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THE UNIVERSITY OF SYDNEY

Faculty of Architecture, Design & Planning

Retrofitting Adaptive Comfort Strategies into Conventionally Air Conditioned Commercial Buildings

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A thesis submitted in fulfilment of the requirement for the degree of
MASTER OF PHILOSOPHY

By

Hisham Allam

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List of Abbreviations and Symbols

HVAC: Heating Ventilation and Air Conditioning

PMV: Predicted Mean Vote

PPD: Predicted Percentage Dissatisfied

AMV: Actual Mean Vote

APD: Actual Percentage Dissatisfied

RH: Relative Humidity

SBS: Sick Building Syndrome

°C: Degrees Celsius

Clo: Clothing Insulation

ε: Emissivity

m/s: Metres per second

Met: Metabolic rate

ASHRAE: American Society of Heating, Refrigeration and Air-Conditioning Engineers

GBCA: Green Building Council of Australia

BMS: Building Management System

BoM: Australian Bureau of Meteorology

Glossary of Terms

Actual Mean Vote (AMV)

A subjects' actual thermal sensation as expressed on the seven-point thermal sensation scale from 'cold' (-3) through 'neutral' (0) to 'hot' (+3). Throughout this thesis, AMV is also referred to as the 'observed thermal sensation'.

Actual Percentage Dissatisfied (APD)

A person in comfort is taken to be one who is 'slightly cool' (-1), 'neutral' (0) or 'slightly warm' (+1) on the seven-point thermal sensation scale (ASHRAE, 2010). APD is calculated as the proportion of AMV thermal sensation votes that fall outside this range of 'comfortable' votes divided by the total number of votes for that sample.

Adaptive Model

The adaptive model relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters (de Dear and Brager, 1998; ASHRAE, 2010). This model recognises the role of human adaptation in establishing thermal comfort, taking into account people's thermal perception, behaviour and expectations, allowing for a wider range of acceptable temperatures in NV buildings.

Comfort Temperature

This is the operative temperature at which either the average person will be thermally neutral, or at which the largest proportion of a group of people, will be comfortable (ASHRAE, 2010).

Neutral Temperature

This is the operative temperature at which either the average person will vote ±0.5 on seven point scale (hot, warm, slightly warm, neutral, slightly cool, cool and cold), or at which the largest proportion of a group of people, will be comfortable do not request any change in indoor environment (ASHRAE, 2010).

Commercial Building

This term refers to a non-residential building that contains office spaces and primarily used for commercial use.

Predicted Mean Vote and Predicted Percentage Dissatisfied (PMV-PPD) Model

Also referred to as the ‘static’ model of comfort, the PMV-PPD model is based on the principles of the human heat-balance equation (Fanger, 1970). The model calculates thermal comfort as the relationship between four environmental variables: air temperature, radiant temperature, air velocity and relative humidity; and two physiological variables: clothing insulation (clo) and metabolic activity.

Predicted Mean Vote (PMV)

Predicted Mean Vote (PMV) is the average thermal sensation vote for a large group of subjects on the seven-point thermal sensation scale when exposed to a particular environment (Fanger, 1970; ASHRAE, 2010).

Predicted Percentage Dissatisfied (PPD)

Predicted Percentage Dissatisfied (PPD) is derived from PMV and is defined as an index describing the percentage of occupants that are dissatisfied with the given thermal conditions (Fanger, 1970; ASHRAE, 2010).

DECLARATION

This is to certify that:

I. This thesis comprises only my original work towards the Master of Philosophy Degree.

II. Due acknowledgement has been made in the text to all other material used.

III. The thesis does not exceed the word length for this degree.

IV. No part of this work has been used for the award of another degree.

V. This thesis meets the University of Sydney's Human Research Ethics Committee (HREC) requirements for the conduct of research.

Hisham Allam

4/4/2014

ABSTRACT

This research presents the findings of a field study on the thermal comfort of occupants in a medium sized air-conditioned office building in Revesby (located in Sydney’s inner west and characterized by a subtropical climate). This study is developing a new approach to the indoor environment in office buildings which adopt the adaptive air-conditioning model in moderate, hot and humid, and cold climatic districts.

A total sum of 30 subjects were involved in this longitudinal field experiment and produced more than 2386 sets of data for winter and summer. The collection of indoor climatic data by light and portable moving instrumentation complies fully with the accuracy requirements of ANSI/ASHRAE Standard-55 and ISO 7726. The questionnaire was based on the standard for thermal environment survey and was modified slightly to suit the research purpose. The study manually tuned the building's HVAC set point using the ASHRAE adaptive comfort standard 55-2010, based on a running seven-day mean outdoor temperature, but capping the set-point band at 26^{o}C and 18^{o}C in summer and winter, respectively. By using the adaptive comfort algorithm for naturally ventilated buildings, a new model of thermal comfort in office buildings was developed called ‘adaptive air-conditioning’.

The research confirmed that occupants of an air-conditioned building are capable of adapting to variable indoor temperatures like the occupants in naturally ventilated buildings, and the notion of ‘adaptive comfort HVAC’ is feasible. Although thermal comfort is covered extensively in this study, emphasis was also given to the consequential economical and ecological outcomes during the

operational phase of the office building in Sydney (the most energy demanding phase).

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This MPhil study was completed at the Faculty of Architecture, Design and Planning at the University of Sydney.

CHAPTER 1

1 INTRODUCTION

The building sector is responsible for 40% to 50% of total global energy consumption in the form of heat or electricity, as per the Building and Climate Change of the United Nations Environment Programme publication (UNEP, 2007). During the period of five year from 1999 to 2004, carbon dioxide emissions (CO_2) from commercial buildings across all energy uses rose by 2.5% per year. Residential buildings rose by 1.7% over the same period (IPCC, 2007). The largest regional increases in CO_2 emissions (including through the use of electricity) for commercial buildings were from developing Asia (30%), North America (29%) and OECD Pacific (18%). The largest regional increase in CO_2 emissions for residential buildings was from Developing Asia accounting for 42%, followed by the Middle East/North Africa with 19% (Metz, et al 2007). Nowadays, the largest part of energy consumption occurs throughout a building's operational and maintenance phase: ventilation, heating, cooling and lighting purposes. This calls for building professionals to produce more energy efficient solutions for buildings and to retrofit existing stocks according to modern sustainability criteria. The existing criteria in the professional guideline must be adjusted to the different climate, economic and social conditions in order to bring existing high energy demands under control.

1.1 Problem

As a reaction to global climate change and carbon gases emission, architects and engineers have introduced significant innovations in terms of sustainable building expansion in recent times. However, thermal comfort research has introduced more effective and efficient ways to reduce building energy consumption. Energy savings became a reality as a result of adopting the adaptive thermal comfort concept in naturally ventilated and hybrid air-conditioned buildings. Massive data has been collected worldwide to prove the application of adaptive thermal comfort. The raw data comprising the RP-884 database came from four continents and a broad spectrum of climatic zones. Nearly 21,000 sets of raw data were compiled from several locations (de Dear and Brager, 1998).

Occupants are able to accept a wider range of temperatures, not only because of their psychological habituation, expectations and physiological acclimation, but also their behavioural adjustments (Brager, 1998). Accordingly, in summer occupants are able to accept temperatures close to outdoor conditions if they are allowed to adjust their clothing to suit the indoor temperature, or permitted more air movement to enable quicker heat transfer and sweat evaporation.

Indeed, adaptive thermal comfort has been under scrutiny for the last three decades as a result of global climate change (Brager, 1998). In 2004, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) adopted a new standard ASHRAE-55 (Thermal Environmental Conditions for Human Occupancy), also known as the European adaptive comfort standard (EN15251). ISSO 7730-2005 (ergonomics of the thermal environment), on the other hand, depends on the analytical determination and interpretation of thermal comfort using calculations of the PMV and PPD indices and local thermal comfort criteria, which also recognizes the significance of adaptation in thermal comfort.

In the pattern of energy use in Australia (Al-Sayed and Al Ragom, 2005), heating and cooling account for between 50% to 60% of the average total energy consumption in commercial buildings. It is very important to reduce building energy consumption, which is both expensive and environmentally destructive. Energy reduction has greater value when it is measured against atmospheric pollution and carbon dioxide emissions. In 1999, buildings were responsible for 27% of all energy related to greenhouse gas emissions. By 2010, emissions from buildings will increase to 48% above the 1990 level (Hyde, 2008). Currently, the international drive towards energy conservation has prompted many new research enquiries into thermal comfort. Much research is directed at the carbon gas emissions from existing and new office buildings and focused particularly on the indoor environment, which is considered the main factor in a building's energy consumption. The air-conditioning industry recognizes that a one degree Celsius difference of the air-conditioning set point temperature is roughly equivalent to 10% of the building's energy. Experimental testing on a 10,555m^2 commercial building showed that raising the thermostat temperature by 1°C during summer could achieve an energy saving of up to 15%. Short duration demand response trials on the building showed that the short-term demand could be reduced by between 20% and 45% (Ward and White, 2007). In other words, narrowing the difference between indoor and outdoor environmental conditions will reduce the heat transfer of a building's envelope and minimize the air-conditioning systems and their elements (ASHRAE, 2001). Indoor dry bulb temperature, relative humidity, mean radiant temperature and air movement are the climate variables that affect the human thermoregulatory system in addition to some other personal factors, mainly clothing insulation and metabolism rate. Note that clothing adjustment represents a more powerful adaptive response in the home than in the workplace. The human thermoregulatory is stimulated by changes in environmental conditions (de Dear, Brager, 1997). This stimulation could be disturbing and affect the productivity of the occupants so it is important to study thermal comfort experimentally and statistically. Thermal comfort measures are determined theoretically using empirical indices beside analytical indices in climatic chambers (ASHRAE, 1990). It is well known that PMV is the thermal comfort index that should support any statistical study. The adaptive model of thermal comfort established a new adaptive comfort standard (ACS) which allows the dynamic environmental conditions for human occupancy to communicate with outdoor ambient temperature (ASHRAE, 2004). This approach of thermal comfort enhances the feasibility of the bioclimatic design, as it widens the range of acceptable operative temperatures and humidity beyond the conventional static conditions (as defined by ASHRAE Standard-55). Together, these factors prompt some fundamental questions about thermal comfort design practices in Australian air-conditioned buildings.

The office buildings have a significant potential for positive change; they could become more efficient in terms of thermal comfort, more sustainable and less environmentally manipulating. Therefore, it is important that decision-makers negotiate in regards to the indoor environment during the design phase. Why is Australia still designing buildings according to twentieth-century thermal comfort standards and disregarding the environmental and financial implications? Can Australian office building occupants accept adaptive comfort conditions like their counterparts in other parts of the world, such as Japan? (2005 CoolBiz press release). The two main adaptive comfort standards (ASHRAE 55-2010 and EN15251) were developed from data within naturally ventilated buildings, and so the scope of their application is limited to that type of building. However, the adaptive concept has been extrapolated in some other countries to the air-conditioned context (eg in Japan). Implicit in Japan's 'CoolBiz' policy is the belief that thermal comfort in air-conditioning can be affected by outside weather and climatic conditions. Therefore, human adaptation is also relevant to air-conditioned buildings. This study addresses these simple research questions.

1.2 Hypothesis

This research investigated occupant satisfaction and comfort expectations, and examined the indoor air temperature set point range that produces 80% and 90% acceptability levels for occupants of an air-conditioned office building in Sydney.

The argument between the sceptics and the environmental activists will never end, however, energy savings when using adaptive air-conditioning is undeniable. Nevertheless, the claimed thermal comfort that was promised in office buildings as a result of PMV values has never been achieved. As a new global culture takes shape that calls for the reduction of carbon gas emissions, developing the concept of adaptive thermal comfort in air-conditioned buildings is a critical innovative and the most effective approach in resolving energy consumption concerns. More research and investigation will guarantee the best thermal comfort under the new indoor conditions which simulate outdoor conditions and the people adaptation power.

The adaptive approach to thermal comfort for use in air-conditioned office buildings can be derived from the adaptive model of naturally ventilated buildings. The thermal comfort set point temperature within the comfort limits in air-conditioned office buildings can be predicted, thereby offering an economic and environmentally-friendly solution. Comfort and energy savings can be achieved with minimal expense by implementing a new control tactic. A hybrid model, called the controlled adaptive model, can be formed between the PMV model and the adaptive model, which contain common comfort conditions. This new controlled adaptive model in air-conditioned buildings imitates the adaptive model in naturally ventilated buildings within a limited range of indoor temperatures. Importantly, this hybrid model will benefit the design of new office buildings. It will be important to use these simple and economic strategies in retrofitting existing air-conditioned office buildings.

1.3 Objectives and Significance

After much research, the major focus of this study is to maintain optimum thermal comfort inside buildings while simultaneously minimising building energy consumption. Reducing the temperature difference between the indoor HVAC set point temperature and the outdoor ambient temperature results in at least a 10% reduction in the cooling equipment, this will lead to a direct reduction in energy consumption. This direct energy saving method requires zero investment since adjusting the set point temperature requires only willing occupants. This field experiment aims to deliberately shift the HVAC set points towards the upper limits of normal engineering practices in Australia through a case study building located in Sydney, near Bankstown Airport. HVAC designers in Sydney currently use a conservative 22 ±2^{o}C as their indoor design target based on (AIRAH, 2003) and the Building Code of Australia (2010).

The research plan aims to refine the adaptive comfort temperature of occupants in air-conditioned buildings, and widen the indoor temperature range from 18^{0}C in winter to 26^{0}C in summer using an adaptive comfort algorithm. Thermal comfort questionnaires modified from the standard ASHRAE thermal survey, indoor and outdoor physical measurements, interviews and observations were conducted during the field studies on air-conditioned building office occupants in the Sydney area. The measurements were made at desk level, in full compliance with ANSI/ASHRAE 55-1992, ANSI/ASHRAE 55a-1995, ISO 7726 and ISO 7730 standards. A quantitative statistical analysis was undertaken to formulate the relationships between the participant's thermal sensations, indoor thermal conditions (delivered by the air-conditioning system), and the outdoor seven day running mean temperature.

The objectives of this study were as follows:

1. Collect enough data on the thermal environments and subjective responses of participants in hot and humid suburban office buildings, and provide the best statistical comparison between the theoretical model using PMV and the adaptive model using AMV.
2. Establish a database for Sydney's summer and winter seasons, optimum thermal conditions acceptable for the majority of occupants. These findings are to be compared with the current ASHRAE Standard-55.

3. Investigate the influence of clothing and study the potential acclimatisation effects by inter-seasonal comparisons.
4. Examine the practicality of the existing predictive thermal indices of PMV and PPD, as calculated by the WinComf algorithms (Fountain and Huizenga, 1996) based on participants' subjective responses.

The significance of this research in the long term is the potential to reduce greenhouse gas emissions from the commercial building sector, not only for newly built establishments but also existing building stock. This concept can be readily applied to retrofit any building with a programmable Building Management System (BMS). The occupants of office buildings are able to maintain thermal comfort and energy conservation when provided with the knowledge of making personal and environmental adjustments.

1.4 Structure

Furthermore, this research will support the process of change for a new practice in air-conditioning design culture and enrich the database of worldwide adaptive thermal comfort investigation. This will be achieved with new information about the feasibility of applying the adaptive model in air-conditioned buildings, which would help advance sustainable buildings by improving thermal comfort standards and implementing design strategies already introduced in many regions.

This research consists of the following six chapters:

- Chapter 1—Introduction.
- Chapter 2—Literature Review: aims to provide an overview of the concepts of thermal comfort in buildings, discussing the difference between the theoretical

model and adaptive model used in the building sector and demonstrating the possible common new strategy that is set between these models.

- Chapter 3—Method: explores how the field study took place and explains the sequence of work and process. It also lists all the components involved throughout the experiment, such as building location, envelope, air-conditioning system, occupants and measuring instruments.
- Chapter 4—Results: presents the results and introduces a number of tables and graphs, such as the relationship between the PMV and AMV.
- Chapter 5—Discussion: analyses the results in Chapter 4 and explores the potential of the new model which adopts adaptive air-conditioning strategies in office buildings under a revised guideline for thermal comfort.
- Chapter 6—Conclusion: presents a set of recommendations and shows a linear relationship between indoor comfort temperatures and the running mean outdoor temperature, similar to that observed for naturally ventilated buildings that formed the basis of ASHRAE's adaptive thermal comfort model.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Definition of Thermal Comfort

Thermal comfort is “that condition of mind which expresses satisfaction with the thermal environment” as defined in ASHRAE’s (American Society of Heating Refrigerating and Air Conditioning Engineers) Standard Number-55 (ASHRAE, 2004) and ISO-7730 (ISO, 1994). Additionally, ASHRAE states that thermal comfort inside buildings is achieved when indoor environmental conditions satisfy 80% of office occupants, owing to the fact that it is practically impossible to please all the occupants even some of the time. Essentially, scholars differ in determining a general theory for thermal comfort because every individual has an exclusive comfort zone which varies from one person to another. Even though people live in the same environment and under the same conditions, they may alter their expectations and thereby their thermal sensation and satisfaction. However, many researchers agree that four environmental factors (temperature, thermal radiation, humidity and air speed) and two personal factors (activity and clothing) influence thermal sensation in humans (ASHRAE, 2004; ASHRAE, 2010; Fanger, 1970; Fanger, 1973). Culture, gender, thermal expectations and psychological dimensions of adaptation may also shape each person’s comfort zone. Therefore, thermal comfort is a thorny issue that becomes even more controversial when investigating thermal satisfaction in a group of people working in a common space, such as the occupants of an office building. A new thermal model was presented by de Dear (1994) and Humphreys (1995) to simplify the definition of thermal comfort, distinguishing its term from the complex formula of the body heat balance equation developed by Fanger in special climatic controlled chambers (1970).

Barger and de Dear (1998) developed a model that considered the three major aspects of adaptation: behavioural, physiological and psychological. Original findings of thermal comfort in the adaptive model stem from the direct responses of individuals, and were compiled from various field studies in office buildings located in four continents and under different climatic conditions. These include North America, the United Kingdom, Greece, Pakistan, Thailand, Indonesia and Australia (de Dear & Brager, 1998; Humphreys, Nicol & Raja, 2007). The experimental basis of the adaptive approach to thermal comfort is the field study (Humphreys, Nicol & Raja, 2007). Accordingly, this research undertakes the field study as a basic method to find thermal preferences; this, in turn, may simplify or add to the definition of thermal comfort in office buildings.

A lot of related literature has defined the meaning of common terms in thermal comfort. These have been broadly debated and defined in ASHRAE-55 2010 (ASHRAE, 2004) and ISO-7730 1995 (EN ISO, 1995), such as:

1. Thermal comfort: condition of mind, which expresses satisfaction under certain thermal environments.
2. Acceptable thermal environment: when at least 80% of the occupants would agree that the thermal environment is acceptable.
3. Thermal sensation: a conscious feeling graded into seven categories: cold, cool, slightly cool, neutral, slightly warm, warm, and hot.

2.2 Heat Balance Approach to Thermal Comfort (PMV)

According to the concept of heat transfer, the heat balance between the internal body and the surrounding environment should be maintained to stabilise the internal resting body temperature at 36.8^{o}C (ASHRAE, 2001). That means that the total heat energy produced in the body is either stored to raise the core and skin temperature, or transferred to the surroundings through either the skin's surface or respiration. This statement can be represented in the following equation known as the heat balance equation (ASHRAE, 2001):

$$M - W = q_{sk} + q_{res} + S = (C + R + E_{sk}) + (C_{res} + E_{res}) + (S_{sk} + S_{cr}) \qquad \text{[Equation 1]}$$

Where:

M = rate of metabolic heat production, W/m^2

W = rate of mechanical work accomplished, W/m^2

q_{sk} = total rate of heat loss through the skin, W/m^2

q_{res} = total rate of heat loss through respiration, W/m^2

$C + R$ = sensible heat loss through the skin, W/m^2

E_{sk} = total rate of evaporative heat loss through the skin, W/m^2

C_{res} = rate of convective heat loss through respiration, W/m^2

E_{res} = rate of evaporative heat loss through respiration, W/m^2

S_{sk} = rate of heat storage in skin compartment, W/m^2

S_{cr} = rate of heat storage in core compartment, W/m^2

S = rate of heat storage in the body, W/m^2

The diagram in Figure 2.1 displays the heat flow in the heat balance equation for a body under steady state experimental conditions, where the blue and green colours represent the cooling process and the red colour represents the warming factor.

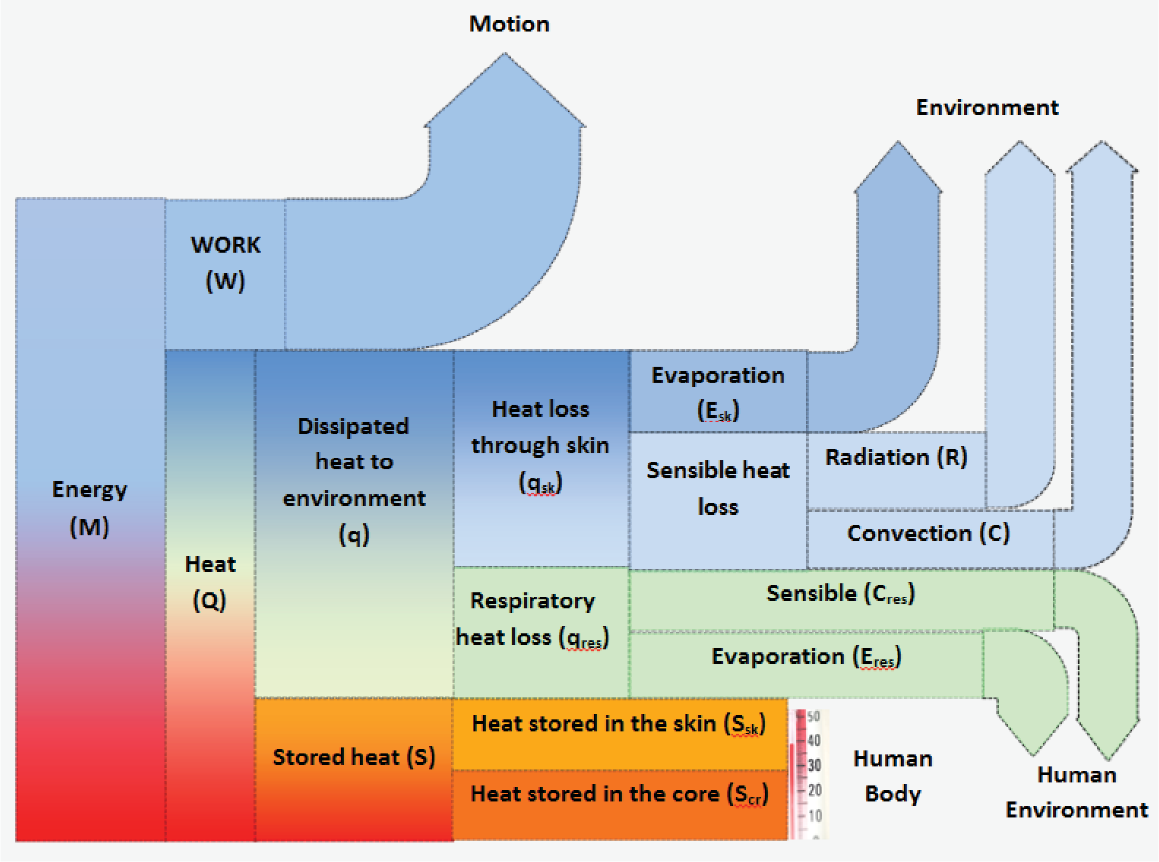


Figure 2.1 Diagram of the heat balance equation for the human body, according to [Equation 1].

Additionally, the diagram shows that heat dissipates in two major forms:

1. Sensible heat transfer, which occurs by convection and radiation. The rate of this heat transfer depends on air temperature (ta) and relative air velocity (V) in the immediate surroundings for convection, and mean radiant temperature (tr) for radiation heat transfer.
2. Latent heat transfer, which occurs by the evaporation of sweat and moisture from the skin, and the evaporation of moisture during respiration. The rate of evaporative heat loss to the surrounding environment depends on the water vapour pressure of the skin (Psk), water vapour pressure in ambient air, and the humidity ratio of inhaled (ambient) and exhaled air, also known as relative humidity (ASHRAE, 2001).

Therefore, six major parameters in the surrounding environment of the human body influence thermal sensation: air temperature (Ta), air moisture or relative humidity (RH), air velocity (v), radiant temperature (Tr), metabolic rate, and clothing (ASHRAE, 2010). Through these parameters, the thermal comfort zone of a person can be outlined. The effect of these parameters is magnified or minimised according to the climate, space and nature of work performed.

2.2.1 Air temperature and Convective Heat Transfer

Earlier researchers state that thermal comfort is strongly related to the thermal balance of the body, which is influenced by body temperature and environmental temperature (Fanger, 1970; McIntyre, 1980). Meanwhile, ambient air temperature surrounding a clothed person determines the convection heat flow (C) from the skin, through clothing and into the environment (ASHRAE, 2001).

$C = f_{cl}\, h_c\, (t_{cl} - t_a)$ [Equation 2]

Where:

f_{cl} = clothing area factor Acl/AD, dimensionless

t_a = dry bulb (ambient) temperature

h_c = convective heat transfer coefficient, $W/(m^2 \cdot K)$

The convection heat transfer coefficient is the coefficient which correlates to air movement within a living space and caused by a human body (ASHRAE, 2001). This coefficient was estimated in many different equations by Colin and Houdas (1967), Gagge et al (Gagge, Nishi & Nevins, 1976; 1970), Mitchell and Seppanen et al (Mitchell, 1974; Seppanen, McNall, Munson & Sprague, 1972). The most acceptable figure of the convection heat transfer coefficient in a controlled indoor environment was presented by Seppanen et al (Seppanen, McNall, Munson & Sprague, 1972) for a person standing in moving air with a velocity variance ranging from 0.15 m/s to 1.5 m/s, as follows:

$h_c = 14.8V^{0.69}$ [Equation 3]

Equation (3) (Seppanen, McNall, Munson & Sprague, 1972) shows the impact of air movement on the convection heat exchange. As the mean velocity (V) increases, the heat flow accelerates. The air velocity impact becomes negligible during the free convection process (Fanger, 1970). Where velocity is less than 0.15 m/s, h_c is estimated as equal to a constant value of around 4 $W/(m^2 \cdot K)$ (Seppanen, McNall, Munson & Sprague, 1972).

Mitchell (1974) suggested 3.1 $W/(m^2 \cdot K)$ as a convection coefficient for a person standing in moving air with a velocity less than 0.2 m/s. In other words, this coefficient can be estimated in air-conditioned buildings within (3 ~ 4) $W/(m^2 \cdot K)$.

2.2.2 Radiant Temperature (and Radiative Heat Transfer)

Radiative (R) heat transfer from the outer surface of a clothed body can be expressed in terms of a radiant heat transfer coefficient and the difference between the mean temperature (t_{cl}) of the outer surface of the body (A_D) and the mean radiant temperature (ASHRAE, 2001):

$R = f_{cl}\, h_r\, (t_{cl} - t_r)$ [Equation 4]

Where:

f_{cl} = clothing area factor A_{cl}/A_D, dimensionless

A_D = DuBois surface area, m^2 (ASHRAE, 2001)

h_r = linear radiative heat transfer coefficient, W/(m^2·K)

t_r = radiant temperature ^oC

2.2.3 Linear Radiative Heat Transfer Coefficient

The value of the radiative heat transfer coefficient (h_r) is directly proportional to the average temperature of clothing and mean radiant temperature cubed. However, for typical indoor temperatures relating to a sitting person of constant clothing area factor, equal to (0.7 ~ 0.73) (Fanger, 1967), the value of this coefficient will be considered nearly constant in typical indoor temperatures.

Where (ε) represents the area weighted average emissivity for the clothing/body surface, the radiative heat transfer coefficient is expressed in this equation (ASHRAE, 2001):

$hr = 4.7\varepsilon$ [Equation 5]

For most calculations of the inside of buildings, the value of 4.7 W/(m^2·K) is adequate (ASHRAE, 2001).

2.2.4 Mean Radiant Temperature

Heat transfer through radiation takes place in the form of electromagnetic waves, mainly in the infrared range. The Stefan-Boltzmann Law determines that the radiation energy flow per area from a hot body to a cold body is proportional to the difference to the fourth power of the absolute temperature (ASHRAE, 2001):

$q_c = \varepsilon\ \sigma\ (T_h^4 - T_c^4)$ [Equation 6]

Where:

T_h = hot body absolute temperature (K)

T_c = cold surroundings absolute temperature (K)

q_c = heat transfer flow per unit area (W/m^2)

σ = 5.6703 10-8 (W/m^{2}K4) - The Stefan-Boltzmann Constant

ε = emissivity of the object (one for a black body)

Mean radiant temperature is the constant temperature of a virtual enclosure in which the radiant heat transfer from the human body is equivalent to the radiant heat transfer in the actual non-uniform enclosure (ASHRAE, 2001). The combination of globe temperature, air temperature and air velocity allows the estimation of mean radiant temperature. Mean radiant temperature can be calculated from the plane radiant temperature as per the following equation (ASHRAE, 2001):

$$T_{mr}^4 = T_1^4F_{p-1} + T_1^4F_{p-1} + \ldots + T_N^4F_{p-N} \qquad \text{[Equation 7]}$$

T_{mr} = mean radiant temperature, °R

T_N = surface temperature of surface N, °R

F_{p-N} = angle factor between a person and surface N

In the case of a slight temperature difference between the surrounding surface of a room and a person sitting in it, mean radiant temperature can be calculated from plane radiant temperature. The plane radiant temperature in six directions should be considered with the projected area factors of a person in the same six directions, as shown in the following equation (ASHRAE, 2001):

$$t_r = w \div [2(0.18 + 0.22 + 0.30)] \qquad \text{[Equation 8]}$$

Where T_{pr} is the uniform temperature of an enclosure in which the incident radiant flux on one side of a small plane element is the same as that in the actual environment (ASHRAE, 2001).

2.2.5 Operative Temperature

As both (C) and (R) represent the total sensible convection and radiation heat exchange respectively, sensible heat loss from the skin through the clothing into the surrounding environment may be expressed as (ASHRAE, 2001):

$$C + R = f_{cl}\, h_c\, (t_{cl} - t_a) + f_{cl}\, h_r\, (t_{cl} - t_r) = f_{cl}\, h\, (t_{cl} - t_o) \qquad \text{[Equation 9]}$$

Where:

h_c = convective heat transfer coefficient, $W/(m^2 \cdot K)$

h_r = linear radiative heat transfer coefficient, $W/(m^2 \cdot K)$

h = total sensible heat transfer coefficient, $W/(m^2 \cdot K)$ (ASHRAE, 2001)

$$h = h_c + h_r \qquad \text{[Equation 10]}$$

t_o = operative temperature (the average of the mean radiant temperature and ambient air temperatures, weighted by their respective heat transfer coefficient), ºC (ASHRAE, 2001)

$$t_o = (h_r\, t_r + h_c t_a)/(h_r + h_c) \qquad \text{[Equation 11]}$$

In order to simplify Equation (11) and form Equations (5) and (3), the values of h_r and h_c are assumed to be equal for indoor temperatures:

$$t_o = (t_r + t_a)/2 \qquad \text{[Equation 12]}$$

It is convenient to include the operative temperature in thermal calculations and use it as a reference temperature in which it represents sensible heat loss.

2.2.6 Humidity (RH)

Relative humidity was considered to have little influence on comfort level until Fanger (1970) entered it in the heat balance equation to predict human thermal satisfaction. Wargocki (1999) revealed that relative humidity is one of the main parameters in indoor quality. Likewise, the *Guide to Best Practice Maintenance & Operation of HVAC Systems for Energy Efficiency in Australia* suggested that for most office type applications, the relative humidity is between 35% and 60% for all comfort temperatures (COAG, Lecamswasam, Wilson & Chokolich, 2012).

A brief review of the theoretical analysis of relative humidity categorises evaporative heat loss from the skin (E_{sk}) and during respiration (E_{res}) as total latent heat loss (ASHRAE, 2001):

$$Q_{Latent} = E_{res} + E_{sk} \qquad \text{[Equation 13]}$$

Latent respiratory heat loss is often expressed as (ASHRAE, 2001):

$$E_{res} = 0.0173M(5.87 - P_a) \qquad \text{[Equation 14]}$$

$$E_{sk} = w(P_{sk,s} - P_a)/(R_{e,cl} + 1/(LRh_c f_{cl})) = w(P_{sk,s} - P_a)/R_{e,t} \qquad \text{[Equation 15]}$$

Where (Pa) water vapor pressure in ambient air is expressed in kPa and (ta) is in °C.

w = skin wettedness, dimensionless

$P_{sk,s}$ = water vapor pressure on the skin, normally assumed to be that of saturated water vapor at (tsk) kPa

LR is the Lewis Ratio and, at typical indoor conditions, equals approximately 16.5 K/kPa. The Lewis Ratio applies to surface convection coefficients.

