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Development of Adaptive Thermal Comfort Models for Residential Buildings in Sarawak Urban Areas

John Tin Yuan En

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Development of Adaptive Thermal Comfort Models for Residential Buildings in Sarawak Urban Areas

John Tin Yuan En

A thesis submitted

In fulfillment of the requirements for the degree of Doctor of Philosophy

(Electrical and Electronics Engineering)

Faculty of Engineering
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2018

DECLARATION

I, John Tin Yuan En (11011558) from Faculty of Engineering UNIMAS hereby declare that the work entitled, Development of Adaptive Thermal Comfort Models for Residential Buildings in Sarawak Urban Areas is my original work. I have not copied from any other students' work or from any other sources except where due reference or acknowledgement is made explicitly in the text, nor has any part been written for me by another person. The thesis has not been accepted for any degree and is not concurrently submitted in candidature for any other degree.

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ABSTRACT

Energy consumption of building sectors has increased rapidly due to the improved living standard and the rise of resident's expectations on thermal comfort. Mechanical ventilations especially air conditioning system is essential for hot and humid countries to achieve their ideal indoor comfort condition. However, such cooling system consumes a huge amount of electricity which is in contradiction with the concept of energy conservation. Thermal comfort assessment is one of the methods to overcome this issue. It evaluates the thermal perception of the occupants and consecutively facilitates the efficient usage of mechanical ventilation systems and attains the purpose of saving the energy. Steady state model and adaptive model are the two main approaches to evaluate thermal comfort. Fanger's Predicted Mean Vote (PMV) model is a prevalent example of steady state model where environmental and personal factors are comprised. On the other hand, adaptive model involves comfort temperature and outdoor temperature to predict the thermal comfort of the indoor environment. Several research studies have indicated that PMV model is not applicable on tropical buildings as it often overestimates the actual thermal sensation of the occupants. Conversely, adaptive model is found to be expressing occupants' thermal perception competently. In this study, thermal comfort analysis was carried out on the free running residential buildings in Sarawak which were naturally ventilated with minimal usage of mechanical ventilation systems. Physical measurements and subjective assessments were performed to evaluate the thermal responses of 287 residents based on ASHRAE scale, Bedford scale, thermal acceptability scale and thermal preference scale. PMV model was also used to predict the thermal sensation of the residents. Bedford scale showed the highest percentage of acceptable votes followed by

ASHRAE scale, thermal acceptability scale and thermal preference scale. The comfort temperatures of the study were obtained from ASHRAE scale, Bedford scale and PMV model which were found to be 27.5 ℃, 28.1 ℃ and 26.2 ℃ respectively. The adaptive thermal comfort models were proposed based on the responses of residents on ASHRAE scale and Bedford scale. According to actual percentage dissatisfied which fulfilled 80% satisfaction, the upper and lower limit of the model for indoor operative temperature, relative humidity and air velocity were from 27.3 ℃ to 29.6 ℃, 74.0% to 92.0 % and 0.18 ms^{-1} to 0.66 ms^{-1} respectively.

Keywords: Thermal comfort; residential buildings; adaptive model; comfort temperature; ASHRAE scale; Bedford scale

Perekaan Model Keselesaan Terma Adaptif untuk Bangunan Kediaman di Kawasan Bandar Sarawak

ABSTRAK

Penggunaan tenaga dalam sektor bangunan telah meningkat dengan drastik disebabkan oleh taraf kehidupan dan permintaan penduduk yang semakin meningkat terhadap keselesaan terma. Pengudaraan mekanikal terutamanya sistem penyaman udara memainkan peranan yang penting untuk negara-negara yang mengalami iklim panas dan lembap demi mencapai keselesaan terma yang memuaskam. Walaubagaimanapun, sistem penyejukan tersebut memerlukan pengunaan elektrik yang besar dan fenomena ini adalah bertentangan dengan konsep pemuliharaan tenaga. Penilaian keselesaan terma merupakan salah satu cara penyelesaian untuk mengatasi masalah tersebut. Cara ini menilai persepsi terma penduduk-penduduk kediaman untuk memastikan penggunaan pengalihudaraan mekanikal secara berkesan dan stereusnya mencapai tujuan penjimatan tenaga. Model keadaan mantap dan model penyesuaian adalah dua pendekatan utama untuk menilai keselesaan terma. Model Fanger Predicted Mean Vote (PMV) ialah salah satu contoh model keadaan mantap yang melibatkan faktor persekitaran dan faktor manusia. Sebaliknya, model penyesuaian melibatkan suhu selesa dan suhu persekitaran luar untuk meramalkan keselesaan terma dalam persekitaran yang tertutup. Beberapa kajian penyelidikan telah menunjukkan bahawa model PMV tidak sesuai untuk digunakan di atas bangunan - bangunan yang beriklim tropika kerana ia sering meremehkan sensasi haba yang dialami oleh para penghuni. Model adaptif pula dikesan dapat menyampaikan persepsi terma penghuni dengan lebih tepat. Dalam penyelidikan ini, kawasan-kawasan perumahan Sarawak yang menggunakan sistem pengudaraan semula jadi dan sistem *pengudaraan mekanikal telah disiasat dari segi keselesaan terma. Tindak balas terma daripada 287 penduduk tempatan telah dianalisis melalui pengukuran fizikal persekitaran dan penilaian subjek berdasarkan soal-soal penyelidikan dengan menggunakan skala ASHRAE, skala Bedford, skala penerimaan terma dan skala kegemaran terma. Model PMV juga digunakan untuk meramalkan reaksi penduduk-penduduk terhadap keadaan persekitran mereka. Skala Bedford memaparkan peratusan penerimaan yang tertinggi diikuti oleh skala ASHRAE, skala penerimaan terma dan skala kegemaran terma. Suhu selesa yang diperolehi daripada skala ASHRAE, skala Bedford dan model PMV masing-masing adalah 27.5 ℃, 28.1 ℃ dan 26.2 ℃. Model-model keselesaan terma adaptif ini adalah dibina berdasarkan maklumat-maklumat yang dibekalkan oleh para penduduk melalui skala ASHRAE dan skala Bedford. Untuk memastikan model-model yang dibina ini memenuhi kepuasan para penduduk sebanyak 80%, had batasan untuk model ini dari segi suhu, tahap kelembapan dan halaju udara adalah dari 27.3 ℃ hingga 29.6 ℃, 74.0% hingga 92.0% dan 0.18* ms^{-1} *hingga 0.66* ms^{-1}.

Kata kunci: *Keselesaan terma; kawasan perumahan; model adaptif; suhu selesa; skala ASHRAE; skala Bedford*

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

A	Factor Accordance
a	Constant Value
AHU’s	Air Handling Units
APD	Actual Percentage Dissatisfied
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASV	Air Speed Vote
b	Constant Value
BPS	Building Performance Simulation
BU	Bias Uncertainty
°C	Degree Celsius
CEN	European Committee for Standardization
CFD	Computational Fluid Dynamics
clo	Clothing Insulation
cm	Centimeter
D	Diameter of the Globe
e	Expectancy Factor
e	Exponential
EAHE	Earth to Air Heat Exchanger
EN	European Standard
$\mathcal{E}_{\mathrm{g}}$	Emissivity of the Black Globe
GHG	Greenhouse Gas Emission

GWh	Gigawatt Hour
HVAC	Heating, Ventilation, and Air Conditioning
IPP	Independent Power Producer
ISO	International Organization for Standardization
K	Kelvin
kWh	Kilowatt Hour
$\mathrm{kWh/m^2y}$	Kilowatt Hour per Meter Square Year
kWh/y	Kilowatt Hour per Year
$\mathrm{m^2K/W}$	Meter Square Kelvin per Watt
m	meter
$\mathrm{ms^{-1}}$	Meter per Second
MATLAB	Matrix Laboratory
met	Metabolic Equivalent of Task/Activity Level
MRT	Mean Radiant Temperature
MS	Malaysian Standard
MTCV	Mean Thermal Comfort Vote
Mtoe	Million Tons of Oil Equivalent
MTSV	Mean Thermal Sensation Vote
n	Sum of the Total Readings
PECW	Passive Evaporative Cooling Wall
PJ	Petajoules
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PTAC	Packaged Terminal Air Conditioner

PV	Photovoltaic
r^2	Correlation Coefficient
RH	Relative Humidity
RHV	Relative Humidity Vote
RP	Research Project
SCAT	Smart Control and Thermal Comfort Project
T_a	Indoor Air Temperature
T_c	Comfort Temperature
$T_{c\text{-raised}}$	Comfort Temperature Raised
TDR	Temperature Difference Ratio
T_g	Globe Temperature
T_{op}	Operative Temperature
T_{out}	Outdoor Temperature
T_r	Mean Radiant Temperature
TRNSYS	Transient System Simulation Tool
TSV	Thermal Sensation Vote
USA	United State of America
v_a	Air Velocity
Wm^{-2}	Watt per Meter Square
X	Measurement Parameters
X_{max}	Maximum Value of the Measured Data
X_{min}	Minimum Value of the Measured Data

CHAPTER 1

INTRODUCTION

1.1 Research Background

Energy saving remains a vital issue for decades in the times of increasing environmental problems. Around 30% to 40% of world's energy consumption is produced by building sector in preserving comfortable indoor state and to supply power for the electrical devices [1-5].

Heating, ventilation and air conditioning (HVAC) systems are the major energy consumers in buildings which use almost 50% of the total supplied energy [1-3, 6] and become one of the major contributors to the global energy consumption. Owing to the improved demand of indoor comfort condition, the application of air conditioning system has increased and become important in different types of buildings such as offices, factories and houses [2].

Therefore, the overall energy consumption for HVAC systems is magnifying and lead to the growth of greenhouse gas emissions [2, 4, 6]. Based on the findings in [4, 5], 40% to 50% of the global greenhouse gas emissions are yielded from building sector.

For hot and humid climate countries, the application of HVAC system is important for occupants to achieve their ideal indoor thermal comfort. Malaysia is one of the countries which rely heavily on the application of cooling systems due to its climate. Thus, buildings in Malaysia are discovered to be very electricity consuming [7, 8]. Studies also attested that the energy consumption of building sector in Malaysia has increased by 34% from 2005 to 2010 [7] and further increased again from 2010 to 2014 by around 10% [9]. Based on the research done by worldwide energy consumption, 19% of the energy in Malaysia is spent on residential sector [10-12].

1.2 Problem Statements

Energy crisis is gaining attention due to the increase of energy usage and Greenhouse gas (GHG) emission. Therefore, energy conservation and energy efficiency has become essential to overcome this issue. Building sector is discovered to be one of the main causes leading to this problem since it involves the application of HVAC system which is electricity consuming.

Due to the climate condition, Malaysia often experiences relative high daily temperature and humidity level. Such phenomenon will generate a sense of thermal discomfort and influences indoor comfortability. As a result, residents incline to rely on HVAC system to achieve their ideal indoor environment which directly cause the increase of energy consumption in building sector [13, 14]. Thus, it is necessary to determine residents demanded comfortable parameters in order to minimize the total energy consumed by HVAC system.

It is discovered that high energy consumption of air-conditioning is not necessarily needed to achieve thermal comfort in many cases [15]. Huge amount of energy could be saved if HVAC systems are managed to operate under a wider range of acceptable indoor temperature. Due to the increase public awareness on climatic change and environmental issues, thermal comfort in buildings has attracted the attention of many researchers worldwide [15]. Efforts need to be done to optimize thermal comfort settings involving both energy usage and climate change [16].

Predicted Mean Vote (PMV) developed by Fanger has been used widely in thermal comfort standards [17], covering a wide range of climates to predict and assess indoor thermal comfort. Unfortunately, PMV often overestimates the actual thermal sensation of the occupants especially under tropical climate.

The existing thermal comfort models are mostly focused on non-residential buildings such as office buildings. Therefore, the applicability of these models on non-air-conditioned residential buildings in hot climate remain an unsolved issue [18]. Adaptive principal on thermal comfort model is found to be an effective approach to identify the environmental criteria required to fulfill the comfort demand of the occupants [19]. A number of researches have been done to develop various adaptive thermal comfort models based on different living indoor ambiences and climates. However, there are not many studies performed in Malaysia [20] especially on residential buildings. Besides, most of the adaptive comfort models are developed via a comfort scale called ASHRAE scale. In fact, Bedford scale is another comfort scale which can be used to determine thermal comfort. However, this scale has not yet been used in developing the adaptive comfort models.

1.3 Objectives of the Study

i. To compile and categorize recent thermal comfort studies.

ii. To evaluate site conditions by performing site measurements.

iii. To analyze thermal comfort conditions of the occupants through thermal comfort analysis.

iv. To discover the comfortable parameters demanded for the residential buildings of the study

v. To develop, analyze and validate the adaptive thermal comfort models for the study.

vi. To predict the impact of the proposed adaptive thermal comfort models.

vii. To define the optimum requirements to achieve thermal comfort in residential buildings.

1.4 Expected Outcomes

i. Comprehension of different types of thermal comfort models.

ii. Determination of thermal characteristics of the residential buildings involved in the study.

iii. Revelation of occupants' thermal sensation state and thermal comfort state.

iv. Identification of comfortable parameters required to attain thermal comfort.

v. Development of adaptive thermal comfort models which are applicable on the residential buildings in the urban areas of Sarawak.

1.5 Structure of the Thesis

The present research is presented by five chapters in this thesis. A brief description of each chapter is described as follows:

Chapter 1 explains the research background, problem statements, objectives and the expected outcomes of the study. It briefly states out a general introduction on energy trend, and also thermal comfort.

Chapter 2 describes on the literature reviews of the study. It shows the energy trend in Malaysia and also the thermal comfort studies that have been done by various researches. Different thermal comfort models and their applications are also studied.

Chapter 3 provides the details of the experimental equipment and experiment procedures. The approaches and methods required to run the experiment works are discussed. The data analysis on thermal comfort evaluation methods are further discussed and explained.

Chapter 4 discusses the methods in detail by evaluating the results obtained from the study. The thermal perceptions of the residents are analyzed based on different thermal comfort scales. The adaptive thermal comfort models are proposed and discussed.

Chapter 5 discusses the concise summary of the overall study and some recommendations are suggested for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this chapter, a comprehensive review of thermal comfort studies is presented. This section also includes the energy usage and energy trend in Malaysia. The definitions of thermal comfort from different climates are discussed. Experimental results and findings of other researchers which would assist in home cooling system design are reviewed in this chapter as well.

2.2 Energy Trend in Malaysia

Since Malaysia is developing at a great pace, the energy demand within the country is also getting higher. The energy usage in Malaysia can be categorized into fuel mix in electricity generation, commercial energy demand by sector and primary commercial energy supply by source.

2.2.1 Fuel Mix Electricity Generation

Fuel mix for electricity generation includes natural gas, coal, hydro, oil and other resources as indicated in Table 2.1. Energy sector in Malaysia is predicted to grow and its demand is expected to rise from 91,539 GWh in 2007 to 108,732 GWh in 2011 and from 165,976 GWh in 2020 to 202,286 GWh in 2030 [21-26]. The growth of electricity demand is due to the high economic development rate and the rapid increase of the population in Malaysia [21, 27]. In fact, the demand of electricity is higher than the predicted value.

From Table 2.1, the electricity demand of 2010 is found to be 137,909 GWh which is higher than the predicted 108,732 GWh in 2011. Therefore, the electricity demand in Malaysia in 2020 and 2030 should also be higher than the anticipated value as well. The latest electricity demand is recorded in 2015 with 144,565 GWh [9]. Currently, renewable energy only contributes 50 MW in electricity generation and is expected to improve to 2,000 MW in the year of 2020 [25]. The electricity demand in Malaysia has increased 246% in 20 years from 1995 to 2015.

