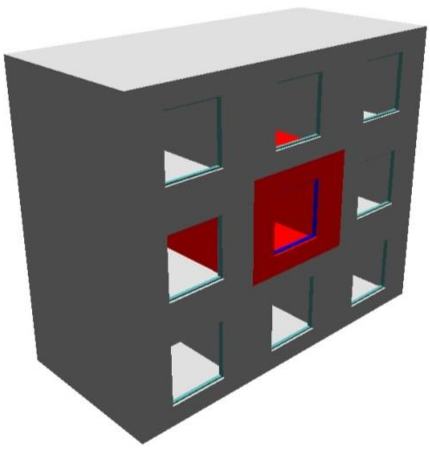


Figure 9.2: Tas model of the cross-ventilated office.

Opaque Construction | Name: External wall | Description:

Solar Absorptance		Emissivity		Conductance (W/m²° C)	Time Constant
Ext. Sur	Int. Surf.	External	Internal		
0.400	0.400	0.900	0.900	1.606	4.821

Layer	M-Code	Width (mm)	Conductivit...	Density (kg...	Specific He...	Description
Inner	Internal cement mo...	20.0	0.85	1700.0	900.0	
2	am1brick\3	240.0	0.42	1400.0	750.0	BRICKWORK 1% m.c. *4
3	am1concl\20	20.0	0.91	1760.0	1063.0	PFA CONCRETE *2
4	External cement m...	5.0	0.9	1800.0	1000.0	For external

Figure 9.3: External wall.

Opaque Construction | Name: Internal wall 1 | Description:

Solar Absorptance		Emissivity		Conductance (W/m²° C)	Time Constant
Ext. Sur	Int. Surf.	External	Internal		
0.400	0.400	0.900	0.900	2.912	3.786

Layer	M-Code	Width (mm)	Conductivity...	Density (kg...	Specific He...	Description
Inner	Internal cement mortar	20.0	0.85	1700.0	900.0	
2	am1brick\7	240.0	0.81	1760.0	800.0	BRICKWORK COMMON 0...
3	Internal cement mortar	20.0	0.85	1700.0	900.0	

Figure 9.4: Internal wall.

Opaque Construction | Name: Upper floor | Description:

Solar Absorptance		Emissivity		Conductance (W/m²° C)	Time Constant
Ext. Sur	Int. Surf.	External	Internal		
0.650	0.650	0.900	0.900	11.592	0.828

Layer	M-Code	Width (mm)	Conductivit...	Density (kg...	Specific He...	Description
Inner	am1concd\3	30.0	1.45	2200.0	920.0	CONCRETE 3% m.c. 10 *3
2	am1concd\4	120.0	1.83	2400.0	920.0	CONCRETE 3% m.c. 11 *3

Figure 9.5: Floor and ceiling.

Gain	Value	Factor	Setback Value	Schedule
Infiltration	0.25 ach	1.0	0.0 ach	24 Hours
Ventilation	Function	1.0	0.0 ach	Office 8am to 6pm We...
Lighting Gain	10.0 W/m²	1.0	0.0 W/m²	Office 8am to 6pm We...
Occupancy Sensible ...	10.0 W/m²	1.0	0.0 W/m²	Office 8am to 6pm We...
Occupancy Latent Ga...	4.0 W/m²	1.0	0.0 W/m²	Office 8am to 6pm We...
Equipment Sensible ...	14.0 W/m²	1.0	0.0 W/m²	Office 8am to 6pm We...
Equipment Latent Ga...	0.0 W/m²	1.0	0.0 W/m²	
Pollutant Generation	0.0 g/hr/m²	1.0	0.0 g/hr/m²	

Figure 9.6: Internal heat gain during working hours.

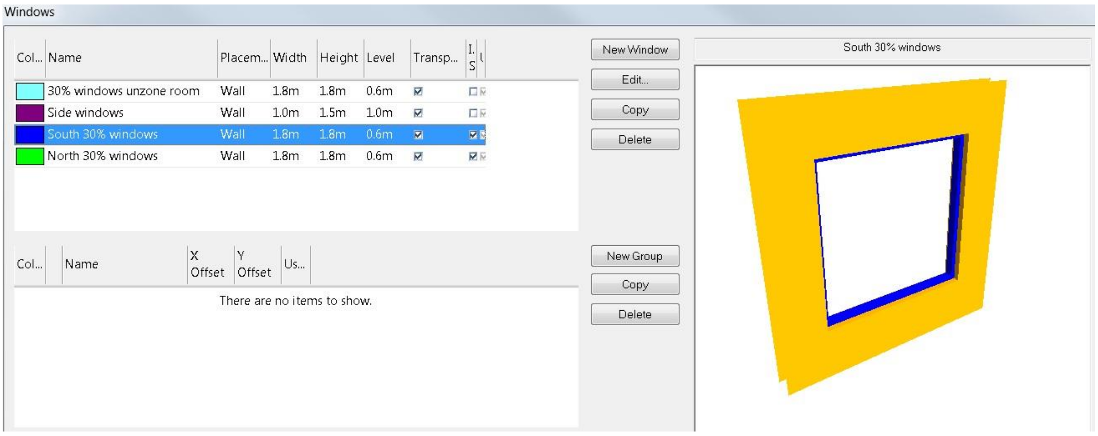


Figure 9.7: Window in the office.

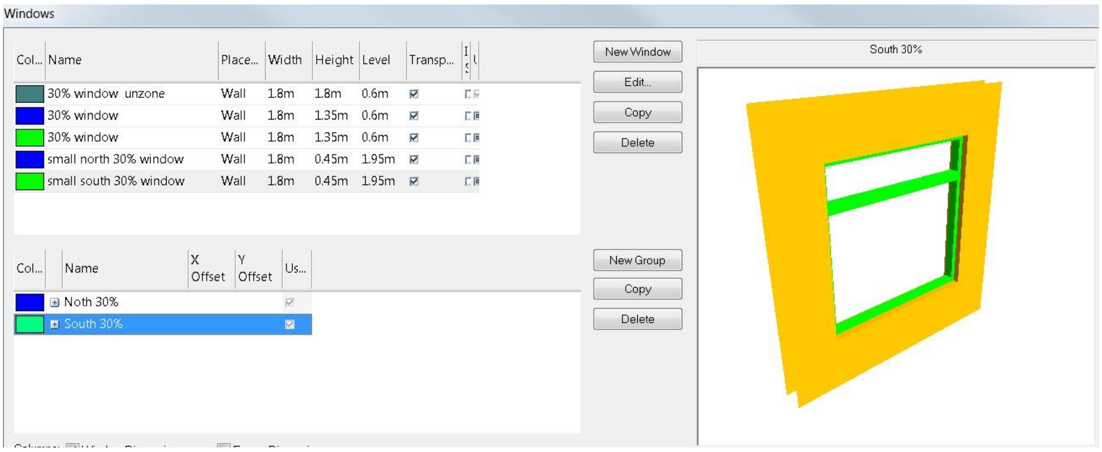


Figure 9.8: Changed window type in office (Chapter 7).