In contrast, RH is a function of P_a; as p_a increases, RH increases based on the following equation of relative humidity (ASHRAE, 2001):

$\%RH = 100.\ p_a/p_s$ [Equation 16]

Where p_s is the saturation pressure of the water at the temperature of the ambient.

According to equations (13) and (14), RH determines the flow of latent heat Q_{Latent}, so as RH increases the evaporative heat decreases.

The high percentage of relative humidity will therefore delay the process and cause discomfort. To avoid these negative effects, there should be a humidity limit set by standards such as (ASHRAE, 2001) for acceptable air temperature ranges for different indoor environments (Jing, Li, Tan & Liu, 2012). When relative humidity is more than 70%, people start experiencing discomfort after a certain period of time (Brown, 1997). However, Hensen (1990) made a remarkable finding; when operative temperature is inside or near the comfort zone, variations of relative humidity from 20% to 60% do not have an appreciable effect on the thermal comfort of sedentary or slightly active, normally clothed people. In other words, most recent research shows that people alter their humidity sensation in different air ambient temperatures; however, humidity variations remain negligible for ambient temperatures equal or around 26°C (Figure 2.2) (Jing, Li, Tan & Liu, 2012).

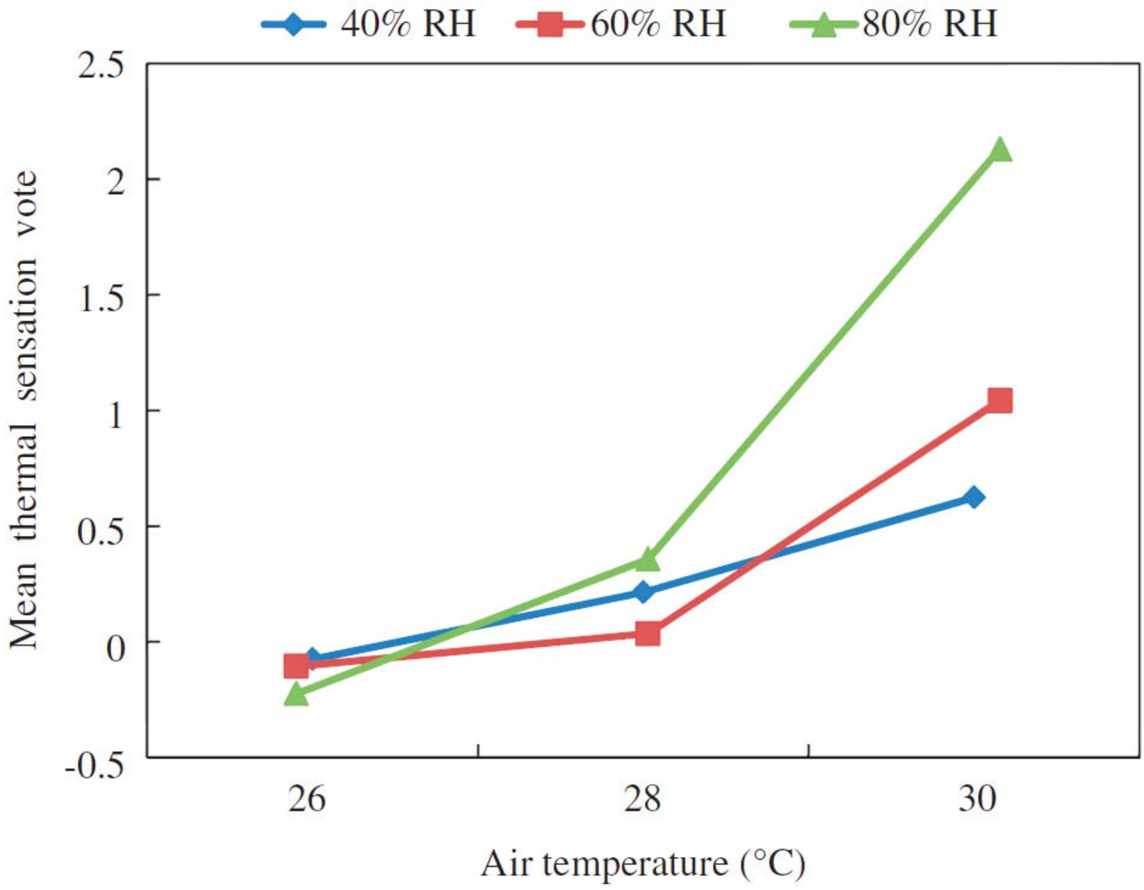


Figure 2.2 Mean thermal sensation vote with different air temperatures and relative humidity (Jing, Li, Tan & Liu, 2012).

Relative humidity may be considered to have minor consequences on thermal comfort in air-conditioned buildings where indoor temperature can be controlled within the comfort zone.

2.2.7 Air Velocity (v)

Based on the previously mentioned equations, the heat gain or heat loss flow rate from and to the body varies with air movement. As convection and evaporative heat transfer increase with higher air movement around the body, natural ventilation in hot and humid climates with higher air speeds may be desirable to improve the subject's thermal comfort (Humphreys, Nicol & Raja, 2007).

No references have been found on the effect of air velocity, although many studies deal with the air turbulence effect on the sensation of a draught. Fanger concluded that air flow with high turbulence results in more complaints of a draught than air flow with low turbulence at the same mean velocity (Fanger, Melikov, Hanzawa & Ring, 1988).

Mean air velocity over a time interval is used in many thermal comfort studies. The comfortable range of average air velocity varies from 0.1016 m/s to approximately 0.3048 m/s. The acceptable air velocity varies depending on the activity level and indoor air temperature (Cândido, de Dear, Lamberts & Bittencourt, 2010).

Air velocity in office buildings has been measured at lower than 0.2 m/s. For example, a field experiment in air-conditioned office buildings in Singapore found the mean air velocity of a high rise building at 0.11 m/s (de Dear, Leow & Foo, 1991); similarly, in Sydney the mean air velocity in an open office building did not exceed 0.2 m/s (Brown, 2006). These low variations in velocity minimise the air movement influence on thermal comfort in air-conditioned buildings. Therefore, many studies have argued for the use of a new model of boosting fan to generate comfort zones in which elevated air speed offsets warm air temperature. New criteria for group local control are specified, making it possible to use air movement in open plan offices (Arens, Turner, Zhang & Paliaga, 2009). This new model confirmed the stratified effect of air velocity on thermal comfort in air-conditioned buildings.

2.2.8 Clothing Clo-Value (clo)

The impact of clothing alterations on thermal neutrality was examined directly by Humphreys and Nicol (Humphreys, Nicol & Raja, 2007). The findings showed that the office workers were thermally comfortable across a wide range of seasonal temperatures because of clothing adjustment capability (Humphreys, 1976; Nicol & Raja, 1996). Baker and Standeven also found a related result, where clothing was not typically used to improve comfort on an hourly basis, but was more strongly based on people's expectations in the morning about what the external thermal conditions might be that day (Baker, et al., 1996). Similarly, the clothing adjustment was found to be functional as a personal thermal comfort motivator which was taken by the occupants as adaptive action (Fanger, 1970). In general, office buildings occupied by different groups of people (of both genders and wearing a variety of clothing) cannot have the same level of thermal sensation. Furthermore, it was observed that there is a relationship between clothing insulation and operative temperature (Mui & Chan, 2003) which presents clothing as a strong influence in all models of thermal comfort. Clothing adjustment will be explored further in subsequent chapters as it has a strong relationship to adaptation and thermal comfort.

2.2.9 Metabolic Rate (M)

Metabolic rate is defined in the ASHRAE standard as follows: "The rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface. In this standard, this rate is expressed in Met units" (Baker, et al., 1996).

Metabolic unit (Met) is defined as the ratio of metabolic rate, the rate of energy consumption during a specific physical activity to a reference metabolic rate, or the amount of energy generated during the oxidisation process, set by convention to 3.5 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ or equivalent (Brown, 1997):

1 Met = 4.174 kJ/kg.h [Equation 17]

For simplification, it is expressed as power liberation from the body over the body's surface area: Met = 58 W/m^2.

Much investigation has discussed the relationship between thermal sensation and comfort using the transient metabolic rate. The results show that even a short duration of low activity (1 min at 20% workload) affects the thermal perceptions and preferences of subjects. However, after about 15 minutes of constant activity, subjective thermal responses tend to approximate the steady state response, after both increases and decreases of activity (Wargocki, Wyon, Baik, Clausen & Fanger, 1999). Hence, survey data should be based on the physical activity of subjects within a thirty-minute window, as applied in the ASHRAE questionnaire.

2.2.10 Predicted Mean Vote (PMV) and (PPD)

Extensive studies and investigations have produced methods for predicting the degree of thermal discomfort of people in a static thermal environment. The most recognised and widely accepted methods are Fanger's 'Comfort Equation' (Fanger, 1970):

$L = F(P_a, T_a, T_{mrt}, T_{cl})$ [Equation 18]

Where core energy stored in the body is a function of the environmental conditions, of which temperature forms a part.

Based on this equation, a set of comfort diagrams was plotted through various combinations of two variables representing comfort (Fanger, 1973). Fanger found that human beings have different thermal sensations and a comfort equation cannot be generalised. In other words, optimal comfort cannot be determined for a group of people gathered in the same indoor environment. However, thermal comfort can be achieved when 95% of the subjects in the group are satisfied (Fanger, 1972). Two indices were used to simplify the comfort and dissatisfaction concepts known as the predicted mean vote (PMV) and the predicted percentage dissatisfaction (PPD) (Fanger, 1973).

Fanger proposed the PMV equation to calculate the predicted mean vote for a group of occupants under the same climatic conditions. The PMV equation only applies to humans exposed for a long period of time to constant conditions at a constant metabolic rate. The equation relates all aspects of heat transfer from the body to the surrounding environment and vice versa. This operation takes place with a constant rate, referred to as steady state heat transformation (Fanger, 1982). Therefore, the predicted mean vote value equation predicts the mean vote number, which determines the thermal condition in the space.

The equation reflects the physiological and psychological responses of the human body to the excess or lack of heat transfer between the body's core and the environment. Grouping the effects of the six physical parameters of PMV and PPD was used widely in standards for air-conditioned premises. It was based on healthy subjects, irrespective of sex, age, acclimatisation or adaptation.

There are seven thermal conditions that determine the balance equation (19) (Fanger, 1972):

$\mathrm{PMV} = \exp[\mathrm{met}]*L$ [Equation 19]

Where:

$L = f(P_a, T_a, T_{mrt}, T_{cl})$ is the thermal load on the body [Equation 20]

$L = H – E_d – E_{sw} – E_{re} – R – C$ [Equation 21]

Where:

H = the internal heat production in the human body

Ed = the heat loss by water vapour diffusion through the skin

Esw = the heat loss by evaporation of sweat from the surface of the skin

Ere = the latent respiration heat loss

L = the dry respiration heat loss

K = the heat transfer from the skin to the outer surface of the clothed body (conduction through the clothing)

R = the heat loss by radiation from the outer surface of the clothed body

C = the heat loss by convection from the outer surface of the clothed body (ASHRAE, 1993).

Then (Fanger, 1972):

[Equation 22]

$$
\begin{aligned}
\mathrm{PMV} = {} & \left(0.352e^{-0.042\left(\frac{m}{A_{Du}}\right)} + 0.032\right)\Bigg[\frac{M}{A_{Du}}(1-\eta) \\
& - 0.35\left[43 - 0.061\frac{M}{A_{Du}}(1-\eta) - P_a\right] - 0.42\left[\frac{M}{A_{Du}}(1-\eta) - 50\right] \\
& - 0.0023\frac{M}{A_{Du}}(44 - P_a) - 0.0014\frac{M}{A_{Du}}(34 - t_a) - 3.4 \\
& \cdot 10^{-8}\, f_{cl}\left[(t_{cl} + 273)^4 - (t_{mrt} + 273)^4\right] - f_{cl}h_c(t_{cl} - t_a)\Bigg]
\end{aligned}
$$

Where:

M = metabolic rate (kcal/hr)

ADu = DuBois Area (m2)

η = mechanical efficiency

Pa = vapour pressure in ambient air (mmHg)

ta = indoor air temperature (°C)

fcl = the ratio of the surface area of the clothed body to the surface area of the nude body

tcl = mean temperature of the outer surface of the clothed body (°C)

tmrt = mean radiant temperature (°C)

hc = convective heat transfer coefficient (kcal/hr m2 °C)

As shown, PMV is a complex mathematical expression involving activity, clothing and the four environmental parameters. PMV is scaled to predict thermal sensation votes on a seven point scale (hot, warm, slightly warm, neutral, slightly cool, cool and cold). The thermal sensation (PMV) can be easily calculated using software (WinComf created by ASHRAE).

Thermal conditions can be determined in seven integers, as follows: (3) hot, (2) warm, (1) slightly warm, (0) neutral, (–1) slightly cool, (–2) cool and (–3) cold (Figure 2.3).

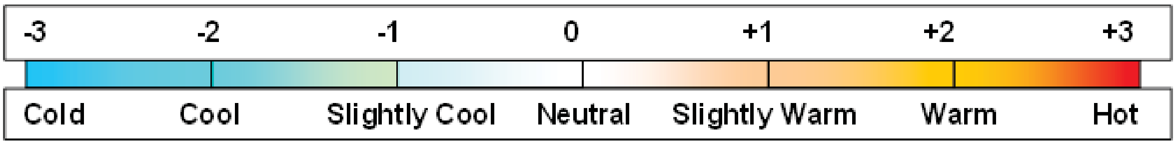


Figure 2.3 The seven integers of thermal sensation.

Another index strongly correlated to the PMV is the PPD index (predicted percentage dissatisfied) (Figure 2.4), which expresses the percentage of people that are displeased with a thermal specific environmental condition. This index is estimated using equation (22) (Fanger, 1972).

$$PPD = 100 - 95 \cdot \exp[-(0.03353 \ PMV^4 + 0.2179 \cdot PMV^2)] \qquad \text{[Equation 23]}$$

WinComf is a software designed by ASHRAE which enables the easy calculation of thermal sensation (PMV) and the predicted percentage dissatisfaction (PPD), expressed as a percentage of dissatisfaction among the occupants of a building. Fanger suggests that individuals can be considered dissatisfied if they give a score of +2 or –2 to the thermal indoor climate (Figure 2.3). The curve in Figure 2.4 shows the predicted percentage dissatisfied (PPD) as a function of the predicted mean vote (PMV).

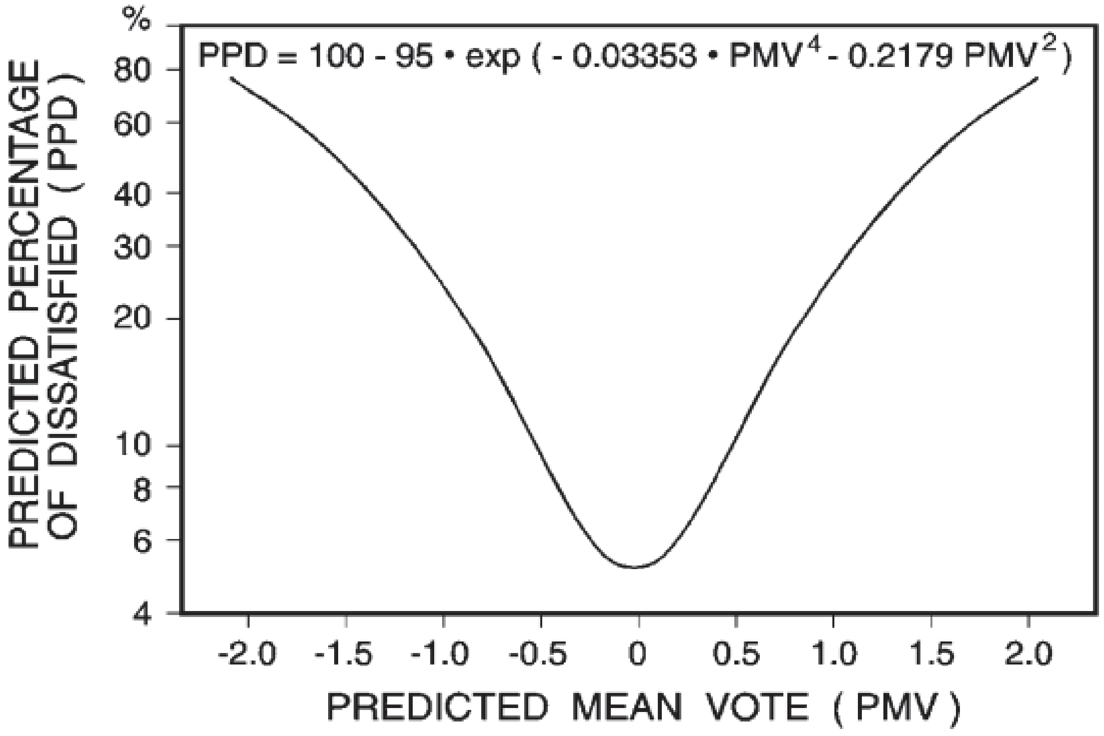


Figure 2.4 Predicted percentage dissatisfied (PPD) as a function of predicted mean vote (PMV).

The above equation (23) reflects the physiological and psychological responses of the human body to the excess or lack of heat flow between the body's core and the environment. However, these responses disregard behavioural factors of adaptation and the unstable state of environmental conditions. In the adaptive model, the deviation of the preferred ambient temperature for an indoor environment includes a wider range than the standard deviation of 1.2°C that was found by using 64 subjects (Fanger & Langkilde, 1975).

2.3 Adaptive Thermal Comfort

The behavioural adaptation of people can be discerned in personal, technical, environmental, cultural and organisational adaptation, which alters thermal acceptability (van der Linden, Boerstra, Raue, Kurvers & de Dear, 2006). These behavioural reactions caused by thermal discomfort define the adaptive model, which was originally observed in naturally ventilated buildings. In the adaptation model, the indoor temperature (identified as the thermal comfort temperature) is related to the outdoor temperature and determined as a straight line equation (ASHRAE, 2004).

The predicted temperature between neutral temperature and mean outdoor temperature is as follows (de Dear & Brager, 2002):

$T_c = a.T_{rm} + b$ [Equation 24]

T_c = comfortable temperature

T_{rm} = the seven day running mean outdoor temperature, measured in ^oC (de Dear, 2006)

$T_{rm} = 0.34.T_{-1} + 0.23.T_{-2} + 0.16.T_{-3} + 0.11.T_{-4} + 0.08.T_{-5} + 0.05.T_{-6} + 0.03.T_{-7}$[Equation 25]

Where:

$T_{-1, -2, -3, -4, -5, -6, -7}$ = the mean outdoor temperature in ^oC, ($_{-1, -2, -3, -4, -5, -6, -7}$) refers to yesterday, 2 days ago, 3 days ago, etc.

The latest form of the above equation that predicts the optimum comfort temperature in naturally ventilated buildings is as follows (ASHRAE, 2010):

$T_c = 0.31\ T_{rm} + 17.8$ [Equation 26]

Extensive field research has demonstrated people's acceptance of adaptive comfort, represented by the graph below (Figure 2.5) with acceptability limits between 80% and 90% (de Dear & Brager, 2002). This figure is based on the adaptive model of thermal comfort derived from a global database of 21,000 measurements, mostly in office buildings using natural ventilation (ASHRAE, 2004).

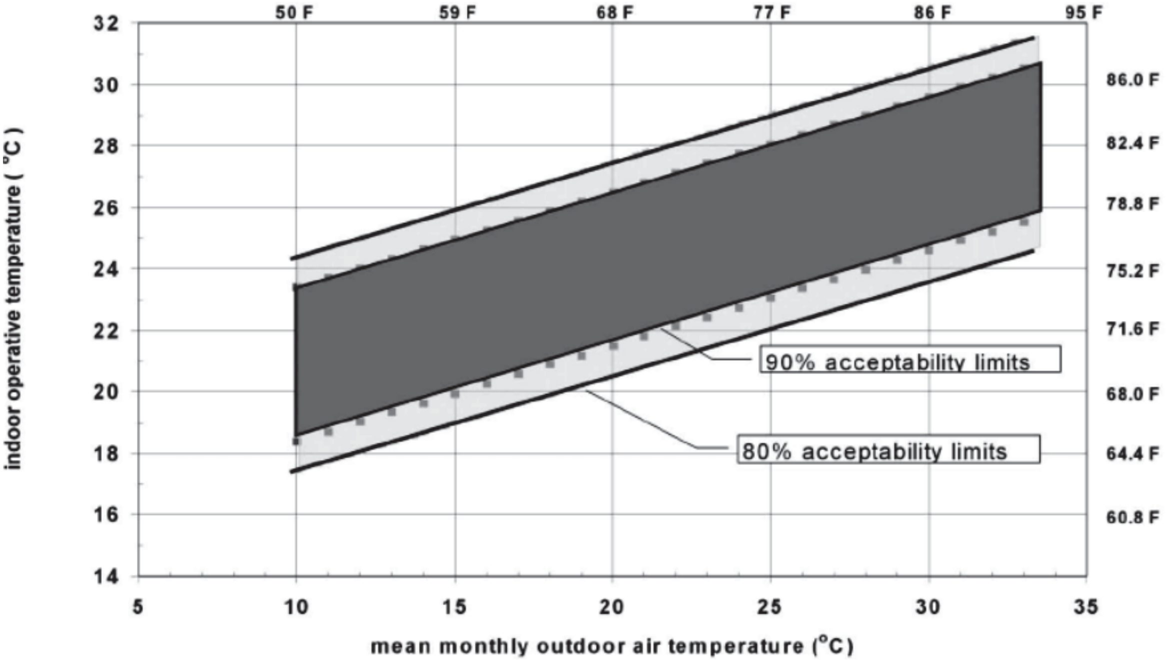


Figure 2.5 Acceptable operative temperature ranges for naturally conditioned spaces. Adaptive comfort standard (ACS) for ASHRAE Standard-55, applicable for naturally ventilated buildings (ASHRAE, 2010).

This linear regression model was primarily constructed for buildings with openable windows and ceiling fans within small offices, not for sealed buildings with an open floor and central air-conditioning (de Dear & Brager, 2002). In addition to Fanger et al (2002), other research confirms the existence of thermal adaptation in air-conditioned buildings within certain limits (Mui & Chan, 2003). Therefore, the same kind of relationship is potentially applicable to air-conditioned buildings because most occupants accept the thermal comfort environment with the integration of the adaptive comfort temperature (ACT) model (Mui & Chan, 2003).

2.3.1 Naturally Ventilated Building Comfort Standards (Adaptive)

One of the main causes of thermal discomfort is building structure and services. Buildings are classified based on their healthy indoor conditions and thermal comfort with respect to energy and the cost of construction. When office buildings are classified based on their indoor environment, they are usually categorised as follows (ASHRAE, 1993):

a) Naturally ventilated buildings: depend on building structure, material, outdoor wind and solar energy to adjust the indoor environment.
b) Air-conditioned buildings: use mechanical ventilation and refrigeration equipment to condition the indoor environment.
c) Hybrid (mixed-mode) buildings: use both methods (natural and air-conditioned) to regulate the indoor environment. This type reduces energy consumption.

Much research investigates occupant opinion of buildings in order to explore the optimal thermal conditions. Recent research has developed hypotheses that relate to the occupants themselves and their attitude towards green buildings (Deuble & de Dear, 2012). Green buildings are considered to have greater thermal variation (based on naturally ventilated and mixed-mode buildings) than those using central air-conditioning. Green building users are more forgiving of their building, consistent with the hypothesis that green buildings need green occupants (ASHRAE, 1993). This increases the influence of the F2 factor (Figure 2.6) and improves the psychological response of the occupants; supporting the adaptive model strategy in these buildings. As green occupants have been proven to exist, the perception of adaptation is applicable in these buildings and could extend to air-conditioned buildings. While buildings take years to build and potentially months to retrofit, the path to altering people's expectations of the built environment presents the easiest option (Wargocki, Wyon, Baik, Clausen & Fanger, 1999). This suggests the efficacy of an adaptive conditioning strategy in air-conditioned buildings, especially with the growing suspicion of energy sources and weather changes in the future.

2.3.2 Testing of Fanger in the Field (failure of parameter PMV model)

The diagram in Figure 2.6 shows the link between the thermal balance model and thermal adaptation model. It is clear that the thermal balance model is part of the adaptive comfort model.

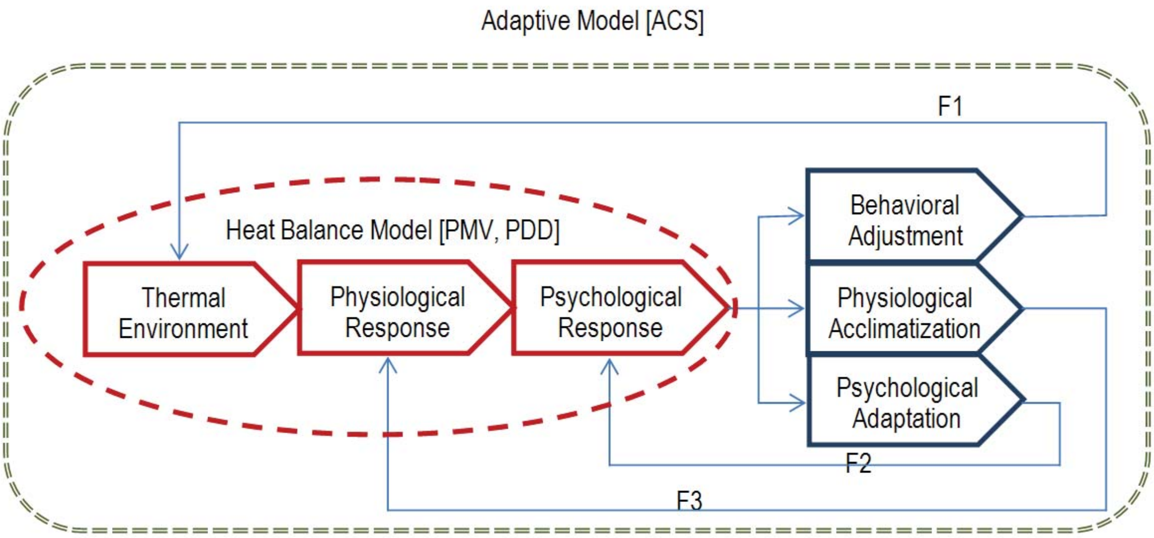


Figure 2.6 Diagram shows the link between the thermal balance and thermal adaptation models (ASHRAE, 2004; ASHRAE, 2010; Brager & de Dear, 1998).

In Figure 2.6, Brager and de Dear's model (represented in F1 and F2 feedback responses) suggests that behaviour adjustment and experience are the major factors for physiological and psychological adaptation (de Dear & Brager, 2002). However, in Goto, Fanger and Toftum's model, which is represented in F2 only, the experience factor is the key to adaption (Goto, Toftum, de Dear & Fanger, 2006). The adaptive model appears to include all action and reaction sequences in order to achieve the desired acceptability by having an impact on the behavioural, physical and psychological adjustments.

2.4 Adaptive Comfort Solution in Air-conditioned Premises

The thermal adaptive model relies on field studies as a necessary source of data, where people can be observed in real environments. Researchers have cited participant response differences between field studies and climatic chamber experiments as proof of the effectiveness of the adaptive model.

Humphreys (1976) first systematically collected thermal comfort data from field studies as evidence of adaptive comfort. His studies were based on standard readings for indoor temperature and humidity at one height, which was categorised as Class III and considered insufficient to verify the thermal adaptive model.

In 1998, de Dear and Brager led a wide systematic data collection in the ASHRAE RP-884 project, covering Class II and I studies (which included all the environmental and essential individual variables required as input to the heat balance models). The information was published as an open to the public database, with a sample scale of nearly 21,000.

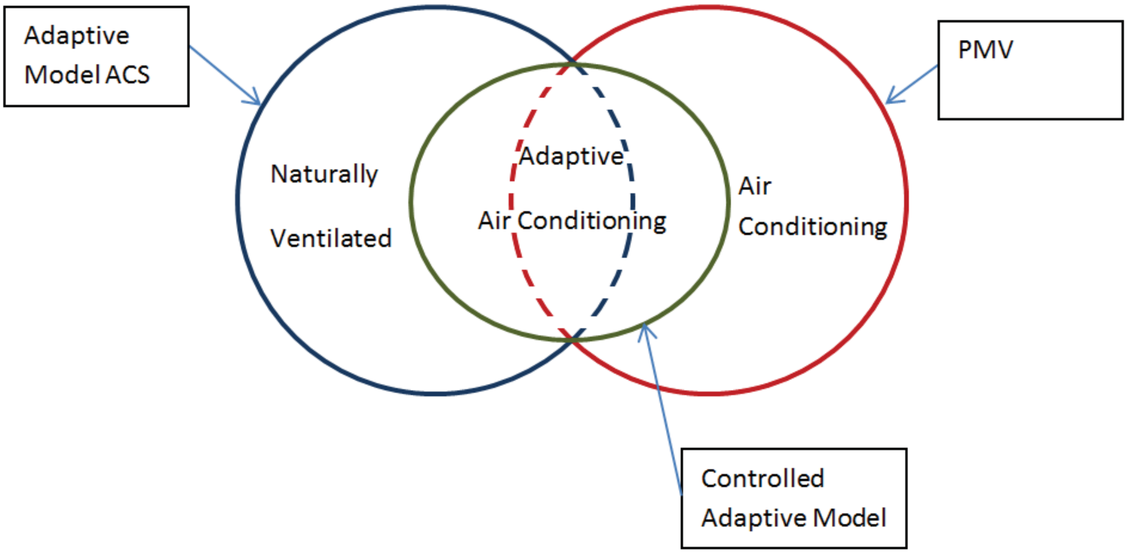


Figure 2.7 The adaptive air-conditioning model is a mix of heat balance equation (PMV) and adaptive model (ACS).

The adaptive approach to thermal comfort for use in air-conditioned office buildings can be derived from the adaptive model of naturally ventilated buildings. Predicting a thermal comfort set point temperature within comfort limits in air-conditioned office buildings will be an easy solution for economic and ecological difficulties. Both increased comfort and energy savings can be provided at the small expense of implementing a control strategy (Egan, 2010). A hybrid model has been formed between the PMV model and the adaptive model, and it contains common comfort conditions. This new controlled adaptive model contains the overlapping area plus characteristics of each model (Figure 3.7). Importantly, it will benefit the design of new office buildings, and provide simple and economic strategies in guiding the retrofitting of existing air-conditioned office buildings.

2.5 Summary

Researchers brought during the last years enormous studies related to thermal comfort in order to develop under the context of sustainable and green buildings as a reaction to global climate change and carbon gases emission. The adaptive thermal comfort concept in naturally ventilated and hybrid air conditioned buildings enhances the model of energy saving hence adaptive thermal comfort for an air-conditioned buildings has set under examination for the last three decades. As a part of knowledge expansion, a new controlled adaptive model will assist in improving a different design in office buildings, and offer valuable opportunity in guiding the retrofitting of sustainable and economic air-conditioned office buildings.

CHAPTER 3

3 RESEARCH METHODOLOGY

3.1 Introduction

The climate chamber methodology is considered the ideal technique for thermal comfort experiments, as it permits an independent environmental variable to be manipulated directly while isolating the dependent variables of thermal comfort from extraneous influences (Feriadi, 2004). However, field study in thermal comfort presents stronger external validity than laboratory experiments. The validity of field studies is easier to defend for many reasons; for example, the large number of subjects, such as the RP-884 database which contains approximately 21,000 sets of raw data from 160 different office buildings located on four continents (de Dear & Brager, 2002). Therefore, a hybrid research design that combines both approaches may enhance the value of collected data by using typical buildings as field study while controlling the indoor environment in the same way as a climate chamber.

This research adopts the longitudinal method in data collection, studying a certain number of subjects over many visits. Therefore, the repetition of the observations from an individual correlates and validates the results under constant conditions. However, the cross-sectional method depends on data collected from various individuals.

The method includes:

- Instrumental measurements: Collected from different locations within the office and a nearby weather station to characterise the conditions relating to the external building microclimate environment and indoor thermal comfort.
- Structured survey: Simultaneously carried out during the field measurement study in order to investigate people's actual thermal sensations, behavioural actions and perception of the thermal environment.
- Analysis: Covers a qualitative and quantitative analysis of these observations and readings by pairing the subjective questionnaires with their corresponding and concurrent indoor and outdoor climatic observations.