Table 2.1: Fuel Mix Electricity Generation [9, 21, 28-32]

Year / **Source**	**1995**	**2000**	**2003**	**2005**	**2009**	**2010**	**2015**
Natural gas (%)	67.8	77.0	72.5	70.2	63.0	55.9	46.3
Coal (%)	9.7	8.8	16.5	21.8	30.4	36.5	41.0
Hydro (%)	11.3	10.0	6.2	5.5	5.4	5.6	10.7
Oil (%)	11.0	4.2	4.1	2.2	1.1	0.2	0.0
Others (%)	0.2	0.0	0.7	0.3	0.1	1.8	2.0
Total (100%)	100	100	100	100	100	100	100
Total (GWh)	41,813	69,280	83,300	94,299	106,530	137,909	144,565

Malaysia is dependent on fossil fuel resources in the electricity sectors [32]. Table 2.1 shows the electricity generation by energy mix for year 1995, 2000, 2003, 2005, 2009, 2010 and 2015. In 1995, 88.5% of the electricity is produced by fossil fuels while the balance is generated by hydroelectric and the other sources [21, 33]. In 2015, fossil fuels still represented 87.3% of the electricity generation in Malaysia. Thus, it can be concluded that the fossil fuels still dominate the electricity generation in Malaysia.

Prior to the Four–Fuel Diversification Strategy, the usage of oil covers a huge percentage in the energy mix of Malaysia. It reached 87.9% in 1980s and this value only started to decrease with the introduction of different strategies and policies. As a result, the usage of oil in mix energy reduced to 11% in 1995. With the implementation of Fifth Fuel Policy, the oil usage is further minimized to 0.2% in 2010 and 0.0% in 2015.

Four-Fuel Diversification Strategy also increases the role of coal in the generation of electricity. The percentage of coal usage increased drastically from 9.7% in 1995 to 21.8% in 2005 and then to 36.5% in 2010 and finally to 41.0% in 2015. This is due to the opening of new coal fired power stations and government licensing independent power producer (IPP) [21]. Coal is considered as an abundant and reliable resource with low and stable price [31]. Malaysia has coal resources in Peninsular Malaysia, Sarawak and Sabah where 80% of them are from Sarawak, 19% from Sabah and another 1% is located in Peninsular Malaysia [31]. Besides, Malaysia also imports coal from other countries such as Indonesia, Australia and South Africa. Therefore, efforts need to be done to utilize other alternative resources to sustain the demand of electricity while reducing the dependency on coal [32].

Natural gas is the main element of energy mix in generating the electricity in Malaysia [31]. It became the major fuel source for electricity generation from 1995 to 2015 as shown in Table 1. In 2015, 46.3% of the energy is generated from the natural gas. It is the highest if compare with other resources and the same applied for the previous years. However, due to the effort by the Malaysian government in promoting energy mix [29], the usage of natural gas has dropped. In 2000, natural gas covered 77.0% of the total electricity produced but this value is reduced to 70.2% in 2005. The clearer result can be seen between 2010 and 2015 where the usage of natural gas is decreased from 55.9% to 46.3%.

Hydro is the third main contributor in the energy mix. The percentage of hydro in electricity generation declined from 11.3% to 5.4% between the year of 1995 and 2009. In 2010, the usage of hydro increased a bit to 5.6% and further increased to 10.7% in 2015. It can be observed that there is an increasing pattern in hydro usage in Sarawak and Sabah. The hydro power generation for Sarawak increased from 14.3% to 31.7% while Sabah increased from 21.3% to 26.5% between 2000 and 2010 [28].

Fifth Fuel Policy has introduced renewable energy as the fifth fuel in the energy mix. Renewable energy is mostly from mill wastes like palm oil, municipal waste and biogas [31]. The contribution of renewable energy in electricity generation is still low but is increasing throughout the years. In 2015, excluding hydro, renewable energy has achieved 2.0% of the electricity generation in Malaysia.

The development of different alternative energy sources such as coal, hydro and renewable energy are the strategies adopted by Malaysia to fulfill the demand of electricity in the coming years [21, 34]. These strategies also indicate the government’s aim to reduce the reliance of oil and natural gas in electricity generation [28]. Oil is no longer the main component of energy mix and is mostly used as reserved supply in the emergency case [31].

2.2.2 Energy Demand in Malaysia by Sector

The main sectors in Malaysia include transport sector, industrial sector, residential and commercial sector, non-energy sector as well as agriculture and forestry sector. Table 2.2 shows the commercial energy distributed to final consumers which excludes gas, coal and oil used in electricity generation [28].

Table 2.2: Final Commercial Energy Demand by Sector [9, 28, 30, 35-37]

Year / **Sector**	**2000**	**2005**	**2010**	**2013**	**2014**
Transport (%)	40.6	40.5	41.1	43.4	46.6
Industrial (%)	38.4	38.6	38.8	26.2	25.2
Residential and commercial (%)	13.0	13.1	12.8	14.3	14.3
Non-energy (%)	7.6	7.3	6.5	14.1	11.9
Agriculture and forestry (%)	0.4	0.5	0.8	2.0	2.0
Total (100%)	100	100	100	100	100
Total (Petajoules)	1243.7	1613.7	2217.9	2160.0	2185.9
Total (million tons of oil equivalent, Mtoe)	29.8	38.7	53.2	51.6	52.2

It can be observed that the transport sector and industrial sector are the two main energy consumers in Malaysia. Both of these sectors covered almost 80% of the energy demand from 2010 to 2014. The transport sector is the largest consumer which covered 40.6%, 40.5%, 43.4% and 46.6% of the energy demand in 2000, 2005, 2013 and 2014, respectively. The industrial sector is the second with 38.4%, 38.6%, 26.2% and 25.2%. However, in 2009, industrial sector became the largest consumer in Malaysia which covered 43% of the total energy consumption while the transport sector became the second largest with 36% [21, 38]. The transport sector is expected to become the largest consumer again in 2010 which will cover 41.1% of the energy demand while industrial sector will become second with 38.8%. Transportation sector in Malaysia is still using fossil fuels which cause negative impact to the environment such as greenhouse gas emissions. Therefore, existing policies and strategies have to be revisited to resolve such problem. Industrial sector also has an important role to play in the energy consumption of Malaysia. Effective usage of energy can save the fossil fuels and conserve the environments [38].

Residential and Commercial sector is the third largest consumers of the commercial energy demand in Malaysia. This sector represented around 13% to 14% of the energy demand in 2000, 2005, 2010, 2013 and 2014. Residential sector involves the energy consumption in buildings which include lightning, heating and cooling. More than one third of the world’s primary energy demand is used in this sector [10]. Based on the research done by worldwide energy consumption, 19% of the energy in Malaysia is spent on residential sector [10-12]. Therefore, energy utilization is important in this sector especially on the application of ventilation and air conditioning system [10].

Non-energy sector covered 7.6% and 7.3% of the energy demand in 2000 and 2005. This demand continued to decrease in 2010 to 6.5%. However, the energy demand for non-energy sector is found to increase from 2013 to 2014, each accounted with 14.3% of the total energy demanded. Agriculture and forestry sector is the smallest consumer which covered less than 1% of the energy demand in Malaysia between 2000 and 2010. However, the energy demand of this sector increased to 2.0% in 2013 and 2014.

2.2.3 Energy Supply in Malaysia by Source

Crude oil and petroleum products, coal and coke, natural gas and hydro are the main sources of primary commercial energy supply in Malaysia as shown in Table 2.3. The total energy supply increased from 2003.1 PJ in 2000 to 2526.1 PJ in 2005, then to 3127.7 PJ in 2010 and finally to 3751.4 PJ in 2015.

Table 2.3: Primary Commercial Energy Supply by Source [28, 30, 35, 36, 39]

Year / **Sector**	**2000**	**2005**	**2010**	**2015**
Crude oil and petroleum products (%)	49.3	46.8	44.7	32.6
Natural gas (%)	42.2	41.3	41.6	44.0
Coal and coke (%)	5.2	9.1	11.2	19.4
Hydro (%)	3.3	2.8	2.5	4.0
Total (100%)	100	100	100	100
Total (Petajoules)	2003.1	2526.1	3127.7	3751.4
Total (Million tons of oil equivalent, Mtoe)	48.1	60.6	75.1	89.6

The main energy supply in 2015 was crude oil and petroleum products which accounted for 32.6% of the total primary energy supplied. This is followed by natural gas with 44.0%, coal and coke with 19.4% and hydro with 4.0%. The usage of oil and petroleum products in 2015 have decreased if compared to the percentage in year 2000, 2005 and 2010, which is recorded to be 49.3%, 46.8% and 44.7%, respectively. On the other hand, it is discovered that the usage of natural gas and hydro turned higher in 2015 if compared to the years before. The use of coal and coke also increased from 5.2% to 19.4% within fifteen years.

In 2015, the usage of crude oil and petroleum products showed decreasing percentage while coal and coke showed increasing percentage. This is the attempt of government in introducing different alternative resources to avoid over dependent on a single energy source. Policy such as Fuel Diversification Strategy is implemented to achieve this purpose [30]. Malaysian government also identifies renewable energy as an additional source of energy supply in Ninth Malaysia Plan which is consistent with Fifth Fuel Policy [36].

2.3 Cooling System

Cooling system is basically a system of removing heat in order to achieve the thermal comfort desired by the occupants [40]. It is mostly applied when the temperature exceeds the thermal comfort range.

2.3.1 Passive Cooling System

Passive cooling system cools the buildings through the utilization of ambient air, upper-atmosphere, water and undersurface soil [41-44]. The term “passive” also includes minimum usage of mechanical ventilation such as fan or pump when their application can enhance the performance [45, 46]. Passive cooling can be classified into natural ventilation, evaporative cooling, radiant cooling and ground cooling [46, 47]. Table 2.4 summarizes the features of each passive cooling system.

Table 2.4: Classification of Passive Cooling System

Type of passive cooling	**Description**	**Application**	**Heat gains reduction**	**Drawbacks**
Natural ventilation [47-50]	Eliminate heat by the flow of natural air	Buildings with low sensible load or periodic load, example: office	20-30 Wm^{-2}	- Not suitable for hot climate. - Noise and air pollution. - High heat gains.
Radiant cooling [46, 77]	Remove heat through radiant heat emission	Moderate sensible cooling load	Maintain heat gain below 40-60 Wm^{-2}	- High internal gains.
Evaporative cooling [1, 47]	Cool the air by the process of water evaporation	Buildings with low internal gains	-	- Not suitable for humid climate. - Require humidity control.
Ground cooling [46, 47]	Utilize cooled soil for heat absorption	Buildings with suitable ground condition and moderate cooling demand	45 Wm^{-2}	- Great depth needed to reach cold water.

Passive cooling system is useful in overcoming the issue of environmental problems. It decreases energy consumption [45] and also greenhouse gas emissions [50]. 2.35% of the world’s energy usage could be avoided through proper application of passive cooling concepts [51].

Natural ventilation has been increasingly proposed in cooling system design as this system is expected to save 10% of annual energy consumption [49]. Unlike other passive cooling techniques, natural ventilation takes advantage on air movement to reduce indoor temperature. This type of passive cooling is suitable for most of the households and buildings since it is easily available. However, natural ventilation is prone to noise and air pollution. Direct solar radiation from the openings or windows causes indoor temperature to exceed the comfortable limit. Therefore, the application of natural ventilation is not really appropriate for hot climate countries.

Advanced natural ventilation can be achieved when solar chimney, windows and more openings are installed in a building [46, 50]. These elements are able to promote and enhance heat dissipation process. Night ventilation is another type of natural ventilation. It cools the building at night and serves as heat sink on the following day to offset the heat gains [41, 46- 48, 50].

Water is one of the solutions to achieve the purpose of cooling especially for countries which are experiencing the dry climate. Evaporative cooling is the alternative to this problem with its low operating cost. Humidity control is needed to control this cooling system in order to have better performance. Evaporative cooling utilizes water vapor to cool the air directly or indirectly [1, 48, 52]. For indirect evaporative cooling, heat is exchanged with another medium separated by a heat exchange element before the cooled air is introduced into the building [52].

Radiant cooling operates differently if compare with other passive cooling techniques. It requires a temperature-controlled surface to remove sensible heat through thermal radiation [46]. Cold energy is transferred to the indoor space by conduction or forced air flow [46]. Radiant cooling is efficient in terms of minimizing the heat gains but it leads to high internal gain. Although temperature-controlled surface can prevent direct heat emission into the indoor environment, some of the heat absorbed will still be dissipated into the living space. This phenomenon causes the increase of internal gain and contributes to higher cooling demand.

The cooling concept of ground cooling is similar with natural ventilation. Both of these cooling systems involve buoyancy effect that enhances the ventilation flow of the building [49, 53]. The difference of ground cooling from other passive cooling systems is the requirement of suitable ground condition which normally include deep ground depth with cold ground temperature. This implementation can reduce the cooling demand of buildings which in turn lower down the energy needed for cooling system.

2.3.2 Developments of Passive Cooling System in Different Climates

Cooling effect can be improved by different types of passive cooling techniques. Roof, wall, ceiling, roof pitch, windows and solar chimney are some of the building elements used for the purpose of cooling. Table 2.5 summarizes the research works of passive cooling systems from different climates.

Table 2.5: Developments of Passive Cooling System

Country	**Climate**	**Research area**	**Cooling type**	**Methodology**	**Results**
Rajasthan, India [54]	hot + dry	Solar Passive Technique for Roof Cooling	Radiant and Evaporative	Thermal model simulation	- Lowering roof temperature at peak hours by 12 ºC-33 ºC.
Malaysia [55]	hot + humid	Thermal Comfort in Residential Building	Radiant and Natural Ventilation	Experimental work	- Comfort was achieved through the application of building envelope.

Table 2.5 continued

Thailand [56]	hot + humid	Solar Chimney and Wetted Roof	Evaporative and Natural Ventilation	TRNSYS simulation and experimental work	- Reduced indoor temperature by 2.0 ºC-6.2 ºC compared with ambient air and 1.4 ºC-3.0 ºC compared with controlled cell.
United State of America (USA) [51]	hot to cold+ humid to dry	Cement-Based Roofs	Radiant	Experimental work	- Reduction in heat conduction between 65% and 85%.
Japan [57]	hot to cold+ semi humid to humid	Cooling Wall	Evaporative	Experimental work	- Supplied cool air to atmosphere. - Maximum cooling efficiency of 0.7 during daytime.
Iran [53]	hot to cold+ humid to dry	Earth to Air Heat Exchanger (EAHE) and Solar Chimney	Natural Ventilation and Soil Cooling	Theoretical analysis and Mathematical model solved by MATLAB	- Retained indoor thermal comfort condition.
Malaysia [58]	hot + humid	Trombe Wall and Roof Solar Collector	Radiant	Experimental work	- Provided cooling effect to the building. - Decreased the room temperature by around 3ºC.
Argentina [59]	hot to cold+ humid to dry	Roof Awning	Radiant	Thermal model simulation	- Reduced household cooling load by 40% during summer period.

Table 2.5 continued

Guangzhou, China [60]	hot to warm+ humid	Building Envelope	Radiant and Natural Ventilation	TRNSYS simulation	- Annual energy demand was reduced from 1.82% to 2.64% through wall insulation. - Annual energy demand was reduced from 19.36% to 33.89% through window insulation.
Jordan [45]	hot to cool+ dry	Roof Design	Radiant	Experimental work	- Decreased temperature of reinforced cement concrete roof by around 10 ºC.
Malaysia [61]	hot + humid	Roof Pitch and Ceiling	Radiant	Experimental work	- The daytime indoor temperature was reduced between 0.4 ºC and 0.8 ºC.