2. Steady study result of single-side ventilated office

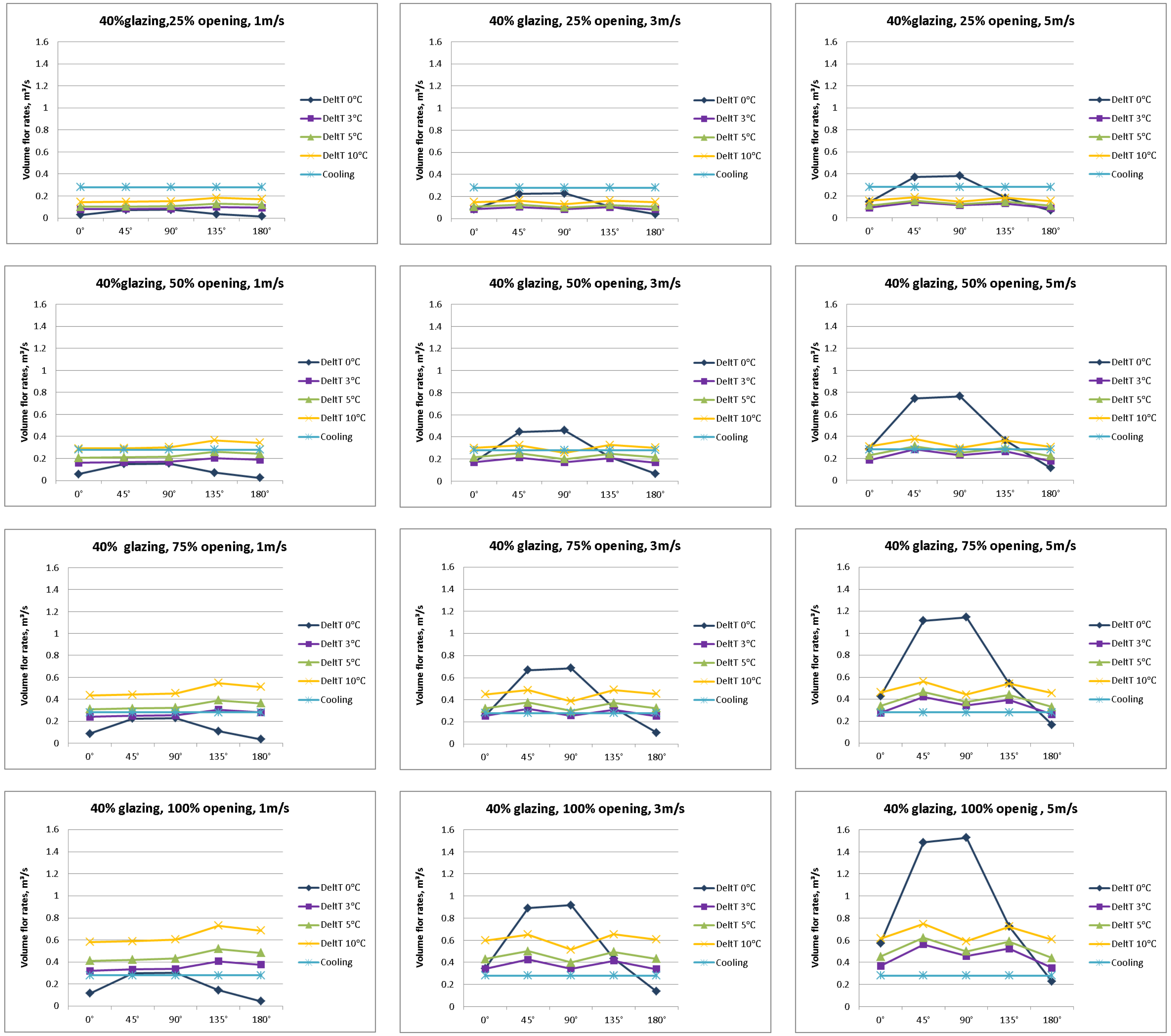


Figure 9.9: The impact on air flow rates by change in the temperature difference at different wind directions and wind speeds; the opening is facing 0° at 40% glazing area.

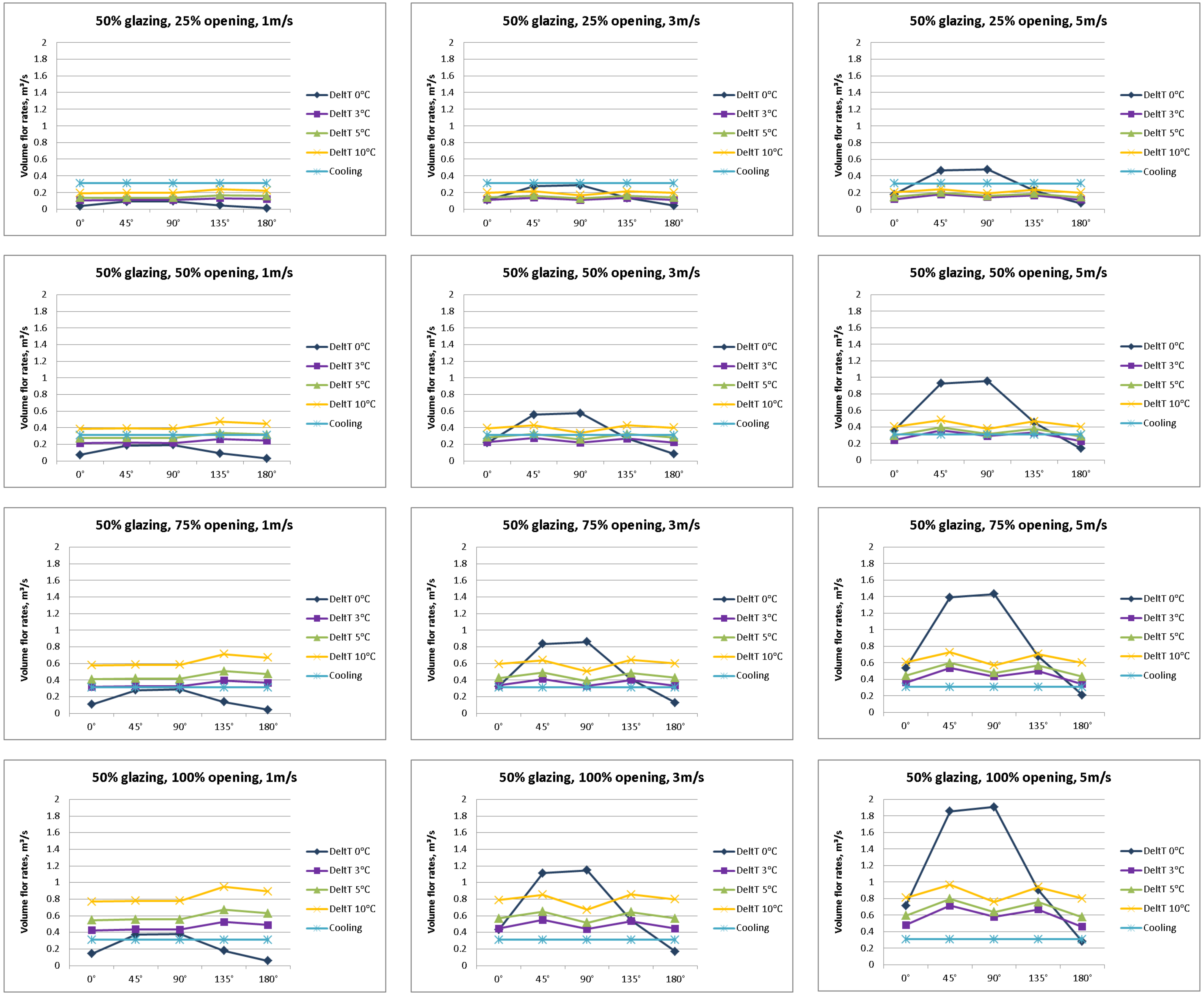


Figure 9.10: The impact on air flow rates by change in the temperature difference at different wind directions and wind speeds; the opening is facing 0° at 50% glazing area.