Figure 3.1 shows the general structure of the research method. After considering the scope of works and the research aims, a field study combined with active intervention in controlling the indoor environment was adopted in this research.

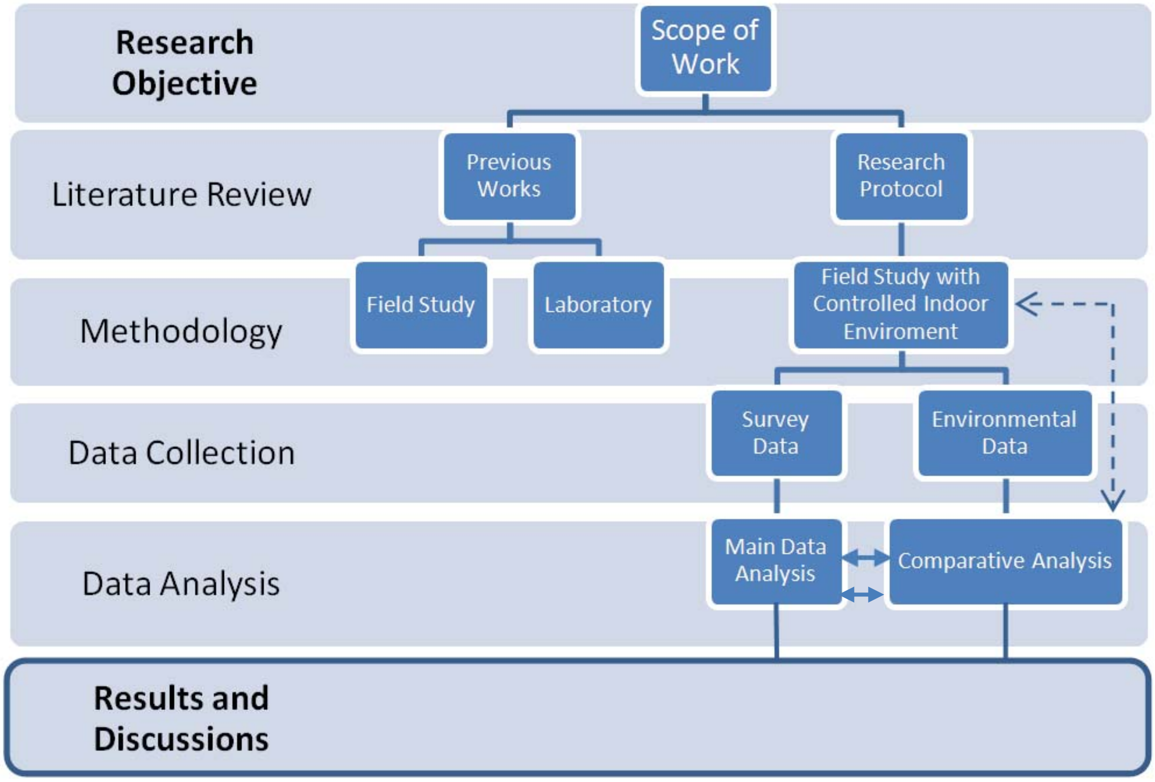


Figure 3.1 Overview diagram of the research method.

3.2 HVAC Design Strategies in Sydney

In Sydney, engineering best practice specifies 22 ±1°C to be a comfortable temperature for general office work (AIRAH) when wearing winter seasonal clothes. Over short periods of time, occupants can accept a few degrees outside the comfort range without any clothing adjustment, but this may affect performance. As it is commonly believed that office workers are increasingly unproductive as the indoor conditions become uncomfortable, the Commonwealth strives to provide conditions that sustain a high level of performance in offices. As per the technical manual IEQ-7 *Thermal Comfort for the City of Sydney*, a temperature range between 21^{o}C and 24^{o}C must be achieved in air-conditioned spaces during standard hours of occupancy and under typical clothing, metabolic rate and air velocity for 98% of the year.

According to the ASHRAE-55 standard (ASHRAE, 2004; ASHRAE, 2005), thermal acceptability can be achieved in an air-conditioned building by maintaining the PMV between +1 and –1. In naturally ventilated buildings, however, this can be achieved by applying the adaptive model where windows represent the primary means of thermoregulation. The adaptive model provides a wider indoor temperature range of acceptability which lessens the difference between indoor and outdoor temperatures. However, in the Australian commercial building sector, both PMV/PPD and adaptive comfort guidelines are largely ignored; buildings are generally regulated with a HVAC set point at about 22^{o}C throughout all seasons. The Green Building Council of Australia (GBCA, 2012) encourages HVAC designers to improve thermal comfort inside office buildings by scoring one point if the designer achieves an average calculated PMV between +1 and –1. However, the adaptive model has been ignored by Australian engineers. This prompts the question: Why do Australian buildings disregard the environmental and financial implications of adaptive thermal comfort standards?

3.2.1 Selection of Climatic Conditions

Sydney enjoys a moderate climate with a mild winter and many sunny days throughout the year. The average minimum temperature in winter (from June to August) is around 9ºC. The summer season extends from December through to February and is described as hot weather with an average maximum temperature of 28ºC (Figure 3.2).

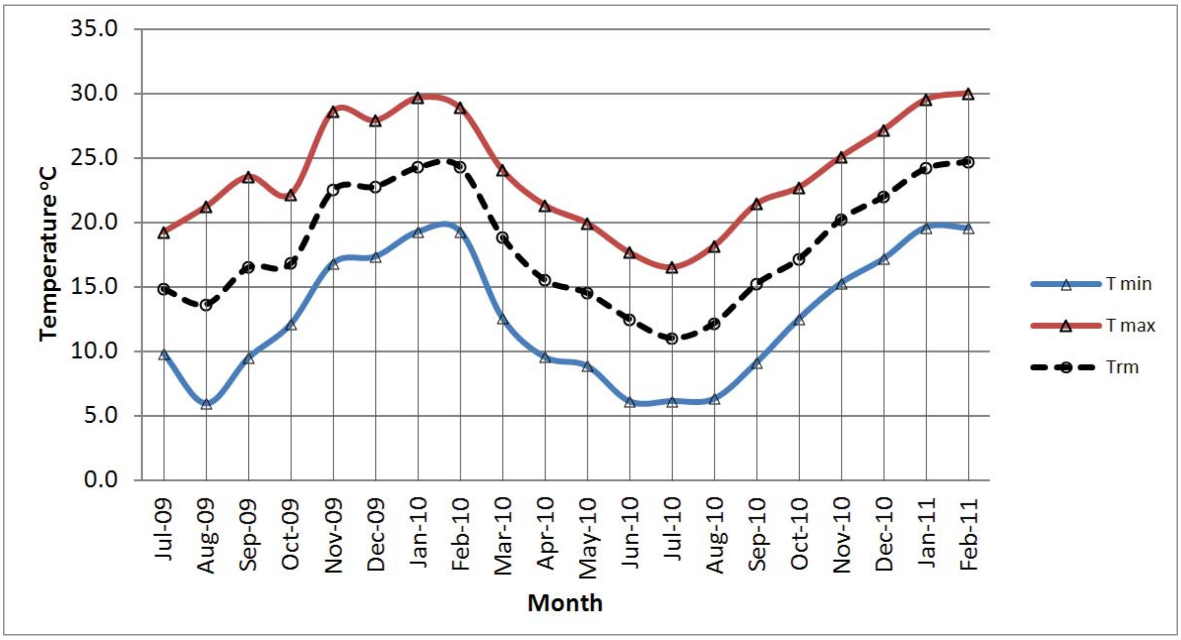


Figure 3.2 Variation of a 7 day running mean outdoor temperature (Trm) with Sydney's average temperature range from July 2009 to February 2011. (Source: Bureau of Meteorology, Australia)

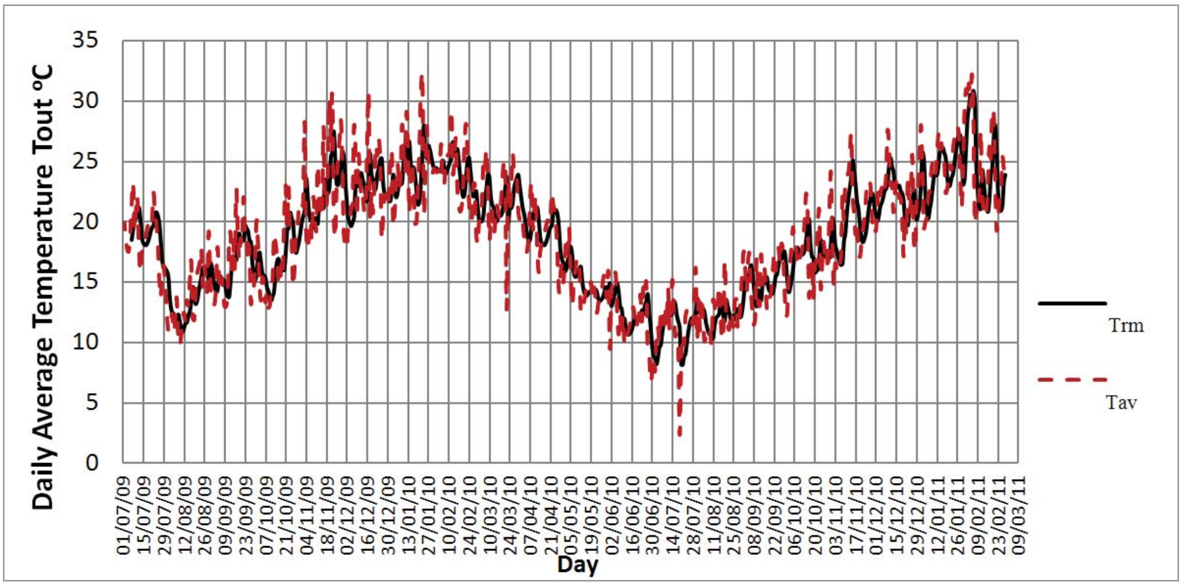


Figure 3.3 Daily average temperature range from July 2009 to March 2011. (Source: Bureau of Meteorology, Australia)

The Bankstown Airport weather station belongs to Climatic Zone 5 which is a seasonal subtropical humid climate. Sydney's highest recorded temperature is 45.3ºC. Its lowest recorded temperature is 2.1ºC. Revesby, a suburb in the Bankstown local government area, is located 22 kilometres south-west of Sydney’s CBD in New South Wales. It forms part of the south-western Sydney region. Revesby’s climate is similar to Sydney’s climate; its office buildings are also comparable to those in Sydney’s CBD, with most commercial buildings equipped with air-conditioning systems.

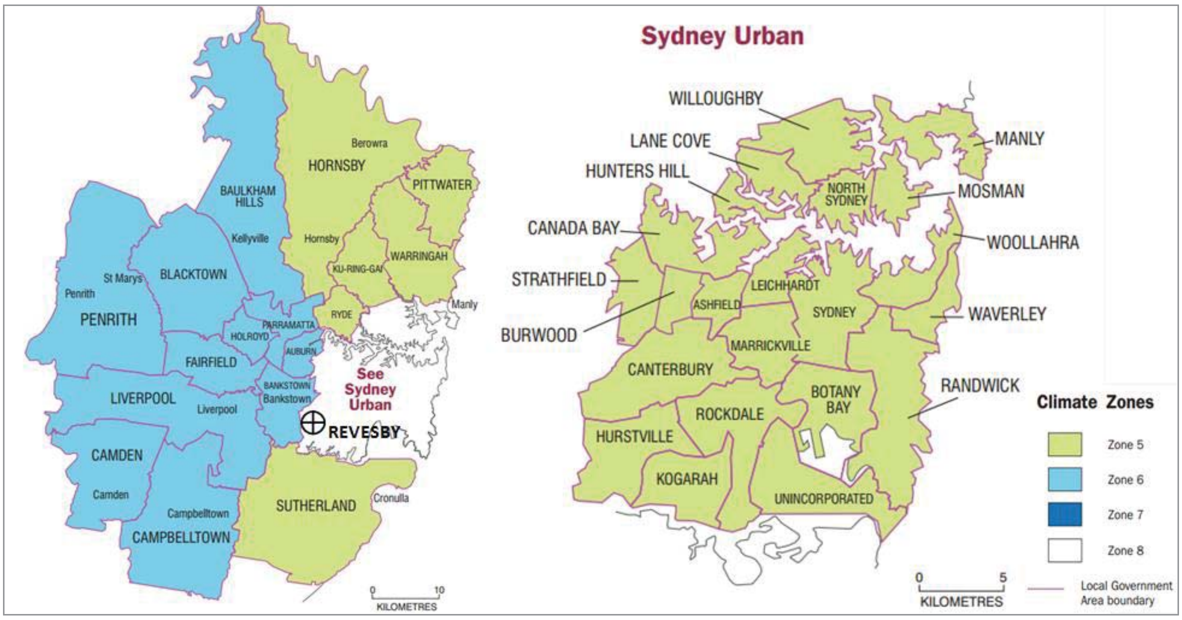


Figure 3.4 Revesby located on a New South Wales Climate Zones map. (Source: ABCB, 2009)

3.2.2 Air-conditioning Equipment and Control

Split ducted systems are very common in Sydney offices, especially in medium sized buildings. This type of system circulates a refrigerant fluid between two separate parts that are connected by insulated copper pipes (Figure 3.5). The cheapest and most common split ducted units provide cooling or heating only; while those that are more expensive operate on an economy cycle. The fan in an economic unit may work without operating the compressors (outdoor units). In other words, the indoor unit will perform simply as a fan and will not change the conditions of the outdoor air. This definitely cannot be considered a natural ventilation process even though it has very similar aspects; it saves energy when instantaneous mean outdoor temperatures match the set point inside the building.

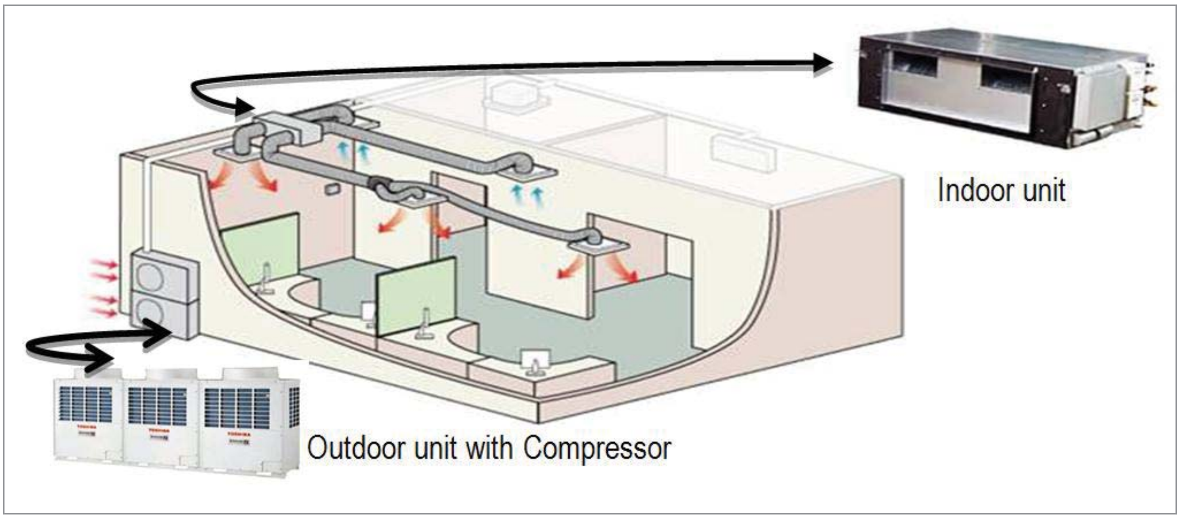


Figure 3.5 Split ducted system in an office building. (Source: Temperzone Air Conditioning, 2013)

One of the key characteristics of a split system is the ability to control the temperature and adjust the set point accurately by a control pad for each individual indoor unit. In the experiment, the indoor set point temperature was controlled manually through a wall mounted touch pad installed on each level for each unit. Both indoor units were designed and sized to maintain an indoor office temperature of 22 ±2^{o}C, as per Australian Standard requirements stated in AIRAH (2007a) and engineering best practice. In this study, the building indoor set point temperature was derived daily from the adaptive model comfort temperature equation. According to the adaptive model for naturally ventilated buildings in Standard 55 (ASHRAE, 2010), the comfort temperature (T_c) is determined by the following equation:

$$T_c = 0.31 \cdot T_{rm} + 17.8 \qquad \text{[Equation 27]}$$

The ability to control the indoor environment in an air-conditioned building enables the capping of the proposed comfort set point temperature (T_c) between the lower and upper temperatures, 18^{o}C and 26^{o}C respectively. The facility management and the occupants agreed to consider these limits as minimum and maximum acceptable temperatures in the office environment and sufficient for the research objectives.

The equation for comfort, limited in a range derived from the original, is:

$$T_c = 0.31 \cdot T_{rm} + 17.8 \left[\begin{matrix} 26^o \\ \\ 18^o \end{matrix} \right.$$

[Equation 28]

Therefore, the proposed comfort temperature (T_c) is calculated from the running mean outdoor temperature (T_{rm}) which can be determined from data collected by the nearest weather station. In the diagram (Figure 3.6), the prospective comfort temperature was then entered into the control pad as a desired set point temperature to maintain thermal comfort in each level of the building. In this case, the indoor temperature can be monitored by a desktop sensor box within the occupied zone and the HVAC control pad mounted on the wall.

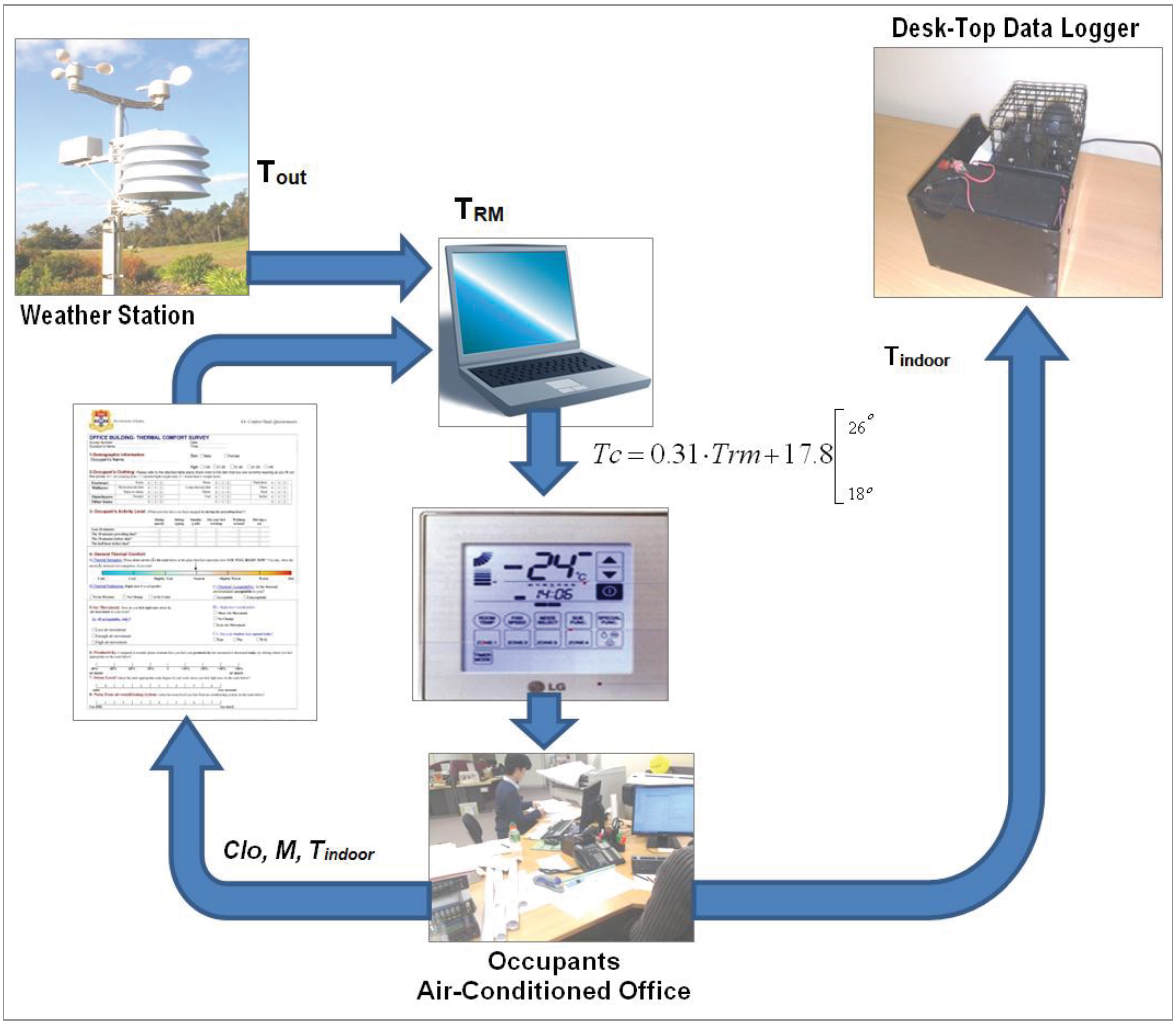


Figure 3.6 Schematic of the control strategy for a comfortable indoor temperature.

3.3 Sample Selection and Preparation

The research design was primarily a field study. Participants were selected randomly from a typical office building. They included men and women from a range of age groups and cultural backgrounds.

3.3.1 Selection of a Conventionally Air-conditioned Building

The selected building is located in the Sydney urban region, approximately 19km from the sea (33°924’ S, 151°039’ E) and 2km away from Bankstown Airport where the weather station data was collected (Figure 3.7). The office complex was built in 2004 and comprises 10 double-storey offices. The buildings in this complex are typical of suburban office buildings and categorized as Class 5 buildings by the Building Code of Australia (ABCB: Australian Building Codes Board, 2009).

The building comprises a warehouse and two levels of offices, however, the study was limited to the office spaces. The building envelope structure is made of prefabricated concrete walls and metal deck roofing. Additional insulation to the roof and walls were added to reduce energy consumption in the heating and cooling processes. These types of office buildings are fitted with air-conditioning systems designed to suit the number of people and the type of work performed in the building. In response to the growing demand for energy conservation, Section J5.2 of the BCA (Building Code of Australia, ABCB, 2009) specifies the use of an outdoor air economy cycle where the air-conditioning system provides the required mechanical ventilation. Economy cycles are possible in most applications, except those that require humidity control; for example, laboratories, paper stores, frozen food sections in supermarkets, etc.

Figure 3.7 The location of the office building in relation to the nearby weather station at Bankstown Airport point A, (Source: Google Maps, 2013)

Figure 3.8 The case study building façade facing north.

The economy cycle integrated well with the adaptive comfort strategy; the outdoor air was mechanically drawn into the building and had the same temperature and humidity characteristics as a naturally ventilated building. Two system types are typically used in suburban office buildings: the split ducted system and the roof package system, both of which are equipped with an economy cycle system.

3.3.2 Building Zoning and Description

The main façade faces north-west and is single glazed with tinted glass, shaded internally by vertical blinds (Figure 3.8). The office area is 440 square metres and occupied by 30 employees. An air cooled split ducted air-conditioning unit of 40kW cooling capacity was used to heat and cool the offices on each level (Figure 3.9). The air handling units were located in the ceiling space, supplying conditioned air to the rooms via insulated ducts connected to ceiling mounted diffusers. The indoor set point temperature was controlled manually by a single wall mounted touch pad on each office level.

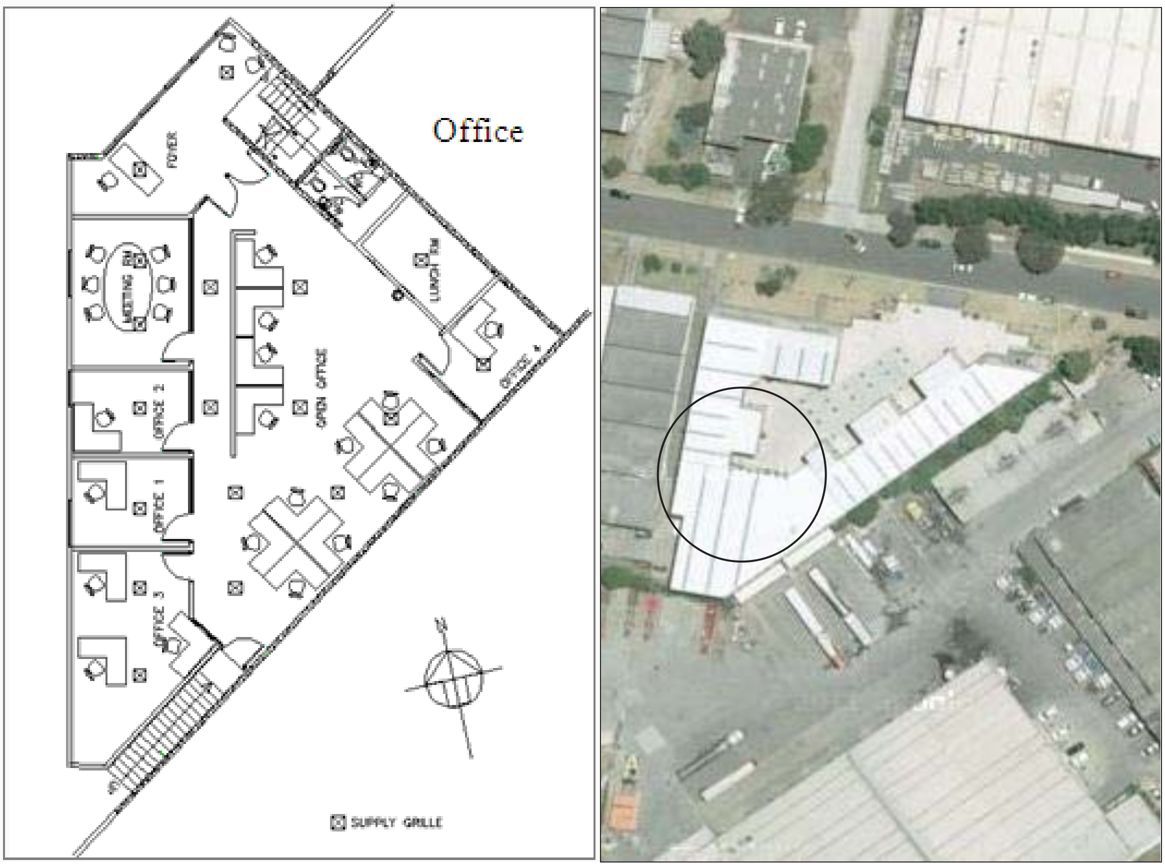


Figure 3.9 Office building plan and office building location on the map. (Source: Google Maps, 2013)

The AHU was sized to maintain an indoor office temperature of 22 ±2^{o}C. The building is surrounded by other buildings of the same height so external shading was not a major factor. Since the building was glazed on one side, two zones that needed to be considered were the west perimeter zone and the internal zone. The air-conditioning system was controlled by two wall mounted sensors.

Table 3-1 Building Design Criteria

Building	**Ground Floor**	**Level 1**
Department	Installers and technicians.	Engineering, Accounting, Marketing, Drafting and Management.
External Design Conditions		
External Ambient Conditions for Air-conditioning Plant Full Load Performance	Summer 36°C DB, 24°C WB. Winter 5°C.	Summer 36°C DB, 24°C WB. Winter 5°C.
Internal Design Conditions		
Internal Temperature Design	Summer and winter: 22 ±2°C. Relative humidity: 60 ±20%.	Summer and winter: 22 ±2°C. Relative humidity: 60 ±20%.
Infiltration	1 ACH (air change per hour) when HVAC is on.	0.25 ACH (air change per hour) when HVAC is on.
Internal Heat Gain	82 W/person sensible (estimated). 80 W/person latent (estimated). Lighting including ballast 11 W/m^2 (max).	82 W/person sensible (estimated). 80 W/person latent (estimated). Lighting including ballast 11 W/m^2 (max).

Table 3-1 Building Design Criteria

Building	**Ground Floor**	**Level 1**
	Equipment machine load: 6 W/m^2 (max).	Equipment machine load: 6 W/m^2 (max).
Outside Air	7.5 l/s/person minimum.	7.5 l/s/person minimum.
Operation Time	10 hours, 6 days a week.	10 hours, 6 days a week.

3.3.3 Demographic Information

Participants were requested to complete comfort questionnaires distributed every morning for one year. The group of participants comprised 30 people from various locations within the building, however, not all of them participated for the full term of the research. Twenty-three subjects formed the continuous research group; six women and ten men in their mid-thirties, and seven young men under the age of thirty. The remaining seven employees comprised the non-continuous participants in the study, as shown in Table 3.2.

Table 3-2 Basic Demographic Information of Participants

Departments	**Installers and Technicians**	**Engineering, Accounting, Marketing, Drafting and Management**
Occupancy		
Office Bases (continuous presence in the office)	Males: 4 (13.4%)	Males: 13 (43.4%)
	Females: 0 (0%)	Females: 6 (20%)
Site Bases (not in the office full-time)	Males: 4 (13.4%)	Males: 1 (3%)
	Females: 0 (0%)	Females: 2 (6%)

The office spaces were equipped with unobtrusive sensors to record data such as temperature, humidity and air speed throughout the month. These instruments did not interfere with the daily activities of the participants. This data was matched against both questionnaire responses and simultaneous outdoor weather observations. A simple single page questionnaire was designed to record occupants' thermal comfort within the office area. The questionnaire was designed to be completed within one minute. All participants agreed to participate and complete the questionnaire at least three times a day.

Each participant in the sample received a Personal Identification Number (PIN) to allow researchers to collect questionnaires from the same person on multiple visits. A list of the PINs and the names facilitated follow-up visits, but were disposed of at the end of the study. Any information or personal details gathered during the course of the study were kept confidential, and no individual will be identified in any publication of the results. Only the researchers had access to the data. Participants were informed that they were free to withdraw from the study at any time, without any penalties or questions asked. A brief summary of the project's findings was distributed to all participants by email upon completion of the study.

3.4 Data Collection

This section outlines the data collection methods and techniques used during the research. The instruments and thermal comfort questionnaire formed the main source of indoor data, however, outdoor weather observations were also collected from the data weather station at Bankstown Airport.

3.4.1 Instruments

A customized 'comfort package' was used to measure the ambient comfort variables within the occupied zone. The package (Figure 3.10) is portable and provides climatic readings every 5 minutes at the participant's desk level, considered the middle of the occupied zone. Our comfort box (Figure 3.10a) could be easily moved and offered a quick reading for the space near the participant at desk level. The desktop comfort box recorded air temperature, globe temperature, relative humidity and air velocity at 5 minute intervals throughout the study. Measurements were collected throughout the study by dataloggers located randomly within each building and the desktop comfort logger located between the subjects under observation. The purpose of having many dataloggers was to capture any serious variation of indoor temperature inside the office. The desktop logger recorded air temperatures, globe temperatures and relative humidity at 5 minute intervals near the larger group of people under observation. The average air velocity was found to be identical in the office area, reading less or equal to 0.15 m/s when tested by the desktop datalogger at different workstations.