Based on Table 2.5, it can be observed that roof is the most popular passive cooling method. Different roof installations were done to validate their cooling abilities. From the studies, roof is effective in reducing heat conduction which in return will reduce the indoor temperature. Materials applied on roof will also affect the cooling performance. Countries like Argentina, USA and Jordan have proved that roof temperature and indoor temperature can be reduced if appropriate materials are used for the roof design.

Evaporative cooling concept is another technique applied on roof. Tropical country like Thailand has shown encouraging results through this cooling method whereby indoor temperature is decreased by 3.0 ºC. The cooling outcome is more obvious for India as the roof temperature can be lowered to a maximum of 33 ºC. Since roof is directly exposed to solar radiation, heat will be generated on top of the roof and transferred into the building through the process of radiation, conduction and convection. Therefore, lower roof temperature will ensure cooler indoor environment and help to reduce the cooling load.

Evaporative cooling can be utilized on wall as well. For example, Passive Evaporative Cooling Wall (PECW) constructed by porous ceramic with high water soaking-up ability is developed in Japan [57]. These ceramics are capable of absorbing water to a higher height of 100 cm whereas general porous material just can reach up to 30 or 40 cm. Therefore, water can be supplied from the rainwater tank below without a pump. The air passing through PECW can be cooled to minimize the environment temperature. The purpose of conserving energy can be achieved through PECW since it avoids the usage of electrical equipment.

Buildings can also be cooled by radiant cooling. The effect of radiant cooling is proven to be significant especially for countries which experience different types of climates such as USA and Argentina. However, this type of cooling system shows less impact on tropical country like Malaysia. It can improve the indoor thermal condition but only with limited effect. Comprehensively, radiant cooling can conserve the energy by reducing the cooling power consumption.

Natural ventilation, radiant cooling and evaporative cooling are the most common techniques used in passive cooling system. The findings indicated that the combination of different passive techniques can ensure better cooling outcome.

Building envelopes also play an important part in passive cooling system. Building elements such as roof, wall, ceiling and solar chimney are capable of providing cooling effect for indoor environments. The result is more promising when more building elements are involved in the cooling system design. Apart from cooling effect, the energy consumption of the buildings can also be minimized through the application of building envelopes.

2.3.3 Active Cooling System

Cooling system which requires energy sources to operate is referred as mechanical ventilation system or active cooling system [4, 62]. The most regular used active cooling systems are ceiling fan, desk fan and standing fan. These systems can provide reliable airflow for the occupants and maintain the comfort level in the buildings [6].

Air conditioner is another active cooling method which is widely used [4]. Packaged Terminal Air Conditioner (PTAC), Air Handling Units (AHUs), desiccant cooling system and absorption cooling system are the types of air conditioner that are applied in the modern buildings [4, 63, 64]. However, such cooling systems are expensive and require a lot of consumption power [1].

2.3.4 Developments of Hybrid Cooling System in Different Climates

Table 2.6 shows the developments of hybrid cooling system. Besides mechanical ventilation system, passive cooling techniques such as radiant cooling and evaporative cooling are applied with active cooling system to achieve optimum cooling performance. The combination of passive and active cooling is referred as hybrid cooling system [65].

Table 2.6: Developments of Hybrid Cooling System

Country	**Climate**	**Research area**	**Cooling type**	**Methodology**	**Results**
Japan [66]	hot to cold + semi humid to humid	Radiational Panel Cooling and Wind-Driven Cross Ventilation	Radiant, Evaporative and Natural Ventilation	Computational Fluid Dynamics (CFD) simulation	- Reduced cooling load by 4000W, 2.5 times lower than underfloor air conditioning system.
California, (USA) [41]	hot to cold + semi humid to dry	Smart Ventilation Controller	Mechanical Ventilation	Experimental work	- Achieve temperature difference ratio (TDR) of 16.3% to 31.9%.
Thailand [67]	hot + humid	Radiant Cooling Panel	Radiant and Evaporative	TRNSYS simulation and experimental work	- Saved 56% (2469 kWh) of thermal energy.
European and Mediterranean Cities [68]	hot to cold + humid to dry	Air Movement	Mechanical Ventilation	EnergyPlus simulation	- Cooling energy savings in the range of 17%-48% in the case of elevated air velocity.

Table 2.6 continued

China [69]	hot to cold + humid to dry	Innovative Solar Window	Evaporative	Experimental work	- Enhanced thermal and visual comfort. - Reduced room heat gain to 196 Wm^{-2} and increased water heat gain by 271 Wm^{-2}.
Taipei, Taiwan [70]	hot to warm + humid	Cooling Ceiling	Radiant and Evaporative	Computational Fluid Dynamics (CFD) simulation and experimental work	- Yielded energy saving of 13.2% for the chiller and 8.0% for the whole cooling system.
Venice, Italy [71]	hot to cool + humid	Thermal and Comfort Control	Radiant	MATLAB simulation	- Reduced 12.1% of the cooling energy and 17.1% of the electric energy.

Japan and Thailand [66, 67] have proved that radiant cooling panels which combine the concept of evaporative cooling and radiant cooling can produce efficient cooling performance. The wall cooling panels which are adopted with these cooling techniques consume less energy than the conventional cooling system. Ceiling cooling panels also show its competence in saving the energy but are inferior if compare with wall cooling panels.

Solar window with forced flow water circuit is demonstrated to be an innovative evaporative cooling system [69]. Water passage in the window can lower inner glass temperature, decrease heat gain of indoor environment and thus, reducing air-conditioning electricity consumption. The cooling result is more obvious with tinted glass compared with reflective glass or clear glass. Tinted glass reveals higher water heat gain which proves that more cooled air is introduced into the building as most of the heat is absorbed by the water.

The energy consumption of mechanical ventilation can be controlled by the introduction of air movement into the indoor space. The results show reduction in cooling power from 10% to 28% [40] due to the increase of air movement. Therefore, more energy can be saved from cooling system. Air movement can be increased by fans, windows and personal ventilation systems. Different fans will show different energy usage and it will affect the amount of energy saved.

Cooling performance of ventilation controller [41] is as prospective as the other cooling techniques where its operation is based on the comfort band set by the users. The findings indicated that the application of ventilation controller with mechanical ventilation can lead to superior TDR [41] which implies better cooling performance.

From Table 2.6, it can be observed that active cooling system is no longer just emphasizing on mechanical ventilation system. The concepts of passive cooling are used not only to enhance the performance but also to increase the diversification of active cooling system. The results also showed that cooling system design which is integrated with various cooling techniques can save more energy and provide more cooling effect than the design which is focusing on just one type of cooling method.

2.4 Thermal Comfort

Thermal comfort is a subjective response [72] which expresses contentment between the state of mind and the present environment [73, 74]. It is also an important element in occupants' perceptions and behaviours in the use of energy in buildings [76, 77]. In other words, thermal comfort is defined as a state in which heat balance across the body is in equilibrium with its environment [78]. The idea of thermal comfort is complicated as it varies from person to person [79]. Different occupants may experience identical comfortable level at different thermal environments and in contrast, they may also perceive differently under the same thermal environment [80].

Thermal comfort can be affected by several factors such as condition of indoor and outdoor environments, climate types, human factor and also geographical location of the countries [81]. It is also discovered that occupants tend to maintain and improve their existing comfortable state by adjusting their physical, physiological and psychological behaviour towards the environment [73, 82, 83]. These findings have ascertained that a specific value cannot be allocated to thermal comfort [84].

Thermal comfort and particularly comfort models for naturally ventilated buildings located in warm and humid regions are topics of wide discussion in the present literature because of their importance in the design of energy-efficient and sustainable buildings [17, 85] as energy saving in commercial and residential buildings have a potential with respect to improvement of thermal comfort standard [78].

Thermal comfort standards determine the energy consumption by a building's environmental systems, therefore they play an important role in building sustainability [86]. International standards like ASHARE Standard 55 and ISO 7730 Standard are used to determine the condition of thermal comfort in a building. Thermal comfort is defined in ISO 7730 Standard [87] as being "that condition of mind which expresses satisfaction with the thermal environment" [88]. Most of the people can agree on this definition but cannot convert it easily into physical parameter [89]. Thermal comfort zone is a region stipulated by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHARE) in the psychometric chart where all the conditions can satisfy 80% of the occupants [90]. The thermal comfort zone stipulated by ASHARE Standard 55 [91] is shown in Figure 2.1.

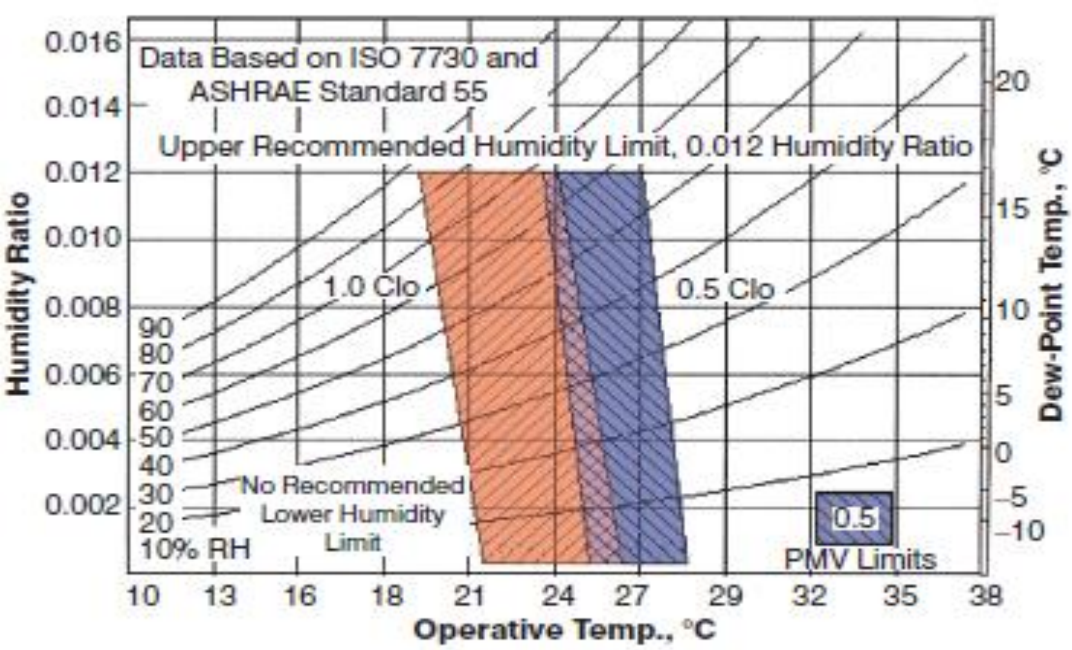

Figure 2.1: Acceptable Range of Operative Temperatures and Humidities for People in Typical Summer and Winter [91]

According to the definition above, thermal comfort is more towards to a state of mind rather than a state condition [82]. Thus, comfort can be influenced by many inputs which include physical, physiological, psychological and other factors [82, 83]. The perception of comfort can be different among occupants even in the same environment [82]. The recommended acceptable thermal comfort conditions by ASHRAE Standard are summarized in Table 2.7.

Table 2.7: Recommendations of ASHRAE Standard [82, 92, 93].

Season	Operative temperature	Acceptable range
Winter	22 ºC	20 ºC-23 ºC
Summer	24.5 ºC	23 ºC-26 ºC

The Malaysian Standard 1525 [94] stipulates a ‘‘comfort cooling zone’’ where the indoor temperature should be maintained within 23 ºC to 26 ºC to sustain the thermal comfort of the non-residential buildings.

Thermal comfort is difficult to define since it involves many factors and aspects. Table 2.8 summarizes the indoor comfort temperature of various countries with different climates, different buildings types and with different cooling systems installed.

Table 2.8: Thermal Comfort Temperature of Different Climates

Country	**Climate**	**Building**	**Cooling type**	**Comfort temperature (ºC)**	**Additional parameter**	
					Relative humidity (RH)	**Air speed ($\mathbf{ms^{-1}}$)**
Central Southern China [95]	hot + humid	Residential house	Air-con and non air-con system	22.0-25.9	44.3-90.1	0.01-0.14

Table 2.8 continued

Hyderabad, India [96]	hot + semi humid	Mid-rise apartment	Natural and mechanical ventilation, air coolers	26.0-32.5	26.7-66.1	0.40-0.50
Singapore [81]	hot + humid	Classrooms	Mechanical ventilation (fans)	27.1-29.3	60.0-90.0	-
Jogjakarta, Indonesia [97]	hot + humid	Low-rise houses	Natural and Mechanical ventilation (fans)	26.0	50.8-87.0	0.10
Johor Bahru, Malaysia [98]	hot + humid	Schools and clinic	Natural and Mechanical ventilation (fans)	26.0-30.7	49.5-75.3	0.40-0.80
		University	Air conditioner	23.1-25.6	60.0-72.0	-
Maceio, Brazil [99]	hot + humid	Classrooms	Natural and Mechanical ventilation (fans)	26.0-30.0	-	0.40-0.90
Bauchi, Nigeria [100]	hot + dry	Residential buildings	Natural and Mechanical ventilation (fans)	25.5-29.5	28.0-80.0	0.13
Turin, Italy [101]	hot to cool+ humid	Classrooms	Natural ventilation	23.3-27.4	-	-
Doha, Qatar [102]	dry + subtropical desert	Office buildings	Air Handling Units (AHUs)	24.6	-	-

Comfort temperatures for hot climate countries are found to be higher than cool climate countries. This is due to frequent exposure of occupants under their environmental climate which caused them to get accustomed to their own living surroundings. Occupants from cooler climate often prefer lower temperature while residents who live in hot climate countries are often adapted to a warmer environment.

Environmental condition is another factor affecting the comfort temperature of the occupants even if they are experiencing the same climate. There was a study conducted to compare the comfort temperature between the air conditioned and non-air-conditioned building [98]. The results showed that occupants from cooler environment have opted for a lower comfort temperature under the same climate condition. Thus, it can be concluded that climate and environmental conditions will influence human perspective on thermal comfort.

The study conducted in Doha, Qatar also showed similar result where the comfort temperature appears to be lower with only 24.6 ℃ [102]. The comfort temperature is expected to be higher since the occupants should have adapted themselves to a higher comfort temperature under a hot environment. This is because occupants of this study were exposed to a fixed constant cooling indoor environment which caused them to accustom to a cooler ambience. As a result, their ideal comfort temperature is found to be lower than anticipated.

Table 2.8 also shows that Singapore, Malaysia and Indonesia have similar comfort temperature range as their geographical locations are close together in the region of Southeast Asia. For countries which are located more to the north direction such as China and Italy, their environment atmospheres are cooler. Therefore, the desired comfort temperatures are found to be lower than the other countries. Geographic location will define local climate and subsequently affect the comfort temperature of different countries.

It is also discovered that India possessed the widest comfort temperature range with temperature difference of 6.5 ºC followed by China, Malaysia, Brazil, Nigeria and Italy with the difference of around 4 ºC. Singapore has the smallest interval with the difference of 2.2 ºC only. The variation in temperature range is due to human factor as different countries might have different level of acceptability.