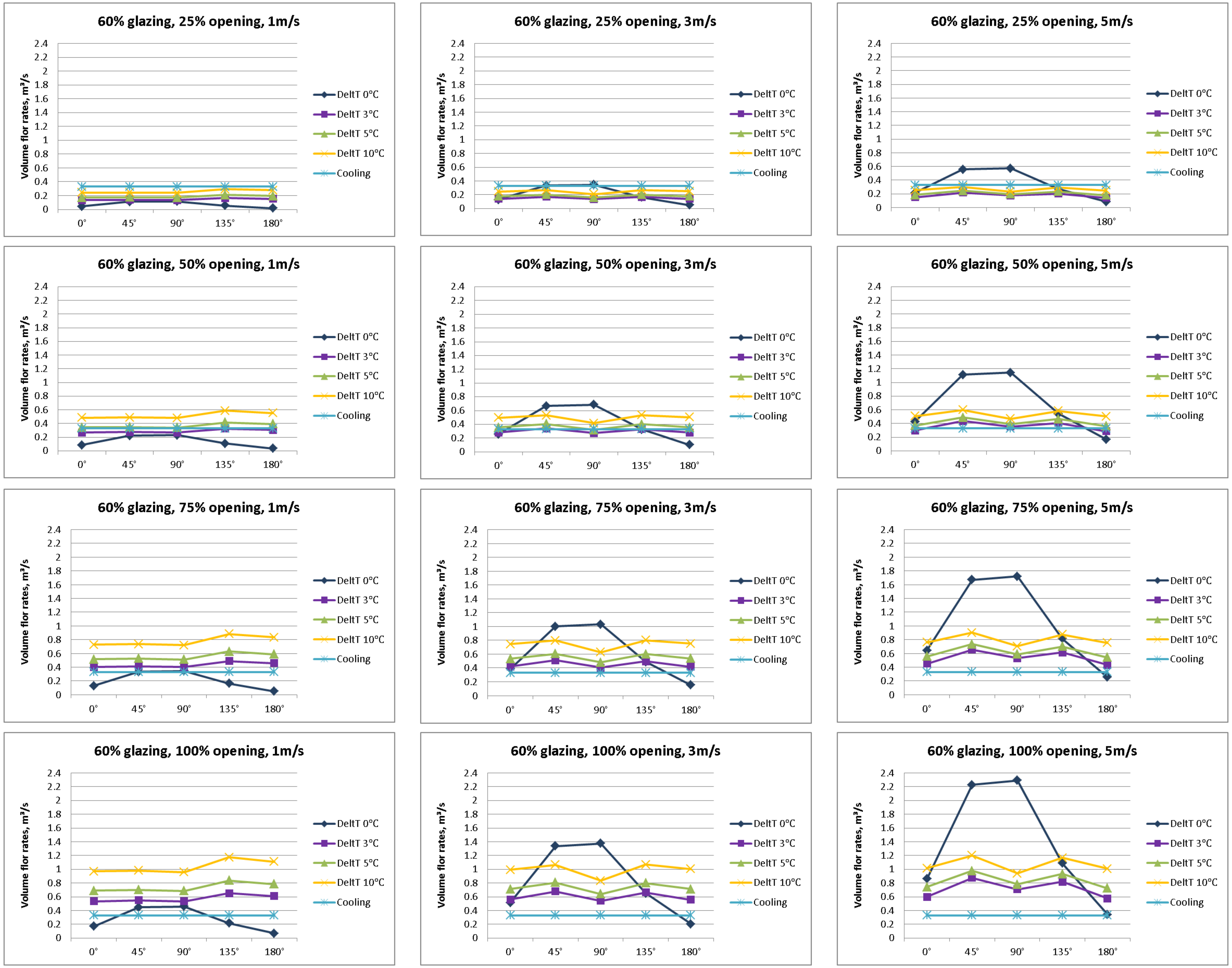


Figure 9.11: The impact on air flow rates by change in the temperature difference at different wind directions and wind speeds; the opening is facing 0° at 60% glazing area.

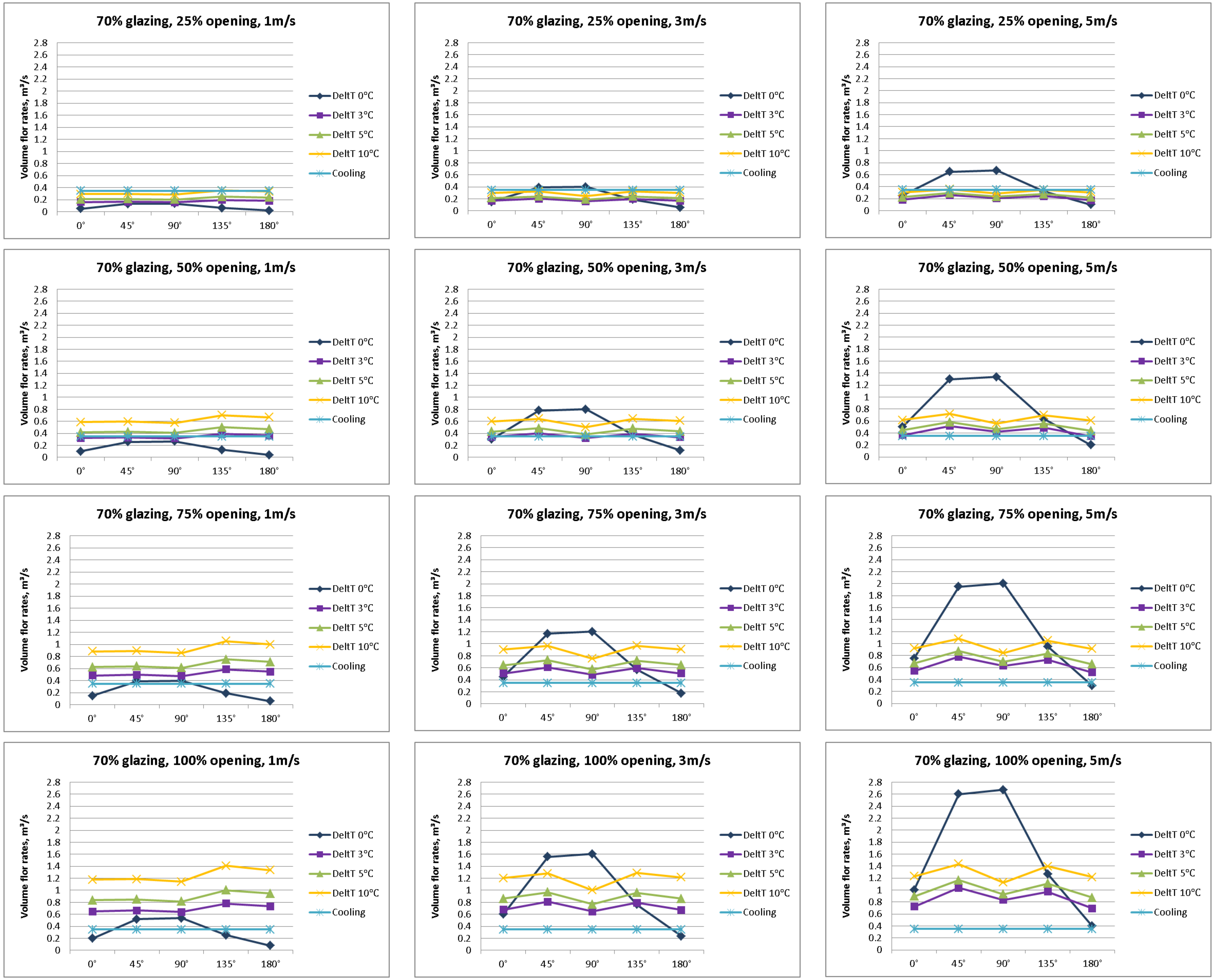


Figure 9.12: The impact on air flow rates by change in the temperature difference at different wind directions and wind speeds; the opening is facing 0° at 70% glazing area.