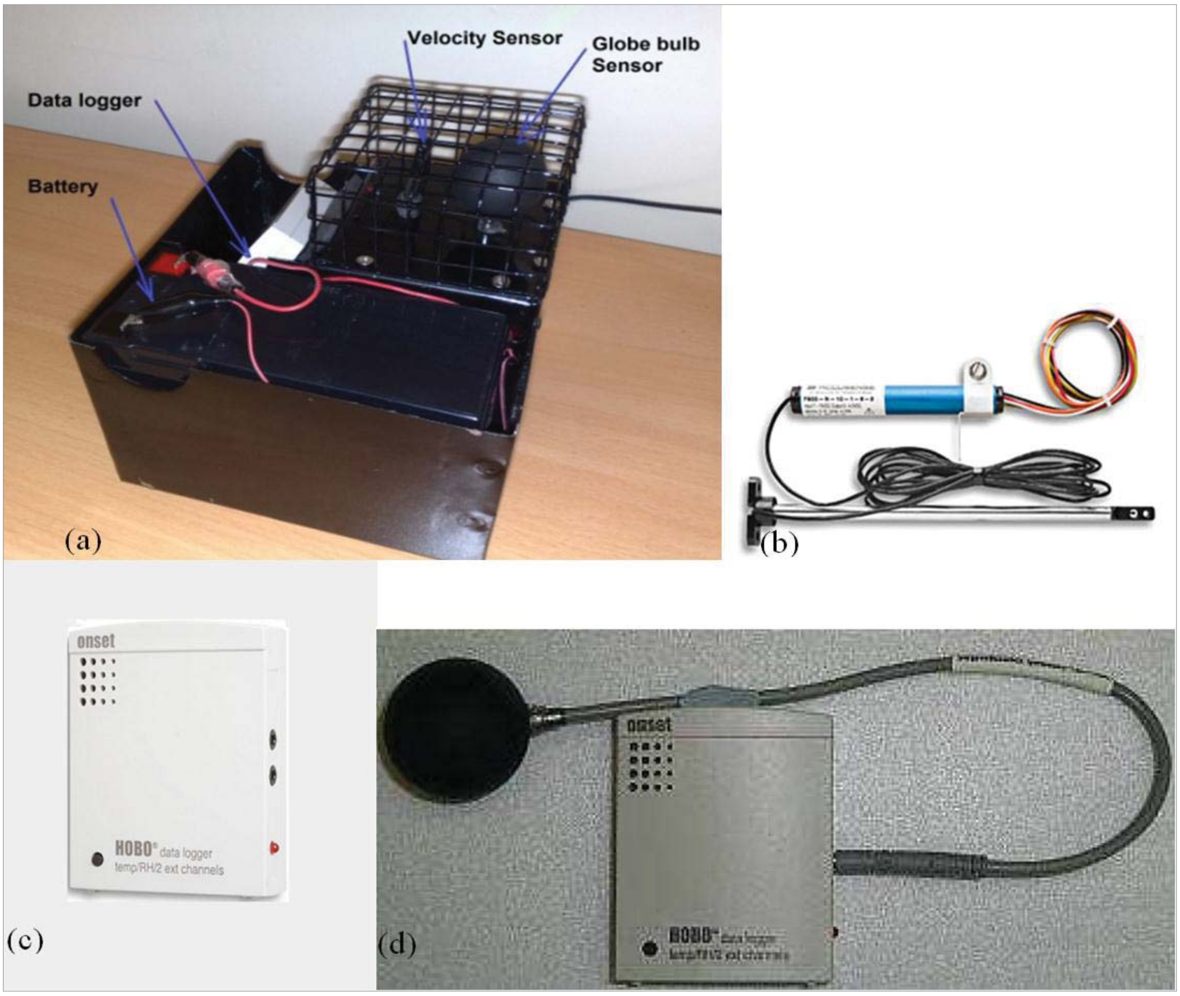


Figure 3.10 (a) Desktop Comfort Instrument, (b) Air Velocity Sensor T-DCI-F900-L-O (Source: Alpha Omega Electronics website), (c) 'HOBO' U12-013 Temperature and Relative Humidity Datalogger and (d) 'HOBO' U12-013 Temperature and Relative Humidity Datalogger with 40mm sphere painted matte black attached to TMC1-HD Water/Soil Temperature Sensor are used to measure the physical indoor environment.

Table 3-3 Specifications of Indoor Climatic Instrument

Figure Reference		**Figures 3.10 (a) & (b)**	**Figure 3.10 (c)**	**Figure 3.10 (d)**
Instrument	Datalogger	‘HOBO’ U12-013 Temperature and Relative Humidity Datalogger	‘HOBO’ U12-013 Temperature and Relative Humidity Datalogger	‘HOBO’ U12-013 Temperature and Relative Humidity Datalogger
	Attached	a) 40mm sphere painted matte black (ε = 0.99) attached to TMC1-HD Water/Air Temperature Sensor b) T-DCI-F900-L-O Air Velocity Sensor		40mm sphere painted matte black (ε = 0.99) attached to TMC1-HD Water/Air Temperature Sensor
Measurement	Air temperature (°C)	√	√	√
	Relative humidity (%)	√	√	√
	Velocity (m/s)	√		
	Radiant globe temperature (°C)	√		√
Specifications				
Range	Air temperature (°C)	20 to +70°C	20 to +70°C	40 to +50°C
	Relative humidity (%)	5 to 95%	5 to 95%	5 to 95%
	Velocity (m/s)	0 to 5 m/s		
Accuracy	Air temperature	±0.25°C (at 20°C)	±0.25°C (at 20°C)	±0.25°C (at 20°C)

Table 3-3 Specifications of Indoor Climatic Instrument

	(°C)			
	Relative humidity (%)	±2.5%	±2.5%	
	Velocity (m/s)	±0.015 m/s (or 3% of reading)		
Resolution	Air temperature (°C)	0.03°C (at 20°C)	0.03°C (at 20°C)	0.03°C (at 20°C)
	Relative humidity (%)	0.03%	0.03%	
Sampling Frequency		every 5 minutes	every 5 minutes	1 sample measured every 5 minutes

3.4.2 Thermal Environment Measurements and Calculations

Field studies represent a fundamental research design in thermal comfort research, as stated by (Brager & de Dear, 1998). Field study is the most effective method to investigate human adaptive thermal comfort, though some evidence for thermal adaptation could be found in the climate chamber. There are significant discrepancies between thermal comfort votes in field study and the results of thermal comfort indices obtained in offices and homes compared to climate chamber studies. These differences can be attributed to contextual and adaptation effects (Ealiwa et al, 2001).

A longitudinal field study was selected as the most appropriate research methodology to examine human adaptive thermal comfort inside an air-conditioned office building because it relies on a relatively small number of cooperative subjects over a prolonged monitoring period. The adaptive approach to thermal comfort is based on thermal comfort survey findings conducted in the field (Nicol & Humphreys, 2002). The method used in this project involved the collection of physical indoor and outdoor measurements along with comfort questionnaires from office occupants (Figures 3.10 and 3.13). Outdoor environmental data was collected from the latest weather observations at Bankstown weather station (Commonwealth of Australia 2010, Bureau of Meteorology [BOM, 2010]), allowing for calculation of a seven day running mean outdoor temperature with the following equation:

$$T_{rm} = 0.34 \cdot T_{-1} + 0.23 \cdot T_{-2} + 0.16 \cdot T_{-3} + 0.11 \cdot T_{-4} + 0.08 \cdot T_{-5} + 0.05 \cdot T_{-6} + 0.03 \cdot T_{-7}$$

[Equation 29]

Where:

T_{rm}: The seven day running mean outdoor temperature measured in ^{o}C [Equation 24, Chapter 2]

$T_{-1,-2,-3,-4,-5,-6,-7}$: The mean outdoor temperature in ^{o}C (–1, –2, –3, –4, –5, –6, –7 refer to yesterday, 2 days ago, 3 days ago, etc).

The above expression for outdoor mean temperature was then put into the adaptive model in order to calculate each day’s target set point temperature (Tc) for the air-conditioning control system. The proposed adaptive model equation was that for naturally ventilated buildings in Standard-55 (ASHRAE, 2004), the air-conditioning set point minimum and maximum temperature range was capped at 18ºC and 26ºC respectively:

$$T_c = 0.31 \cdot T_{rm} + 17.8 \left[\begin{matrix} 26^o \\ \\ 18^o \end{matrix} \right. \qquad \text{[Equation 30]}$$

Where:

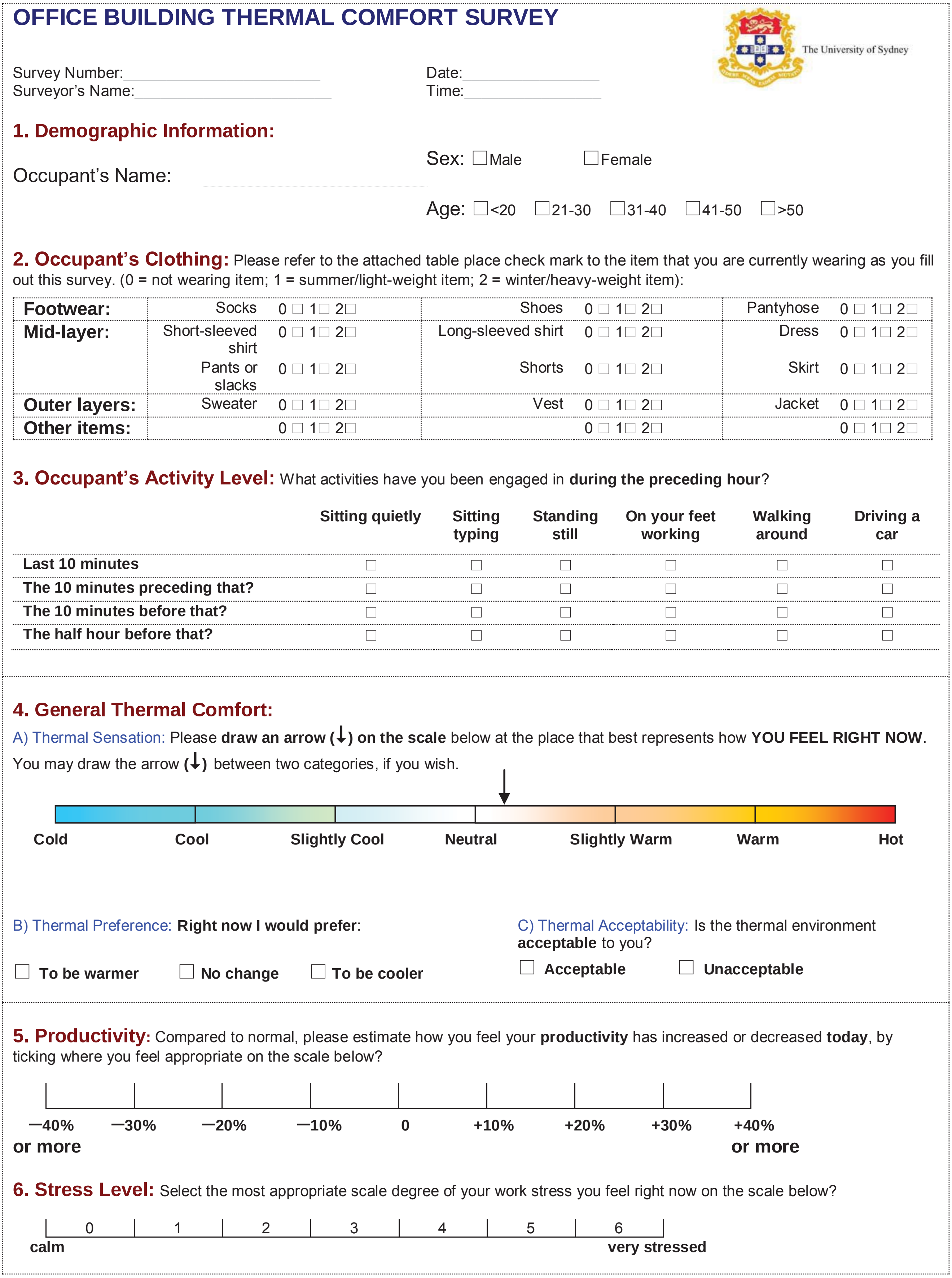
T_{rm}: The seven day running mean outdoor temperature is measured in ºC from Equation (29).

T_c: The indoor comfort temperature is between 18ºC and 26ºC.

The survey method had two distinct components: a) questionnaires were used to collect subjective comfort assessments from the occupants; and b) simultaneous physical indoor conditions were collected (including air temperature, relative humidity, air velocity and radiant temperature); and participants were asked to complete the comfort questionnaire at the same time and location as microclimatic measurements were taken.

3.4.3 Thermal Comfort Questionnaire Survey Procedures

The American Society of Heating, Refrigeration and Air Conditioning Engineers designed a standard questionnaire for thermal environment survey (ASHRAE, 2004) that was used and modified to suit this research purpose. The questionnaire is intended to characterise whole body thermal comfort and comprises eight major questions. The first related to demographic information such as age, height, weight and gender. Occupant’s clothing questions followed and provided information needed for the calculation of clo-value. The third question dealt with participant activity within half an hour of taking the survey in order to determine metabolic rate. The fourth section included questions relating to thermal comfort; namely, thermal sensation, thermal preference and thermal acceptability. Thermal sensation was measured on the ASHRAE seven point scale ranging from cold (–3) to hot (+3). Thermal preference classified subjects into three groups: those who preferred a warmer place, those who preferred a cooler place, and the remainder who preferred the temperature to remain the same. Thermal acceptability was captured with a binary ‘right here right now’ question (acceptable/unacceptable). The last two questions allowed the occupants to assess their own productivity and stress level as a percentage and on an integer scale respectively.



OFFICE BUILDING THERMAL COMFORT SURVEY

The University of Sydney

Survey Number:______________________ Date:_______________

Surveyor's Name:______________________ Time:_______________

1. Demographic Information:

Occupant's Name: ______________________

Sex: ☐Male ☐Female

Age: ☐<20 ☐21-30 ☐31-40 ☐41-50 ☐>50

2. Occupant's Clothing: Please refer to the attached table place check mark to the item that you are currently wearing as you fill out this survey. (0 = not wearing item; 1 = summer/light-weight item; 2 = winter/heavy-weight item):

Footwear:	Socks	0 ☐ 1☐ 2☐	Shoes	0 ☐ 1☐ 2☐	Pantyhose	0 ☐ 1☐ 2☐
Mid-layer:	Short-sleeved shirt	0 ☐ 1☐ 2☐	Long-sleeved shirt	0 ☐ 1☐ 2☐	Dress	0 ☐ 1☐ 2☐
	Pants or slacks	0 ☐ 1☐ 2☐	Shorts	0 ☐ 1☐ 2☐	Skirt	0 ☐ 1☐ 2☐
Outer layers:	Sweater	0 ☐ 1☐ 2☐	Vest	0 ☐ 1☐ 2☐	Jacket	0 ☐ 1☐ 2☐
Other items:		0 ☐ 1☐ 2☐		0 ☐ 1☐ 2☐		0 ☐ 1☐ 2☐

3. Occupant's Activity Level: What activities have you been engaged in **during the preceding hour**?

	Sitting quietly	**Sitting typing**	**Standing still**	**On your feet working**	**Walking around**	**Driving a car**
Last 10 minutes	☐	☐	☐	☐	☐	☐
The 10 minutes preceding that?	☐	☐	☐	☐	☐	☐
The 10 minutes before that?	☐	☐	☐	☐	☐	☐
The half hour before that?	☐	☐	☐	☐	☐	☐

4. General Thermal Comfort:

A) Thermal Sensation: Please **draw an arrow (↓) on the scale** below at the place that best represents how **YOU FEEL RIGHT NOW**. You may draw the arrow **(↓)** between two categories, if you wish.

Cold **Cool** **Slightly Cool** **Neutral** **Slightly Warm** **Warm** **Hot**

B) Thermal Preference: **Right now I would prefer**:

☐ **To be warmer** ☐ **No change** ☐ **To be cooler**

C) Thermal Acceptability: Is the thermal environment **acceptable** to you?

☐ **Acceptable** ☐ **Unacceptable**

5. Productivity: Compared to normal, please estimate how you feel your **productivity** has increased or decreased **today**, by ticking where you feel appropriate on the scale below?

−40% or more **−30%** **−20%** **−10%** **0** **+10%** **+20%** **+30%** **+40% or more**

6. Stress Level: Select the most appropriate scale degree of your work stress you feel right now on the scale below?

0 1 2 3 4 5 6

calm **very stressed**

Figure 3.11 Thermal comfort questionnaire.

3.4.3.1 *Clothing Insulation Estimates*

Clothing insulation (clo) values were calculated according to standard checklists defined in ASHRAE's Handbook Fundamentals (ASHRAE, 2010), Standard-55 (ASHRAE, 1992) and ISO 7730 (EN ISO, 1995). The total clothing insulation values were calculated from the sum of each part of clothing that was marked on a participant's questionnaire. Clothing values were determined from Table 3-3 which was derived from garment insulation values defined by ASHRAE (2004).

Total clothing value was calculated as per equation (31), adding the value of each item of clothes:

$I_{cl} = \sum_{I} I_{clu,I}$ [Equation 31]

Table 3-4 Garment Insulation Values (modified from ASHRAE, 2009)

Garment Description	**Footwear**	**Mid-layer**		**Outer Layers**	**Other Items**
	Socks	**Short-sleeved shirt**	**Pants or slacks**	**Sweater**	**eg Chair**
Light (clo)	0.03	0.19	0.24	0.25	0.1
Heavy (clo)	0.06	0.25	0.28	0.36	0.2
	Shoes	**Long-sleeved shirt**	**Shorts**	**Vest**	**Scarf**
Light (clo)	0.02	0.25	0.08	0.13	0.01
Heavy (clo)	0.1	0.34	0.15	0.22	0.02

Table 3-4 Garment Insulation Values (modified from ASHRAE, 2009)

	Pantyhose	**Dress**	**Skirt**	**Jacket**	**Other**
Light (clo)	0.02	0.23	0.14	0.32	
Heavy (clo)	0.04	0.46	0.23	0.48	

Number 1 in the questionnaire represents ‘light’ summer garments made of thin fabric. Number 2 in the questionnaire represents ‘heavy’ winter garments made of thick fabric.

The chair insulation value was taken equal to 0.2 for all chairs, owing to the closed shape of all chairs in the office (Figure 3.12).

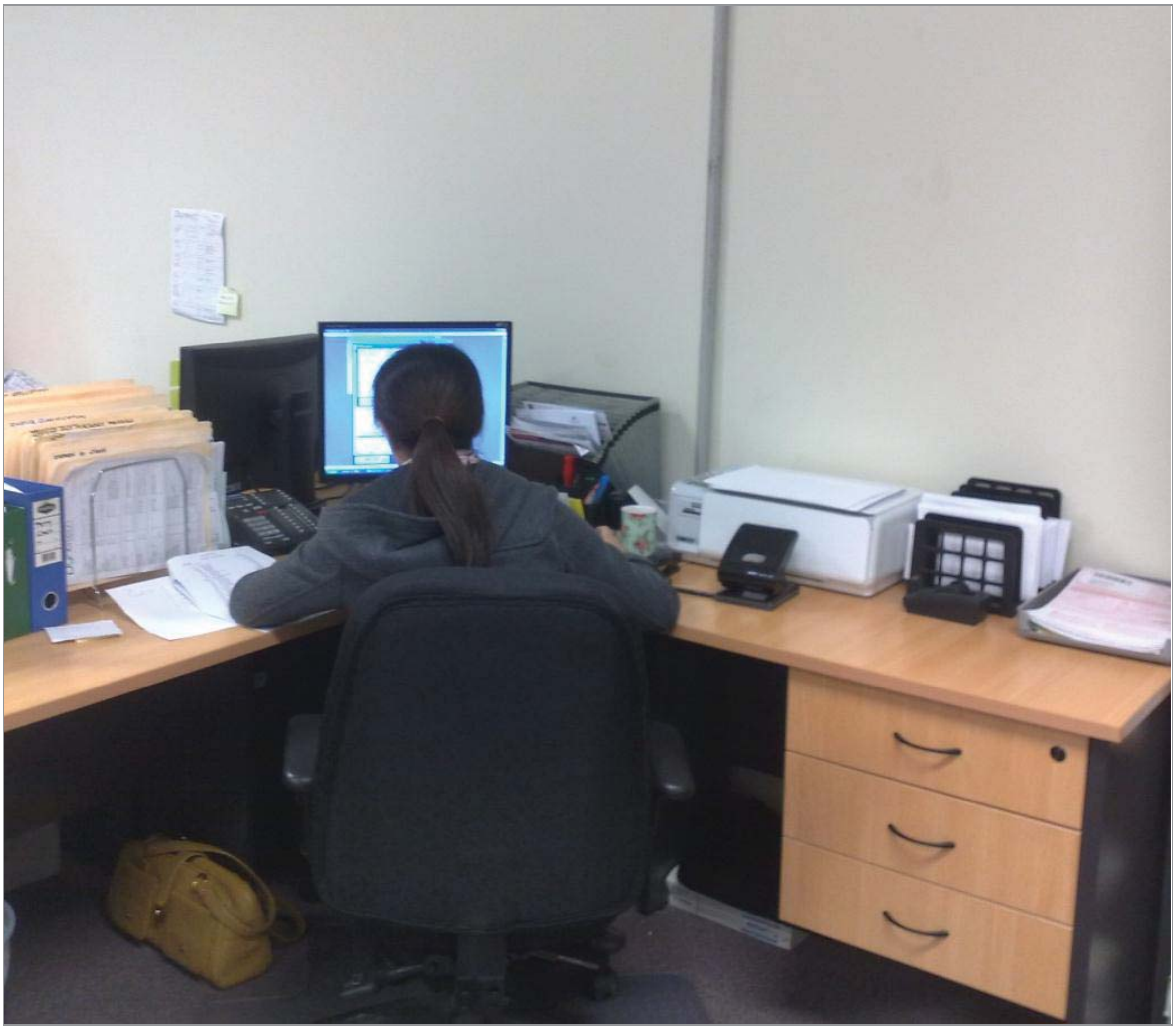


Figure 3.12 Typical example of an office chair used in the office.

3.4.3.2 Metabolic Rate Calculation

The rate of metabolic heat produced by the body is most accurately measured by the rate of respiratory oxygen consumption and carbon dioxide production (ASHRAE, 2001). Metabolic rates can be estimated more accurately by tabulation rather than calculation if the duration of activity is to be taken into consideration. According to ASHRAE, the standard metabolic rate value (Met) can be calculated and determined from the typical metabolic heat generation tables defined in ASHRAE's Handbook Fundamentals (ASHRAE, 2001). This is achieved by staging the activity into five durations, then calculating the average value for the entire estimated period. The five stages can be calculated from Table 3-5.

$$\mathrm{Met}_{total} = \sum_{l=1} \mathrm{Met}_{,l} \qquad \text{[Equation 32]}$$

Table 3-5 Metabolic Heat Generation for Various Activities (modified from RP-702, ASHRAE Report 1993)

Time	**Activity (Met)**					
Duration↓	**Sitting quietly**	**Sitting typing**	**Standing still**	**On your feet working**	**Walking around**	**Driving a car**
Last 10 minutes	1	1.2	1.4	1.9	2.2	2
The 10 minutes preceding that?	1	1.2	1.4	1.9	2.2	2
The 10 minutes before that?	1	1.2	1.4	1.9	2.2	2
The half hour before that?	1	1.2	1.4	1.9	2.2	2

3.4.4 Thermal Comfort Index Calculations

The predicted mean vote (PMV) and the predicted percentage dissatisfaction (PPD) values were used in this project for comparison with the Actual Mean Vote (AMV). The PMV and PPD were calculated using the WinComf program (Fountain & Huizenga, 1997); however, the value of the AMV and APD were determined from the questionnaire.

3.5 Summary

This chapter provides details of the method used in this research. The selected participants and instruments discussed with their relation to thermal comfort and environmental conditions were described broadly. The method developed in four aspects: (1) describe the methodology explain the sample selection, (3) describe the procedure used in using the instrument and collecting the data, and (4) provide an explanation of the statistical procedures used to analyse the data. The following chapter provides the results and discussion, largely presented in a peer-reviewed paper presented at the Healthy Buildings 2012 Conference.

CHAPTER 4

4 RESULTS

4.1 Sample Description

The group of participants comprised 30 people from various locations within the building, however, not all of them contributed for the full term of the research. Twenty-three subjects formed the continuous research group. Six women and ten men in their mid-thirties, and seven young men under the age of thirty formed the sample. The seven other employees were non-continuous participants in the study, as shown in Table 4-1.

Table 4-1 Participants' Basic Demographic Information

Departments	Installers and Technicians	Engineering, Accounting, Marketing, Drafting and Management
Occupancy		
Office bases (continuous presence in the office)	Males: 4 (13.4%)	Males: 13 (43.4%)
	Females: 0 (0%)	Females: 6 (20%)
Site bases (not in the office fulltime)	Males: 4 (13.4%)	Males: 1 (3%)
	Females: 0 (0%)	Females: 2 (6%)

This thermal comfort analysis includes survey responses from air-conditioned (AC) spaces in a Sydney office building during 2010/2011 (01/03/10 until 01/03/11). The survey was conducted throughout the day (8am until 6pm), and the survey period varied between normal working hours and after hours. Participant gender and the sample size (N) of each season are summarised in Table 4.1. A total of 2,428 questionnaire responses were obtained from the participants.

Table 4-2 Summary of Survey Samples

Season	Female (N)	%	Male (N)	%	Sub-total (N)
Winter	210	22.9%	709	77.1%	919
Summer	361	24.6%	1106	75.4%	1467
Total	571	23.9%	1815	76.1%	2386

4.2 Indoor and Outdoor Measurements

4.2.1 Outdoor Temperature:

Outdoor temperatures were collected for Revesby. Revesby's climate is similar to Sydney's climate, and its office buildings are comparable to those in Sydney's CBD, with most commercial buildings equipped with air-conditioning systems. The daily average temperature range from 2009 to 2011 was taken from the Bureau of Meteorology at Bankstown Airport (Appendix A).

4.2.2 Indoor Temperature:

The comfort package, together with other data-loggers, provides climatic readings every five minutes at the participant's desk level, considered the middle height of the occupied zone. The desktop comfort box recorded air temperature at five-minute intervals throughout the study. Measurements were collected throughout the study by dataloggers located randomly within each building, and the desktop comfort logger located between the subjects under observation (Figure 4.1). These temperatures represent the instantaneous indoor comfort temperatures which were set to be delivered by conditioned air.

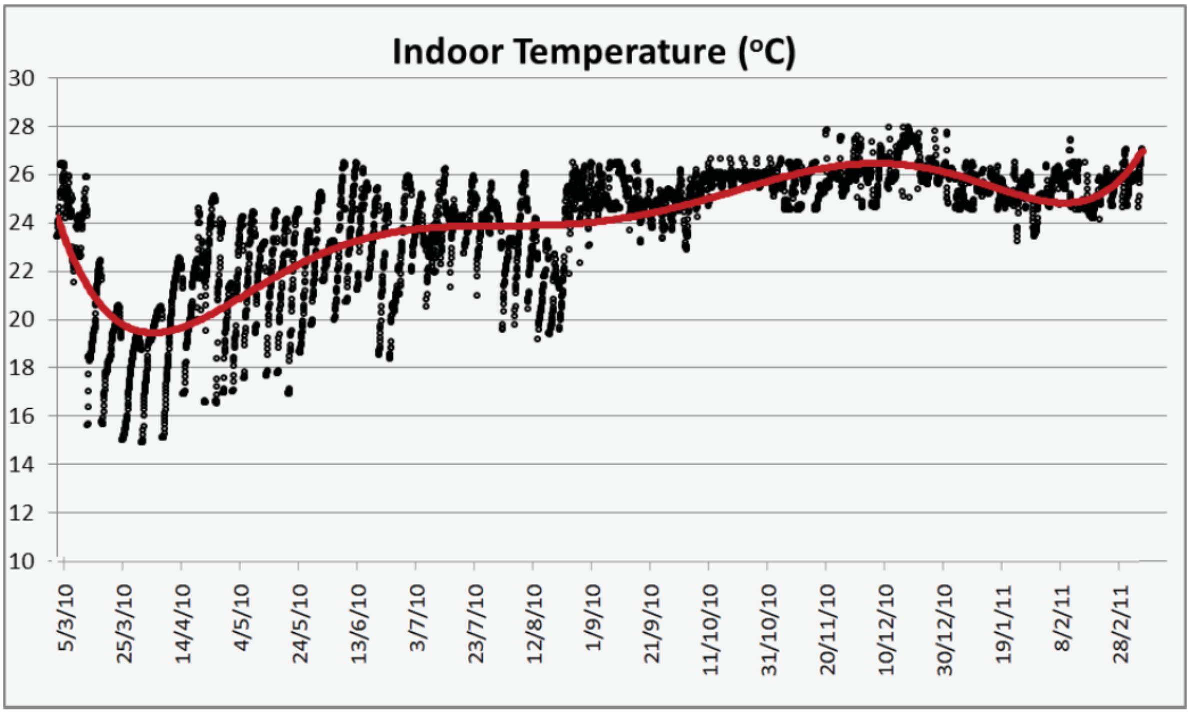


Figure 4.1 Daily instantaneous indoor temperature Tin during 2010 to 2011. (Source: Bureau of Meteorology in Australia.

4.3 Clothing and Metabolic

Table 4-3 presents a summary of the main personal thermal variables of clothing insulation, broken down by season. Clothing insulation (clo) values were calculated according to standard checklists defined in ASHRAE's Handbook Fundamentals (ASHRAE, 2010), Standard-55 (ASHRAE, 1992) and ISO-7730 (EN ISO, 1995). Total clothing value was calculated as per Equation 5, Chapter 3.

Table 4-3 Variation of Personal Thermal Variables (clothing insulation) with Average Indoor Temperature.

	Winter	**Summer**
Average Indoor Temperature (^oC)	**Intrinsic Clothing Insulation (Clo)**	**Intrinsic Clothing Insulation (Clo)**
17	1.63	-
18	1.62	-
19	1.67	1.41
20	1.62	1.41
21	1.55	1.17
22	1.35	1.14
23	1.31	1.14
24	1.09	0.89
25	1.06	0.85
26	1.04	0.65
27	-	0.64

The average of the Intrinsic Clothing Insulation (Clo) value across the whole year is presented in Figure 4.2. The chair insulation value was taken as equal to 0.2 because of the closed shape of all chairs in the office; this is included in the graph values.

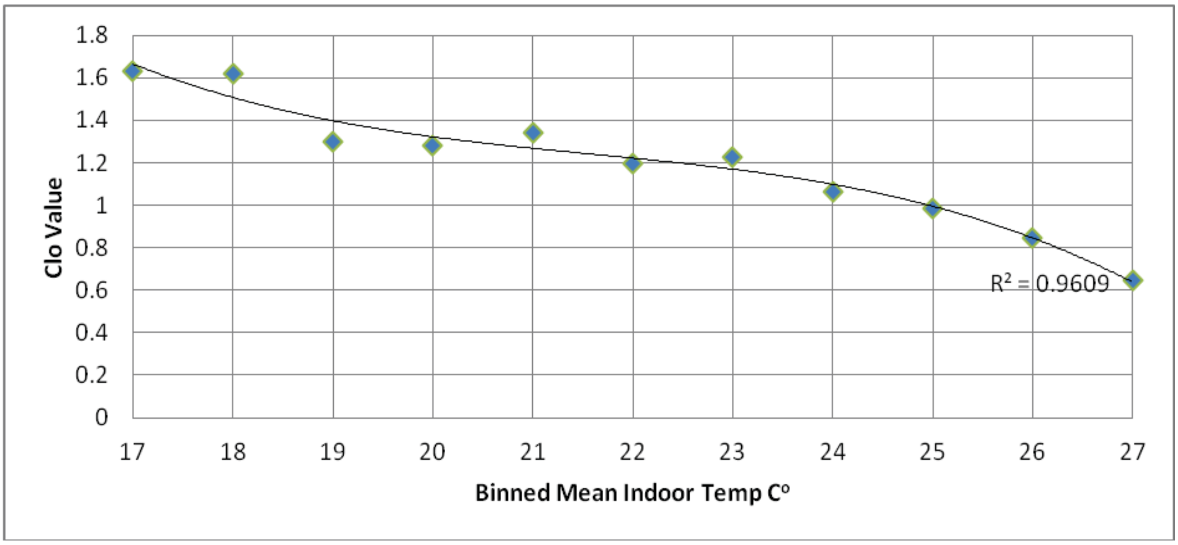


Figure 4.2 Variation of average clothing insulation with the average yearly indoor temperature.

Figure 4.3 shows that the participants adjust their clothing to adapt to the environmental conditions. This was observed more in winter than in summer, as the removal of heavy clothing is more likely in winter.

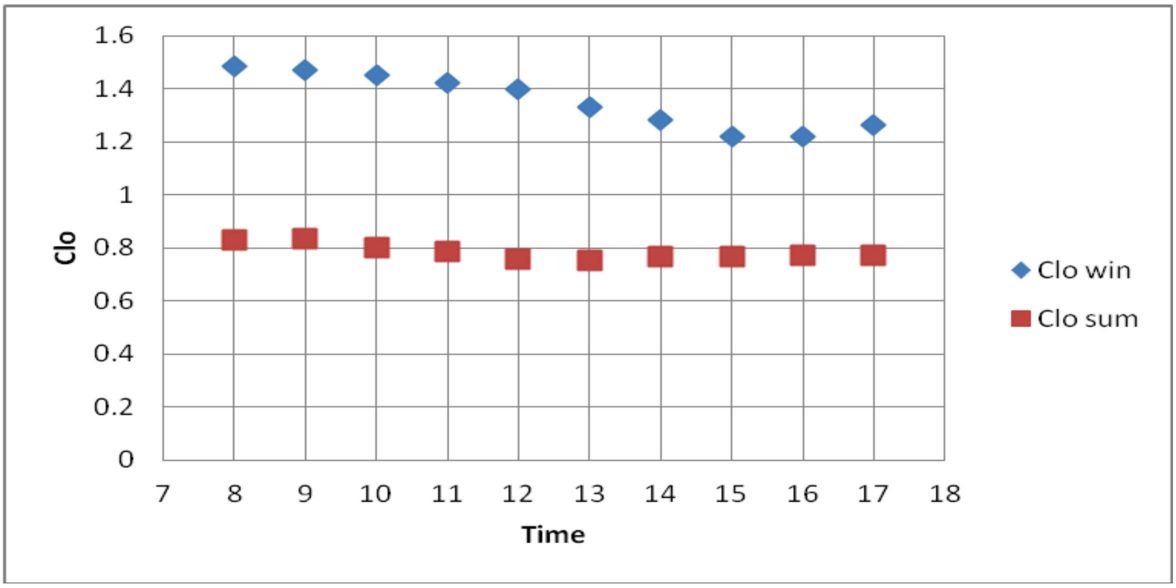


Figure 4.3 The variation of average clothing insulation throughout the day during summer and winter.