Relative humidity and air speed have the impact on comfort temperature as well. Relative humidity will affect evaporative heat loss from a person especially when higher level activities and warmer environment are involved. Meanwhile, the presence of air speed can facilitate air ventilation and provide reliable air flow within the building. Occupants might feel comfortable under warm temperature if suitable amount of air speed is introduced to the living space. From the findings, the acceptable comfort temperature for India, Malaysia and Brazil are more than 30 ºC which exceed the comfortable range set by ASHARE standard. However, they still recognized this condition as comfortable due to the existence of air velocity in their indoor environment. Hence, it is proven that air movement can improve thermal comfort even under hot circumstances.

2.4.1 Approaches of Thermal Comfort

There are two approaches in contemporary thermal comfort research to develop predictive thermal comfort models which are static heat balance models of human body based on laboratory studies and adaptive models based on field studies [78, 103-106]. These two different models use different rules for determining comfort zone prescriptions and have dissimilar assumptions about how buildings are designed and environments are taken care of [107].

The mostly known static heat balance is the lab-based Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) method [86, 108]. However, these parameters completely ignore the psychological dimensions of adaptation, social and cultural aspects of an occupant, which are otherwise so prominent in any naturally ventilated buildings. These parameters are important because of the strong relationship between occupant's behavioural adaptation and their environment [109]. The Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) method developed by Fanger have been used worldwide to predict and assess indoor thermal comfort in buildings [86]. PMV uses a seven-point index to measure the thermal comfort sensation of the respondents in a given environment under a steady state condition [97, 110, 111].

2.4.2 Factors of PMV and PPD

The physical variables of PMV and PPD are air temperature, air velocity, mean radiant temperature (MRT) and relative humidity. Meanwhile the two personal variables are clothing insulation and activity level. Hence, a person's thermal sensation does not only depend on the ambient air temperature. Thermal comfort is achieved when the heat produced by the metabolism is dissipated and is in thermal equilibrium with its surroundings. In addition, thermal acceptability or the predicted percentage dissatisfied (PPD) can be determined from the PMV value [112-115].

2.4.3 Weakness of PMV Model

Fanger's model underestimates the thermal impression in the actual case and thus, it is no longer valid for use in certain climates [112]. It is argued that the PMV model which is developed from the laboratory studies has restrictions regarding on environmental parameters as they are quite different from real buildings [86]. Field evidences have showed differences between the thermal comfort predicted by PMV and the actual thermal sensation expressed by the occupants [116-122]. Field studies in tropical climates also discovered that Fanger's PMV equations do not effectively express comfortable conditions especially in buildings that are not heated or cooled mechanically [123].

The errors in PMV also exist in air-conditioned buildings [124] as proven by Nicol and Humphreys. The reasons of this error include the constraints of the applicability of the PMV, wrong predictions of thermal sensation given by the steady state heat balance approach, occupants' adaptive behaviors' [125] and the limitations of the Fanger's equation [112].

Many field studies indicated that PMV model fails to predict the thermal sensation of occupants living in "free running" buildings, not only in hot climates but also in temperate climates [114]. The failure to predict the sensation happens because the PMV model cannot take into account complicated human interactions with their surrounding environment by changing their behavior and slowly adapted by adjusting their expectations and preference [114]. The inapplicability of the PMV index in tropical buildings is found in many studies due to the overestimation of actual thermal sensation of the occupants [7].

According to field studies, the misinterpretation in expected value such as metabolism rate in PMV equation is one of the cause due to which deviation occurs from neutral sensation [126]. Expectancy factor 'e' in PMV model is introduced in the naturally ventilated buildings due to different field studies verifying under the prediction of PMV model [127-129]. Apart from expectancy factor, adaptive coefficient is also proposed to reduce the difference between PMV predictions and the actual thermal sensations [86, 130]. A number of over predictions are discovered among the end user with respect to PMV model for air-conditioned buildings [78]. It is shown in the field studies that PMV model works well in air-conditioned environment but not in buildings which are ventilated naturally. PMV tends to overpredict the subjunctive's sensation in the built environment especially in warmer climates [131].

2.4.4 Adaptive Principle

The adaptive approach to thermal comfort is based on the findings of surveys of thermal comfort conducted in the field. The fundamental assumption of the adaptive approach is expressed by the adaptive principle where people react in ways to restore their thermal comfort if there is a change which caused thermal discomfort to them [16, 17, 132, 133]. In other words, the people's satisfaction with an indoor climate is achieved by matching the actual thermal environmental conditions at the existing time and space with their individual thermal expectations [132].

The adaptive thermal comfort model is a linear regression model that correlates indoor temperatures to its outdoor temperatures [112, 114, 134]. Across a number of adaptive comfort studies, outdoor temperature is proven to have the dominant effect on defining thermal comfort conditions [104, 135]. With the use of adaptive thermal comfort model, it is possible to reduce the thermal comfort dissatisfaction rate of the occupants [19, 20, 86, 97, 113].

The adaptive approach also provides another concept to determine thermal comfort rather than just heat exchange between human and their environments [114]. Human physiological indicators would produce certain adaptive changes in indoor operative temperature through their self-adaptation and self-feedback regulation [97].

Occupants in a given environment can achieve thermal comfort through personal adjustments in the form of changing clothes, opening or closing the windows and switching on or off on their cooling systems [103] - the more the adaptive opportunities, the wider the comfort zone can become [136].

The majority of adaptive models are applied to define the comfort temperature as a function of outdoor and indoor temperatures [80]. It is argued that the adaptive thermal comfort model does not explicitly include the environmental parameters such as air temperature, relative humidity, mean radiant temperature and air velocity as well as the personal variables such as clothing insulation and metabolic rate.

As the adaptive approach to thermal comfort is based on the thermal comfort conducted in the field, the physical measurements and subjective assessments are done simultaneously**.** The surveys done have revealed that there is a strong relationship between occupant's behavioural adaptation and environment [103].

In addition, adaptive comfort models are also adopted in indoor environment standards such as International Standard Organization 7730 [137], European Standard EN

15251 [138], and American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 55 [90].

Nowadays, most of the air-conditioned buildings are facing the same problem where their indoor space is either too cold or too warm. This is frequently found in tropical countries because the PMV model is unsuitable to be used in hot and humid climate. Therefore, the adaptive model is important to determine the thermal comfort of the occupants and concurrently conserving the energy [112].

It can be concluded that the adaptive approach is comparatively more applicable for setting the thermal comfort standards in the buildings due to its characteristics which can consider the adaptation of people towards their thermal environment. In addition, using the adaptive method to find the thermal comfort conditions is found to be energy saving [139].

In thermal comfort field studies, the normal method for predicting the comfort temperature is to use linear regression analysis [140]. Humphreys suggested that the desired comfort temperature can be determined by correlating the indoor comfort temperature with its outdoor temperature [18, 88, 126]. The function of the correlation is shown in Equation (2.1).

$$T_c = a\,T_{out} + b \tag{2.1}$$

where

T_c = comfort temperature, °C

T_{out} = outdoor air temperature, °C

a and b = constant values

2.5 Adaptive Thermal Comfort Models

There are studies done on thermal comfort models based on adaptive principle across the world which include different kinds of climates, buildings and ventilation systems. It is discovered that the developed thermal comfort models varied from countries to countries and their applications are different depending on their thermal environment.

Nicol and Humphreys [124] suggested that an algorithm could be constructed to determine the ideal indoor temperature for the free running buildings or buildings which are using HVAC systems. Free running buildings refers to the buildings which do not consume energy for the purpose of either heating or cooling [123]. Nicol and Humphreys predicted the indoor comfort temperature (neutral temperature) with the correlation of the outdoor temperature. The algorithm is based on the field work done by Humphreys [141] on the relationship between comfort temperature and outdoor temperature, using a mixture of the instantaneous and the running mean outdoor temperatures.

Based on Nicol and Humphreys, the elements to define an adaptive standard are building designs, outdoor conditions and ventilation designs [124]. They also stated that the development of thermal comfort model includes the indoor environment which most likely to provide comfort, the acceptable range of environments and the rate of change of indoor environment which is acceptable to the occupants. Nicol and Humphreys conducted their study on worldwide free funning buildings using the data presented by Humphreys in the 1970s [141] and also the data from 1998 ASHRAE database [142]. They concluded that the correlation between the indoor comfort temperature and outdoor temperature is stable and the equation to represent the correlation is written in Equation (2.2).

$$T_c = 13.5 + 0.54\ T_{out} \tag{2.2}$$

The correlation coefficient r^2, for the data from 1970s is 0.95 while the correlation coefficient of the data from 1998 AHSRAE database is discovered to be 0.90. Nicol and Humphreys also found that the relationship between comfort temperature and outdoor temperature for the heated and cooled buildings are more complex. This is because when the buildings are heated or cooled, the outdoor temperature can no longer affect the indoor temperature directly since the indoor conditions are controlled by the customization of the occupants.

Another thermal comfort study was done by Aynsley [143] which involved the subjective assessments on the human thermal response on both naturally and mechanically ventilated buildings in the region of Southeast Asia. The thermal neutrality equation correlating with the outdoor temperature is shown in Equation (2.3).

$$T_c = 17.6 + 0.31\ T_{out} \tag{2.3}$$

Aynsley also recommended that the comfort temperature should be ± 3.5 °C to fulfill the 80% acceptability where the indoor temperature cannot exceed or go below the acceptable temperature range in order to preserve the thermal comfort state of the occupants.

Another research of thermal comfort model was done by Humphreys [141]. He conducted a Meta analysis on a large group of samples for the free running buildings of tropical climate worldwide. The linear correlation derived by Humphreys between the comfort temperature and its mean outdoor temperature is written in Equation (2.4).

$$T_c = 12.9 + 0.534\ T_{out} \tag{2.4}$$

Humphreys suggested that the proposed comfort model can become a guideline for the building professionals to predict the indoor comfortable temperature for the free funning buildings through the monthly mean outdoor temperature obtained from meteorological records. Humphreys also added two parameters into his thermal comfort model for tropical climates where air velocity is assumed to be $\leq\ 0.1\ \mathrm{ms}^{-1}$ and relative humidity is set to be 50%. He added that air velocity and relative humidity will have significant effect on thermal comfort especially on occupants who live in a warmer climate. If the air velocity is above $0.1\ \mathrm{ms}^{-1}$ and fairly constant, the comfort temperature raised can be calculated by using Equation (2.5).

$$T_{c\text{-raised}} = 7 - \frac{50}{4+10v_a{}^{0.5}}\ \ °C \tag{2.5}$$

where

$T_{c\text{-raised}}$ = comfort temperature raised, °C

v_a = air velocity, $v \geq\ 0.1\ \mathrm{ms}^{-1}$

It was shown that the presence of air movement can allow the occupants to adapt themselves to a higher comfort temperature [144, 145]. Relative humidity is found to have a significant effect on the comfort temperature as well, however, the size of the effect is generally small [123, 146]. It is assumed that under a hot condition, the heat is dissipated from the human body through convection and evaporation, thus, increased humidity level will increase thermal discomfort.

DeDear, Brager and Cooper [79] carried out a specific research project funded by ASHRAE which accumulated the data from worldwide field studies of the sample size of 2,100 to determine the thermal comfort model. The study included two types of buildings, naturally ventilated buildings and HVAC buildings. The equations for naturally ventilated buildings and HVAC buildings are written in Equation (2.6) and Equation (2.7).

$$T_c = 17.8 + 0.31\, T_{out} \tag{2.6}$$

$$T_c = 21.45 + 0.11\, T_{out} \tag{2.7}$$

The slope of the equation from naturally ventilated buildings is higher than the slope of HVAC buildings which indicated that the adaptive capability of the occupants from naturally ventilated buildings is higher than those from HVAC buildings. The 80% and 90% acceptability range was used to determine the comfortable range of the model. The interval of comfort temperature of naturally ventilated buildings is found to be ± 3.5 °C and ± 2.5 °C, respectively with the outdoor temperature range of 10 °C to 33.5 °C. The activity level recorded was less than 1.3 met.

European Commission [147] promoted the Smart Control and Thermal Comfort project, SCAT in the effort to reduce the energy usage of air conditioning systems in naturally ventilated buildings, climatized buildings and mixed mode buildings across European countries. A thermal comfort model for European countries, which is also called as Adaptive Comfort Algorithm was developed by combining the studies from different types of buildings. The adaptive comfort equation is written in Equation (2.8).

$$T_c = 19.39 + 0.302\ T_{out} \tag{2.8}$$

However, the mentioned comfort model above is only applicable for outdoor temperature above 10 °C. The constant comfortable temperature of 22.88 °C is standardized if the outdoor temperature is below 10 °C. The acceptability of comfortable temperature range is calculated by

$$6.35 - 0.189\ T_c \tag{2.9}$$

The European Committee for Standardization (CEN) proposed the adaptive comfort model for the free running buildings as indicated in Equation (2.10) [148].

$$T_c = 18.8 + 0.33\ T_{out} \tag{2.10}$$

This equation is applicable for the outdoor temperatures between 10 °C and 30 °C. In this study, PPD of PMV model was used to determine the acceptable temperature range based on three categories, PPD < 6%, PPD < 10% and PPD < 15%. The comfortable temperature range calculated based on these three categories is ± 2 °C, ± 3 °C and ± 4 °C, respectively.

Nicol had conducted thermal comfort studies on commercial buildings in Pakistan during both summer and winter periods from 5 different cities, covering tropical and subtropical climate [149]. The average activity level of the occupants was in between 1.11 met and 1.25 met. The buildings involved in the study were all free running buildings except one building which was using the centralized air conditioning system. The relationship between the indoor comfort temperature and the outdoor temperature of the commercial buildings in Pakistan is derived in Equation (2.11) with the r^2 value of 0.73. Nicol suggested that by using the thermal comfort model proposed, the energy used in air-conditioning system can be saved and concurrently reduce the maximum cooling load of the buildings.

$$T_c = 18.5 + 0.36\ T_{out} \tag{2.11}$$

Another study in Pakistan involving buildings with heating and air conditioning system was also carried out by Nicol [150] and the correlation between the comfort temperature and outdoor temperature is shown in Equation (2.12).

$$T_c = 17.0 + 0.38\ T_{out} \tag{2.12}$$

Mui had performed thermal comfort study in sub-tropical climate of Hong Kong [19]. A large survey study which involved 55 air-conditioned offices was carried out throughout the season. 29 of them were done in summer while the remaining 26 were done in winter. The thermal sensation votes of ASHRAE scale was used to evaluate the thermal responses of the occupants. Different types of offices were chosen in this study and different geographical areas within the offices were chosen to be measured at different periods of time.

The comfort temperature in summer is found to be 23.7°C, which is 2.5 °C higher than the comfort temperature found in winter. The adaptive thermal comfort model for the offices in Hong Kong is derived in Equation (2.13) with the r^2 value of 0.59. The upper limit and lower limit of the model was determined by using the unacceptability vote below 20%. The acceptable indoor comfortable temperature is discovered to be in between 19.1 °C and 24.8 °C with the outdoor temperature not exceeding 41.1 °C or go below 5°C. It was concluded that 7% of the energy is saved by applying the proposed thermal comfort model into the cooling system.

$$T_c = 18.303 + 0.158\ T_{out} \tag{2.13}$$

Thermal comfort study was also done in hot and humid climate of India by Indraganti [151]. The total of 28 offices from naturally ventilated and air-conditioned offices with 6,048 responses from 2,787 respondents, was carried out in the study. The thermal comfort evaluation was done separately on naturally ventilated offices and air-conditioned offices. The comfort temperature was determined by using Griffith's method. From the study, the comfort temperature of the naturally ventilated offices is found to be 28 °C and 26.4 °C for the air-conditioned offices. The relative humidity of both modes is in between 45% and 48%. The air velocity was reported to be varying from 0.11 ms^{-1} to 0.17 ms^{-1}. It is also discovered that air velocity of 1.0 ms^{-1} can increase the comfort temperature by 2.7 K. The correlation between the thermal neutrality and the outdoor temperature is defined in Equation (2.14) and Equation (2.15).