3. Building plan and section for pilot study

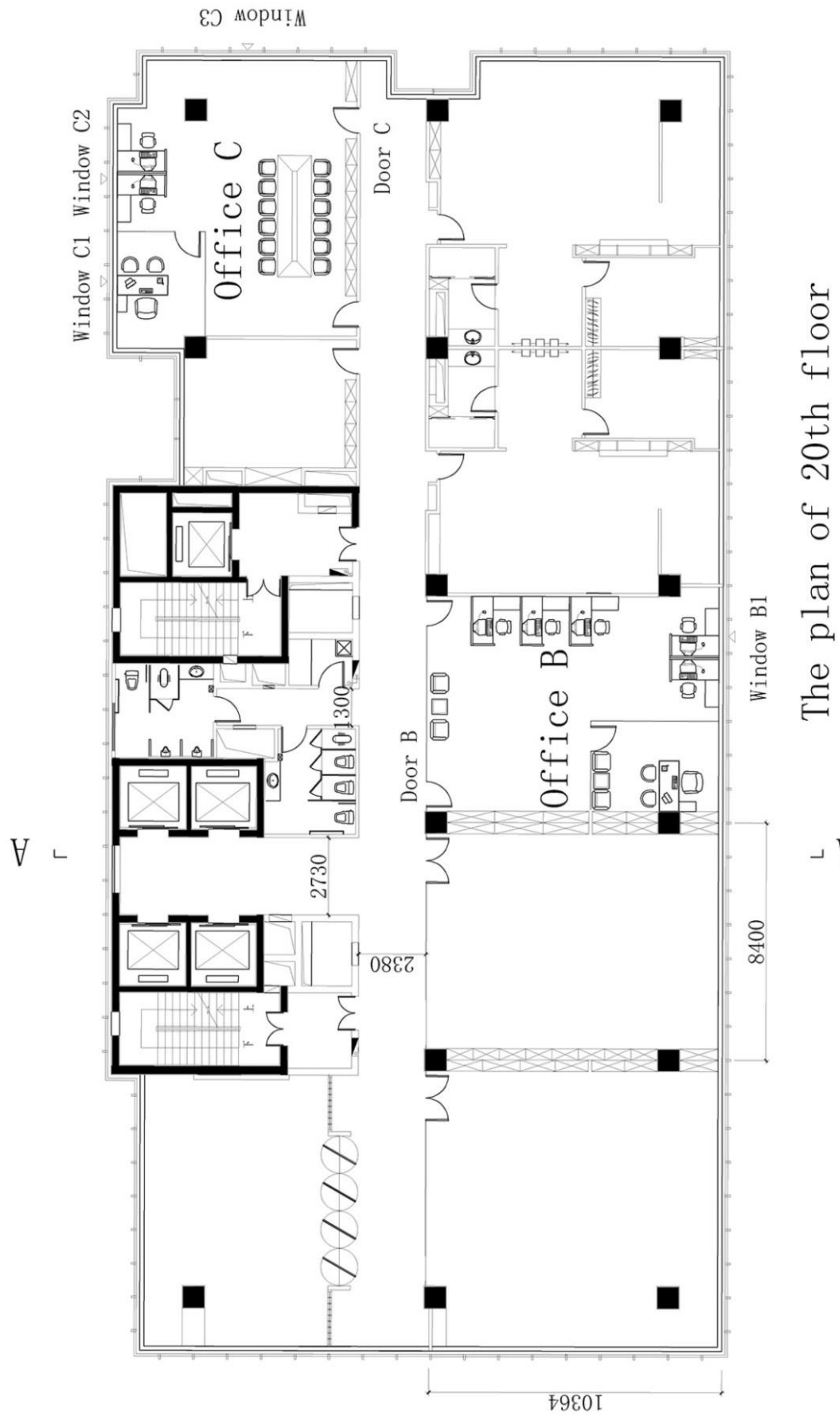


Figure 9.13: The paln of 20th floor.

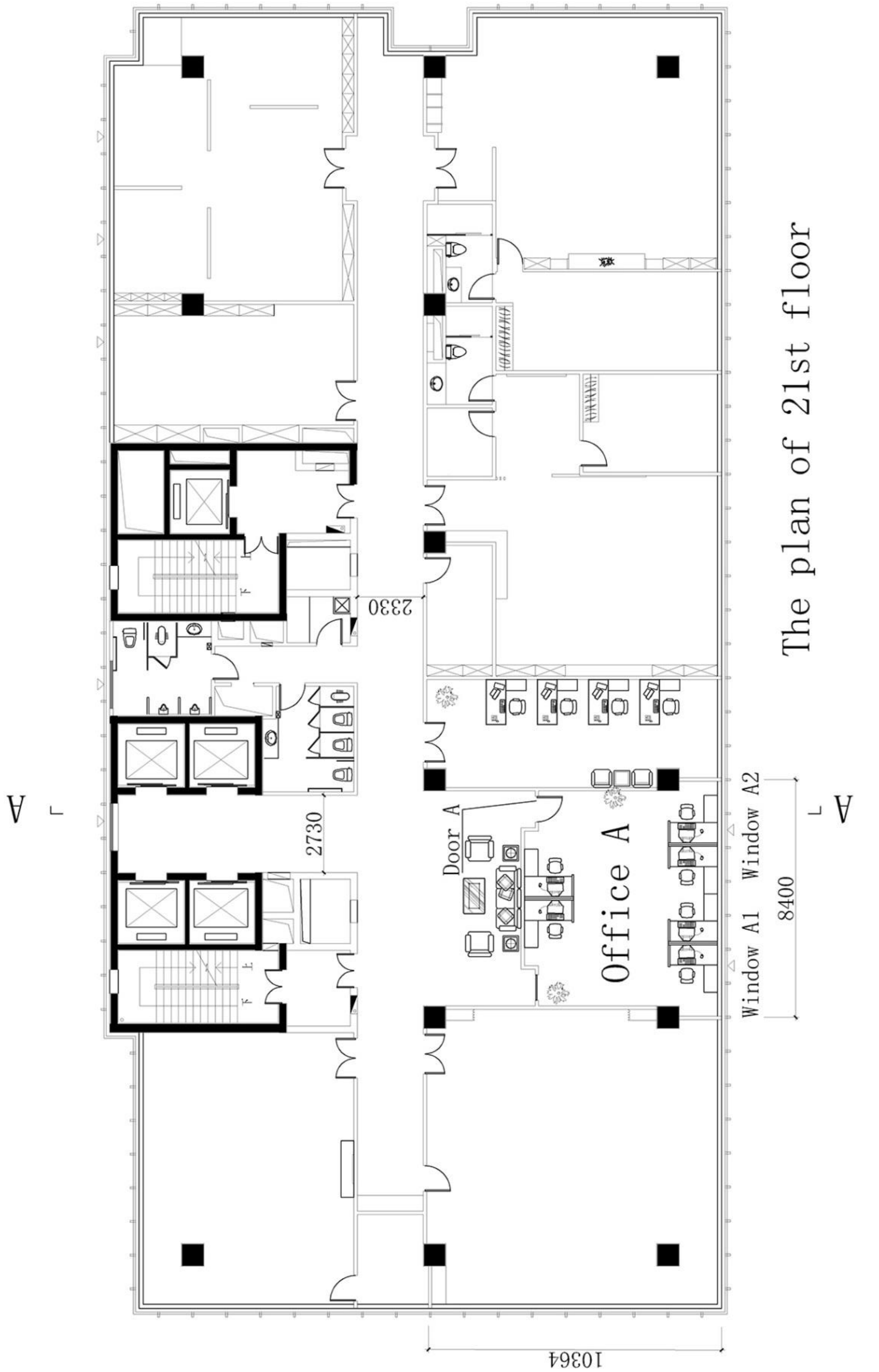


Figure 9.14: The plan of 21st floor.

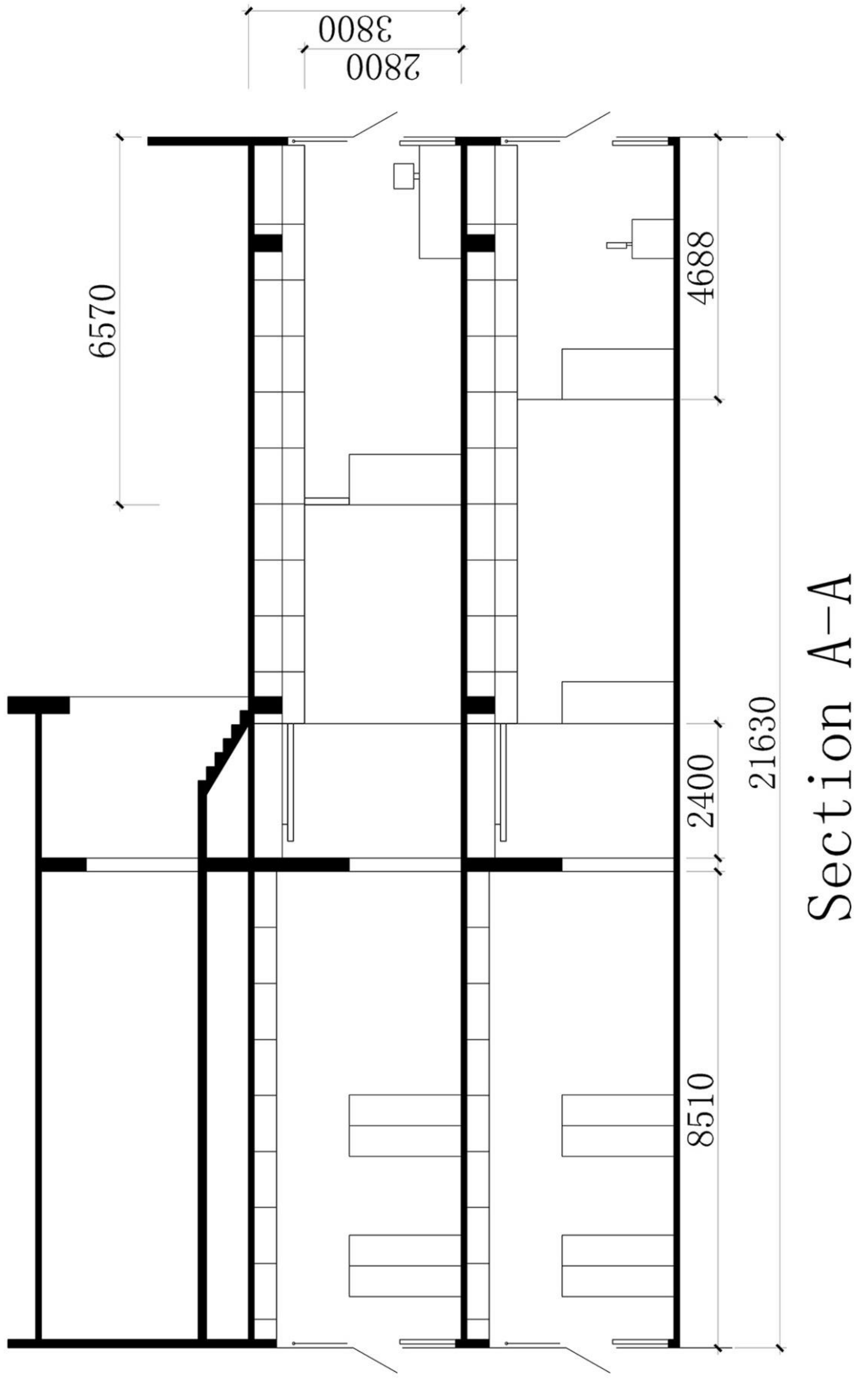


Figure 9.15: Section A-A.