4.4 Calculated Comfort Indices

Table 4.5 presents a statistical summary of the thermal environmental and comfort indices broken down by season (winter and summer). These indices include operative temperatures (average of ta and tr), thermal preference, thermal acceptability, productivity, stress and thermal sensation (AMV with the PMV). As noted in acceptability which was calculated as the average of two values (0,1) and rounded to nearest from (0) acceptable and (1) unacceptable, the APD index was considered as the opposite of these values in 100 percent. Table 3.5 indicates that, on average, the votes of participants during the winter season fell within the 16-28°C, while the PMV calculations indicate marginally cooler than neutral conditions (-0.5 to 1.3). These values confirm the interference between the seasons where some indoor operative temperatures indicates summer season. During the summer (Table 4.6) the average indoor temperature values fell within the 22-24°C while the

Table 4-4 Statistical Summary of Calculated Indoor Climatic and Thermal Comfort Indices (winter season).

No. of Votes	Mean Temp (^{o}C)	AMV	PMV
17	16	0.2	0.03
34	17	0.3	-0.09
50	18	0.2	-0.12
82	19	0.4	0.03
83	20	0.4	0.17

No. of Votes	Mean Temp (^{o}C)	AMV	PMV
86	21	0.5	0.26
120	22	0.5	0.27
138	23	0.6	0.46
181	24	0.4	0.48
81	25	0.7	0.79
35	26	1.0	1.07
12	27	0.7	0.99

Table 4-5 Statistical Summary of Calculated Indoor Climatic and Thermal Comfort Indices (summer season).

No. of Votes	Mean Temp (^{o}C)	AMV	PMV
4	19	0.5	-0.55
22	20	0.2	-0.39
19	21	0.2	0.09
36	22	0.3	0.24
53	23	0.1	0.54
93	24	0.3	0.66
325	25	0.6	0.80
340	26	0.8	0.74

No. of Votes	Mean Temp (^oC)	AMV	PMV
205	27	0.6	1.04
287	28	0.3	1.31
83	29	0.8	0.91

Table 4-6 Statistical Summary of Indoor Climatic and Thermal Comfort Indices.

Season	Winter			Summer			Annual
	Mean	Max	Min	Mean	Max	Min	**Total**
No. of Votes	919	919	919	1467	1467	1467	**2386**
Mean Tin ^oC	21.99	28	17	26.08	29	19	**24.53**
Clo	1.36	1.7	0.6	0.75	1.2	0.6	**0.98**
Meta	1.28	1.53	1.2	1.25	1.39	1.2	**1.26**
AMV	0.49	1	0.1	0.55	0.8	0.1	**0.53**
PMV in	0.36	1.3	-1.55	0.87	1.38	-1.55	**0.68**

Environmental parameters which influence thermal comfort were gathered throughout this study. Table 4-6 presents a summary of the indoor environment and thermal comfort indices measured and calculated for each questionnaire; operative temperature (To), which was calculated as the average of air and mean radiant temperatures; and other simple thermal comfort measures, relative humidity (RH), air velocity (Vair), clo value (Clo), metabolic rate (MET), actual mean vote (AMV), predicted mean vote (PMV) and predicted percentage dissatisfied (PPD).

The office plan is triangular with a wide open area in the middle where most office stations are located. The air handling split unit and ducting system operates from 8am in the morning. Indoor operative temperatures (To) recorded during this study fell within the range of 17.8°C to 26°C, with a mean value of that summer season at 25.3°C (Table 2.1). With a mean speed less than 0.15 m/s, air movement within the occupied zone exerted a negligible effect on participants' thermal sensation. RH ranged from 27% to 75% with an average of 48%; mean metabolic rate was calculated equal to 1.28 met which indicates that most of the participants were sitting during the time of surveys registration. Clothing value approximates including chair insulation, 1.36 (Clo) in winter and 0.75 (Clo) in summer, ranged from 0.6 (Clo) to 1.7 (Clo) and were similar to those typically assumed for adult office workers (ASHRAE, 2010), with an average value of 0.45 (Clo) excluding chair insulation. The actual mean vote on the thermal sensation average (AMV = +0.53) for all participant samples was recorded mid-way between neutral (0) and slightly warm (+1). Alternatively, the mean of the predicted PMV index across this study was equal to 0.68. From Table 5.2, the range of PMV in both seasons is wider than the range of PMV; so participants' actual vote is more flexible to some extreme indoor conditions which were traditionally considered unacceptable (such as PMV>1).

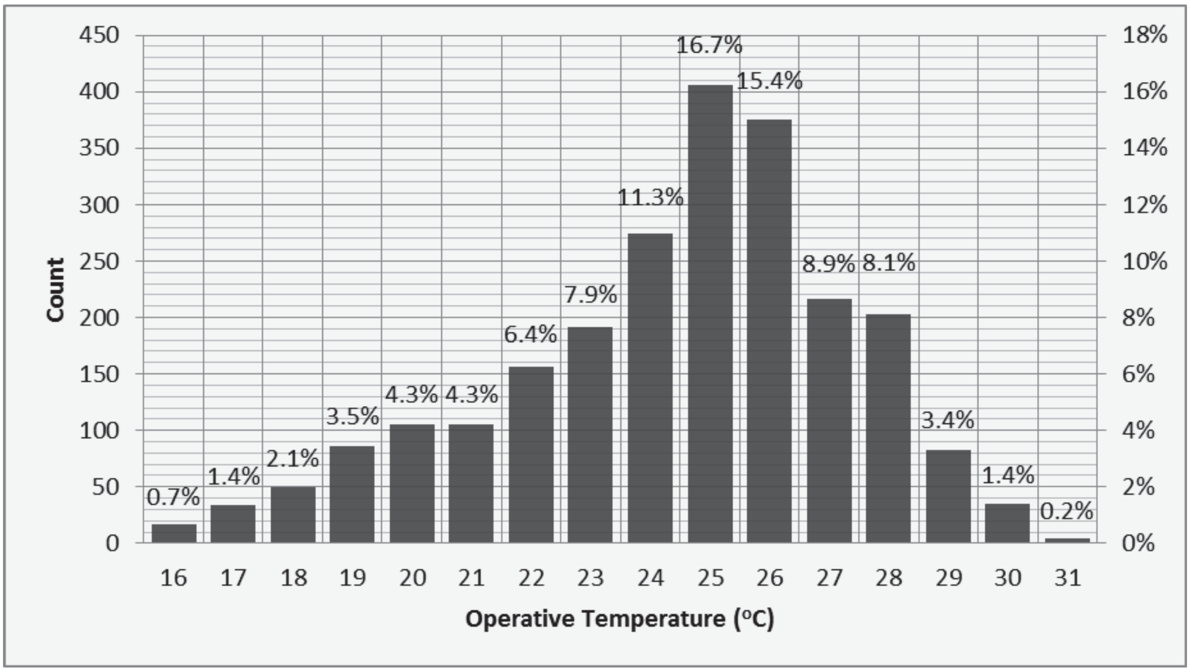


Figure 4.4 Distribution of indoor operative temperature recorded within the office building throughout the 2010-2011 survey.

The indoor operative temperature was binned against the number of votes within the office building during the study is shown in Figure 5.1. Each bar shows the number and percentage of survey samples completed within each operative temperature bin. Three quarters of all observed operative temperature measurements fell within the range of 22°C to 28°C all the way through the survey. About half of the surveys (52%) were administrated when indoor operative temperature was recorded between 24°C and 26°C. It could be easier to undertake this comparison for every season separately.

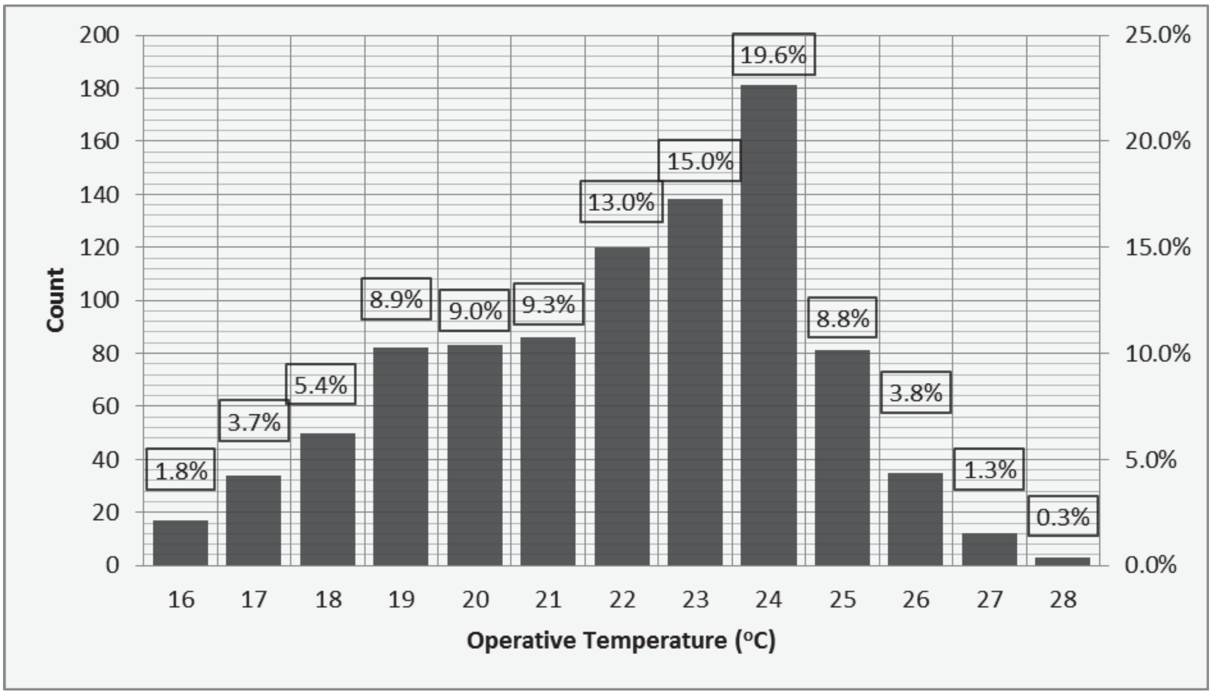


Figure 4.5 Distribution of indoor operative temperature recorded within the office building throughout the winter 2010 survey.

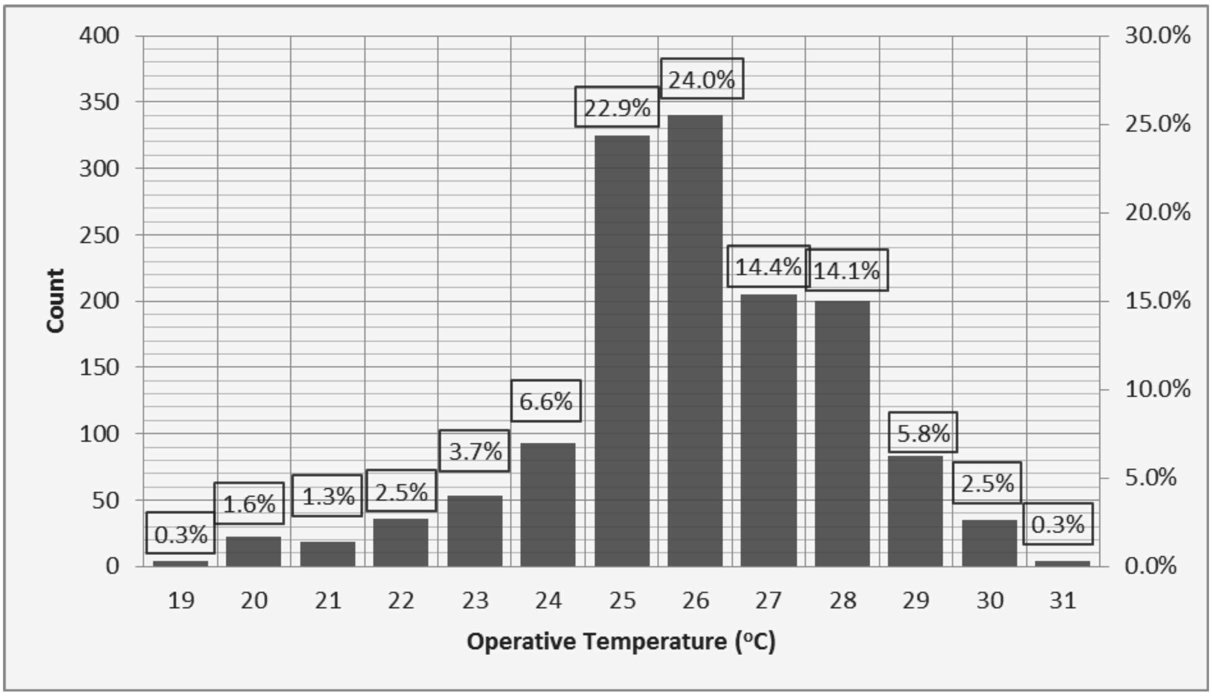


Figure 4.6 Distribution of indoor operative temperature recorded within the office building throughout the summer 2010-2011 survey.

When comparing the surveys conducted in winter 2010 and summer 2011 (Figures 5.2 and 5.3 respectively), the percentage of comfort operative temperature represents about three-quarter of total votes claiming acceptable indoor conditions. The comfort indoor operatuive temperatures varies between the range of 25 - 28°C in summer. Similar ratio of votes represents about three quarter of total acceptable votes were conducted when indoor operative temperature fell between 19 and 24°C in winter.

4.5 Subjective Assessment of the Thermal Environment

4.5.1 Participants' Thermal Sensation

Figure 4.4 displays a simple comparison between actual mean vote (AMV) and predicted mean vote averaged (PMVav). Predicted mean vote is an index calculated for each participant on the basis of four environmental parameters (ta, tr, v and rh) and two personal parameters (clo, met). For all votes within the cooler operative temperature bins from 18°C to 21°C, the average PMVav registered lower thermal sensation than the actual votes from these participants (AMV). Therefore, these participants felt more comfortable (neutral) in the cooler temperatures than the six thermal comfort parameters would suggest. However, for the operative temperature bins (22°C through 26°C), there was generally close agreement between predicted and actual thermal sensations.

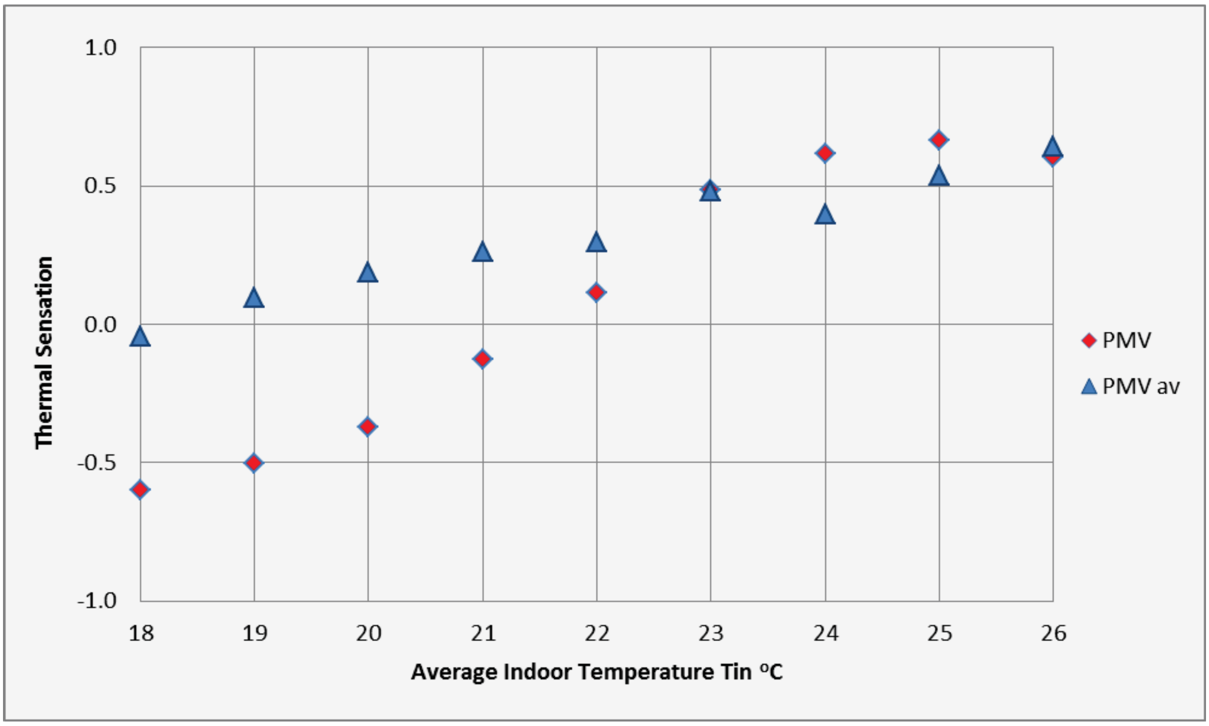


Figure 4.7 Comparison between average actual votes (AMV) and average predicted mean vote (PMV) with respect to indoor operative temperature bins.

The thermal preferences mentioned above can be mixed to provide the average acceptable thermal sensation. The resulting percentages within each bin have been subjected to the same type of analysis (refer to Figure 4.2). According to Figure 4.7, the operative temperatures in winter and summer were virtually identical (between 18°C and 28^{o}C); with participants recording ±0.7 AMV and considering these temperatures acceptable.

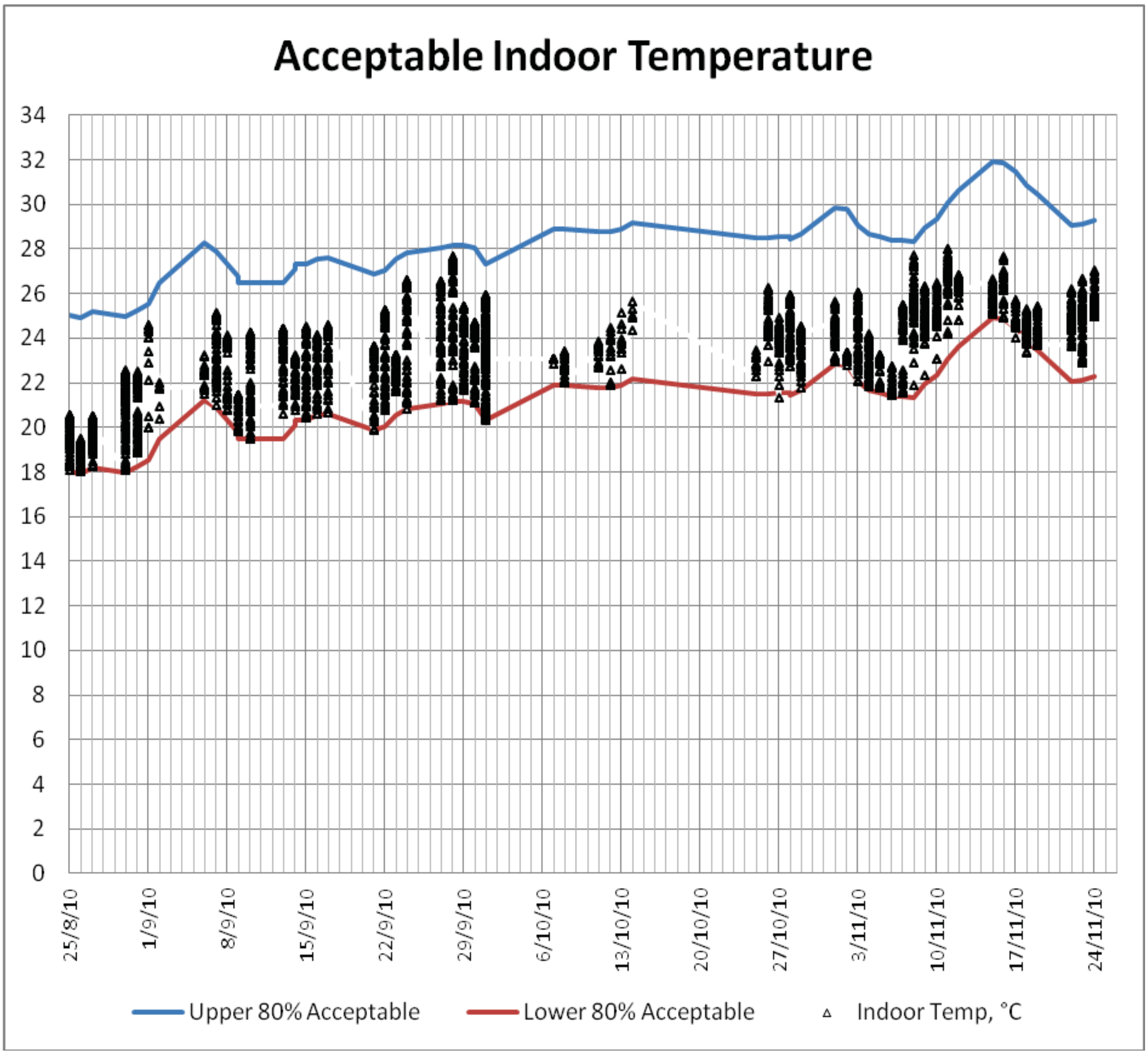


Figure 4.8 Daily instantaneous indoor temperature (Tin) during 2010 to 2011 and the average voted acceptability.

Figure 4.8 represents the distribution of indoor temperatures within the maximum and minimum calculated adaptive comfort temperatures (indicated as the upper and lower 80% acceptability). The data was filtered based on the calculated APD, which was calculated from the AMV during summer and winter seasons.

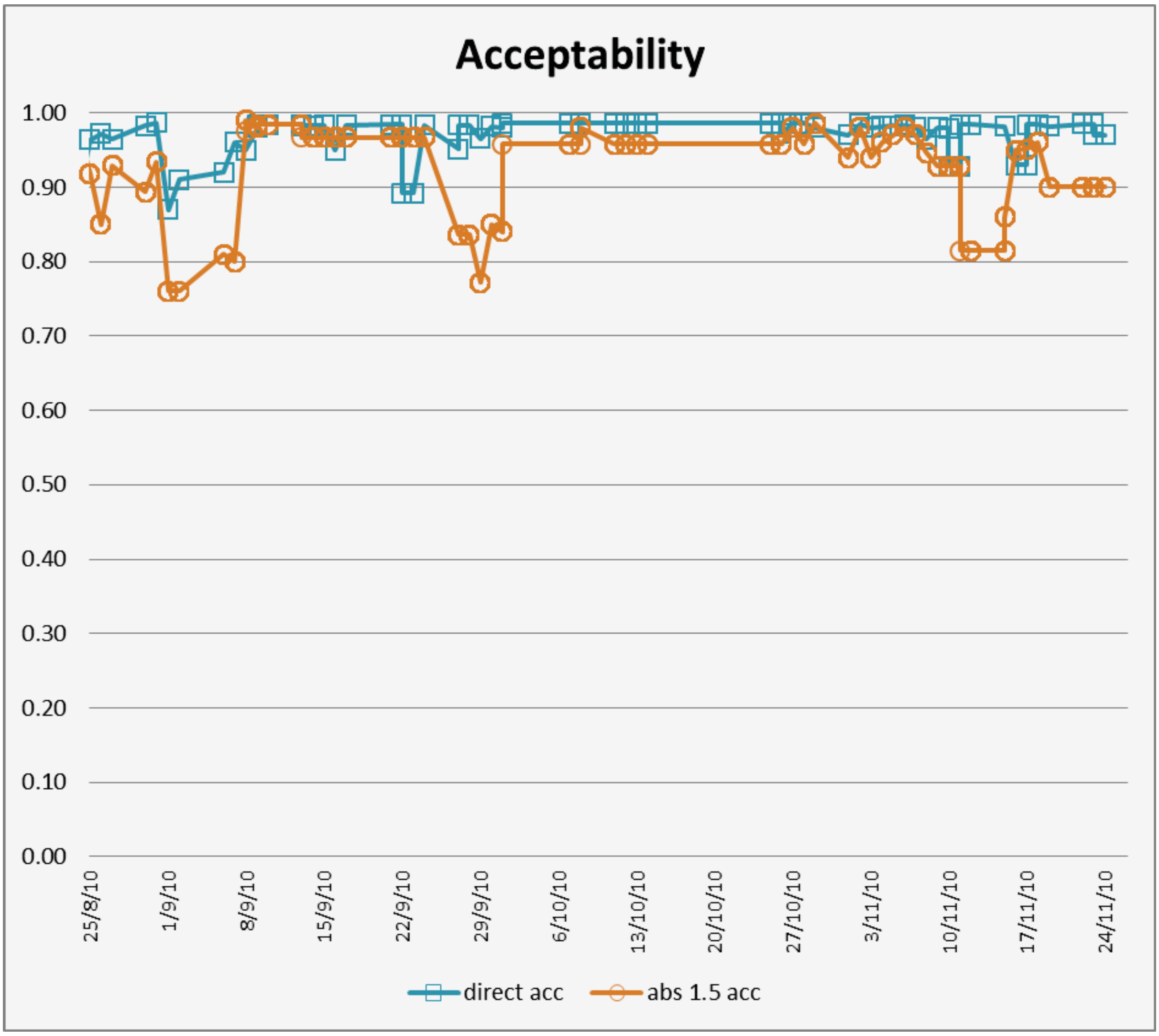


Figure 4.9 Comparison between the ratio of average direct acceptability and calculated acceptability for participants who voted between slightly cooler and slightly hotter.

In Figure 4.9, direct acceptability (as voted by participants on a daily basis) claims 10% of dissatisfaction toward the indoor temperature settings within proposed comfort zone. However, the correspondence absolute acceptability (as calculated by the Wincomf from AMV) claims 25% of unacceptable conditions. In general, the absolute acceptability fluctuates between -1.5 and 1.5, but this was considered acceptable for 90% of participants.

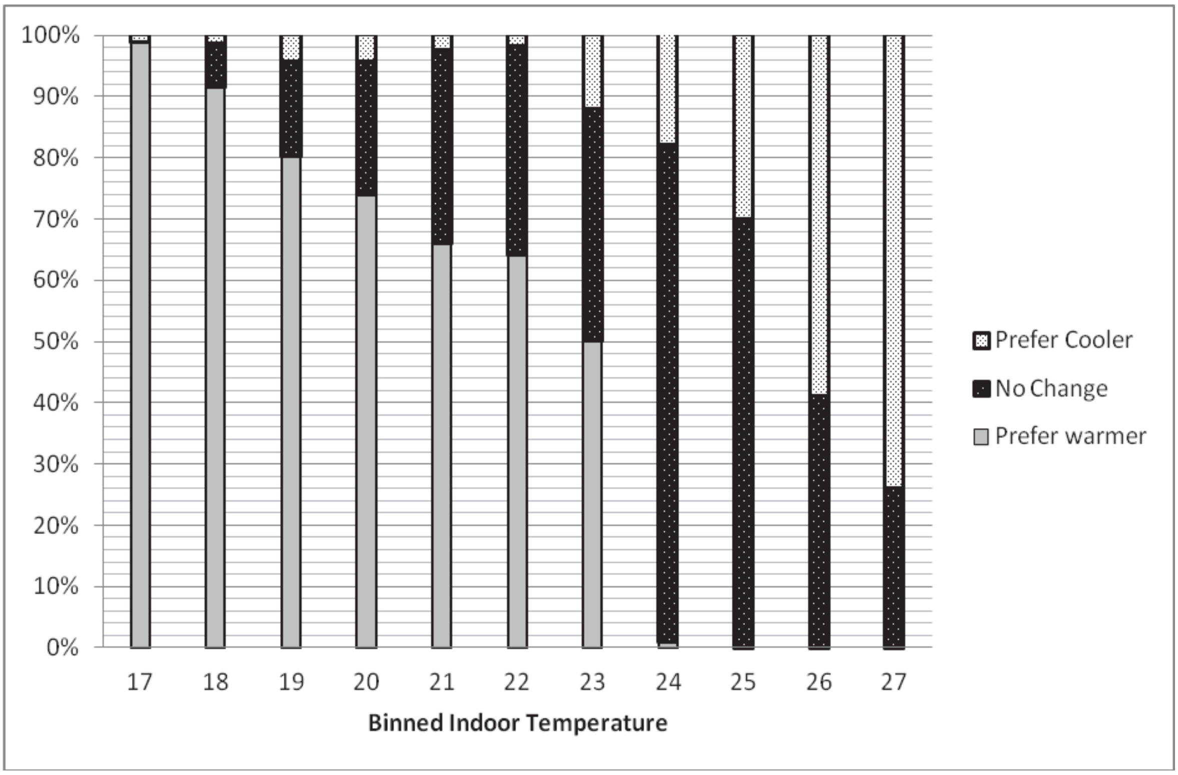


Figure 4.10 Statistical data for all votes shows the participants' indoor temperature preferences.

Total comparison for the total preferences in Figure 4.10 is based on direct votes in the survey. Neutrality is indicated by a dark hatched line; these participants preferred no change. A preference for cooler conditions is indicated by dotted bars. A preference for warmer conditions is indicated by shaded lines (NB occurring only when temperatures dropped below 23oC).

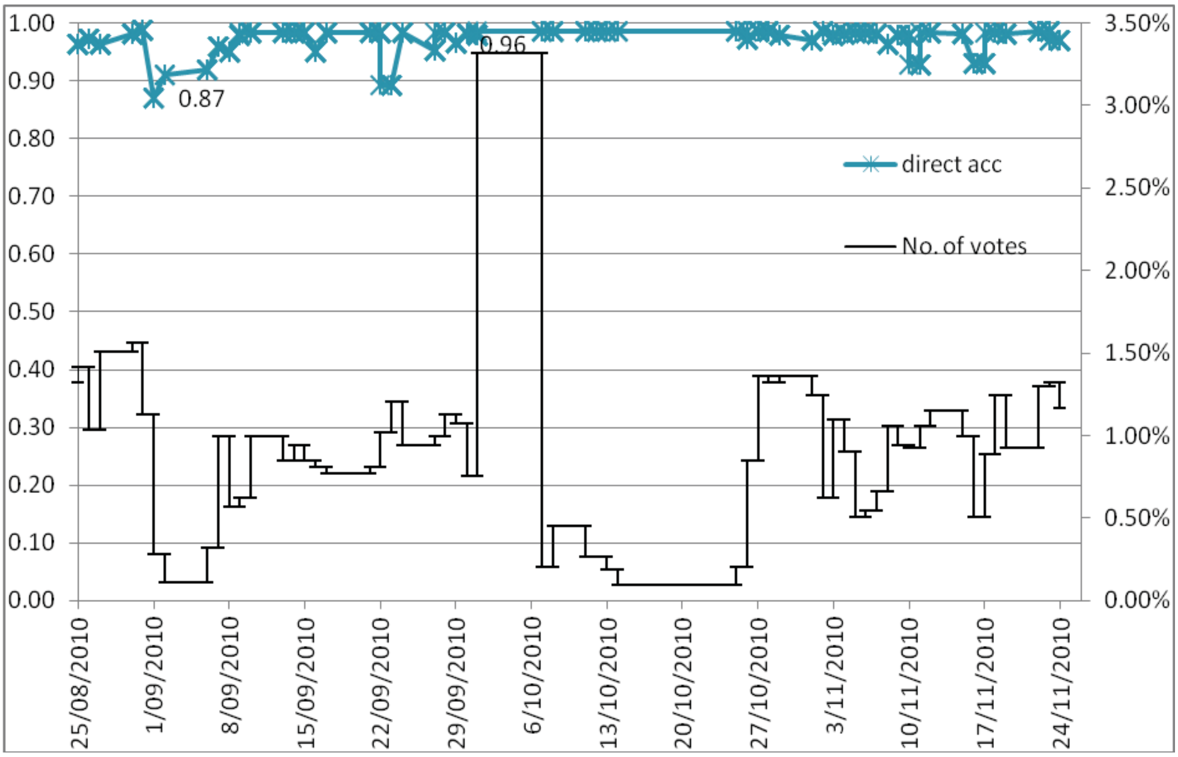


Figure 4.11 The ratio of average direct acceptability (direct ACC) on the left axis; and average ratio of the number of votes over the total number of votes in the study on the right axis.