For naturally ventilated offices,

$$T_c = 21.4 + 0.26\ T_{out} \tag{2.14}$$

For air-conditioned offices,

$$T_c = 22.1 + 0.15\ T_{out} \tag{2.15}$$

Chew [20] conducted his study in Malaysia which experiences hot and humid climate throughout the year. His study was focusing on thermal comfort of air-conditioned lecture halls in University of Malaya. A large field study which involved six lecture halls and 178 students was performed. Thermal sensation votes collected from the survey was analyzed and compared with the predicted mean vote calculated from PMV model. The comfort temperature obtained from thermal sensation votes is 25.7 °C whereas the comfort temperature calculated from PMV model is 25 °C. This proved that PMV model overestimated the thermal sensation of the students in this study. Chew emphasized that this finding is important for local HVAC engineers since increasing the setting of comfort temperature by 0.7 °C on air conditioning system could save a considerable amount of energy used in the building. By correlating the comfort temperature of each lecture halls and their respective outdoor temperature, the adaptive thermal comfort model is established and shown in Equation (2.16).

$$T_c = 16.487 + 0.275\ T_{out}, \quad r^2 = 0.72 \tag{2.16}$$

The upper and lower limit of the adaptive model were determined by using the actual percentage dissatisfied below 20%. The acceptable indoor comfort temperature range is found to be in between 23.9 °C and 26 °C whereas the outdoor temperature range is between 27 °C and 34.6 °C.

Another thermal comfort study was carried out in hot and humid climate of South East Asia by Nguyen [114]. A Meta analysis was performed to evaluate the occupants' thermal behavior in naturally ventilated buildings. Griffith's method was used to determine the comfort temperature. For naturally ventilated buildings, the comfort temperature is discovered to be 27.9 °C, which is higher than the comfort temperature found in air-conditioned buildings with only 25.8 °C. Nguyen compared the thermal sensation votes of the study with the predicted mean vote calculated from Fanger's model. The correlation between the two is derived in Equation (2.17). The small r^2 value indicated that the relationship between thermal sensation vote (TSV) and predicted mean vote (PMV) is relatively low. Thus, Nguyen suggested that PMV model is not suitable to be used in climatic region.

$$\mathrm{TSV} = 0.82\ \mathrm{PMV} - 0.358, \quad r^2 = 0.195 \tag{2.17}$$

The thermal comfort model proposed by Nguyen for naturally ventilated buildings in South East Asia is shown in Equation (2.18). The comfortable temperature range which fulfilled 80% and 90% acceptability is ± 5.7 °C and ± 3.2 °C, respectively.

$$T_c = 18.83 + 0.341\ T_{out}, \quad r^2 = 0.52 \tag{2.18}$$

Bouden and Ghrab conducted their research work in Tunisia, Africa, covering five towns from two climatic zones [152]. Two hundred respondents from different houses and working places were assessed. Most of the buildings were free running buildings with only a few of them installed with heating system. Griffith's method and Brager's method were used in this study to determine the comfort temperature. A strong correlation is found between the comfort temperature and its outdoor temperature with r^2 value of 0.96 and 0.99 as indicated in Equation (2.19) and Equation (2.20). Therefore, Bouden and Ghrab concluded that the thermal comfort models derived from their study are important to determine the indoor comfort temperature.

$$T_c = 10.35 + 0.518\ T_{out}, \quad r^2 = 0.96, \text{ Griffith's method} \tag{2.19}$$

$$T_c = 6.88 + 0.68\ T_{out}, \quad r^2 = 0.99, \text{ Brager's method} \tag{2.20}$$

Toe and Kubotaa performed worldwide Meta analysis on naturally ventilated buildings from hot and humid climate, hot and dry climate and also from moderate climate by using the data from ASHRAE RP-884 database [88]. The field study which included 10,065 subjects was refined into 7,662 subjects. The naturally ventilated buildings involved were residential buildings and offices. The thermal comfort models developed from the study are shown in Equation (2.21), Equation (2.22) and Equation (2.23). By observing the daily mean outdoor temperature ranges, the indoor operative temperature range can be calculated from the proposed thermal comfort models. The acceptable indoor comfortable temperature range for hot and humid climate is between 24.9 °C and 31.2 °C.

For hot and dry climate, the comfort temperature range is from 24.8 °C to 33.7 °C and for moderate climate, the acceptable comfort temperature is ranged from 19 °C to 24.7 °C.

For hot and humid climate,

$$T_c = 13.8 + 0.57\ T_{out}, \quad r^2 = 0.64 \tag{2.21}$$

For hot and dry climate,

$$T_c = 13.7 + 0.58\ T_{out}, \quad r^2 = 0.59 \tag{2.22}$$

For moderate climate,

$$T_c = 18.6 + 0.22\ T_{out}, \quad r^2 = 0.09 \tag{2.23}$$

A thermal comfort study was carried out by Mishra on free running buildings of India [153]. A total of 338 responses from 121 subjects were collected from the laboratory classrooms and evaluated based on ASHRAE scale, Bedford scale and PMV model. The relationship between these scales and their indoor operative temperature are shown in Equation (2.24), Equation (2.25) and Equation (2.26). The comfort temperature obtained from these scales is 26.5 °C, 26.6 °C and 19.8 °C, respectively.

$$MTSV = 0.18\ T_{op} – 4.77, \quad r^2 = 0.86 \tag{2.24}$$

$$MTCV = 0.14\ T_{op} – 3.72, \quad r^2 = 0.87 \tag{2.25}$$

$$PMV = 0.18\ T_{op} – 3.57, \quad r^2 = 0.95 \tag{2.26}$$

where

MTSV = Mean thermal sensation vote

MTCV = Mean thermal comfort vote

PMV = Predicted mean vote

T_{op} = Operative temperature, °C

The acceptable temperature range for ASHRAE scale and Bedford scale was determined by solving the fitted polynomials for 80% acceptability. For ASHRAE scale, the acceptable temperature range is discovered to be in between 22.7 °C and 28.9 °C while for Bedford scale, the acceptable temperature range is from 17.9 °C to 32.8 °C. The adaptive thermal comfort model of this study is defined in Equation (2.27) by using Griffith's method. High r^2 value indicated that there is a robust relationship between the indoor comfort temperature and its outdoor temperature.

$$T_c = 15.23 + 0.53\ T_{out}, \quad r^2 = 0.93 \tag{2.27}$$

There was another thermal comfort study performed in India, covering 3 seasons, 16 buildings, five cities with five climatic seasons which included warm and humid climate, hot and dry climate, composite climate, moderate climate and cold climate [154]. The study was focusing on naturally ventilated buildings and mixed mode buildings. 6,330 responses from different types of office buildings were involved in the thermal comfort assessments. Griffith's method was used to determine the thermal neutrality of the occupants. The correlation between indoor comfort temperature and outdoor temperature is shown in Equation (2.28) and Equation (2.29).

For naturally ventilated buildings,

$$T_c = 12.83 + 0.54\, T_{out}, \quad r^2 = 0.81 \tag{2.28}$$

For mixed mode buildings,

$$T_c = 17.9 + 0.28\, T_{out}, \quad r^2 = 0.72 \tag{2.29}$$

The comfortable temperature range for naturally ventilated buildings and mixed mode buildings which fulfilled 80% acceptability is ± 4.1 °C and ± 5.9 °C, respectively. Based on the recorded outdoor temperature of the study, the acceptable indoor temperature for naturally ventilated buildings is ranged from 19.6 °C to 28.5 °C. For mixed mode buildings, the acceptable indoor temperature range is found to be in between 21.5 °C and 28.7 °C. PMV model was used in this study as well but it was discovered that this model overpredicted the thermal sensation of the occupants especially on the warmer side of the scale. The literature studies of thermal comfort models are summarized in Table 2.9.

Table 2.9: Adaptive Thermal Comfort Models

Region	Building type	Thermal comfort model	Year	Findings
Worldwide [124]	Free running buildings	$T_c = 13.5 + 0.54\ T_{out}$	1970s-1998	r^2 = 0.95 for 1970s. r^2 = 0.9 for 1998.
Southeast Asia [143]	Naturally ventilated buildings + mechanically ventilated buildings	$T_c = 17.6 + 0.31\ T_{out}$	-	For 80% acceptability, T_c can be ± 3.5 °C where indoor temperature cannot exceed or go below the acceptable temperature range.
Tropical worldwide [141]	Free running buildings	$T_c = 12.9 + 0.534\ T_{out}$	1978	- Air movement is an important factor to determine comfort. - Assume air velocity of 0.1 $\mathrm{m s^{-1}}$ and relative humidity of 50%. - Comfort temperature can be raised by $7 - \frac{50}{4+10Va^{0.5}}$°C if the air velocity is above 0.1 $\mathrm{m\,s^{-1}}$ and fairly constant.
Worldwide [79]	Naturally ventilated buildings HVAC buildings	$T_c = 17.8 + 0.31\ T_{out}$ $T_c = 21.45 + 0.11\ T_{out}$	1990s	- For 80% and 90% acceptability, the interval of comfort temperature for naturally ventilated buildings is ± 3.5 °C and ± 2.5 °C, respectively. - Outdoor temperature range of 10 °C to 33.5 °C. - Activity level less than 1.3 met.
European countries [147]	Naturally ventilated buildings, climatized buildings and mixed mode buildings	$T_c = 19.39 + 0.30\ T_{out}$	2000	- Reliable only for outdoor temperature higher than 10 °C, if below this limit, a constant value of T_c = 22.88 °C has to be considered. - Acceptability range = 6.35 – 0.189 T_c.

Table 2.9 continued

Region	Building type	Thermal comfort model	Year	Findings
European countries [148]	Free running buildings	$T_c = 18.8 + 0.33\ T_{out}$	2007	- Applicable for the outdoor temperatures between 10 °C and 30 °C. - Comfort temperature range is ± 2 °C, ± 3 °C and ± 4 °C for PPD < 6%, < 10% and < 15%, respectively.
Pakistan [149]	Commercial buildings – all of them were free running buildings, only one was having a centralized air conditioning system	$T_c = 18.5 + 0.36\ T_{out}$, $r^2 = 0.73$	-	Activity level was between 1.11 met and 1.25 met.
Pakistan [150]	Buildings with heating and air conditioning system	$T_c = 17.0 + 0.38\ T_{out}$	-	-
Subtropical climate of Hong Kong [19]	Air-conditioned office buildings	$T_c = 18.303 + 0.158\ T_{out}$, $r^2 = 0.59$	2003	- Comfort temperature for summer is 23.7 °C. - Comfort temperature for winter is 21.2 °C. - Acceptable indoor comfort temperature range is in between 19.1 °C and 24.8 °C with the outdoor temperature not exceeding 41.1 °C or go below 5 °C. - 7% of the energy is conserved by applying the model into the cooling systems.

Table 2.9 continued

Region	**Building type**	**Thermal comfort model**	**Year**	**Findings**
Hot and humid climate of India [151]	Naturally ventilated offices Air conditioned offices	$T_c = 21.4 + 0.26\ T_{out}$ (Griffith's method) $T_c = 22.1 + 0.15\ T_{out}$ (Griffith's method)	2014	- Comfort temperature of naturally ventilated offices is 28 °C. - Comfort temperature of air-conditioned offices is 26.4 °C. - Relative humidity of both modes is in between 45% and 48%. - Air velocity varied from 0.11 $\mathrm{m\ s^{-1}}$ to 0.17 $\mathrm{m\ s^{-1}}$ for both modes. - Air velocity of 1.0 $\mathrm{m\,s^{-1}}$ can help to increase the comfort temperature by 2.7 K.
Hot and humid climate of Malaysia [20]	Air-conditioned lecture halls	$T_c = 16.487 + 0.275\ T_{out}$, $r^2 = 0.72$	2015	- Comfort temperature is found to be 25.7 °C. - Upper and lower limit of the model were determined by using the actual percentage dissatisfied below 20% where the acceptable indoor comfort temperature range is from 23.9 °C to 26 °C with the outdoor temperature range of 27 °C to 34.6 °C.
Hot and humid climate of Southeast Asia [114]	Naturally ventilated buildings	$T_c = 18.83 + 0.341\ T_{out}$, $r^2 = 0.52$ (Griffith's method)	2012	- Comfort temperatures of naturally ventilated buildings and air-conditioned buildings are 27.9 °C and 25.8 °C, respectively. - Correlation between TSV and PMV is low with the r^2 value of 0.195. - Comfort temperature which fulfilled 80% and 90% acceptability is ± 5.7 °C and ± 3.2 °C, respectively.

Table 2.9 continued

Region	**Building type**	**Thermal comfort model**	**Year**	**Findings**
Climatic zones of Tunisa, Afirca [152]	Free running buildings, only a few were installed with heating system	$T_c = 10.35 + 0.518\ T_{out}$, $r^2 = 0.96$ (Griffith's method) $T_c = 6.88 + 0.68\ T_{out}$, $r^2 = 0.99$ (Brager's method)	2005	- Strong correlation between indoor comfort temperature and outdoor temperature. - The thermal comfort models proposed are important to determine the indoor comfortable temperature.
Hot-humid, hot-dry and moderate climate of different countries [88]	Naturally ventilated residential buildings and offices	Hot and humid climate $T_c = 13.8 + 0.57\ T_{out}$, $r^2 = 0.64$ Hot and dry climate $T_c = 13.7 + 0.58\ T_{out}$, $r^2 = 0.59$ Moderate climate $T_c = 18.6 + 0.22\ T_{out}$, $r^2 = 0.09$	2013	- Acceptable indoor comfort temperature range: 24.9 °C to 31.2 °C. - Acceptable indoor comfort temperature range: 24.8 °C to 33.7 °C. - Acceptable indoor comfort temperature range: 19 °C to 24.7 °C.
Tropical climate of India [153]	Free running buildings of laboratory classrooms	$T_c = 15.23 + 0.53\ T_{out}$, $r^2 = 0.93$ (Griffith's method)	2013	- For ASHRAE scale, MTSV = 0.18 T_{op} – 4.77 with T_c of 26.5 °C. - For Bedford scale, MTCV = 0.14 T_{op} – 3.72 with T_c of 26.6 °C. - For PMV model, PMV = 0.18 T_{op} – 3.57 with T_c of 19.8 °C. - Temperature range which fulfilled 80% acceptability for ASHRAE scale is 22.7 °C to 28.9 °C. - Temperature range which fulfilled 80% acceptability for Bedford scale is 17.9 °C to 32.8 °C.

Table 2.9 continued

Region	Building type	Thermal comfort model	Year	Findings
Climatic zones of India [154]	Naturally ventilated office buildings	$T_c = 12.83 + 0.54\ T_{out}$, $r^2 = 0.81$ (Griffith's method)	2014	- Comfort temperature range is ± 4.1 °C for 80% acceptability. - Acceptable indoor temperature range is 19.6 °C to 28.5 °C.
	Mixed mode office buildings	$T_c = 17.9 + 0.28\ T_{out}$, $r^2 = 0.72$ (Griffith's method)		- Comfort temperature range is ± 5.9 °C for 80% acceptability. - Acceptable indoor temperature range is 21.5 °C to 28.7 °C. - PMV overpredicted the thermal sensation of respondents on the warmer side of ASHRAE scale.