4. Instruments

1. 

Measuring tape: 5 meters long.

2.  Hilti Laser range meter (PD40): the measuring range is 0.05m-200m and the accuracy is ±1mm.

3. 

Tinytag Plus2 data logger (TGP-4500): recording temperature from -25℃ to +85℃ and relative humidity from 0% to 100%. The accuracy of temperature reading is ±0.25℃ between 0℃ -40℃. The accuracy for relative humidity is ±3%RH at 25℃. The reading resolution is 0.01℃ for temperature and 0.3% for relative humidity.

4. 

LUGE L9 data logger (L92-1+): recording air temperature from -40℃ to +70℃ and relative humidity from 0% to 100%. The accuracy of temperature reading is ±0.2℃ and the accuracy for relative humidity is ±2%RH. The reading resolution for temperature and relative humidity are 0.1℃ and 0.1%.

5. 

LUGE L9 data logger (L92-1+): recording radiant temperature from -40℃ to +70℃ and relative humidity from 0% to 100%. The accuracy of temperature reading is ±0.2℃ and the accuracy for relative humidity is ±2%RH. The reading resolution for temperature and relative humidity are 0.1℃ and 0.1%.

6. 
Non-contact infrared thermometer with laser sight: the temperature range is -50℃ to 350℃, the accuracy of temperature reading is ±2% with the reading resolution of 0.1℃.

7. 
AIRFLOW thermal anemometer (TA-2-2): the working velocity range is between 0- 2m/s, with accuracy of ±3%FSD at 20℃ and 1013mbar.

8. 
TES hot-wire anemometer (Tes-1341): the air velocity range is from 0 m/s to 30m/s, with accuracy of ±3%FSD. The reading resolution is 0.01m/s.

9.  DVA 30VT: the air velocity range is 0.25 m/s to 30m/s and accuracy is ±1%FSD at air density 1.2kg/m^3.

10. 

OMEGA window state recorder (OM-51): the time accuracy of this state recorder is ±100ppm at 20℃. The output records include the window state (close/open), the changing time and the duration.

5. Questionnaires for pilot study

Questionnaire

Location: SUPOR office building, Hangzhou, China.
Date: ____________ Time: ____________ Cloth level ___________

Comfort Evaluation

1. How would you describe typical conditions in your office when you first arrive in the office in the morning?

1.1 Temperature
Very Uncomfortable 1 2 3 4 5 6 7 Very Comfortable Too cold 1 2 3 4 5 6 7 Too hot

1.2 Air
Very stuffy 1 2 3 4 5 6 7 Very fresh

2. How would you describe typical conditions in your office area in the morning?

2.1 Temperature
Very Uncomfortable 1 2 3 4 5 6 7 Very Comfortable Too cold 1 2 3 4 5 6 7 Too hot

2.2 Air
Very stuffy 1 2 3 4 5 6 7 Very fresh

---

3. How would you describe typical conditions in your office area in the afternoon?

3.1 Temperature
Very Uncomfortable 1 2 3 4 5 6 7 Very Comfortable Too cold 1 2 3 4 5 6 7 Too hot

3.2 Air
Very stuffy 1 2 3 4 5 6 7 Very fresh

Thanks for your help
If you have any comment, please give them:

6. Questionnaires for field work

Thermal comfort evaluation

Office: Date:

This survey is being conducted to help the analysis of monitoring data. The information collected will be treated as completely confidential.

Thank you for your help

Queries:
If you have any queries please contact Jindong Wu
Email: laxjdw1@nottingham.ac.uk

Background

		Please tick		
What is your gender ?	Male	☐	☐	Female
Do you sit next to a window in the office?	Yes	☐	☐	No
How long have you worked in this building?	Less than a year	☐	☐	A year or more

	Please write it down
How long have you worked in present work area?	☐
How many days do you spend in the building in a normal working week?	☐
How many hours per day do you spend in the building?	☐

Thanks for your help.
If you have any comment, please give them:

Thermal comfort evaluation

Office: Date:

How would you describe the environmental conditions in your office? (Please tick one)

Morning

Time: Clothing level:

1. Temperature	Very uncomfortable	-3	-2	-1	0	1	2	3	Very comfortable
	Too cold	-3	-2	-1	0	1	2	3	Too hot
2. Humidity	Too dry	-3	-2	-1	0	1	2	3	Too humid
3. Air quality	Stuff	-3	-2	-1	0	1	2	3	Fresh

Time: Clothing level:

1. Temperature	Very uncomfortable	-3	-2	-1	0	1	2	3	Very comfortable
	Too cold	-3	-2	-1	0	1	2	3	Too hot
2. Humidity	Too dry	-3	-2	-1	0	1	2	3	Too humid
3. Air quality	Stuff	-3	-2	-1	0	1	2	3	Fresh

Afternoon

Time: Clothing level:

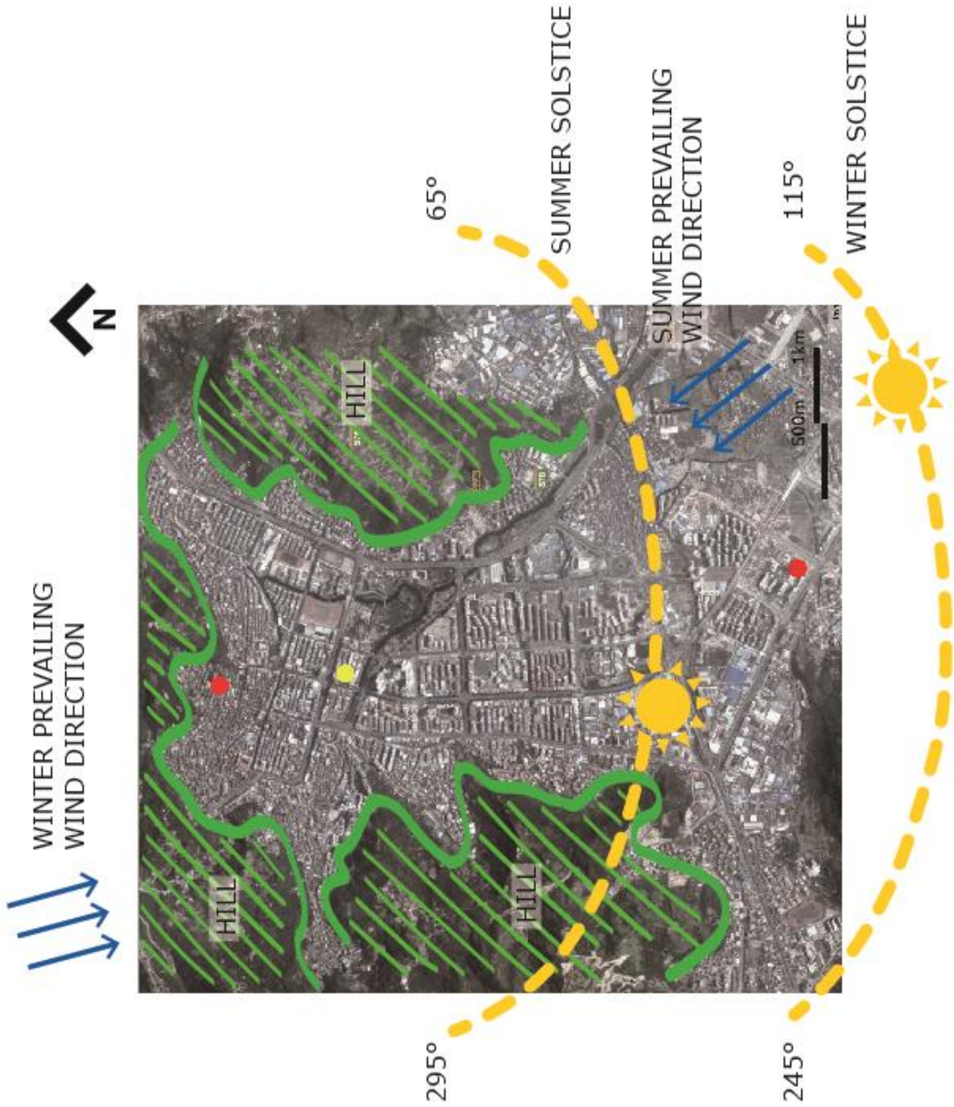
1. Temperature	Very uncomfortable	-3	-2	-1	0	1	2	3	Very comfortable
	Too cold	-3	-2	-1	0	1	2	3	Too hot
2. Humidity	Too dry	-3	-2	-1	0	1	2	3	Too humid
3. Air quality	Stuff	-3	-2	-1	0	1	2	3	Fresh