4.6 Thermal Sensation (ASHRAE scale) and Neutrality

4.6.1 Thermal Acceptability

Participants were asked to indicate on the questionnaire (Section 3.4.3) whether they considered the thermal environment acceptable or unacceptable. These thermal acceptability votes have been binned into daily intervals.

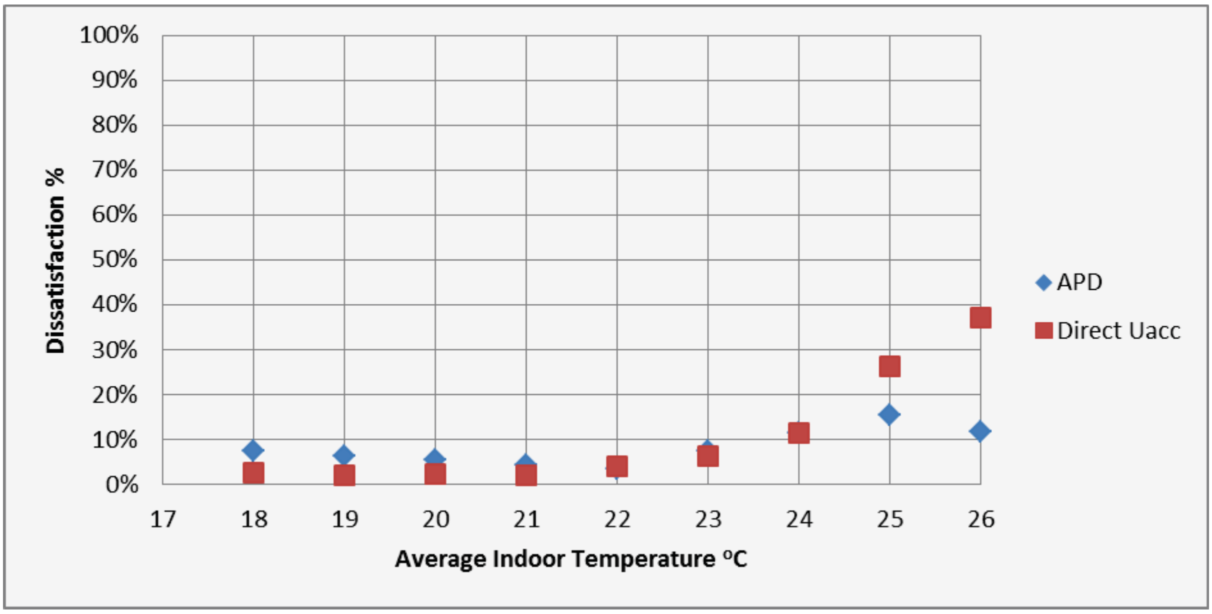


Figure 4.12 Comparison between average Direct unacceptability votes (Direct uacc) and average Predicted percentage dissatisfaction (PPD) with respect to indoor operative temperature bins.

The resulting percentages within each bin are shown as a bar line that describes participants' acceptability for the thermal comfort range that is used in the naturally ventilated comfort model.

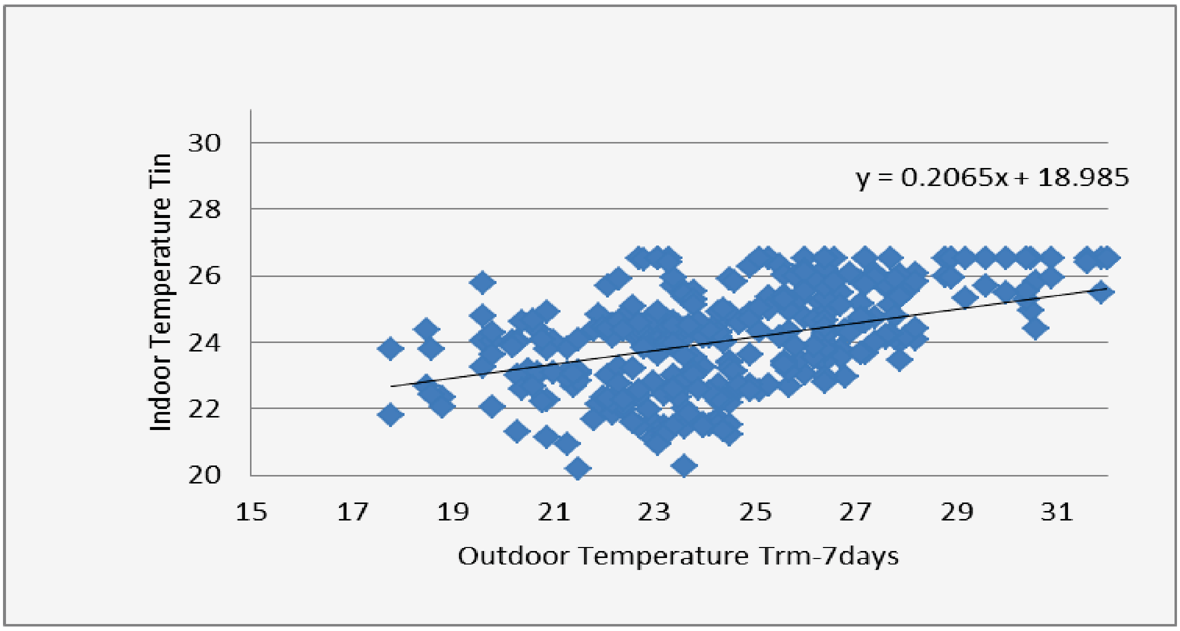


Figure 4.13 Variation of the 7 day running mean outdoor temperature, with Sydney's average temperature range during 2008 to 2010 (Source: Bureau of Meteorology, Australia).

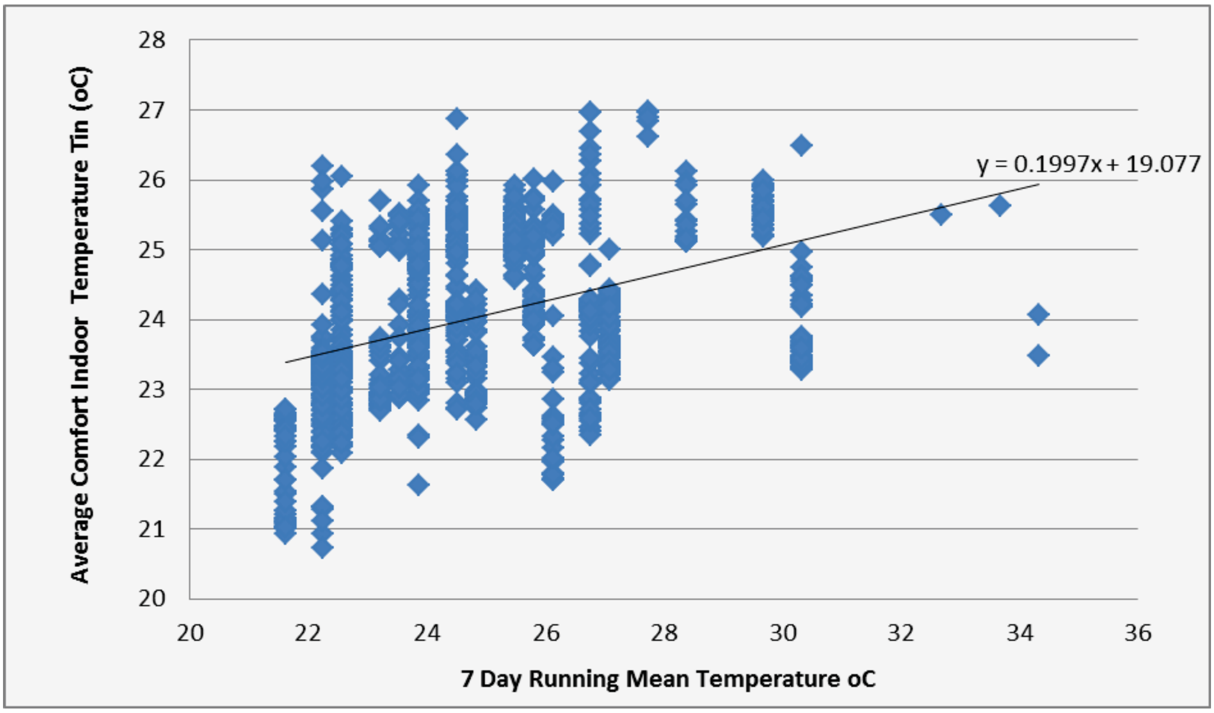


Figure 4.14 Variation of the 7 day running mean outdoor temperature with the binned indoor comfort temperature during the summer season.

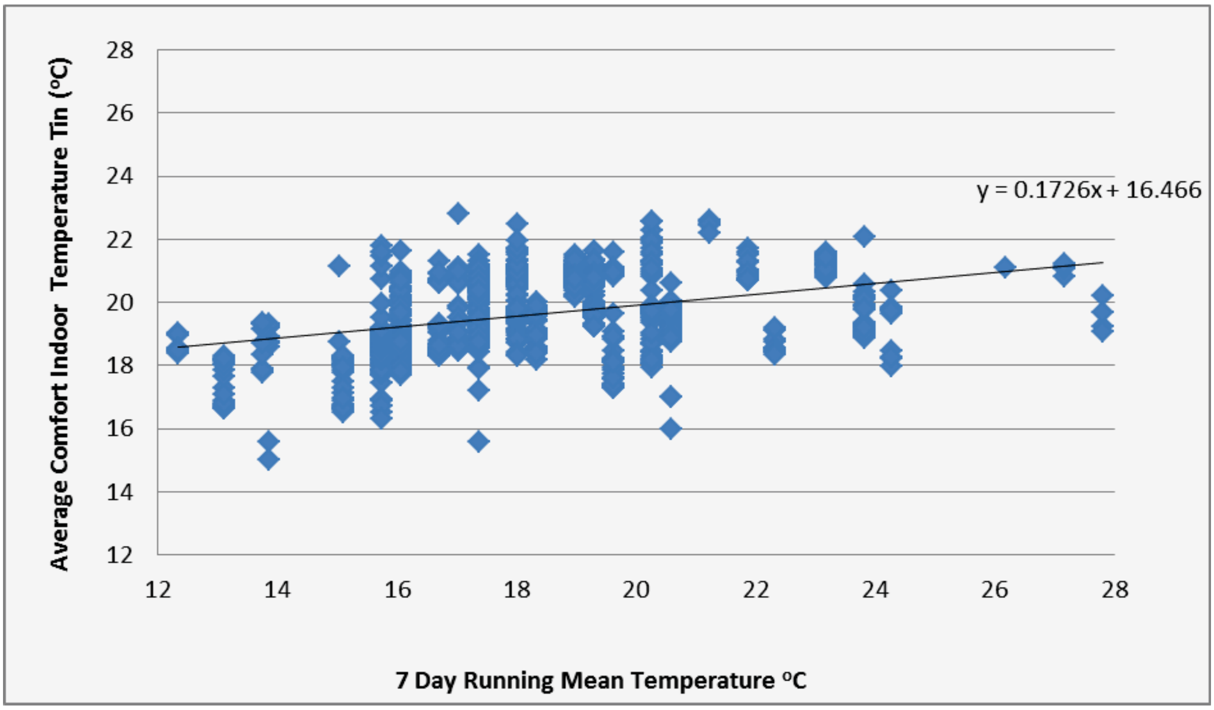


Figure 4.15 Variation of the 7 day running mean outdoor temperature with the binned indoor comfort temperature during the Winter season.

4.6.2 Thermal Preference

Subjects were also asked to indicate on the questionnaire (Section 3.4.3) whether they would prefer to feel warmer or cooler. These thermal preferences have been binned into 0.5°C intervals and the resulting percentages within each bin subjected to the same type of probit analysis (Section 3.8.1). The resulting models are depicted in Figure 3.21.

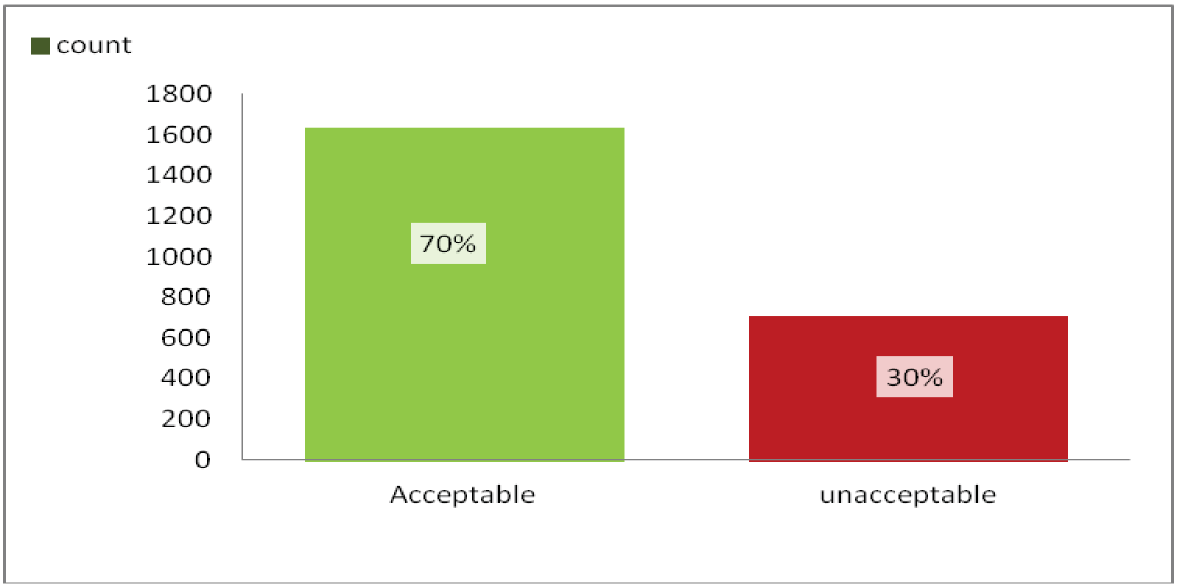


Figure 4.16 Distributions of thermal acceptability according to votes.

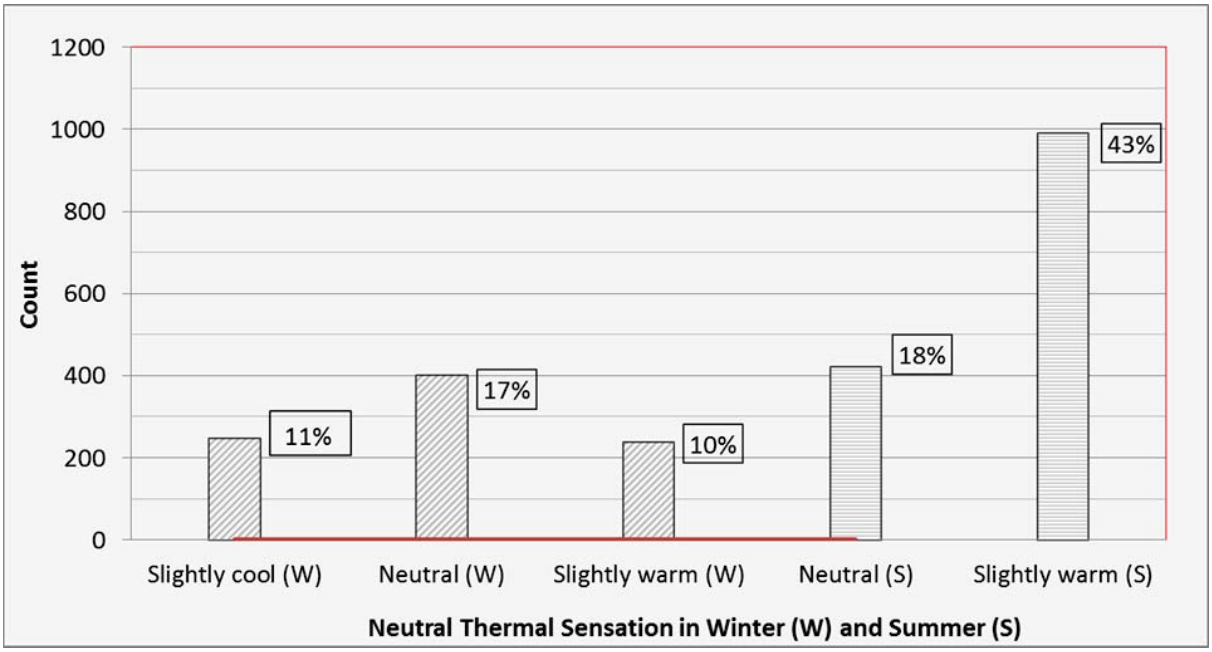


Figure 4.17 Distribution of actual thermal sensation in summer and winter.

4.7 Thermal Neutrality

Figure 4.16 plots the relationship between the average indoor neutral operative temperature (To) and the corresponding running seven day outdoor temperature mean. The red curve in Figure 4.16 represents the indoor operative temperatures recorded every time a participant expressed thermal neutrality (i.e. voted between -0.5 and +0.5). It clearly indicates that thermal neutrality inside an air-conditioned building is related to the prevailing outdoor temperature. We found the linear equation link between acceptable indoor temperature (To) and the seven day running mean outdoor temperature (Trm) plateaued at about 25-26°C during the hottest weather conditions. However, this is probably reflecting the way we implemented the adaptive comfort algorithm in this building's BMS system (we capped the set point algorithm at 26°C). While a simple linear regression model has been fitted in Figure 4, a parabolic equation explains more variance (73% versus 84%).

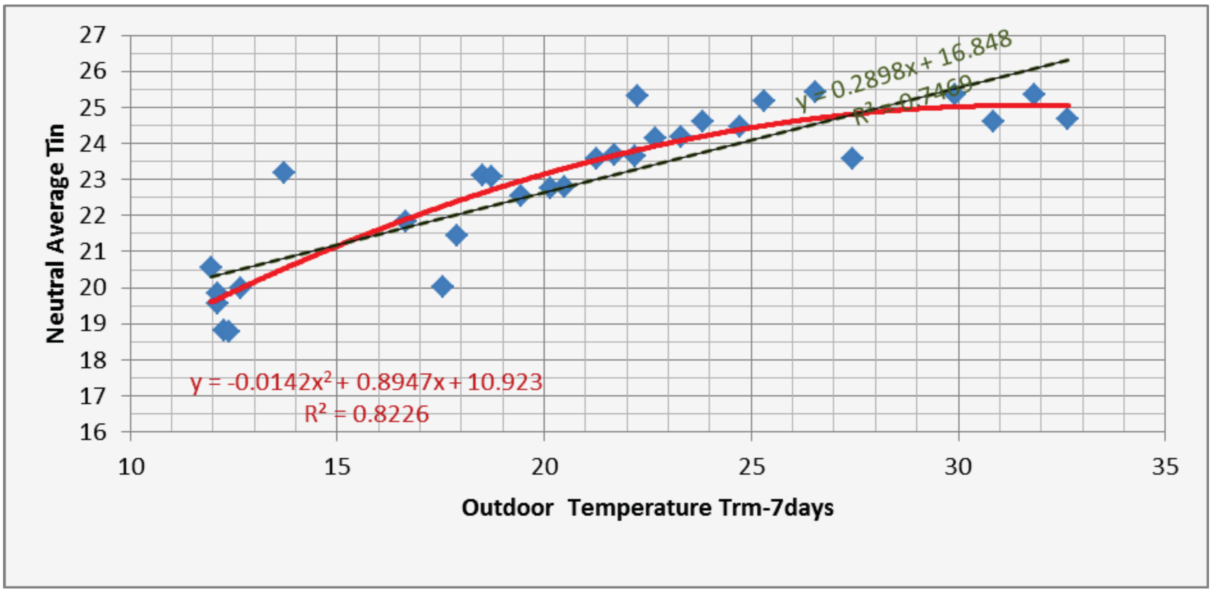


Figure 4.18 Indoor acceptable operative temperature (To) with respect to running 7 day outdoor temperature (Trm).

4.8 Summary

The findings provide the standards of thermal comfort with supplementary data for adaptive model in a controlled environment. The perceptions and tolerance towards adaptive thermal comfort in air-conditioned buildings within predetermined indoor temperatures range develop a new approach in HVAC design. The reported findings from this work concentrate on the development of the adaptive model toward the adaptive air-conditioning which will help in improving the application of “best practice” in the engineering and design of buildings. Future research could be applied, similarly, to explore the occupants’ tolerance beyond this research temperatures set point range on different type of air conditioned buildings, such as (educational and residential..etc.), to expose the untested parts of the parabolic equation.

CHAPTER 5

5 DISCUSSION

This chapter discusses the results obtained from a thermal comfort study of an office building in Sydney, conducted between 2010 and 2011. It explores the application of adaptive thermal comfort in an air-conditioned office building. The participants' subjective assessments of thermal environment using thermal sensation, preference, and acceptability rating scales (presented in a questionnaire) were analysed and compared with corresponding indoor and outdoor measurements of climatic data.

5.1 Indoor Environment Observations

The trend line in Figure 4.1, which indicates daily instantaneous temperature (Tn), confirms that the average indoor temperature throughout the study was warmer than 22°C; and 60% of the time the average temperature exceeded 22°C. This could refer to the relatively short winter season in seasonal subtropical humid climate. This also explains the high percentage of votes (62%) taken for the indoor operative temperatures above the 22°C band (Figure 4.4).

5.2 Comparison between Indices, Models and Observed Data

The HVAC industry uses a predictive index called PMV to determine occupant thermal comfort in air-conditioned spaces. This index represents the main indicator of thermal comfort when occupants tested under steady state environmental conditions. Human behaviour is proven to be unsteady due to the adaptive nature of humans. However, actual mean vote (AMV) provides a true participant thermal sensation through the direct recording of thermal sensation during a survey. The value of AMV differs from PMV depending on the participant's ability to adapt to the climatic environment, as well as background culture and past climatic influences.

A simple comparison between AMV and PMV enabled exploration of the adaptation level in the office building studied. The prediction of the calculated PMV index was found to be significantly cooler than the average actual thermal sensation observed on the questionnaire scale for the winter season; however, this difference was reduced in the hot season (Figure 4.7). The standard PMV calculations indicated cooler conditions than neutral for the winter season; these conditions would be even cooler if the insulation of the office chairs was factored in the PMV calculations. Meanwhile, the actual sensation remains close to neutrality line and the difference was significant at 18^{o}C within 0.5 of a PMV unit.

In the summer season, the standard PMV indicates higher values than the actual sensation AMV; but when the thermal insulation effect of the office chairs was deducted from the PMV calculations, this difference was reduced entirely. It looks like the PMV and AMV correlate at a temperature higher than 22^{o}C, but they show a tendency towards neutrality in AMV values.

Although the high level of clo value resulting from the inclusion of the effects of chair,s insulation, the calculated PMV index was predicting “cooler sensation “ for the office occupants at lower temperature range under 18^{o}C changed to “neutral sensation” as indoor temperature increased The standard PMV was underestimated by 0.5 in winter. The regression lines of the mean binned thermal sensation votes and PMV predictions were nearly parallel, particularly for winter (Figure 4.7) and temperatures less than 20^{o}C. There was an increase of voted sensitivity of about a third the votes (on the ASHRAE scale) per one degree of change in operative temperature. The slope of PMV and AMV on operative temperature was similarly small, which indicates that the participants adjusted their clothing insulation and/or their activity levels to balance for any ambient conditions that differ from neutrality. This regression model was suitable for winter (Figure 4.7) and changed when transferred to warm indoor conditions. The models of AMV on operative temperature (Tin) were less sensitive than those of PMV, but overlapped at two indoor temperature bins (23^{o}C and 26^{o}C, respectively).

The questionnaire item about thermal sensation of the current indoor environment addressed some general mood questions about the occupants (Figure 4.16). Disregarding thermal sensation, 70% of participants considered the indoor conditions acceptable throughout the duration of the project. The distribution of thermal sensation indicates that the indoor average temperature during summer was acceptable. Even though 43% of the votes considered the indoor environment slightly warm; 18% of participants voted it as neutral. On the other hand, during winter about 17% of the remaining participants voted as neutral; 11% slightly cool; and 10% slightly warm. The winter season shows more spreading for the participants between slightly cool to slightly warm. It can only be speculated that the participants may have easily altered their clothing insulation in winter because they had access to more insulation, if required, to avoid the sensation of cold. But this advantage was not possible in summer because of the limited light clothing options. Occupants in air-conditioned offices are still affected by seasonal climate and wear heavy clothes in winter. This heavy clothing varies throughout daily working hours (Figure 4.2). The high average Clo value drops gradually from 1.5 in the morning time to 1.2 in the afternoon an act of instantaneous adaptation, which is not possible in the hot season and reflective in the common minimal average Clo value.

In the questionnaire, the participants' thermal acceptability (acceptance of the thermal environment) related to the current indoor environment and did not produce well defined answers. The data distributed between acceptable and unacceptable votes (Figure 4.16). Both in winter and in summer, the calculated percentage of direct unacceptable votes was virtually identical at about 5% of total votes (Figure 4.12). This shows high unacceptability of indoor temperatures less than 19°C, with votes dropping to less than 3.5% and rising (again) to high percentages of about 5% when the indoor temperature increases above 23.5oC. The direct votes for acceptability recorded a high tendency to accept the new set point in the office area which deviated from the standard (usual) set point.

The questionnaire item about the participants' thermal preference (whether they would prefer to feel warmer or cooler) provided quite definite answers. Both in winter and summer, the binned preferred temperatures (Figure 4.10) were virtually identical between 24°C and 25°C operative temperatures (about midway between summer and winter). Even though participants claimed the neutral sensation on the seven scale thermal comfort questionnaires, they preferred the temperature to be warmer, perhaps in order to get rid of extra layers of clothing. Adaptation is applied in this case to maintain thermal neutrality, although the ideal thermal environment is preferable because it does not require additional action or effort.

5.3 Comparison between the Seasons

In both seasons, about one third of votes considered the indoor environment unacceptable (Figure 4.16); however, they still classified it within the comfort zone's limits (between -0.6 and 0.6). The modifications imposed on the set point of indoor temperature based on Standard 55 did not significantly affect the number of participants dissatisfied with the air-conditioning system's performance in the office building. This can be seen in AMV average values in Figure 4.7. However, the percentage of dissatisfaction is considered bias to the summer season as there were more votes claiming higher deviation from neutrality during this period (Figure 4.12). In winter this partiality may be influenced positively by low velocities at most of the workstations in the offices, which reduce the heat losses from the body surface. In this case, stagnated air is considered insulation around the participants' bodies. In contrast, it has a negative influence on the cooling process in summer. So it can be noted that about three quarters of the surveys (74.8%) resulted in acceptable votes when indoor operative temperature recorded between 19°C and 24°C (Figures 4.5) in winter. Comparing the survey conducted in the summer of 2011 (Figure 4.6), the same ratio of about three quarters was recorded as acceptable when indoor operative temperature fell between 25°C and 28°C.

There was a marked difference between the summer and winter conditions (Table 4.6). The average intrinsic clothing ensemble insulation in summer was 0.9 Clo, less than 1.15 Clo in winter (including chair insulation). Chair insulation lifted all values by 0.2 Clo. The activity level was similar throughout the whole study which was almost constant at 1.26 met for both males and females in summer, and about 1.3 for winter; an expected result for office building occupants.

It may be worth noting that during very hot summers in this particular office, the minimum values of clothing insulation were approximately 0.4 Clo, excluding chair insulation. However, this minimum value was two times greater in the summer season, reaching 0.8 Clo. This observation confirms that all participants in winter climate changed their light clothing from (e.g. T-shirts) to heavy clothing (e.g. jackets), as a necessary adjustment to the new thermal comfort conditions. Furthermore, the margin between the maximum and minimum Clo value in winter (1.1 Clo) is much wider than the difference in summer (0.6 Clo), which indicates greater adaptive opportunity in winter as observed in Figure 4.7.

5.4 Comparisons between Thermal Neutrality, Preference and Acceptability

Referring to acceptability and thermal preference observed in Figures 4.10 and 4.12, the preferred operative temperatures in winter and summer were almost identical at 23.5^{o}C, which is in between summer and winter neutralities. The participants of the office building preferred the warm climate more in the conventional standard neutral zone, and claimed thermal neutrality even though the direct unacceptability increased more than 10% beyond 24^{o}C (Figure 4.12). A possible explanation proposed by McIntyre (1978) is that people in hot climates may describe their ideal thermal state as 'slightly cool' while people in cooler climates may choose words like 'slightly warm' to describe their thermal preference, instead of 'neutral'. This helps to understand the discrepancies between thermal sensation scale results and thermal preferences. The average thermal acceptability trend (as shown in Figure 4.11) indicates that participants accept the indoor conditions and vote acceptable, despite their uncomfortable feelings towards the indoor conditions. Figure 4.13 plots the relationship between average hourly indoor comfort temperature (Tin) and the corresponding running seven day outdoor temperature mean. This graph represents the indoor operative temperatures recorded every time a subject expressed thermal comfort (i.e. voted between -0.5 and +0.5). It indicates clearly that thermal comfort inside an air-conditioned building is related to the prevailing outdoor temperature. It was found that the linear equation link between acceptable indoor temperature (To) and the seven day running mean outdoor temperature (Trm) plateaued at about 26^{o}C during the hottest weather conditions. However, this probably reflects the adaptive comfort algorithm implementation in this building's BMS system (the set point algorithm was capped at 26^{o}C). A simple linear regression model has been fitted in Figure 4.13.

Figure 4.14 shows the variation of the seven day running mean outdoor temperature with the binned indoor comfort temperature during summer. The difference between Figure 4.13 and Figure 4.14 designates rev eals a common curve that combines two or three linear equations to form the final equation of thermal comfort.

The linear regression in Figure 4.15 represents the variation of the seven day running mean outdoor temperature with the binned indoor comfort temperature during winter, fluctuating between 18^{o}C and 21^{o}C as a result of the equation of the less sloped straight line. This curve, if added to the previous equation, completes the final relationship between the neutral temperature and the seven day running mean temperature which is explored in the thermal neutrality section.

5.5 Gender, Personal and Psychological Factors

A total of 2386 responses were obtained during this study. These were provided by 30 participants, all of whom participated in both winter and summer surveys. These numbers substantially exceed the minimum sample sizes of 600 for each season and provide increased confidence in the results by substantially expanding the size of the distributed questionnaires. The size of potential samples was large enough to make sure that an acceptable minimum number of votes could be reached even when some participants were not completely involved for the duration of the study. Twenty-three percent of subjects couldn't participate continuously in the questionnaires because of their site commitments. One third of participants indicated English as their first language; the others graduated in Australia as professionals and skilled migrants. All participants (without exception) achieved at least tertiary education'. Each participant properly understood the lengthy ASHRAE questionnaire. However, the ethnic and cultural differences in thermal responses could not be explored thoroughly in this study. It is believed that if there were differences, it would not have had a significant effect on the results.

Gender effects: The female sample formed about 27% of the total sample. The difference between males and females has been related to clothing differences (e.g. Fishman and Pimbert, 1979), with females having greater interseasonal and intraseasonal variability in Clo levels than males. In terms of clothing, no significant clothing differences between the sexes were observed in this office. This may affect thermal sensations and acceptability outcomes marginally. Similar clothing value could be explained by the unusual indoor temperature that led to a common change in behaviour; all participants were informed about the alteration of the indoor set point temperature and were prepared for the new control strategy in the office.

The mean thermal sensation cast by male participants during the winter season's survey was +0.2 on the ASHRAE seven point scale, which was marginally cooler than the female participants' mean of +0.4. In summer the difference narrowed to just 0.1 sensation units, with the males again cooler than the females.

Additionally, thermal sensations changed within the same gender, based on cultural custom or even religious practice.

Managerial effects: There was no method to find out what caused occupants to cease complaining about thermal dissatisfaction. Participants voted for thermal neutrally and acceptability for the indoor environment beyond the theoretical preferred thermal comfort predictions one. In Figure 4.11, the participants requested to be cooler or warmer despite voting as neutral sensations on seven scales. Also, the level of dissatisfaction with the thermal environment was less than those participants in management who claimed that the environment was unacceptable most the time.