2.6 The Impact of Different Thermal Comfort Models on Zero Energy Residential Buildings

The selection of a thermal comfort model for establishing indoor optimal hygrothermal conditions during the hot period has a major impact on energy consumption of Net Zero Energy Buildings especially in hot climate [18]. A Net Zero Energy Building is a very low energy building that balances its low energy consumption through the usage of renewable energy yielded from its site on an annual basis [155].

European standard EN 15251 states that an energy declaration without a declaration related to the indoor environment makes no sense [156]. This indicates that criteria for the indoor environment need to be specified in terms of design, energy calculations, performance and operation [156].

Most of the energy efficiency researches are conducted in cold climate and the impact of thermal comfort models in hot climates have been scarcely studied [18]. Therefore, Net Zero Energy Buildings in warmer climate especially hot and humid climate needs to be quantitively defined through explicit assessments. Moreover, national legislations do not impose any thermal comfort models to become a set-point for building energy systems but only indicate reference temperature range to be maintained during winter or summer [157].

There are several thermal comfort models available in standardizing indoor environment such as Fanger's model [156], American adaptive comfort model [158], European adaptive comfort model [124, 156] and Givoni's Building Bioclimatic Chart [159]. These models tend to minimize thermal discomfort and can be used as a guideline to achieve optimum indoor condition [18].

In a recent study conducted in hot and humid climate of Cairo, Egyot [18], all the aforementioned thermal comfort models were used to analyze the energy consumption and comfort performance of Net Zero Energy Building via Building Performance Simulation (BPS) programs and EnergyPlus. Table 2.10 compares the impact of the four thermal comfort models according to their annual energy consumption respectively.

Table 2.10: Annual Energy Consumption of Four Thermal Comfort Models [18]

Thermal comfort model	Annual energy consumption (kWh/year)
ISO 7730	2526
EN 15251	2114
ASHRAE 55	1995
Givoni's Building Bioclimatic Chart	1900

In order to achieve optimum comfort condition under different thermal comfort models, the reference set-point conditions of each comfort model were used in the study. The comfort model of ISO 7730 possessed the highest annual energy consumption with 2526 kWh/year. By using ISO 7730 as a comparison to EN 15251, ASHRAE 55 and Givoni's Building Bioclimatic Chart, it is discovered that the annual energy consumption is reduced to 2114 kWh/year (16.3%), 1995 kWh/year (21.0%) and 1900 kWh/year (24.8%), respectively.

The difference of energy consumption between different thermal comfort models is due to the different temperature range standardized by each comfort model. Fanger's model (ISO7730) has a very narrow temperature range while Givoni's model provides a wide temperature range reaching 30 ℃ [18]. ASHRAE 55 and EN 15251 are using adaptive principle on their comfort models which covers a wider temperature range than the Fanger's model. As a result, the condition of indoor environment can be maintained adaptively by natural means [160] and subsequently reduce the energy needed for cooling. Thus, it can be inferred that adaptive comfort model is more appropriate for mixed-mode non-air-conditioned buildings especially in hot climate [161, 162].

French National research project, Positive Energy Building (ENERPOS) was carried out to focus on the design of Net Zero Energy Buildings in hot climates [155]. In terms of comfort criteria, the ENERPOS project suggested the use of resultant temperature of Givoni comfort zones as a well-adapted tool for the assessment of thermal comfort in the tropical regions. One of the main requirements of the project is to achieve the energy index less than 80 kWh/m^{2}y. The first simulation results of this study have led to an energy index below 50 kWh/m²y and a photovoltaic (PV) supply of 78 kWh/m²y. As an accurate energy monitoring system was applied, it appeared that the actual energy index is around 31 kWh/m²y after one year of operation instead of 50 kWh/m²y [155]. This project is a success since its energy consumption can be covered by its yielded renewable energy.

Another research work was done by Francesco [163] on EnergyFlexHouse located in Denmark, around 20 km from Copenhagen. The objective of the work is to determine how much climate conditions can influence the design choices on a building. The technical and architectural solutions which had the highest energy impact on the building in its original climate was moved to a completely different location and the energy performance of the new site was evaluated. The refined solutions were carried out to achieve the best performance at the new location. Givoni comfort analysis was used in this study with the heating and cooling set points of 18 °C and 26 °C. The EnergyFlexHouse was concluded as a Net Zero Energy Building since its overall electrical energy usage is accounted for 51 kWh/ m²y, while the electricity generation which was achieved through the PV system, is equal to 53 kWh/ m²y [163].

The building was then moved to La Reunion, France and re-evaluated again. The overall consumptions are found to be 59 kWh/ m²y which initially appeared to fulfil the requirement to be a Net Zero Energy Building. However, after a more in-depth analysis, it was discovered that the thermal loads are equal to 94 kWh/ m²y, which is not acceptable as a Net Zero Energy Building. Even though the building could reach the balance through a much-oversized PV plant with electricity production of around 90 kWh/m²y, the main purpose is to optimize the load side according to climate, not the sizing of the PV system.

After implemented various passive ventilations techniques to the building, the cooling loads are reduced by more than 85 kWh/ m^2y to 6.5 kWh/ m^2y [163]. Therefore, it was proven that a Net Zero Energy Building can be achieved by maximizing passive techniques as it can minimize energy consumptions and concurrently reduce environmental problems.

Future researches need to focus on more dataset to come up with a guideline in defining the application of different thermal comfort models according to different climate contexts and building envelopes. The study should extent to a wider aspect as well, not just merely focusing on Net Zero Energy Building but also on regular residential buildings.

2.7 Chapter Summary

A review on thermal comfort and different types of cooling system were carried out with the summary provided in Table 2.4, 2.5, 2.6 and 2.8. Since the residential sector is one of the main contributors to energy usage in Malaysia, energy efficiency on cooling system have to be underlined. Hybrid cooling is found to be the most effective cooling system. Therefore, the application of passive cooling and active cooling are integrated to implement an energy efficient home cooling system.

In order for the cooling system to work effectively, the demanded thermal comfort need to be identified and adopted into the home cooling system design. There are two main approaches to determine thermal comfort which are steady state model and adaptive model. Steady state model is not that precise due to its restriction on environmental parameters, therefore, it often overestimates the thermal sensation of the people. In contrast, adaptive model is a better model to define thermal comfort since it includes human adaptive behavior in the study. By using the adaptive model, indoor comfortable temperature can be determined through the correlation of outdoor temperature.

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter explains the procedures involved to develop the adaptive thermal comfort models for the residential buildings in the urban areas of Sarawak, Malaysia. Site measurements were carried out to collect the data and the analysis were performed to determine the thermal comfort demanded by the residents. Furthermore, the upper and lower limits of the parameters within the models were also identified.

3.2 Field Measurements

Several locations from the urban areas of Sarawak, which in this case, Kuching and Sibu, two of the major cities in Sarawak, were selected for the study.

The study was conducted from May 2015 until February 2017, covering from 11.30am in the morning to 11.40pm in the evening. Before the commencement of the field study, initial field visits were done to obtain information regarding the dimensions and characteristics of the site such as the sample size, age and genders of the subjects. The field measurements were divided into two categories, physical measurements and subjective assessments.

3.2.1 Physical Measurements

The physical conditions of each residential area which consisted of indoor air temperature (T_a), globe temperature (T_g), outdoor temperature (T_{out}), relative humidity (RH) and air velocity (v_a) were measured at 1.1 m above the floor level [97, 115]. The setups of the devices are illustrated in Figure 3.1(a) and Figure 3.1(b). The devices used were hygrometer model testo 625, hot wire anemometer model TA 888 and globe thermometer as shown in Figure 3.2, 3.3 and 3.4, respectively. All of these parameters were collected, compared and tabulated accordingly.

Figure 3.1(a): Set up of the Devices

Figure 3.1(b): Devices Located 1.1m above the Floor Level

3.2.1.1 Hygrometer Model Testo 625

Figure 3.2: Hygrometer Model Testo 625

Hygrometer testo 625 was used to measure the indoor air temperature, outdoor temperature and humidity level of the residential buildings. This instrument consists of built-in humidity probe head to measure temperature and air moisture of the surroundings. The values of temperature and relative humidity were taken when the readings were stable.

3.2.1.2 Hot Wire Anemometer Model TA 888

Indoor air velocity of the residential buildings was measured by using hot wire anemometer model TA 888 as shown in Figure 3.3. This device uses a very fine wire which will electrically heat up to some temperature above the ambient. Air flowing through the wire experienced cooling effect and will be converted into the fluctuation values of air velocity.

Figure 3.3: Hot Wire Anemometer Model TA 888

The mean values of air velocity were calculated from its lowest and highest values to represent the actual air speed experienced by each residential area. These values were recorded subsequently.

3.2.1.3 Globe Thermometer

Globe thermometer was used to obtain the globe temperature. The globe thermometer was installed by inserting the thermometer into a matt black painted globe ($\mathcal{E}_g = 0.95$), with the diameter of 15 cm (standard globe). The black globe was mounted in the central position as shown in Figure 3.4. The globe temperatures were recorded.

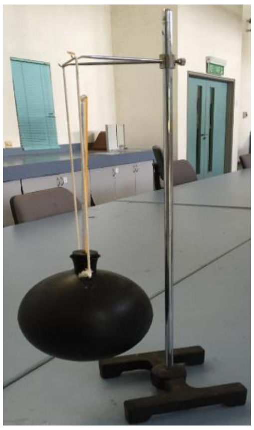

Figure 3.4: Globe Thermometer

The globe temperature obtained was used to calculate the mean radiant temperature, T_r, which will then be used to determine the indoor operative temperature, T_{op}. The mean radiant temperature was calculated based on the formula written in Equation (3.2) [164] and recorded. Mean radiant temperature is the uniform temperature of black surroundings which will have an important influence on human's heat balance [165].

$$T_r = [(T_g + 273)^4 + \frac{1.1 \times 10^8 \times Va^{0.6}}{\varepsilon g \times D^4} (T_g - T_a)]^{1/4} \qquad (3.1)$$

For standard globe, D = 0.15m, $\mathcal{E}_g = 0.95$

$$T_r = [(T_g + 273)^4 + 2.5 \times 10^8 \times V_a^{\ 0.6} (T_g - T_a)]^{1/4} - 273 \qquad (3.2)$$

where

T_r = mean radiant temperature, °C

T_g = globe temperature, °C

v_a = air velocity, ms^{-1}

$\mathcal{E}_g$ = emissivity of the black globe without dimension

D = diameter of the globe, m

T_a = air temperature, °C

The indoor operative temperature was determined by combining indoor air temperature, mean radiant temperature and factor accordance of air velocity as written in Equation (3.3) [166]. The values of factor accordance are shown in Table 3.1 [166]. The calculated values of operative temperature were recorded. Operative temperature was used to define the comfort conditions throughout the study. The relationship between indoor operative temperature with outdoor temperature, relative humidity and air velocity were analyzed.

$$T_{op} = A \times T_a + (1 - A)\, T_r \tag{3.3}$$

where

T_{op} = operative temperature, °C

T_a = air temperature, °C

T_r = mean radiant temperature, °C

A = factor accordance

Table 3.1: Factor Accordance of Air Velocity

v_a (ms^{-1})	< 0.2	0.2-0.6	0.6-1.0
A	0.5	0.6	0.7

3.2.2 Subjective Assessments

Field surveys were carried out by distributing the questionnaires to the residents of every residential area to evaluate their thermal conditions. The questionnaires were clarified verbally to the residents to ensure that they conveyed their immediate thermal response on their indoor environment. The sample of the questionnaire is attached in Appendix A.

The aspects of the questionnaires included residents' thermal perception based on ASHRAE scale, Bedford scale, direct votes of acceptability and thermal preference scale. Activity level and clothing insulation of the respondents were also added into the assessments as personal parameters. The examples of activity level and clothing insulation are shown in Table 3.2 and Table 3.3 together with their respective values. The activity level and clothing insulation obtained from the study were analyzed for their correlation with indoor operative temperature.

Table 3.2: Activity Level

Activity	**W/m^2**	**met**
Seated relaxed	58	1.0
Standing at rest	70	1.2
Sedentary activity	70	1.2
Standing, light activity	93	1.6
Standing, medium activity	116	2.0

Since thermal comfort will be influenced by physical and personal parameters, subjective assessments were done simultaneously with the physical measurements. The thermal environments were ensured to be unrestrained from any manipulations or interferences so that the residents' respond on their climate conditions can be investigated.

Table 3.3: Clothing Insulation

Clothing		**Insulation**	
		Clo	**m^{2}K/W**
Shirts, dresses	Short sleeve	0.09	0.029
	Light shirt with long sleeves	0.20	0.031
	Normal shirt with long sleeves	0.25	0.039
	Light dress sleeveless	0.25	0.039
	Dress long sleeves	0.40	0.062
Trousers, skirts	Shorts	0.06	0.009
	Light trousers	0.20	0.031
	Normal trousers	0.25	0.039
	Light skirt 15cm above knee	0.01	0.016
	Light skirt 15cm below knee	0.18	0.028
Footwear	Socks	0.02	0.003
	Thick long socks	0.10	0.016
	Slippers	0.03	0.005
	Thin soled shoes	0.02	0.003
	Thick soled shoes	0.04	0.006

3.3 Validation Test for Measurements Data

The validity of the measurements data was checked by using error analysis, which can also be referred as bias uncertainty, BU. The bias uncertainty for the measurements data were determined by using Equation (3.4) [167]. The data set is only considered valid if the bias uncertainty value is less than 10%.

$$\mathrm{BU} = (\mathrm{X}_{\mathrm{max}} - \mathrm{X}_{\mathrm{min}}) / n \tag{3.4}$$

where

X = measured data such as air temperature, outdoor temperature, globe temperature, relative humidity and air velocity

$\mathrm{X}_{\mathrm{max}}$ = maximum value of the measured data

$\mathrm{X}_{\mathrm{min}}$ = minimum value of the measured data

n = sum of the total readings

3.4 Thermal Comfort Evaluation

The thermal perceptions of the respondents from each residential area were evaluated based on different scales in the questionnaire, ASHRAE scale, Bedford scale, thermal acceptability scale and thermal preference scale. Beside the aforementioned scales, the information acquired from the questionnaire can be applied into Fanger’s model to assess thermal comfort as well. In this study, the parameters obtained from the questionnaire were implemented into Fanger’s model for further analysis and comparison. The findings of each scale were compared and analyzed.

3.4.1 ASHRAE Scale

The votes of ASHRAE scale were referred as thermal sensation vote, TSV. The distribution of the votes for ASHRAE scale were assessed and analyzed. Scales for thermal sensation vote are shown in Table 3.4.

Thermal environment was presumed to be comfortable or acceptable if the votes were within the central three categories of the scale (-1, 0, 1). The assessment of votes for ASHRAE scale was compared to Bedford scale, thermal acceptability scale and thermal preference scale.

Table 3.4: ASHRAE Scale

Thermal sensation scale	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**
Description	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

3.4.1.1 Analysis of Comfort Temperature, T_c from ASHRAE Scale

Regression analysis was used to determine the comfort temperature from ASHRAE scale. The actual mean vote, MTSV of the thermal sensation votes for each operative temperature was calculated and tabulated. Then, the graph of MTSV against operative temperature was plot and evaluated.

The comfort temperature, T_c was the interception point where MTSV = 0. The value of the comfort temperature was recorded and compared with the comfort temperature obtained from Bedford scale and PMV model. The regression between thermal sensation vote, TSV and thermal comfort vote, TCV as well as TSV and predicted mean vote, PMV were assessed.