Time: Clothing level:

1. Temperature	Very uncomfortable	-3	-2	-1	0	1	2	3	Very comfortable
	Too cold	-3	-2	-1	0	1	2	3	Too hot
2. Humidity	Too dry	-3	-2	-1	0	1	2	3	Too humid
3. Air quality	Stuff	-3	-2	-1	0	1	2	3	Fresh

Thanks for your help.
If you have any comment, please give them:

7. Local microclimate



8. Building plans and sections for field work

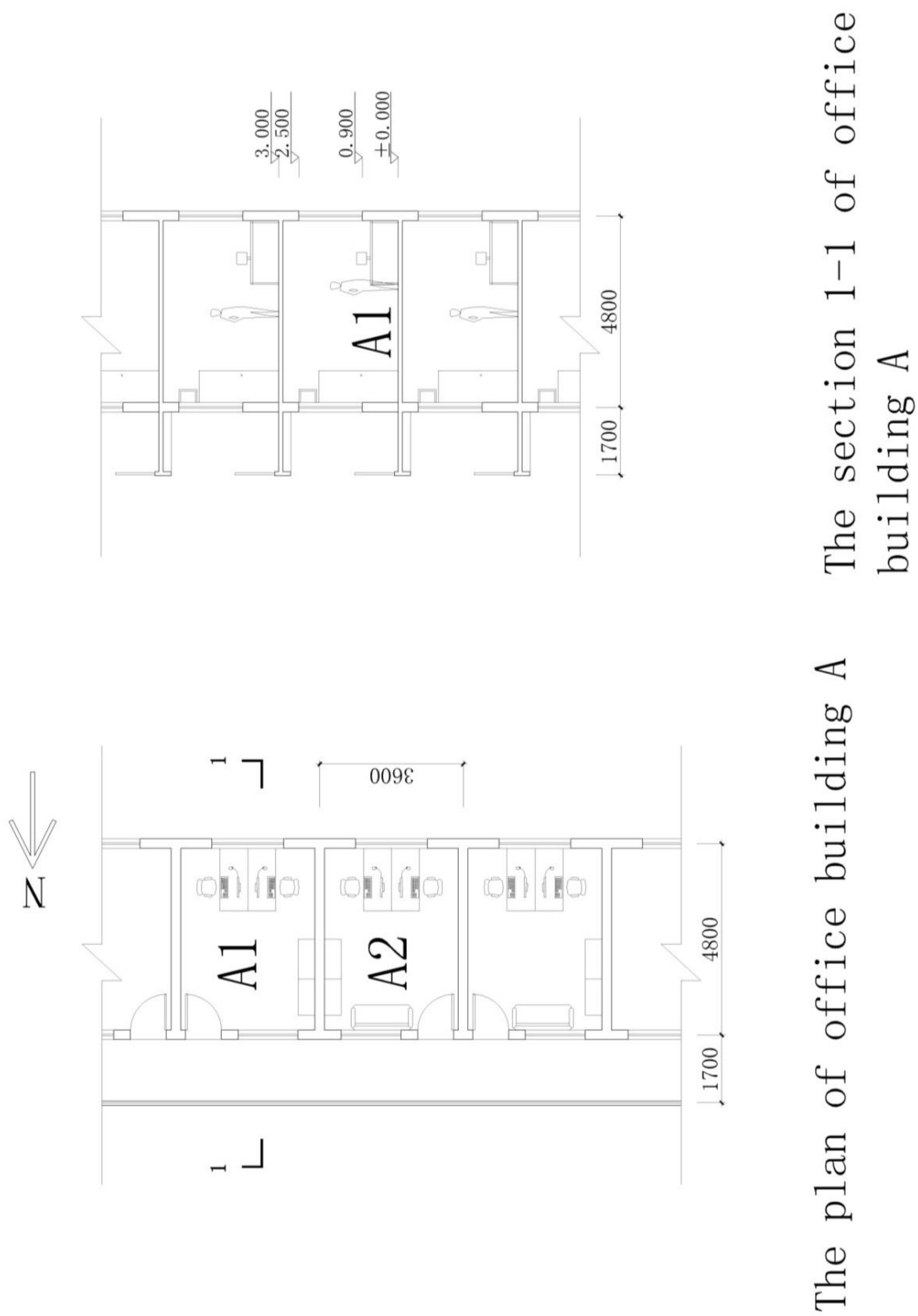


Figure 9.16: The plan and section of building A.

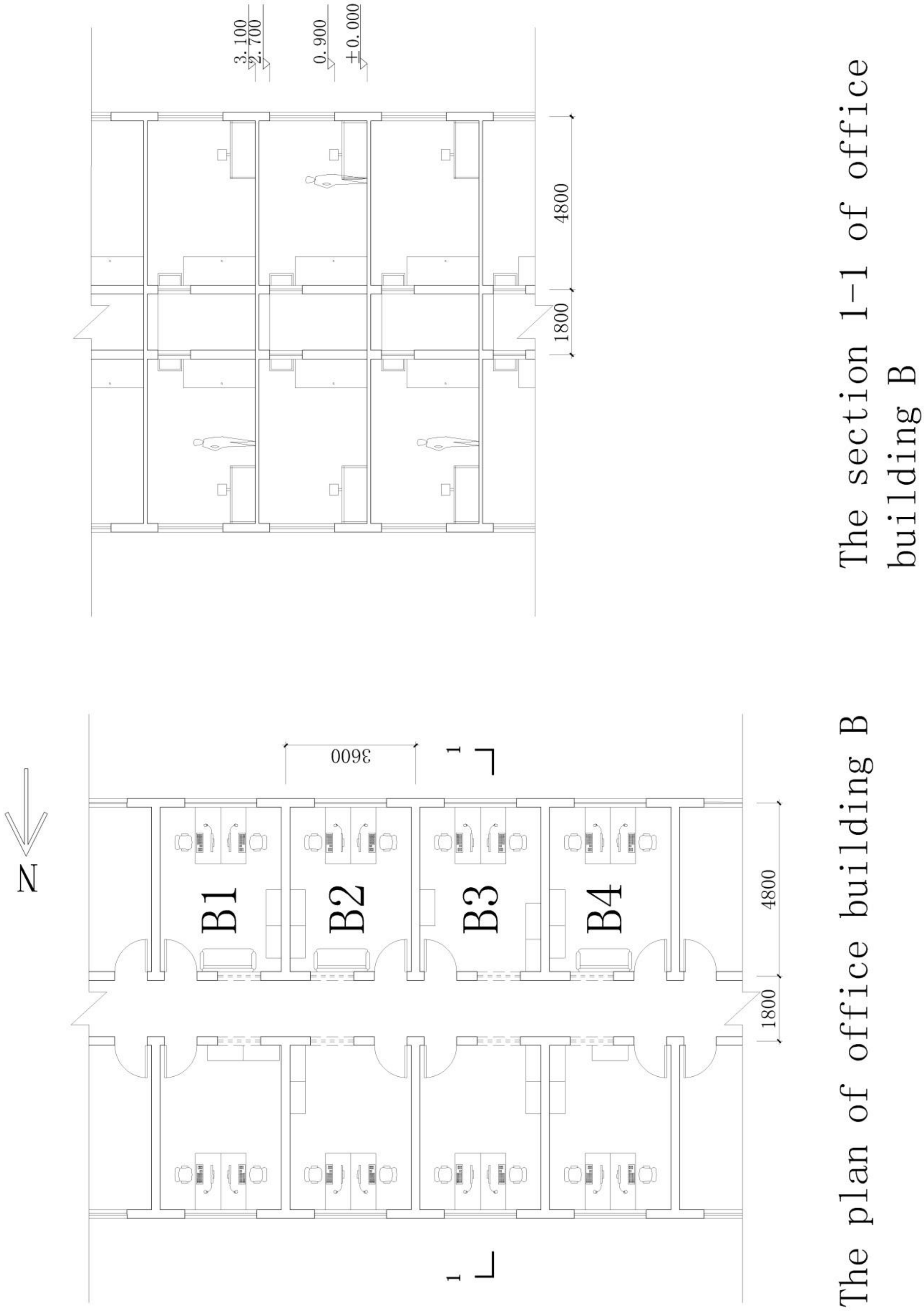


Figure 9.17: The plan and section of building B.