Acclimatization effects: About 17% of participants reported that they had air-conditioning at home; while 90% of participants reported that they had air-conditioning in their car. An average of 73% of all participants actually used air-conditioners in their cars and 6% were exposed to conditioned air in public transport during summer. These findings indicate that the majority of participants in this study were exposed to artificial ambient conditions in summer as they were constantly in air-conditioned spaces. The acclimatization did not happen in the beginning of the research (the first weeks in Figure 4.9); subjects voted the highest unacceptable environment in the first month, and adaptation abilities appears later when occupants experienced the new indoor set point.

Also, it is observed that any change in indoor temperature caused a change in the participants' level of satisfaction.

Clothing insulation (Clo) values were calculated according to standard checklists defined in ASHRAE's Handbook Fundamentals (ASHRAE, 2010), Standard 55

(ASHRAE, 1992) and ISO 7730 (EN ISO, 1995). The average clothing measured 1.1 Clo in winter and 0.8 Clo in summer, including office chair insulation which was considered 0.2 Clo. The metabolic rates were calculated based on participants' activity during the previous half hour. Over 70% of participants lived, travelled and worked in air-conditioned environments. Thermal comfort was tested between 18°C and 26°C on the ASHRAE seven point sensation scale; however, thermal neutrality was accrued at 21°C in winter and 24.2°C in summer.

5.6 Comparisons with Previous Thermal Comfort Field Studies

The PMV model is still considered an influential tool in assisting with various adjustments to thermal comfort models, although the new models are not adopted widely in ecological engineering practice. Therefore, the comparisons were referred to as PMV and PPD indices to evaluate the proposed thermal comfort model in this study. In Figures 4.7, 4.14 and 4.15, the PMV model acts as a kind of adaptive model if behavioural adjustments are taken in account; it fully explicates that adaptation occurs in air-conditioned buildings. The new extension acknowledges the importance of expectations, accounted for by the adaptive model; while at the same time not discarding the current PMV model's input parameters that impact the heat balance. Humphreys et al (in Nicol and Humphreys) conclude that the more complex the index (PMV, ET*, SET*), the less calibration with field study results, suggesting that more error and discrepancies between the field and theoretical results would be introduced as completing the heat equation. Combining the PMV model and adaptive approaches may be more acceptable; this was made by Yao et al for the Chinese context. The researchers employed statistical approaches to test the data using the factors in natural conditions. The purpose was to calculate the temperature or arrangement of thermal parameters (such as temperature, humidity and air velocity) which would provide the environment of thermal comfort. The problems with a field study are firstly that it is difficult to measure environmental conditions precisely; and secondly that it is difficult to generalise from the statistical analysis (Nicol and Humphreys, 2001). In addition to errors in data input, the statistical analysis errors give inaccurate predictable relationships.

In 1976 Humphrey presented the variation of comfort temperature with mean indoor temperature from surveys throughout the world. The curve shows a wider temperature range at the comfort temperature than the one shown in Figure 4.13. In naturally ventilated buildings, indoor and outdoor temperatures are very close and vary with a lead or lag time based on the transit of building thermal mass. Therefore, the indoor comfort temperature alters promptly with the variation of outdoor temperature. In summer, three degrees of outdoor temperature to one degree of indoor comfort temperature is the ratio of change in naturally ventilated buildings. However, in an air-conditioned building, four degrees of outdoor temperature to one degree of indoor temperature is the variation of comfort temperature with the mean indoor temperature (Figure 4.13). The access to control and ability to adjust the indoor environment has a direct effect on participant perception of indoor thermal comfort. In air-conditioned buildings, people expect that the machine can cool the space beyond the limits of cooling in naturally ventilated buildings. Therefore, the change of outdoor temperature in summer (Figure 4.12) should be significant to justify a one degree change in the indoor temperature in order to retain the comfort conditions.

The outcomes of field studies shown in the San Francisco area (Schiller et al., 1988; and Brager et al., 1994) introduced minor adjustments for clothing insulation and discussed these limited modifications. During the studies of Auliciems (1983), more than 50 comfort studies from several climatic countries were analysed, and it was found that the practical thermal neutralities rely on the mean indoor and outdoor temperatures.

5.7 Thermal Neutrality in Field Studies

The equation of the relationship found by Auliciems was used to calculate and compare thermal comfort for many studies, such as the Kalgoorlie-Boulder study. Thermal neutrality was assumed by Auliciems on the ASHRAE or Bedford seven point scale. It was found that it is a function of (ti) the mean air, globe or operative temperature; and (tm) the average of the mean daily minimum and maximum monthly outdoor temperatures (Brager and de Dear 1998).

$$T = 0.48\,(ti) + 0.14\,(tm) + 9.22 \qquad \text{[Equation 33]}$$

This equation represents free running buildings more than air-conditioned offices. Humphreys (1981) also regressed field study neutralities depending on outdoor temperatures for both ‘climate controlled’ and ‘free running’ buildings. The relevant regression equation for ‘climate controlled’ buildings (Brager and de Dear 1998) which can be considered for this study is:

$$T = 23.9 + 0.295\,(Trm - 22)\ \exp\{-[(Trm - 22)/(24*(2)½\ )]^2\} \qquad \text{[Equation 34]}$$

This equation can be written in simpler form:

$$T = 23.9 + 0.295\,(Trm - 22)\ \exp([-(Trm - 22)/33.941]^2) \qquad \text{[Equation 35]}$$

Much comfort studies suggest the similar equations for thermal comfort as used in this study. The results in this study can also be graphically compared to those from earlier projects (RP Brager de Dear, 1998). The relation between neutral indoor operative temperature (based on ASHRAE actual sensation votes) and seven day mean outdoor temperature has been plotted in Figure 4.18. It can be observed that the linear regression will not represent the neutrality as the parabolic equation, particularly due to the capping of indoor temperature.

$Tin = -0.0142 (Trm)^2 +0.89Trm +10.9$ [Equation 36]

Therefore, a parabolic equation explains more variance (75% versus 84%). Interestingly, the gradient on the linear adaptive comfort model in Figure 6 is virtually identical to its counterpart in ASHRAE's adaptive comfort standard (2010) for naturally ventilated buildings. However, because the range of indoor temperatures in this air-conditioned building was capped at 26^oC, we can't read too much into this coincidence.

Building management controlled the indoor temperature between 18^oC and 26^oC, and this led to the limited regression between the upper and lower set point temperatures; however, the points of this relationship were spread in a very similar way to the Barger and de Dear equations, despite the different nature of each equation.

For the purpose of comparison, Figure 5.1 plots the neutralities predicted with equation (34) and the equation (36) derived in Figure 4.18 with the main equation (37), which is suggested in Chapter 3 to predict the comfort set point temperature without limitation.

$Tin = 0.31 (Trm) + 17.8$ [Equation 37]

The latter was based on inputs of seasonal mean values for operative indoor temperature (Tin), representing the neutral thermal comfort temperature and seven day mean running temperature (Trm).

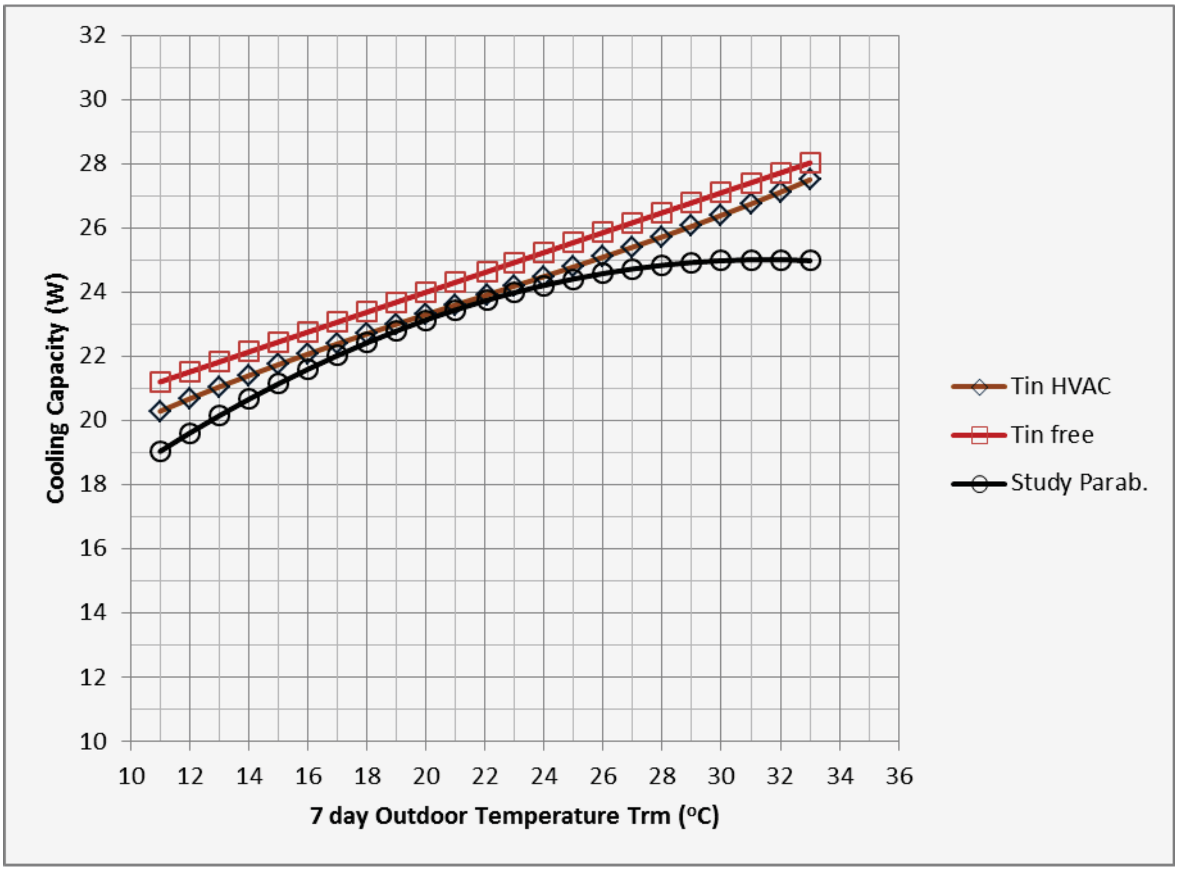


Figure 5.1 The observed and predicted neutral temperatures for the predictive equations (Tin free), neutral temperature in air-conditioned buildings (Tin HVAC), and experimental neutral temperature (Tin) impact on cooling capacity.

Figure 5.1 shows the trends of observed and predicted neutral temperatures for the predictive equations, derived from field experiment projects for neutral temperature in naturally ventilated buildings (Tin free), neutral temperature in air-conditioned buildings (Tin HVAC), and neutral temperature established from the Sydney study (Tin) in an air-conditioned office building.

Figure 4.16 plots the relationship between the average indoor neutral operative temperature (To) and the corresponding running seven day outdoor temperature mean. The red curve in Figure 4.16 represents the indoor operative temperatures recorded every time a participant expressed thermal neutrality (i.e. voted between -0.5 and +0.5). It clearly indicates that thermal neutrality inside an air-conditioned building is related to the prevailing outdoor temperature. We found the linear equation link between acceptable indoor temperature (To) and the seven day running mean outdoor temperature (Trm) plateaued at around 25°C to 26°C during the hottest weather conditions.

Figure 5.1 shows a relatively weak linear relationship between neutrality in air-conditioned buildings as the temperature reached 27°C in equation (36) and an outdoor temperature near 32°C. While the variance power of the parabolic relationship between observed preference and outdoor climate is stronger than the linear regression variance. It was observed that the extreme indoor neutral temperature will not be accepted when the proposed comfort temperature regress linearly and spotted above the upper and below the lower temperatures limitations (18°C and 26°C). This limitation may be referred to the high humidity levels during the study. In addition to the main psychological factor which allows people to tolerate with slight alteration in indoor temperature but they will not accept to shift the indoor environment to the extreme conditions in the presence of cooling machine. Even though there is a wide difference between the previous neutrality equation and the findings made in extreme summer conditions; these findings are entirely consistent with the so-called ‘adaptive model’ of thermal comfort which predicts that building occupants' comfort temperatures converge on the temperatures they experience in their buildings because of their positive tendency to adapt. The parabolic and linear regression lines indicate that the variances in neutralities are relatively correlated at temperatures between 16°C to 28°C, and could be accounted for by outdoor temperatures. However, this correlation will differ completely for temperatures beyond 28°C, or below 18°C which needs to be investigated further.

A change of approximately 6°C in outdoor temperature (Trm) corresponded to a change of around 2°C in preference or neutrality indoors. However, the small number of points in this analysis combined with the large amount of unexplained variance in the models, making it inappropriate to attribute this adaptive effect to behavioural (clothing), psychological (expectation) or physiological (acclimatization) processes.

5.7.1 Economic and Ecological Impacts on Thermal Comfort

In 2007, CSIRO and Sustainability Victoria reported that major heating and cooling energy consumption is responsible for approximately 60% of commercial building greenhouse gas emissions and around 12% of Australia's total energy related greenhouse gas emissions. It is also responsible for a similar proportion of peak electricity demand in the national electricity market. Furthermore, in certain geographic locations, commercial building HVAC can account for up to 40% of peak electricity demand. It is becoming critical to follow more sustainable strategies to reduce the negative impact of energy consumption.

The equation of sensible heat content of air, stated in the Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH, 2010), is considered the major equation to select the air-conditioning equipment and determine its size.

Sensible heat gain (watts) = 1.213 x Supply Air volume (l/sec) x Temperature difference between final and initial air (deg.C)

$$Q_{sensible}\,[W] = 1.213\,[kJ/kg.k]\ V_{Air\ flow}\,[L/s] \times (T_{final} - T_{initial})\,[C] \qquad \text{[Equation 38]}$$

During cooling mode in summer, the cooling equipment lowers the set point temperature inside the building. In contrast, during heating mode in winter, the heating equipment increases the indoor set point temperature to maintain the thermal comfort inside the building. The challenge is to maintain this requirement economically, even achieving a reduction in the overall energy use of the building. Energy savings can be achieved in our predictive neutrality equation because of the following:

i. the reduction of temperature difference between indoor and outdoor conditions resulting in the reduction of heat load on the building; and
ii. the air-conditioning system reduces in size and operates more efficiently with a smaller differential between indoor and outdoor temperatures.

Therefore, the increase in energy savings will lead to lower overall energy costs, and a consequential reduction in greenhouse gas emissions.

Figure 5.2 shows a set of curves that represent the heat content of outside air calculated from equation (38). This outside air is usually dragged into the building to provide a high quality indoor environment under the green star requirement in IEQ. IEQ-1 in the green star requirement increases the outside air provided to each space and improves on the AS1668.2-1991. It is based on the nettable floor area (NLA) of each floor and the percentage of NLA being served with at least 200% improvement on the area of integrated fit-out. The values of heat content will be influenced by indoor and outdoor temperatures.

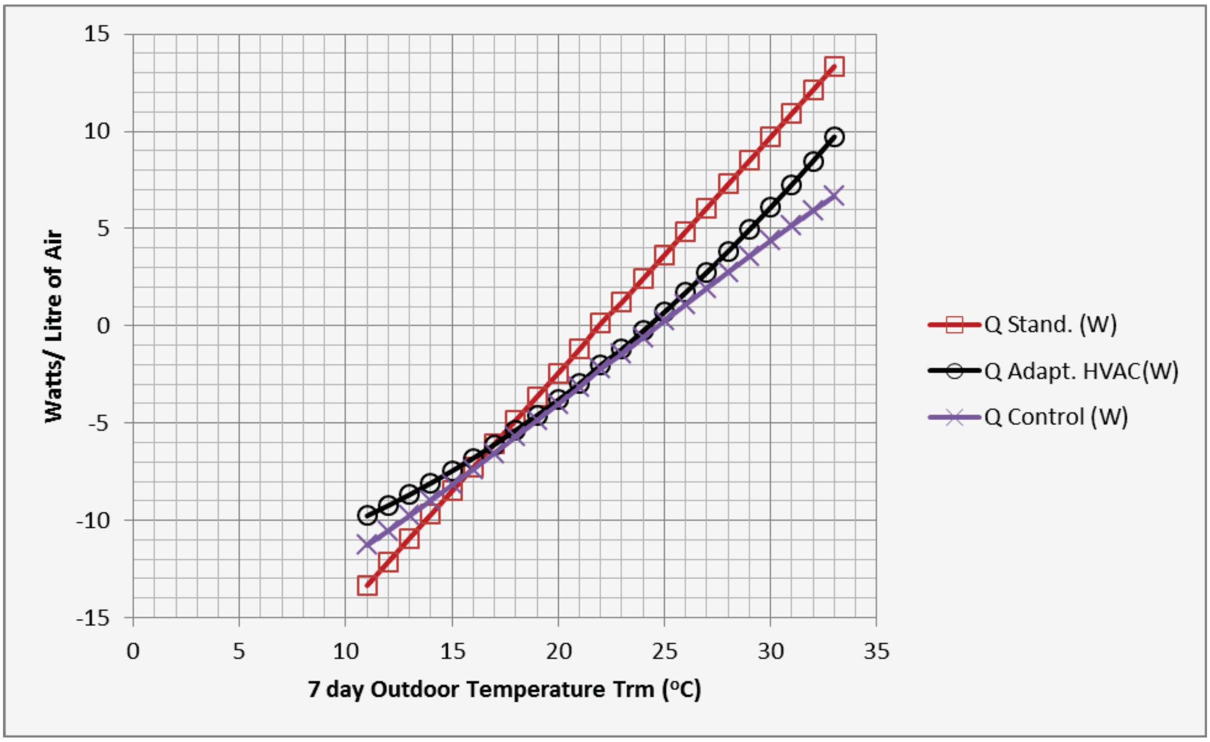


Figure 5.2 Heat content representing HVAC energy consumption required to heat or cool the building for three predictive comfort indoor set point temperatures.

Figure 5.2 shows the heat content which represents the power consumption for standard cooling of the supplementary HVAC system in the buildings, using 22°C as a set point temperature (Q Stand.), the Brager de Dear equation for adaptive controlled buildings (Q Control.), and the parabolic predictive equation for adaptive air-conditioning (Q Adapt. HVAC). Note that these units are affected by the set point changes during operation.

One significant aspect of thermal comfort observed between these curves was the impact heat content used by the parabolic regression to predict the indoor temperature. This was briefly discussed earlier in Chapter 2. The heat required to be added or extracted from the air is less than the one used for the standard cooling requirement in Sydney to 22°C. There is a slight difference between the controlled building equation (Q Control.) and (Q Adapt. HVAC). This difference is advantageous for the controlled building equation in saving energy.

The impact of adaptive air-conditioning will be considerable for multistorey office buildings which require a massive number of liters for ventilation. The saving on cooling and heating as shown in Figure 5.3 is always possible at extreme outdoor conditions. It appears constant at 3.5 Watts per litre of air for an outdoor running mean temperature greater than 26^{o}C.

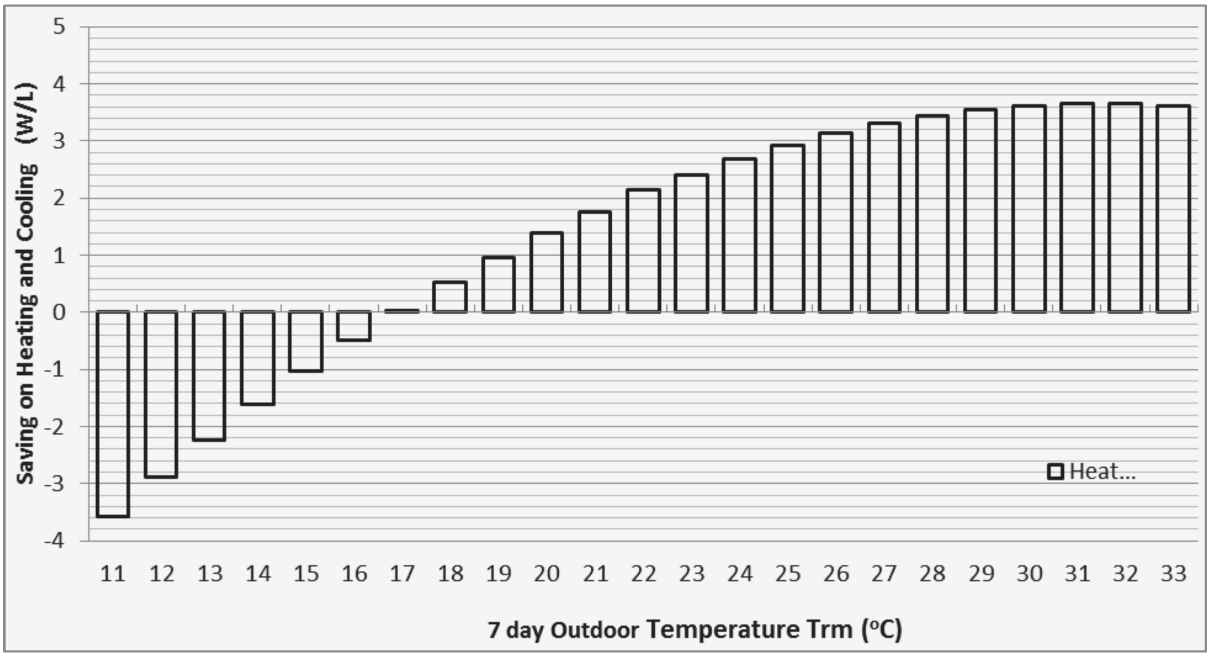


Figure 5.3 The saving values on cooling and heating between an indoor set point temperature of 22^{o}C and based on the parabolic adaptive air-conditioning equation.

In a heating mode, savings reach 3.5 Watts per liter of outside air, but was not recorded beyond 11^{o}C. As the running mean outdoor temperature is close to 18^{o}C, the saving value was minimized, which explains the correlation of indoor set point in Figure 5.2 between the standard and adaptive air-conditioning.

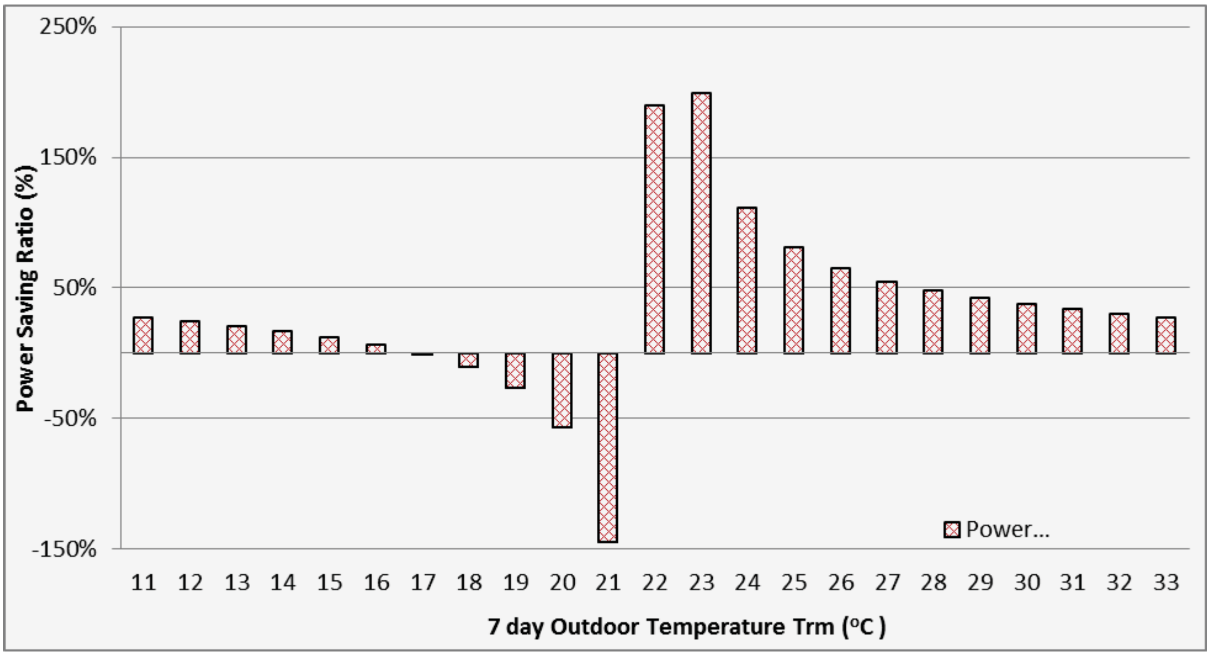


Figure 5.4 The saving percentage on cooling and heating between an indoor set point temperature at 22°C and based on the parabolic adaptive air-conditioning equation.

The percentage of heating or cooling ratio with respect to heat rejection value to a 22°C set point temperature is more representative of the savings opportunity when considering the parabolic equation of the adaptive cooling strategy (Figure 5.4). The negative values represent the losses in power which may reach 150%, but for a mean outdoor temperature between 19°C and 20°C.

Consequently, the hotter the conditions, the less the load difference. Initially, cool savings were higher than 150% at an outdoor mean running temperature of 24°C, and started to decrease as outdoor conditions became hotter. However, the overall savings exceeded 15%, particularly for the extreme outdoor temperature outside the 15°C to 28°C range.

5.7.2 Adaptive Opportunities Provided by Determining New Indoor Temperatures

Comfort considerations are clearly an important aspect for heating, cooling and ventilation; these need to be investigated further in future studies to ensure the adaptive opportunity is fully explored for any compound strategy. The new strategies will depend on an indoor environment that maintains thermal comfort and satisfies ecological challenges. Researchers should not be radical in their views or take an extreme approach to the adaptive model, such as what happened with the ‘Cool Biz’ program in Japan. In this study, set point temperatures as high as 28°C were used with a promotional campaign encouraging workers to come to work dressed with appropriate (lighter) clothing. This model of adaptive air-conditioning applies especially to the occupant, where the outdoor climate is allowed to influence the behaviour of adaptation. The indoor conditions may determine the comfort zone to a certain extent because studies by de Dear and Brager show that occupants in naturally ventilated buildings were tolerant of a wider range of temperatures. However, the occupants in air-conditioned buildings are never given the opportunity to explore their abilities in adaptation. Therefore, it has been observed that the indoor set point temperature of 22°C in air conditioned spaces becomes culturally acceptable but not linked to our thermal comfort. This is due to both behavioural and physiological perceptions, since many different types of adaptive models are not adopted in design standards. Although ASHRAE Standard 55-2010 states that differences in recent thermal experiences, changes in clothing, availability of control options and shifts in occupant expectations can change people’s thermal responses, engineers and the HVAC industry continue to waste this opportunity.

5.8 Summary

Adaptive models of thermal comfort are applied in other standards, such as the European EN 15251 and ISO 7730 standard. Although there are slightly derived methods and results from the ASHRAE 55 adaptive standard, the substantial outcome in all models is almost the same. The difference between these models is in their applications. While the ASHRAE adaptive standard only applies to naturally ventilated buildings without any mechanical cooling equipment, the European standard EN15251 can be applied to mixed mode buildings which are considered naturally ventilated and cooled buildings in extreme conditions. This study provides a real opportunity to apply the adaptive model in fully air-conditioned buildings and presents the adaptive model as a solution.

CHAPTER 6

6 CONCLUSION

During the last two decades, we have witnessed remarkable progress in our knowledge in the field of thermal comfort, shaped by literature from the previous century. The PMV model is still recommended as the most conventional method to predict the thermal comfort of humans inside the built environment. The development of the advanced models of adaptive thermal comfort restrains the widespread application of the PMV model. The importance of the adaptive model lies in the practical analysis of the results from the field; it deals with human responses and direct survey analysis, which challenges the theoretical model. If PMV calculations predict the occupants' satisfaction under certain indoor conditions, surveys record their actual satisfaction under the same conditions. These comfortable indoor conditions in naturally ventilated buildings can be simulated in air-conditioned buildings. Therefore, the flexibility of adaptation has the same influence and effects for both naturally or mechanically controlled environments in terms of comfort and satisfaction.

The current thermal comfort standards still face problems in office buildings; the key challenge is to simultaneously maintain thermal comfort and achieve economic goals. Therefore, the main goal should be to explore the best approach in finding an ideal thermal comfort model in real life terms of human satisfaction and energy savings.

In light of recent global warming data, the Australian summer of December 2012 to February 2013 was the hottest on record with average conditions exceeding the observed 1911–1940 mean by 1.32^{o}K. Summer temperature records were broken from daily through to seasonal time scales: the hottest month on record occurred as well as the hottest day for the entire Australian continent (Bureau of Meteorology, 2013). These severe conditions labelled Australian summers as the ‘angry summer’ (Steffen, 2013); this weather shift will continue for many decades despite efforts to mitigate it. So to minimise the impact of climate change within commercial buildings, designers should plan an indoor environment design which meets comfort expectations and conserves energy, accurately and with sensible strategies. This thesis presents findings which will advance these strategies and increase opportunities to maintain indoor thermal comfort, while improving the performance of air-conditioned buildings.

The research also covers the psychological aspects of thermal comfort and building occupancy studies to differentiate between attitudes, expectations and a theoretical approach. It offers indications of how to change the cultural behaviour and concepts of an office in terms of thermal comfort satisfaction, and experience and interaction with outdoor and indoor environmental conditions. This chapter addresses the ideas and objectives achieved from this research and offers recommendations for future research.

6.1 Summary of Aims and Objectives Addressed in This Thesis

This study assessed occupants’ expectations and ecological approaches in relation to thermal comfort and satisfaction, and shed light on sustainable energy options related to indoor thermal environments, as found in air-conditioned buildings. The research confirmed that occupants of an air-conditioned building are capable of adapting to variable indoor temperatures like the occupants in naturally ventilated buildings; and that the notion of ‘adaptive comfort HVAC’ is feasible. Although thermal comfort features highly in all chapters, this study emphasized the consequential economic and ecological outcomes in an air-conditioned office building in Sydney, the most energy demanding building in use. Therefore, two main topics were covered as a result of a specific study and conference paper; namely, environmental approaches and occupant satisfaction in air-conditioned buildings, and thermal comfort under the adaptive air-conditioning model. The research objectives and outcomes of this study are summarised below:

6.1.1 Environmental Approaches and Occupant Satisfaction in Air-conditioned Buildings

This study aimed to evaluate the occupants' actual mean vote index in relation to the controlled adaptive indoor conditions. After analysing the indoor environment and outdoor weather conditions for an air-conditioned office building, the indoor set point temperatures were found to show a similar degree of dependence on outdoor weather conditions as those in a naturally ventilated building. Although the indoor environment in an air-conditioned building during the extreme outdoor conditions was found to differ significantly in comparison to indoor temperatures in naturally ventilated buildings, occupants behaved similarly. Furthermore, the range of temperatures experienced throughout the study was limited due to the set point algorithm controlling the air-conditioning unit and maintaining the indoor temperature between 18^oC and 26^oC.

The office building thermal comfort questionnaires were used to measure the levels of occupant satisfaction in terms of three categories. These categories explored the thermal sensation, preferences and acceptability of each participant. The indoor environment was generally acceptable, but also voted as hot and cool during the severe weather conditions. As thermal neutrality is hard to maintain in extreme conditions, air-conditioned building occupants are able to accept the building's indoor environmental conditions in the same way as their counterparts in a naturally ventilated building. The occupants were shown significantly higher levels of adaptation regardless of the degree of adaptive opportunity; that is, operable windows within the controlled indoor range of 18°C and 26°C. The limitation of indoor conditions beyond this range prevents us exploring another possible extension in neutrality regression that may be associated with higher or lower indoor temperatures observed in naturally ventilated buildings. To eliminate any potential bias, it was noticed that some participants in this study had strong environmental attitudes according to the educational discipline; that is, they associated strongly with environmental and sustainable science (e.g. air-conditioning, sustainable development and solar technology). However, the other participants recorded similar results despite their indifferent environmental attitudes.

6.1.2 Thermal Comfort under the Adaptive Air-conditioning Model

The main objective of this thesis was to recognize how air-conditioning influences thermal comfort values by comparing both observed and predicted thermal sensation votes, recorded in buildings operated under air-conditioning modes. Although ASHRAE's Standard 55 is currently well recognized from the adaptive model and its sustainability, it still limits the application of the adaptive comfort strategy to air-conditioned buildings rather than buildings under a free-running or naturally ventilated mode. The aim is to apply the adaptive model to air-conditioned buildings to explore whether this model is acceptable to the same level as naturally ventilated buildings.