The comfort temperature for each residential area was also determined. The relationships between these comfort temperatures and their respective average relative humidity and air velocity were evaluated.

3.4.2 Bedford Scale

The votes of Bedford scale were referred as thermal comfort vote, TCV. The distribution of the votes for Bedford scale were assessed and analyzed. Indicators for thermal comfort vote are shown in Table 3.5.

Thermal environment was assumed to be comfortable or acceptable if the votes were within the central three categories of the scale (-1, 0, 1). The assessment of votes for Bedford scale was compared to ASHRAE scale, thermal acceptability scale and thermal preference scale.

Table 3.5: Bedford Scale

Thermal comfort scale	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**
Description	Much too cool	Too cool	Comfortably cool	Comfortable	Comfortably warm	Too warm	Much too warm

3.4.2.1 Analysis of Comfort Temperature, T_c from Bedford Scale

Similar to Section 3.4.1.1, regression analysis was used to determine the comfort temperature from Bedford scale. The actual mean vote, MTCV of the thermal comfort votes for each operative temperature was calculated and tabulated. Then, the graph of MTCV against operative temperature was plot and evaluated.

The interception point where MTCV = 0, was the comfort temperature, T_c of the Bedford scale. The value of the comfort temperature was recorded and compared with the comfort temperature obtained from ASHRAE scale and PMV model. The regression between TCV and thermal sensation vote, TSV as well as TCV and predicted mean vote, PMV were assessed.

The comfort temperature for each residential area was also determined. The relationships between these comfort temperatures and their respective average relative humidity and air velocity were evaluated.

3.4.3 Fanger’s Model

The predicted mean vote, PMV of Fanger’s model was used to analyze the thermal environment experienced by the residents. ASHRAE scale was referred in this model since its evaluation was also based on the thermal sensation of the respondents, varying from -3 to 3 as indicated in Table 3.4.

3.4.3.1 Analysis of Comfort Temperature, T_c from Fanger's model

Similar to Section 3.4.1.1 and Section 3.4.2.1, regression analysis was used to determine the comfort temperature from Fanger's model. The predicted mean vote, PMV for each operative temperature was calculated and tabulated. In this study, the PMV value was computed by using CBE thermal comfort tool which was complied with ASHRAE Standard 55-2013 [168]. The parameters of operative temperature, relative humidity, air velocity, activity level and clothing insulation were used in this computation.

The graph of PMV against operative temperature was plot and evaluated. The comfort temperature T_c, of the Fanger's model was the interception point where PMV = 0. The value of the comfort temperature was recorded and compared with the comfort temperature obtained from ASHRAE scale and Bedford scale. The regression between PMV and thermal sensation vote, TSV as well as PMV and thermal comfort vote, TCV were assessed.

3.4.4 Thermal Acceptability Scale

Thermal acceptability scale was a scale where respondents were asked to assess their thermal environment in a direct way, either they found their environment acceptable or unacceptable. The distribution of votes was evaluated and compared to ASHRAE scale, Bedford scale and thermal preference scale. The allocation of the acceptability votes was tabulated according to Table 3.6.

Table 3.6: Thermal Acceptability Scale

Acceptability scale	Acceptable	Unacceptable
Number and percentage of votes (%)		

3.4.5 Thermal Preference Scale

In thermal preference scale, respondents were assessed based on their thermal preference, either they wanted their indoor ambience to be warmer, no change or cooler. It was presumed that respondents who voted on “warmer” or “cooler” were not satisfied with their environment since they demanded for a change. Respondents who voted on “no change” were assumed to recognize their thermal environment as acceptable. The thermal preference scale was evaluated and compared to ASHRAE scale, Bedford scale and thermal acceptability scale. The distribution of votes was tabulated according to Table 3.7.

Table 3.7: Thermal Preference Scale

Thermal preference	Warmer	No change	Cooler
Number and percentage of votes (%)			

3.4.6 Analysis of Relative Humidity

The average relative humidity of each residential area was calculated and recorded. The actual perception of respondents towards their environment’s humidity level was determined via relative humidity vote (RHV). The relative humidity scale used in this study is shown in Table 3.8. The mean relative humidity vote for each residential area was determined and compared with their corresponding average relative humidity.

Table 3.8: Scale for Relative Humidity

Scale	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**
Description	Too dry	Dry	Slightly dry	Just right	Slightly humid	Humid	Too humid

The correlation between average relative humidity and the comfort temperature for each residential area was also assessed.

3.4.7 Analysis of Air Velocity

The average air speed of each residential area was calculated and recorded. The actual perspective of residents on the air speed which they experienced was identified via air speed vote (ASV). The scale of air velocity is shown in Table 3.9.

Table 3.9: Scale for Air Velocity

Scale	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**
Description	Too still	Still	Slightly still	Just right	Slightly breezy	Breezy	Too breezy

The mean air speed vote for each residential area was determined and compared with their corresponding average air velocity. The correlation between average air velocity and the comfort temperature for each residential area was evaluated.

3.5 Proposed Adaptive Thermal Comfort Model

The adaptive thermal comfort model was developed by correlating the thermal neutrality of each residential area with their respective outdoor temperature through regression analysis. In this study, two thermal comfort models were developed, the linear regression models of ASHRAE scale and Bedford scale. These models were compared and evaluated in terms of r^2 value.

3.5.1 Upper and Lower Limit of the Adaptive Model

The upper and lower limit of the operative temperature were determined based on the minimum satisfaction of 80% [90, 169]. Actual percentage dissatisfied, APD for each operative temperature was calculated. Then, the graph of actual percentage dissatisfied, APD against operative temperature was plot. The operative temperature range which fulfilled 80% satisfaction (APD below 20%) was defined and compared with the temperature range obtained from PMV model.

For Fanger's model, predicted percentage dissatisfied, PPD for each operative temperature was calculated according to Equation (3.5). The graph of predicted percentage dissatisfied, PPD against operative temperature was plot. The temperature range below 20% was defined and compared with the temperature range obtained from actual percentage dissatisfied, APD.

$$\text{PPD} = 100 - 95e\ (0.03353\ \text{PMV}^4 + 0.2179\ \text{PMV}^2) \qquad (3.5)$$

The upper and lower limit of relative humidity were also determined based on the minimum satisfaction of 80% [90]. Actual percentage dissatisfied, APD for each relative humidity was calculated. Then, the graph of actual percentage dissatisfied, APD against relative humidity was plot. The relative humidity range which fulfilled 80% satisfaction

(APD below 20%) was determined. The upper and lower limit of the air velocity were determined with the same procedures.

Predicted percentage dissatisfied, PPD for each humidity level and air velocity value was determined. The graph of predicted percentage dissatisfied, PPD against relative humidity and air velocity was plot respectively. The relative humidity and air velocity range below 20% dissatisfaction were identified and compared with the range obtained from actual percentage dissatisfied, APD.

3.5.2 Validation of the Adaptive Model

The adaptive models obtained earlier in Section 3.5 were validated by conducting another experiment on different residential areas. The physical measurements and subjective assessments were carried out similarly according to the procedures in Section 3.2. Then, the thermal comfort evaluation was done and the new comfort temperature was determined from ASHRAE scale and Bcedford scale. The new average outdoor temperature was applied into the proposed adaptive thermal comfort models to calculate their comfort temperature respectively. The comfort temperatures calculated from the models were compared with the aforementioned new comfort temperatures. The discrepancies between the comfort temperature values were evaluated.

3.6 Chapter Summary

In order to develop an adaptive thermal comfort model, thermal comfort evaluation has to be done to assess the thermal environment experienced by the residents. Physical measurements and subjective assessments were carried out to gather the parameters required for the evaluation. The measurements data were validated by using error analysis.

In this study, ASHRAE scale, Bedford scale, PMV model, thermal acceptability scale and thermal preference scale were used to analyze the thermal perception of the residents. The findings of each scale were compared and assessed. The comfort temperature which can also be referred as neutral temperature, was determined from ASHRAE scale, Bedford scale and PMV model. The comfort temperatures obtained from these scales were observed, compared and analyzed. The relationship between comfort temperature, relative humidity and air velocity were also assessed.

ASHRAE scale and Bedford scale were used to develop the adaptive thermal comfort models through regression analysis. Comfort temperature and average outdoor temperature of each residential area in the study were determined and the graph between the two parameters was plot. The adaptive thermal comfort models produced from ASHRAE scale and Bedford scale were compared and evaluated.

Thermal acceptability scale was used to determine the upper and lower limit of the models. The comfort temperature, relative humidity and air velocity range which fulfilled the minimum 80% satisfaction were defined. The procedures to validate the adaptive thermal comfort models were also explained. Figure 3.5 summarizes the overall methodology flow for the development of adaptive thermal comfort models.

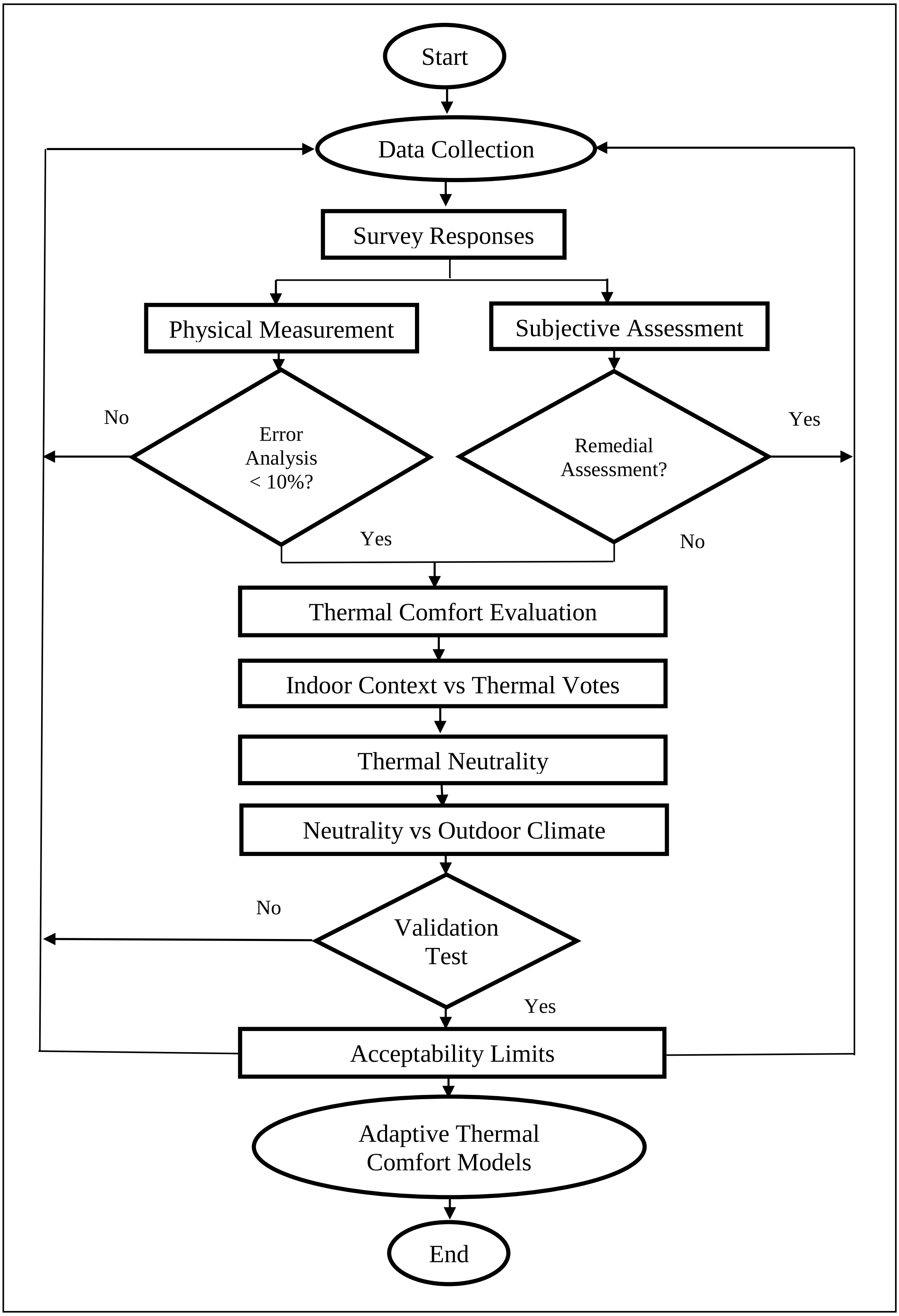

Figure 3.5: Flow Chart for0 Adaptive Thermal Comfort Models Development

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

This chapter presents the thermal perception of the residents on their environments from different residential areas. Field measurements which included physical measurements and subjective assessments were carried out and 287 residents were involved in this study, 148 females and 139 males. For the validation study, there was 31 residents involved with 15 females and 16 males.

The residential buildings of this study can be referred as free running buildings [123] since they were ventilated via natural ventilation and light mechanical ventilation systems such as ceiling fans and standing fans. Only minority of them were using air conditioning system.

The environmental and personal parameters collected from the study were analyzed and applied in the development of adaptive thermal comfort models. Thermal comfort evaluations based on ASHRAE scale, Bedford scale, PMV model, thermal acceptability scale and thermal preference scale were performed.

4.2 Field Measurements Results

Field measurements were divided into physical measurements and subjective assessments. There were ten residential areas involved in this study. Photos of the residential buildings are illustrated as attached in Appendix B.

4.2.1 Indoor and Outdoor Environmental Parameters

Physical measurements which included indoor and outdoor environmental parameters such as air temperature, globe temperature, outdoor temperature, relative humidity and air velocity were collected. The mean radiant temperature and operative temperature were calculated according to Equation (3.2) and Equation (3.3).

The measurements for each residential area were done for five different periods of time and all the parameters collected are attached in Appendix C. The average value of each parameter was calculated and tabulated.

4.2.1.1 Air Temperature

The highest air temperature collected from the study was found to be 32.8 °C at Residential Area 5 while the lowest air temperature was recorded at Residential Area 7. The average air temperature for each residential area is tabulated in Table 4.1.

The difference of air temperature for each residential area was due to the weather variations during the measurements. The weather varied randomly between hot, humid and windy conditions.

It was discovered that the average air temperature of Residential Area 1 and Residential Area 6 were the highest, both exceeding 30.0 °C. The lowest average air temperature was found on Residential Area 9 with 28.2 °C.

Table 4.1: Average Air Temperature for each Residential Area

Residential area	**Average air temperature (°C)**
1	31.7
2	29.0
3	29.5
4	29.7
5	29.8
6	30.6
7	29.7
8	29.9
9	28.2
10	28.4

4.2.1.2 Globe Temperature

The highest globe temperature obtained from the study was located at Residential Area 1 with 32.5 °C. Residential Areas 6 and 9 were both recorded with the lowest globe temperature value of 26.0 °C. The average globe temperature for each residential area is tabulated in Table 4.2. It was observed that the highest average globe temperature was located at Residential Area 1. Residential Areas 2 and 9 had the same lowest globe temperature of 27.0 °C.

Table 4.2: Average Globe Temperature for each Residential Area

Residential area	**Average globe temperature (°C)**
1	31.6
2	27.0
3	28.0
4	28.2

Table 4.2 continued

5	28.5
6	29.2
7	28.8
8	28.4
9	27.0
10	27.1

4.2.1.3 Mean Radiant Temperature

The highest mean radiant temperature of the study was 32.4 °C, which was 8 °C more than its lowest value. According to Table 4.3, the highest average mean radiant temperature of 31.6 °C was discovered at Residential Area 1 while the lowest temperature value was recorded at Residential Area 2 with 26.1 °C.