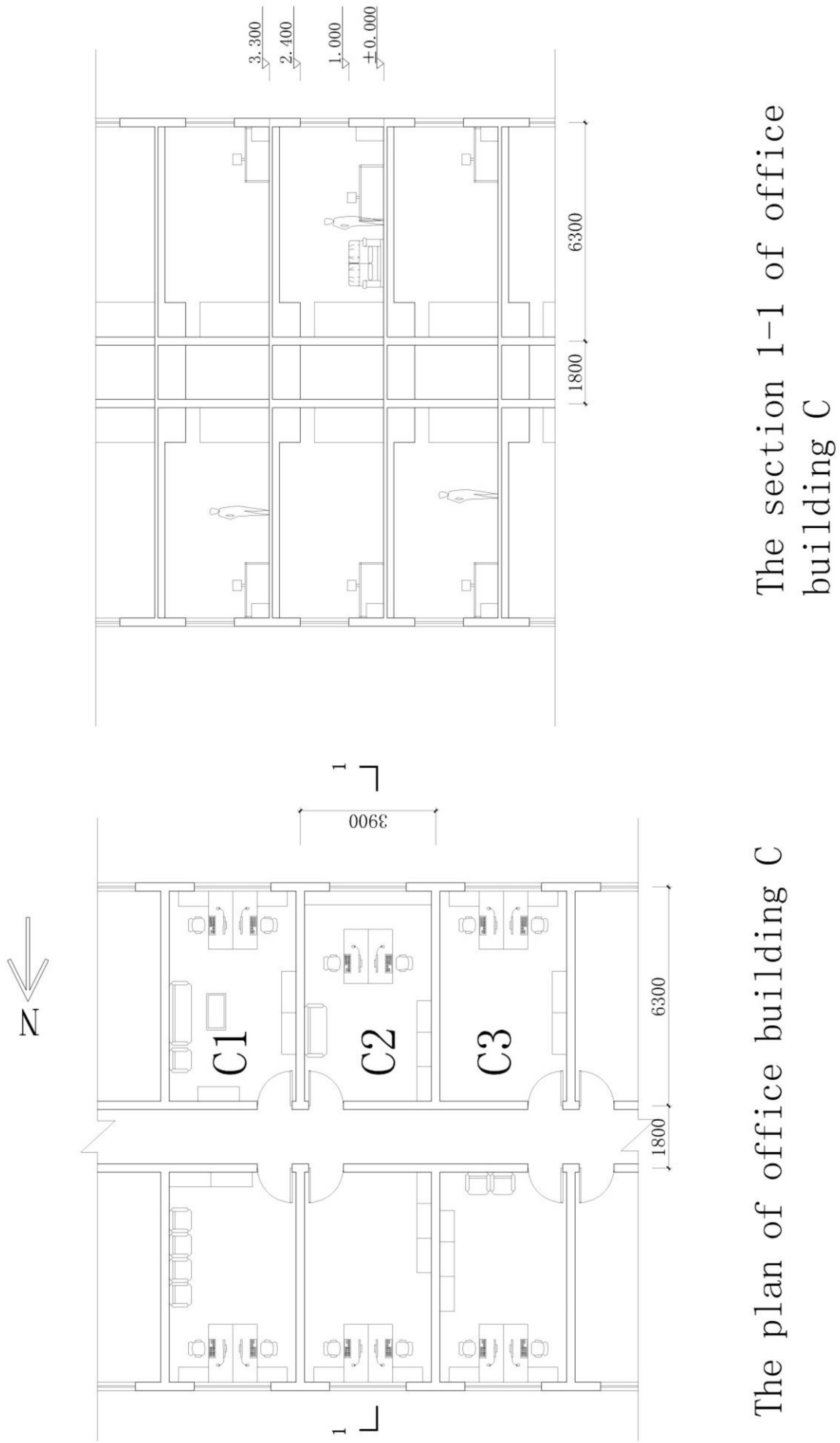


Figure 9.18: The plan and section of building C.

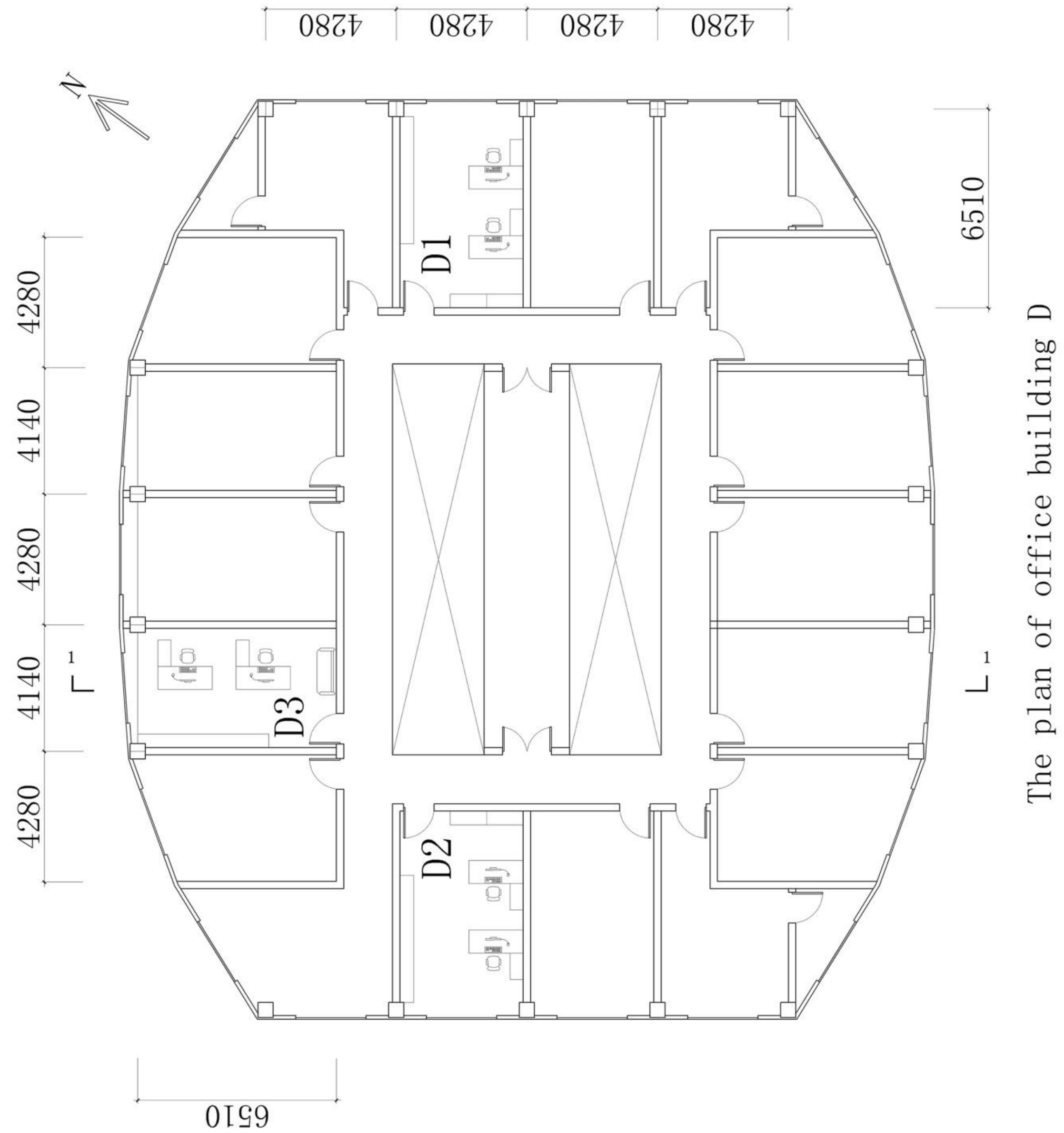


Figure 9.19: The plan of building D.