This thesis introduces the findings of a field study on occupants' thermal comfort in medium size air-conditioned office buildings in the subtropical climate of Sydney. A longitudinal thermal comfort field study was conducted within the air-conditioned building under a variety of objective (indoor and outdoor climate conditions) and subjective (comfort questionnaires) methods (outlined in Section 3.4.3). The actual thermal sensation responses data was collected and indoor operative temperature was calculated based on the adaptive model values. Although the adaptive indoor temperature was capped between 18^{o}C and 26^{o}C , the participants' AMV values did not conform to the PMV values, suggesting that occupants were more adaptive to the building's indoor thermal environment when the building was set under the same indoor conditions as a naturally ventilated building.

Throughout the study, hotter indoor operative temperatures were found to comfort much 'slightly warmer than neutral' thermal sensations than the same environmental conditions calculated using the PMV index. This suggests that the occupants' thermal comfort sensitivities were adapting to the building's new set point temperature over and above the conventional indoor climatic conditions. These divergences advocate that attitudes and expectations could stimulate the occupants to change their physical and behavioural reactions to accommodate the new conditions, especially within a building controlled by BMS. The new unusual conditions induced the adaptation opportunities, such as changing clothing insulation in both seasons. Expectations of the thermal environment seem to increase the acceptability of greater ranges of indoor temperature. Therefore, a new approach in conventional air-conditioned environments is developed to improve occupants' perception of thermal comfort and direct decision-makers to retrofit new and existing commercial buildings under a new energy efficiency strategy associated with the successful mitigation of the impact of climate change.

By considering the adaptive comfort standards in ASHRAE 55-2010 (ASHRAE, 2010) and EN15251-2007, this research hypothesized and discussed whether adaptive comfort standards for naturally ventilated buildings should be applied to air-conditioned buildings. Beyond ASHRAE and the European standard EN15251 requirements (CEN, 2007), designers limit the operation of buildings equipped with mechanical cooling systems to more restrictive PMV-PPD range of indoor thermal conditions, worsening their energy saving prospects and any reduction in carbon dioxide emissions.

The field study evaluated both the actual and predicted thermal sensation votes recorded. It was found that the adaptive comfort model was applicable to the air-conditioned building, but within limitations. The findings provide indications that air-conditioned buildings should be treated as naturally ventilated buildings for indoor temperature ranges between 18°C and 26°C, with the assistance of cooling/heating during extreme climatic conditions.

This study confirms that the adaptive comfort standard, as expressed in ASHRAE Standard 55-2010, is only applied to indoor temperature ranges between 18°C and 26°C. Furthermore, the application of the adaptive comfort model in the European standard and ASHRAE 55-2010 has proven to be the more appropriate alternative to PMV-PPD for air-conditioned buildings with indoor temperatures between 18°C and 26°C. Despite applying the adaptive model for air-conditioned buildings, the indoor operative temperatures recorded (at the time that thermal comfort questionnaires were delivered) were warmer in winter and cooler in summer than the naturally ventilated building set point temperatures for alternative outdoor temperatures. This may enhance the influence of the adaptive model on occupant comfort in air-conditioned buildings, and introduce a new control strategy in future retrofitting plans, which will be more economical, manageable and convenient.

The observed levels of thermal dissatisfaction (APD) were found to be lower than those predicted (PPD) on the basis of instantaneous environmental conditions, especially when compared at temperatures lower than 19^{o}C and higher than 25^{o}C. It also appears that occupant perceptions of comfort and thermal acceptability differed between seasons; participants expressed cool environmental conditions as neutral because of their heavy clothing in winter, and high levels of satisfaction and acceptability with their thermal environment across a broad range of indoor temperatures (i.e. 19^{o}C to 25^{o}C) compared to theoretical predicted values.

The tendency of the occupant to accept the adaptive model rather than the PMV model is due to a perception about what can be offered in terms of indoor environment conditions, and what action and behaviour should be applied to maintain thermal comfort. This tendency represents additional non-building related factors which could impact the occupants' perceptions of thermal comfort, and satisfaction in their workplace's environment, (e.g. staff morale, job (dis)satisfaction, and levels of tolerance and adaption). In this study, objective and subjective parameters formed the building's environment perception, which evaluated occupants' thermal (dis)satisfaction under indoor environment conditions.

6.1.3 Economic Impact

In addition to the development of more healthy buildings in terms of the indoor environment, this research shed light on the sustainable aspect of applying the adaptive model in air-conditioned buildings. It presented findings that the energy saving percentage is more than 15%, which is considered very important in the HVAC industry. While the cooling/heating equipment size would be minimised, the green gas emission would be reduced as a process of reducing damage to the earth’s atmosphere. Furthermore, this energy saving method can be widely applied to existing and new buildings at minimal capital cost. Therefore, the key to energy saving in this model is to establish a building management system based on the adaptive HVAC, which will automatically reduce heating and cooling by decreasing the temperature difference between indoor and outdoor environments. Furthermore, the set point temperature alteration strategy proved to be more valued when weighed against available equipment efficiencies, optimum electric power rate savings and adaptive temperature ranges. It was observed that the energy saving is considerable in the range of moderate temperature and much greater during the warmer months of the hot season (as the ‘angry summer’ will continue for many years to come) and the coldest time of the year.

6.2 Future Research and Recommendations

This thesis addressed many topical issues in the fields of thermal comfort and building performance for a commercial air-conditioned building. These topics should encourage future building occupancy studies to evaluate the adaptive air-conditioning model to utilise all positive aspects of the building’s performance, such as the physical, psychological and economic aspects. Therefore, cooperation among building owners/investors, managers and academics is required to make this complex decision which will assist in establishing an advance universal method in approaching future building research. If studies are conducted from many different climatic zones and countries on different type of buildings, it will validate a set of reliable building performance measurements and data. This validation will then establish consistent building performance research, which considers occupant thermal satisfaction and indoor environment conditions along with energy consumption and psychosocial factors. This study will contribute to enriching the standards of thermal comfort and improve the application of best practice in the engineering and design of buildings. Additionally, it will increase our understanding of how occupants' environmental attitudes are related to their perceptions and tolerance towards adaptive thermal comfort in air-conditioned buildings. This thesis has raise numerous other lines of enquiry, highlighting the need for further research into adaptive air-conditioning under the framework of occupants' views and expectations to the indoor thermal environment. In addition to the environmental and economic benefits of adaptive air-conditioning application in buildings, what are the possible advantages of applying this model in terms of occupant health? If the significant difference between outdoor and a building's indoor set point temperatures are minimised, it reduces the risk of occupant illness, caused by thermal stress.

Although other studies have recently presented similar findings on occupant thermal comfort corresponding to neutral temperature by means of the linear regression method in air-conditioned buildings (such as Buratti and Ricciardi et al, 2013), future studies across a wider range of different buildings are necessary to confirm the relationship between environmental sensations and tolerance factors in different climatic zones. Questionnaires, surveys and interviews proved to be a powerful tool to investigate and explore building occupants' attitudes towards the building's indoor conditions and performance, similar to physical parameters.

Otherwise, the correlation between environmental aspects of sustainable development and actual occupant satisfaction in buildings would not be implicit.

Finally, the recommendations offered in this study emphasize improving the indoor environment and encouraging a more systemic approach to the ecological performance of air-conditioned buildings. It also encourages the development of a new orientation/education of occupants on building design, thermal comfort and environmental control, in addition to the environmental consequences of occupants in air-conditioned buildings.

Furthermore, this thesis contributes towards investigating change in the existing codes and definitions of the adaptive comfort standard to include the air-conditioned buildings in ASHRAE Standard 55-2010 and in the European standard EN2007. It also improves the energy conservation strategies in air-conditioned buildings by using a simple alteration process to the building management system, adjusting the indoor set point temperatures within the 18°C and 26°C range, based on the adaptive comfort algorithm. Nevertheless, further research is still needed in order to reveal the strengths and weaknesses in each study and to come up with a much more comprehensive model of thermal comfort to incorporate air-conditioned buildings in ASHRAE's adaptive air-conditioning model. As the effects of global warming continue and air-conditioned buildings are built, urgent field study is critical to present an updated code and new adaptive air-conditioning standard in thermal comfort.

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7 REFERENCES

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APPENDICES

APPENDICES

7.1 Appendix A: Healthy Building 2012 Conference Paper

Retrofitting Adaptive Comfort Strategies into Conventionally Air Conditioned Commercial Buildings

Hisham Allam [1,*], Richard de Dear[1]
[1]The University of Sydney, NSW, Australia
[*]*Corresponding email: hall9648@uni.sydney.edu.au*

SUMMARY

Reducing the temperature difference between indoor HVAC set-point and outdoor ambient temperatures represents a direct energy conservation measure that requires minimal capital investment in commercial buildings. This paper reports on an intervention study that shifted the HVAC set-points from their normal engineering practices in Australia in an office building located in Sydney. The study manually tuned the building's HVAC set point using the ASHRAE adaptive comfort standard 55-2010 based on a running seven-day mean of outdoor temperature, but capping the set-point band at 26oC and 18oC in summer and winter respectively. Thermal comfort questionnaires, interviews and observations were conducted during the intervention study using a daily sample of twenty office occupants. This longitudinal field study started mid winter and ran till late summer eight months later. Statistical analysis of results showed a linear relationship between indoor comfort temperatures and the running mean outdoor temperature similar to that observed for naturally ventilated buildings that formed the basis of ASHRAE's adaptive thermal comfort model. The research confirmed that occupants of an air conditioned building are capable of adapting to variable indoor temperatures like the occupants in naturally ventilated buildings, and the notion of "adaptive comfort HVAC" is feasible.

KEYWORDS

HVAC energy conservation, sustainable offices, field study, indoor temperature, adaptive comfort.

1 INTRODUCTION

1.1 Adaptive Thermal Comfort

The major role of heating, air conditioning and ventilation system is to maintain acceptable temperature and humidity to the human body. Recent years have seen significant innovation in sustainable buildings in response to global climate change and carbon dioxide emissions. The case for fossil-fuel energy conservation has strengthened the case for adoption of the adaptive thermal comfort concept in naturally ventilated and hybrid air conditioned buildings. But to date there has been scant research on thermal comfort in "adaptive HVAC" situations – i.e. centrally air conditioned buildings in which occupants have limited adaptive opportunity and windows are inoperable.

In naturally ventilated situations it is now accepted that occupants are able to accept a wider range of temperature than simplistic heat-balance models of comfort like PMV suggest, not only because of their psychological habituation and expectation and physiological acclimation, but also their behavioural adjustments (de Dear and Brager, 1998). In 2004, ASHRAE adopted a standard (ASHRAE-55 Thermal Environmental Conditions for Human Occupancy) which featured an adaptive comfort zone for naturally ventilated spaces, then the European adaptive comfort standard known as EN15251 followed suit in 2007.

1.2 Main Problem

The building sector is responsible for almost 40% of the total energy consumption in a form of heat or electricity in many countries (kordjamshidi and King, 2005). International concern about greenhouse mitigation through energy conservation in buildings has prompted many new research enquiries into thermal comfort. A rule-of-thumb in he Australian HVAC sector suggests that one degree Celsius difference of air conditioning set point temperature is roughly equivalent to 10% of HVAC energy. According to the ASHRAE 55 standard (2004, 2010), thermal comfort is managed in an air conditioned building by applying the PMV concept, and in naturally ventilated buildings in which windows represent the primary means of thermoregulation by applying the adaptive model. The adaptive model provides wider indoor temperature range of acceptability which narrows the difference between indoor and outdoor temperature. However, in the Australian commercial building sector both PMV/PPD and adaptive comfort guidelines are largely ignored, and buildings are generally regulated with HVAC at about 22^{o}C, summer and winter. This information prompts two questions; why do Australian buildings disregarding the environmental and financial implications of adaptive thermal comfort standards? Can Australian office building occupants accept adaptive comfort conditions like their counterparts in other parts of the world such as Japan? (CoolBiz press release, 2005). The two main adaptive comfort standards (ASHRAE 55-2010 and EN15251) were developed from data within naturally ventilated buildings, so the scope of their application is limited to these types of buildings though human adaptation is also relevant to air conditioned buildings, so there is a need for research into the concept of “adaptive HVAC”.

1.3 Research Objectives and Significance

The main aim of this study was to apply the adaptive model in an air conditioned commercial building. The significance of this research in the long-term is the potential to reduce greenhouse gas emissions from the commercial building sector, not only for new-build but also existing building stock, as this concept can readily be retrofitted to any building with a programmable Building Management System (BMS). The occupants of office buildings are able to maintain thermal comfort and energy conservation when provided with the knowledge of making personal and environmental adjustments.

2 MATERIALS/METHODS

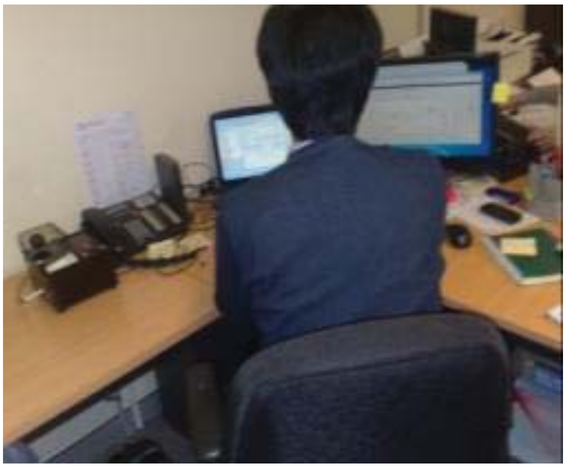
Longitudinal field study was selected as the most appropriate research methodology to examine human adaptive thermal comfort inside an air-conditioned office building because it relies on a relatively small number of cooperative subjects over a prolonged monitoring period. The adaptive approach to thermal comfort is based on the findings of surveys of thermal comfort conducted in the field (Nicol & Humphreys, 2007). The method used in this project involved collection of physical indoor and outdoor measurements along with simultaneous comfort questionnaires from occupants of the building offices Figure 1 and Figure 2. Outdoor environmental data was collected from Latest Weather Observations in Bankstown weather station (Commonwealth of Australia 2010, Bureau of Meteorology) which allowed calculation of a seven-day running mean outdoor temperature with the following equation:

$$Trm = 0.34 \cdot T_{-1} + 0.23 \cdot T_{-2} + 0.16 \cdot T_{-3} + 0.11 \cdot T_{-4} + 0.08 \cdot T_{-5} + 0.05 \cdot T_{-6} + 0.03 \cdot T_{-7} \qquad (1)$$

Where:

Trm: The seven days running mean outdoor temperature measured in ^{o}C (de Dear, 2006).

$T_{-1,-2,-3,-4,-5,-6,-7}$:The mean outdoor temperature in ^{o}C,(-1, -2, -3, -4, -5, -6, -7) refer to yesterday, the day before yesterday, the day before the day before yesterday etc.



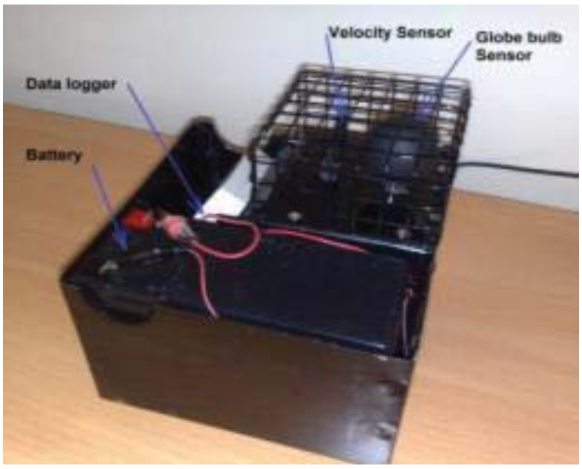


Figure 1: Occupant questionnaire completion. *Figure 2: Desk-top comfort instrument.*

This expression for outdoor mean temperature was then input to the adaptive model in order to calculate each day's target set-point temperature (*Tc*) for the air conditioning control system. The proposed adaptive model equation was that for naturally ventilated buildings in ASHRAE's Standard 55 (ASHRAE, 2010). building order to gain cooperation of the building owner/tenant we capped the air conditioning set-point lower- and upper-temperature range at 18 ^{o}C and 26 ^{o}C respectively:

$$Tc = 0.31 \cdot Trm + 17.8 \left[\begin{matrix} 26^{o} \\ \\ 18^{o} \end{matrix} \right. \tag{2}$$

2.1- Office Building Description:

The selected building is located in Sydney, two kilometers away from Bankstown Airport where the weather station data was collected. The weather station belongs to climatic zone 5 which is a seasonal subtropical humid climate. The building recognized as a typical suburban office building and categorized under Class 5 building in the Building Code of Australia (BCA, 2009). The building comprises a warehouse and two levels of offices. The building envelop structure was made of pre-fabricated concrete walls and metal deck roofing. Single glazed façade, facing North West, made of tinted glass and shaded internally by vertical blinds. Office area was 440 *square meters* occupied by 26 employees. An air-cooled split ducted air conditioning unit of 40kW cooling capacity was used to cool and heat the offices in each level. The air-handling units were located in the ceiling space, supplying air-conditioned air to the rooms via insulated ducts connected to ceiling-mounted diffusers. The indoor set point temperature was controlled manually by a wall-mounted touch pad on each office level.

2.2 Measurement equipment and Questionnaire

A customized "comfort package was used to measure the ambient comfort variables within the occupied zone. The package (Figure 2) very portable and provides 3-minute climatic readings at the desk-level of the respondent. The American Society of Heating, Refrigeration and Air Conditioning Engineers designed a standard questionnaire for thermal environment survey (ASHRAE 2004) that we have used and modified to suit our research purpose. The questionnaire is intended to characterise whole-body thermal comfort and comprised eight major questions. The first corresponded to the demographic information such as age, height, weight and gender. Occupant's Clothing questions followed and provided information needed for calculation of clo value. The third question dealt with occupants' activity within half an hour in order to determine metabolic rate. The fourth section included questions relating to thermal comfort, (thermal sensation, thermal preference and thermal acceptability). Thermal sensation was measured on the ASHRAE seven-point scale ranging from cold (-3) to hot (+3). Thermal preference classified subjects into three groups; those preferring to be in a warmer place, those who preferred cooler, and the remainder who preferred temperature to remain as is. Thermal acceptability was captured with a binary "right-here right now" question (acceptable/unacceptable). The last two questions allowed the occupants to assess their own productivity and stress level on percentage and integer scale respectively.

Each office space was equipped with unobtrusive sensors to record temperature, humidity and air speed throughout the month. Every subject completed sets of comfort surveys, distributed every morning to all building occupants. The indoor environmental data checked against the proposed adaptive comfort temperature (Tc) which was derived from the outdoor weather observations. The one-page questionnaire was been designed to record the thermal comfort within the office and did not take longer than two minutes to complete.

3 RESULTS AND DISCUSSION

3.1 Occupants Thermal Sensation

Figure 3 displays a simple comparison between Actual Mean Vote (AMV) and Predicted Mean Vote averaged (PMVav). Predicted Mean Vote is an index calculated for each respondent on the basis of four environmental parameters (t_a, t_r, v, rh) and two personal parameters (clo, met). It can be seen for all votes within the cooler operative temperature bins from 18°C to 21°C that the average PMVav registered lower thermal sensation than the actual votes from these occupants (AMV), meaning that these occupants felt more comfortable (neutral) in the cooler temperatures than the six thermal comfort parameters would suggest. However, for the operative temperature bins 22 through 26°C, there was generally close agreement between predicted and actual thermal sensations.

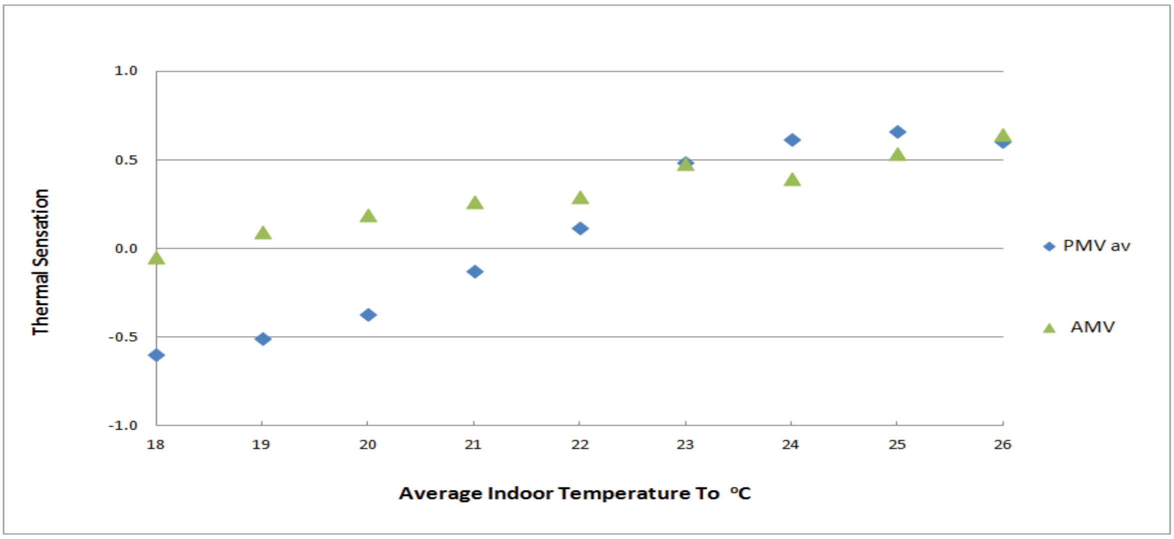


Figure- 3: Comparison between average actual votes (AMV) and average Predicted Mean Vote (PMV) with respect to indoor operative temperature bins.

3.2- Indoor comfort temperature and seven days running mean outdoor temperature relationship.

Figure 4 plots the relationship between average indoor neutral operative temperature (To) and the corresponding running seven-day outdoor temperature mean. This graph represents the indoor operative temperatures recorded every time a subject expressed thermal neutrality (i.e. voted between -0.5 and +0.5). It indicates clearly that thermal neutrality inside an air conditioned building is related to the prevailing outdoor temperature. We found the linear equation link between acceptable indoor temperature To and seven-day running mean outdoor temperature (Trm) plateaued at about 25~26^{o}C during the hottest weather conditions, but this is probably reflecting the way we implemented the adaptive comfort algorithm in this building's BMS system (we capped the set-point algorithm at 26^{o}C). While a simple linear regression model has been fitted in Figure 4, a parabolic equation explains more variance (73% versus 84%). Interestingly the gradient on the linear adaptive comfort model in Figure 6 is virtually identical to its counterpart in ASHRAE's adaptive comfort standard (2010) for naturally ventilated buildings, but because the range of indoor temperatures in this air conditioned building was capped at 26, we can't read too much into this coincidence.

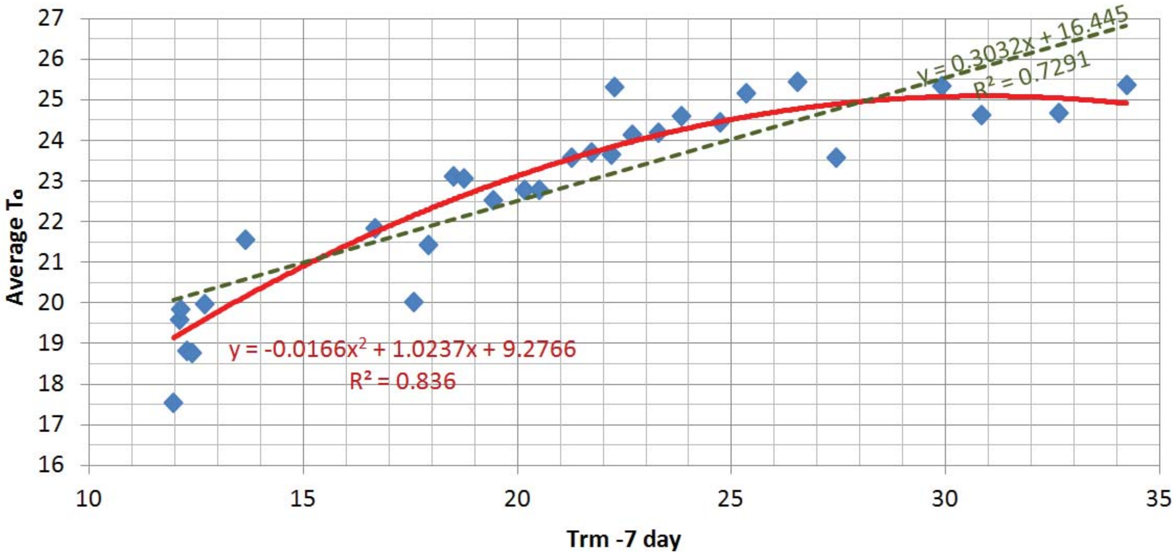


Figure- 4; Indoor acceptable operative temperature (To) with respect to running 7 day outdoor temperature (Trm).

4 CONCLUSIONS

The results found a relationship between neutral operative temperature recorded inside an air conditioned office building, and the outdoor temperature prevailing over the last seven days (exponentially weighted). While this kind of adaptive comfort relationship is very familiar in a naturally ventilated (or free running) context, we think this study is one of the first to confirm the relevance of the adaptive comfort concept in air conditioned buildings where occupants have more constrained adaptive opportunity.

ACKNOWLEDGEMENT: This research was supported by Human Research Ethics Committee in The University of Sydney

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7.2 Appendix B: Thermal Comfort Study Ethics Approval

Hisham Allam <allamengineers@gmail.com>

Annual Report Form Approved (12185)

1 message

Human Ethics <ro.humanethics@sydney.edu.au> Thu, Jul 12, 2012 at 4:38 PM
To: Richard de Dear <richard.dedear@sydney.edu.au>
Cc: "hall9648@uni.sydney.edu.au" <hall9648@uni.sydney.edu.au>

Dear Associate Professor de Dear

Title: Retrofitting Adaptive Comfort Strategies in Conventionally Air Conditioned Commercial Buildings

Protocol No: 12185

First Approval Date: 14 January, 2010

Thank you for forwarding the Annual Report Form for the above study. Your protocol has been renewed to **31 January, 2013.**

Please note that if your project is not completed within four (4) years from the first approval date, you will have to submit a Modification Form requesting an extension. Please refer to the guidelines on extension of ethics approval which is available on the website at: http://sydney.edu.au/research_support/ethics/human/extension.

Any amendments/modifications to the protocol must be approved by the Human Research Ethics Committee (HREC) [refer to the website at: http://sydney.edu.au/research_support/ethics/human/forms for a Modification Form].

Please do not hesitate to contact the Research Integrity (Human Ethics) should you require further information or clarification.

Yours sincerely

Human Research Ethics Committee

The University of Sydney

7.3 Appendix C: Thermal Comfort Study Occupant Consent Form

Hisham Allam <allamengineers@gmail.com>

Thank you

Thank you

https://mail.google.com/mail/u/0/?

Hisham Allam <allamengineers@gmail.com>

Hisham Allam <hisham.allam@dtigroup.com.au> Mon, Oct 26, 2009 at 2:02 PM

To: Sam Bachir <sam.bachir@dtigroup.com.au>

Dear Sam,

I would like to thank you for giving me the employment opportunity at Dynatech Industries . Although, I have been here for a short period of time, I have to say that I have met with remarkable people and had the chance to know your company closely as one of the largest companies in Mechanical Services Industry. Hoping to have further cooperation in the future during my work in the new company (details attached below).

On the other hand, I would truly appreciate your assistance so much in making my research project happens at your company which will give Dynatech a leading position in this new innovative air conditioning design strategy, such research, is known by adaptive air conditioning, will improve thermal comfort in office buildings, save energy and reduce carbon gases emissions. In this matter, Stephen Carpenter is trying to organise building access and shape the best participation of Dynatech in this project. I am requesting a permission from Dynatech to allow me conduct my data collection at Revesby office building, using one page questionnaire will be distributed to the Company employee during multiple visits. Please find attached documents related to my research project which provide research advertisement and participation information.

For further information please do not hesitate to call me at any time on 0408555598 or
Email: hall9648@uni.sydney.edu.au.

Regards
Hisham Allam
Design Engineer

M 04 0855 5598 | T +61 02 9947 7600

<<THERMAL ENVIROMENTAL SURVEY.doc>> <<poster_Thermal Comfort - Hisham Allam Oct.ppt>>
<<090823-Participant_Consent_Form.doc>> <<091018-Participant_Information_Statement.doc>>

5 attachments

THERMAL ENVIROMENTAL SURVEY.doc
113K

poster_Thermal Comfort - Hisham Allam Oct.ppt
1369K

090823-Participant_Consent_Form.doc
101K

091018-Participant_Information_Statement.doc
103K

Dynatech industries

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Date: 2/11/2009
Attn: Hisham Allam

COMPANY CONSENT FORM

I, ... Sam Bachir ....[PRINT NAME],
The......Directing Manager...................[POSITION] of
, ...Dynatech Industries ....[COMPANY NAME], give consent to my participation in the research project

TITLE: Retrofitting Adaptive Comfort Strategies in Conventionally Air Conditioned Commercial Buildings

In giving my consent I acknowledge that:

1. The procedures required for the project and the time involved have been explained to me, and any questions I have about the project have been answered to my satisfaction by Mr Hisham Allam.

2. I have read the Participant Information Statement and have been given the opportunity to discuss the information and my involvement in the project with the researcher/s.

3. I understand that I can withdraw from the study at any time, without affecting my relationship with the researcher(s) or the University of Sydney now or in the future.

4. I understand that my involvement is strictly confidential and no information about me will be used in any way that reveals my identity.

5. I understand that being in this study is completely voluntary – I am not under any obligation to consent.

6. I understand that I can stop the questionnaires at any time if I do not wish to continue, the information provided will not be included in the study.

7. I consent to receive: –

i) 1-minute questionnaires YES ☒ NO ☐

iii) a project summary upon completion of this study YES ☒ NO ☐

If you answered YES to receiving a project summary at the end of the study (iii above), please provide your details i.e. mailing address, email address.

Yours sincerely,
Dynatech Industries

Sam Bachir
Managing Director

Dynabuilt Pty Ltd
ABN 26 108 925 453

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7.4 Appendix D: Thermal Comfort Study Participant Information Statement

The University of Sydney

Research Office
Discipline of Architectural Science
Faculty of Architecture Design & Planning

ABN 15 211 513 464

CHIEF INVESTIGATOR
Associate Professor Richard de dear;
Director of Research Training

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Facsimile: +61 2 9351 3031
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Web: www.usyd.edu.au/

PARTICIPANT INFORMATION STATEMENT
Research Project

Name of Project: Retrofitting adaptive comfort strategies into conventionally air-conditioned buildings.

This research aims to investigate adaptive comfort concepts and strategies in large-scale air conditioned buildings. The major objective is to achieve optimum thermal comfort in this office building. In particular it will explore your comfort responses to various air conditioning target temperatures.

Occupants of the office building will complete a comfort survey distributed via local network of their organization. The approach of this project is to select group of participants (about 30 people) from various locations within the building. After being selected for the study, office spaces will be equipped with unobtrusive sensors to record data such as temperature, humidity and air speed throughout the month (these instruments WILL NOT interfere with the daily activities of the participants). These data will be matched against your questionnaire responses and simultaneous outdoor weather observations. A simple one-page questionnaire has been designed to record your thermal comfort within your office and WILL NOT take longer than ONE MINUTE to complete each time. If you agree to participate you may be asked to complete this questionnaire up to three times each day. Each participant in this sample (30 people) will have a Person Identification Number (PIN) to allow researchers to collect questionnaires from the same person on multiple visits. A list of your PIN and name will facilitate our follow-up visits, but will be disposed of at the end of the study, any information or personal details gathered in the course of this study are confidential and no individual will be identified in any publication of the results. Only the two researchers listed below will have access to the data. You may withdraw from the study at any time, without any penalties or questions being asked. A brief summary of the project's findings will be distributed to all participants by email upon completion by the end of 2010. Upon completion of this research project, building occupants will enjoy an optimum indoor environment and have the psychological benefit of knowing that they are working in an environmentally sustainable workplace.

This study is being conducted by the following researcher to meet the requirements for the Master of Philosophy degree. If you have any questions or concerns please contact any of the researchers below:

Associate Professor Richard de Dear,
The University of Sydney, Faculty of Architecture, Design & Planning
Phone: 02 9351 5603
Fax: 02 9351 3031
Email: rdedear@usyd.edu.au

Hisham Allam, Postgraduate Research Student, The University of Sydney, Faculty of Architecture, Design & Planning
Phone: 04 08 555 598
Email: hall9648@uni.sydney.edu.au

Any person with concerns or complaints about the conduct of a research study can contact the Deputy Manager, Human Ethics Administration, University of Sydney on (02) 8627 8176 (Telephone); (02) 8627 7177 (Facsimile) or human.ethics@usyd.edu.au (Email).

This information sheet is for you to keep

7.5 Appendix E: Co-Author Statement of Contribution