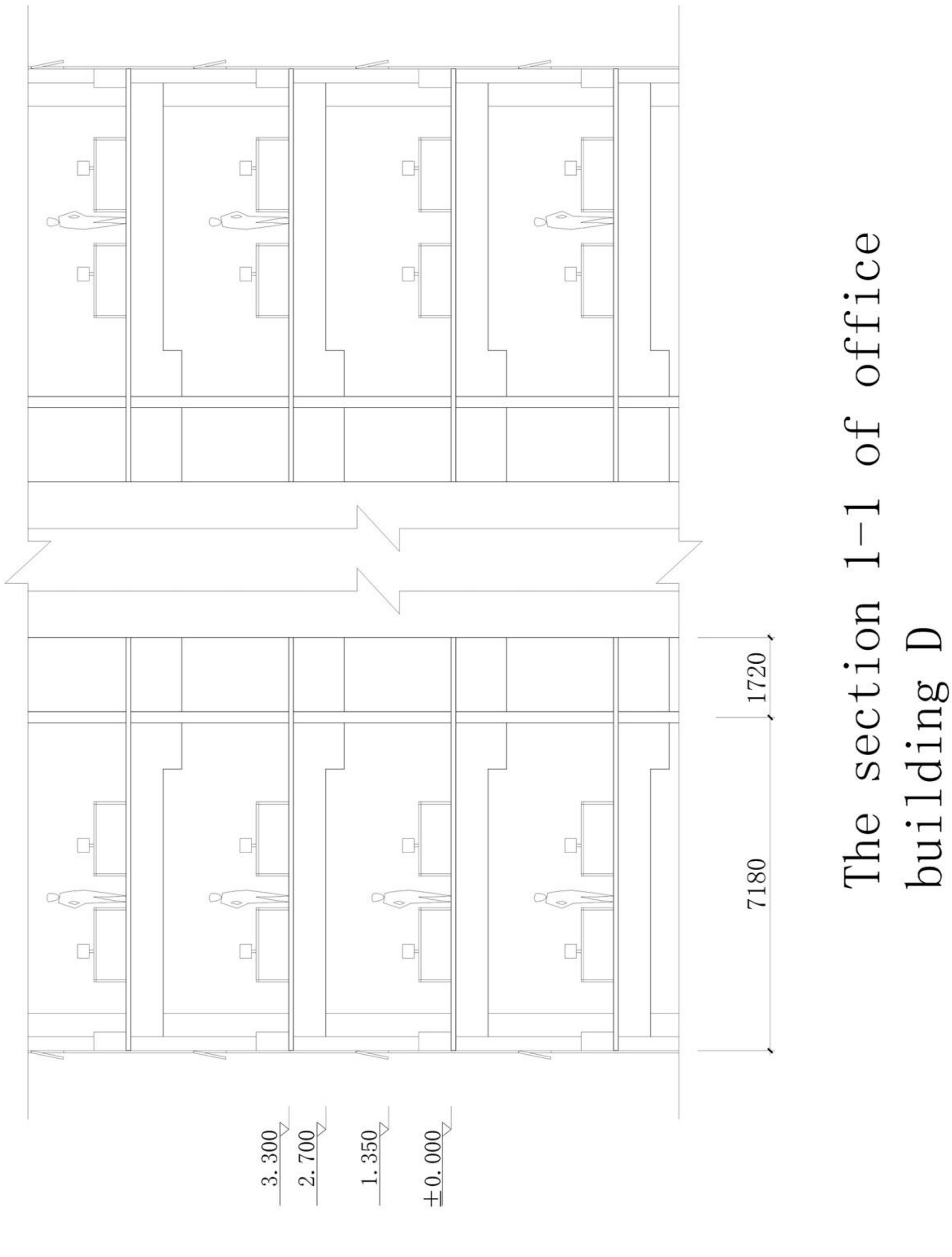


Figure 9.20: The section 1-1 of building D.

9. Window typologies in office building

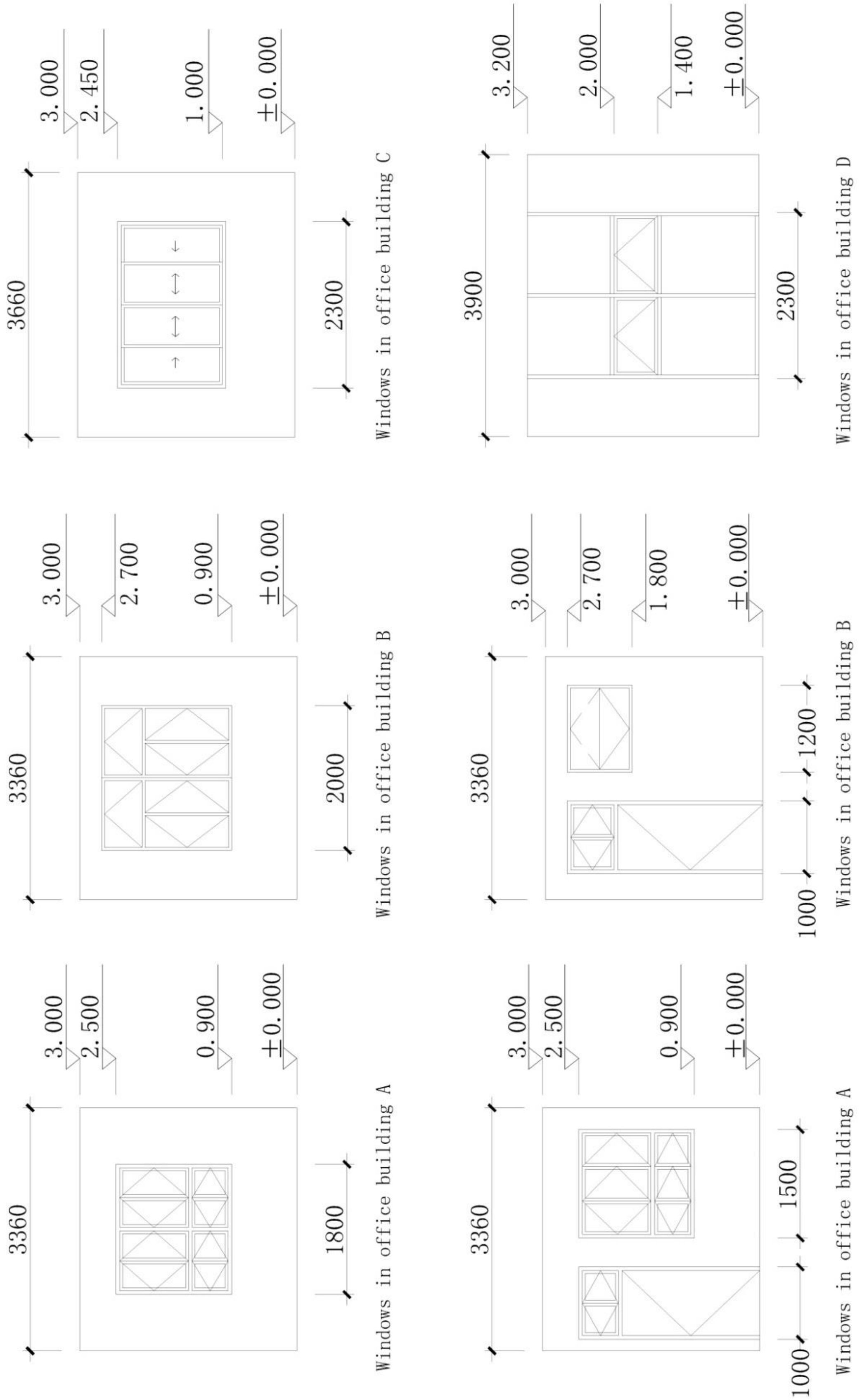


Figure 9.21: Window typologies in office buildings.