Table 4.3: Average Mean Radiant Temperature for each Residential Area

Residential area	Average mean radiant temperature (°C)
1	31.6
2	26.1
3	27.0
4	27.5
5	27.4
6	28.1
7	28.2
8	27.1
9	26.3
10	26.3

4.2.1.4 Operative Temperature

Operative temperature was used in this study for thermal comfort evaluation since it contains a weighted value between the air temperature and the mean radiant temperature [19, 164,170].

The highest operative temperature in this study was 32.6 °C while its lowest temperature was found to be 26.4 °C. Residential Area 9 had the lowest average operative temperature of 27.3 °C, which was 4.4 °C less than the highest average operative temperature obtained at Residential Area 1. Table 4.4 shows all the average operative temperature value of the study.

Table 4.4: Average Operative Temperature for each Residential Area

Residential area	Average operative temperature (°C)
1	31.7
2	27.5
3	28.3
4	28.6
5	28.7
6	29.4
7	29.0
8	28.7
9	27.3
10	27.5

4.2.1.5 Outdoor Temperature

The highest outdoor temperature was discovered to be 37.5 °C while the lowest outdoor temperature of 26.6 °C was recorded. Most of the outdoor temperatures exceeded 30 °C due to the direct exposure of solar radiation.

The average outdoor temperature was calculated and tabulated in Table 4.5. The highest and lowest average outdoor temperature was located at Residential Area 1 and Residential Area 10, respectively with the temperature of 34.2 °C and 29.1 °C. The average outdoor temperature of each residential area was used in the development of adaptive thermal comfort models which will be discussed later.

Table 4.5: Average Outdoor Temperature for each Residential Area

Residential area	Average outdoor temperature (°C)
1	34.2
2	30.2
3	31.3
4	31.9
5	29.6
6	32.8
7	31.5
8	31.9
9	29.2
10	29.1

4.2.1.6 Relative Humidity

The relative humidity of the study varied from the lowest level of 56.6% to the highest level of 85.2%. The humidity level was found to be higher especially on rainy days, early in the morning and late at night. The relative humidity was at its lowest particularly in the afternoon when the indoor temperature was at its peak. Table 4.6 shows the average relative humidity of each residential area.

Residential Areas 9 and 10 had the highest average humidity level followed by Residential Area 2. The average relative humidity of the remaining residential areas was found to be similar with one another where the values were in between 66.4% and 72.1%.

Table 4.6: Average Relative Humidity for each Residential Area

Residential area	Average relative humidity (%)
1	66.4
2	76.5
3	69.1
4	72.1
5	69.1

Table 4.6 continued

6	67.0
7	70.2
8	71.0
9	81.4
10	81.6

4.2.1.7 Air Velocity

Due to the fluctuation values of air velocity at the measuring points, the average air velocity was calculated from its highest and lowest value. The average air velocity of each residential area is shown in Table 4.7.

Residential Areas 1, 5, 6 and 8 experienced higher air velocities averagely with the air speed values exceeding 0.15 ms^{-1}. All of the residential areas were considered to be windy since their average air velocity was more than 0.1 ms^{-1}, respectively. Only Residential Area 4 possessed the lowest air velocity of 0.08 ms^{-1}.

Table 4.7: Average Air Velocity for each Residential Area

Residential area	**Average air velocity (ms^{-1})**
1	0.16
2	0.12
3	0.14
4	0.08
5	0.19
6	0.19
7	0.14
8	0.20
9	0.10
10	0.13

4.2.1.8 Bias Uncertainty

The bias uncertainty of the measurement parameters was calculated by using Equation (3.4). According to Yau [167], the measurements data are valid to be used if the error for the bias uncertainty is less than 10%. Table 4.8, 4.9, 4.10, 4.11 and 4.12 show the bias uncertainty of air temperature, globe temperature, relative humidity, air velocity and outdoor temperature for each residential area respectively. Operative temperature and mean radiant temperature were not included in this section since their values were calculated from Equation (3.2) and (3.3).

Table 4.8: Bias Uncertainty for Air Temperature

Residential area	Maximum air temperature (°C)	Minimum air temperature (°C)	Sum of the measurement readings	Bias uncertainty (%)
1	32.7	30.7	158.3	1.26
2	29.4	28.6	144.8	0.55
3	30.6	28.2	147.7	1.63
4	30.4	28.8	148.6	1.08
5	32.8	27.8	148.9	3.36
6	32.4	27.6	153.0	3.14
7	31.1	27.5	148.7	2.42
8	30.7	28.8	149.5	1.27
9	29.9	27.7	141.2	1.56
10	29.3	27.6	141.8	1.20

The bias uncertainty calculated for air temperature was relatively small with all the values lying below 10% as indicated in Table 4.8. The minimum error was found to be 0.55% whereas the maximum error was recorded to be 3.36%. Similar error percentage can be observed on globe temperature in Table 4.9. The range of bias uncertainty for globe temperature varied from 0.37% to 3.43% with the interval difference of approximately 3%, which is similar to the interval difference of air temperature.

The small error percentage of air temperature and globe temperature are due to the small variation changes of these two parameters within the indoor environment which were properly ventilated and insulated from the outdoor conditions. Therefore, the change of indoor air temperature and globe temperature are only affected by the outdoor environment with minimal effect.

Table 4.9: Bias Uncertainty for Globe Temperature

Residential area	**Maximum globe temperature (°C)**	**Minimum globe temperature (°C)**	**Sum of the measurement readings**	**Bias uncertainty (%)**
1	32.5	31.0	158.0	1.00
2	28.0	26.0	136.0	1.47
3	29.0	27.0	140.0	1.43
4	29.0	27.0	141.0	1.42
5	30.5	26.8	142.3	2.60
6	31.0	26.0	146.0	3.43
7	30.0	27.0	144.0	2.08
8	30.0	27.0	142.0	2.11
9	28.0	26.0	135.0	1.48
10	27.5	27.0	135.5	0.37

Relative humidity of each residential area was valid to be used since the bias uncertainty determined were all below 10%. According to Table 4.10, the highest bias uncertainty percentage recorded for relative humidity was 7.52 % while the lowest percentage recorded was 0.37%. The bias uncertainty of relative humidity was averagely higher than the bias uncertainty of air temperature and globe temperature. This is because relative humidity relies not only on air temperature but also on vapor pressure [123]. Vapor pressure varies inconsistently depending on the moisture level in the air which is often influenced by weather conditions and other external factors. Therefore, the variation in relative humidity was higher than the variation in air temperature and globe temperature during the measurements, leading to a higher percentage of bias uncertainty.

Table 4.10: Bias Uncertainty for Relative Humidity

Residential area	**Maximum relative humidity (%)**	**Minimum relative humidity (%)**	**Sum of the measurement readings**	**Bias uncertainty (%)**
1	71.6	62.6	332.0	2.71
2	78.9	75.3	382.6	0.94
3	73.2	65.8	345.3	2.14
4	82.5	68.0	360.5	4.02
5	80.5	56.7	345.7	6.89
6	81.8	56.6	335.0	7.52
7	78.2	57.7	351.2	5.84
8	74.8	66.6	354.8	2.31
9	85.2	72.8	407.2	3.05
10	84.5	73.4	407.9	2.72

Among the five measured parameters, the bias uncertainty for air velocity was much higher than the other four parameters. In this research, there were three residential areas with bias uncertainty exceeding 20%. The highest error percentage recorded was 43.76%. From Table 4.11, it can be observed that air velocity for most of the residential areas were having relatively high bias uncertainty values, ranging between 10% and 20%. This is ascribed to the big fluctuation change of air velocity during the measurements which is inevitable since the indoor air velocity is also affected by outdoor circumstances besides its own indoor ventilation systems. Moreover, it is difficult to obtain an accurate measurement especially at low air velocity [171] as a more dependable sensor reading is only possible if the air velocity is more than 2.0 ms^{-1} [172]. The air velocity measured from this study was mostly in the range of 0.04 ms^{-1} to 0.20 ms^{-1}. This indicates that the air velocity is low and difficult to be measured accurately. However, the bias uncertainty of air velocity in this study was still at an acceptable level since its average error percentage of 18.92% was only slightly above 10%. Similar incident was found in Chew's study [20] where the highest bias uncertainty recorded for air velocity was 13.79%. Nevertheless, the error percentage in Chew's study was lower than the percentage found in present study because Chew was conducting his research in a controlled indoor environment. In contrast, the current research was focusing on free running residential buildings where the indoor environment was ventilated by natural ventilation system with minimal usage of mechanical cooling systems. As a result, the bias uncertainty of this study was higher if compared to the error percentage of a controlled indoor environment.

Table 4.11: Bias Uncertainty for Air Velocity

Residential area	**Maximum air velocity ($\mathbf{ms^{-1}}$)**	**Minimum air velocity ($\mathbf{ms^{-1}}$)**	**Sum of the measurement readings**	**Bias uncertainty (%)**
1	0.19	0.15	0.80	5.00
2	0.19	0.07	0.60	20.00
3	0.20	0.08	0.68	17.65
4	0.15	0.04	0.41	26.83
5	0.23	0.13	0.95	10.53
6	0.48	0.06	0.96	43.76
7	0.19	0.09	0.71	14.09
8	0.27	0.17	1.02	9.80
9	0.14	0.05	0.52	17.31
10	0.21	0.05	0.66	24.24

Table 4.12 shows that the bias uncertainty of outdoor temperature for each residential area was under 10%. The highest and lowest bias uncertainty percentage recorded for outdoor temperature in this study was 6.96% and 0.94%, respectively. The bias uncertainty of outdoor temperature was higher than the error percentage of air temperature, globe temperature and relative humidity. It is because the measurement of outdoor temperature was done outside the residential buildings which was exposed directly

under the solar radiation without much shading effect. Therefore, the variation of outdoor temperature was significant particularly between day and night or between hot and cool condition. The outdoor temperature measured in this study was between 26.1 ℃ and 37.5 ℃. This high interval of difference has caused the bias uncertainty of outdoor temperature to be higher than the other parameters. However, the variation of outdoor temperature was less significant if compared to the variation of air velocity. Thus, the bias uncertainty of outdoor temperature was lower than the bias uncertainty of air velocity in this study.

Table 4.12: Bias Uncertainty Outdoor Temperature

Residential area	**Maximum outdoor temperature (℃)**	**Minimum outdoor temperature (℃)**	**Sum of the measurement readings**	**Bias uncertainty (%)**
1	34.9	33.3	170.8	0.94
2	34.0	27.5	151.2	4.30
3	36.4	26.6	156.4	6.27
4	33.8	28.7	159.6	3.20
5	34.5	26.6	148.1	5.33
6	37.5	26.1	163.8	6.96
7	34.2	27.2	157.3	4.45
8	35.4	27.8	159.4	4.77
9	33.5	27.2	145.9	4.32
10	34.0	27.5	145.3	4.47

4.2.2 Personal Parameters

Personal parameters of activity level and clothing insulation were analyzed from subjective assessments. The detailed results of activity level and clothing insulation are attached in Appendix C.

4.2.2.1 Clothing Insulation

Most of the respondents were staying in their house during the subjective assessments. Therefore, a lot of them were wearing casually with T-shirt, shorts, slippers or barefooted. Only minority of them were wearing formal attire with long sleeve shirt, normal trousers, socks and shoes.

The average clothing insulation of the residents are tabulated in Table 4.13. Residents from Residential Areas 2 and 7 recorded the highest clothing insulation values of 0.30 clo and 0.33 clo, respectively. Most of the residents were wearing similar outfit with the clothing insulation values lying in between 0.20 clo and 0.26 clo.

Table 4.13: Average Clothing Insulation for each Residential Area

Residential area	**Average clothing insulation (clo)**
1	0.22
2	0.30
3	0.24
4	0.26
5	0.20
6	0.25
7	0.33
8	0.20
9	0.25
10	0.23

4.2.2.2 Activity Level

Since most of the residents were residing in their own living environment during the assessments, most of them were found seating and standing relaxed. Some of them were doing light activity while minority of them was doing medium activity such as cleaning or doing housework.

Table 4.14 shows the average activity level for each residential area. The average activity level of the residents was found to be similar, mostly varied from 1.1 met to 1.3 met. Only Residential Area 4 had a slightly higher activity level of 1.4 met.

Table 4.14: Average Activity Level for each Residential Area

Residential area	**Average activity level (met)**
1	1.3
2	1.3
3	1.4
4	1.2
5	1.2
6	1.2
7	1.1
8	1.1
9	1.3
10	1.1

4.2.3 Average Indoor Operative Temperature vs Average Outdoor Temperature

The average indoor operative temperature was discovered to be directly proportional to the average outdoor temperature as shown in Figure 4.1. The high r^2 value indicates that all the points are located close to the fitted regression line.

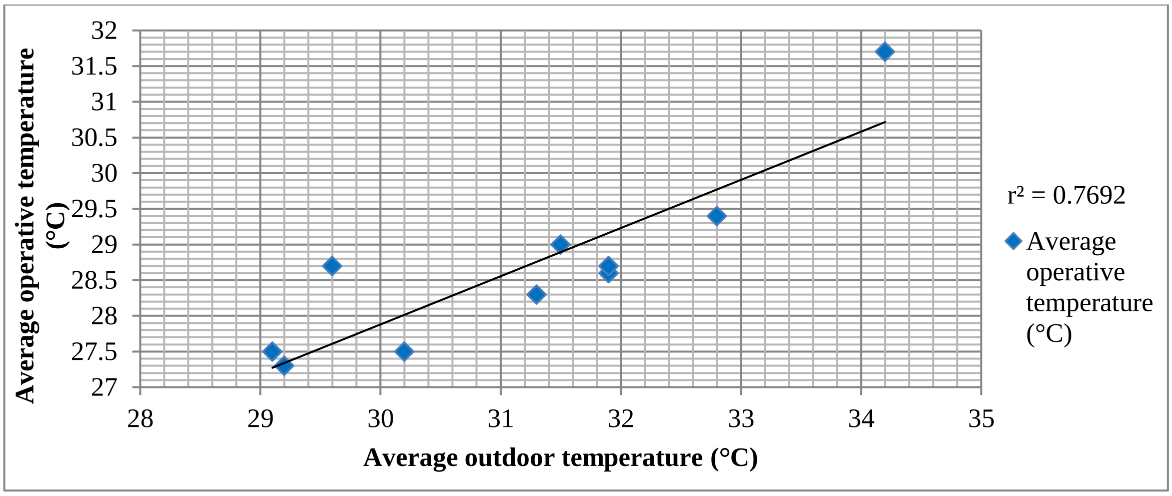

Figure 4.1: Average Indoor Operative Temperature vs Average Outdoor Temperature

Therefore, it can be concluded that the average indoor operative temperature of each residential area is correlating well with their respective outdoor temperature. Table 4.15 shows the values between the average indoor operative temperatures and their average outdoor temperatures.

Table 4.15: Average Indoor Operative Temperature vs Average Outdoor Temperature

Residential area	**Average indoor operative temperature (°C)**	**Average outdoor temperature (°C)**
1	31.7	34.2
2	27.5	30.2
3	28.3	31.3
4	28.6	31.9
5	28.7	29.6
6	29.4	32.8
7	29.0	31.5
8	28.7	31.9
9	27.3	29.2
10	27.5	29.1

4.2.4 Average Relative Humidity vs Average Indoor Operative Temperature

It was implied from the study that humidity level in the air decreased when the surrounding temperature increased. The relative humidity of the indoor environment was found to be decreasing when the indoor operative temperature increased correlatively as shown in Figure 4.2.

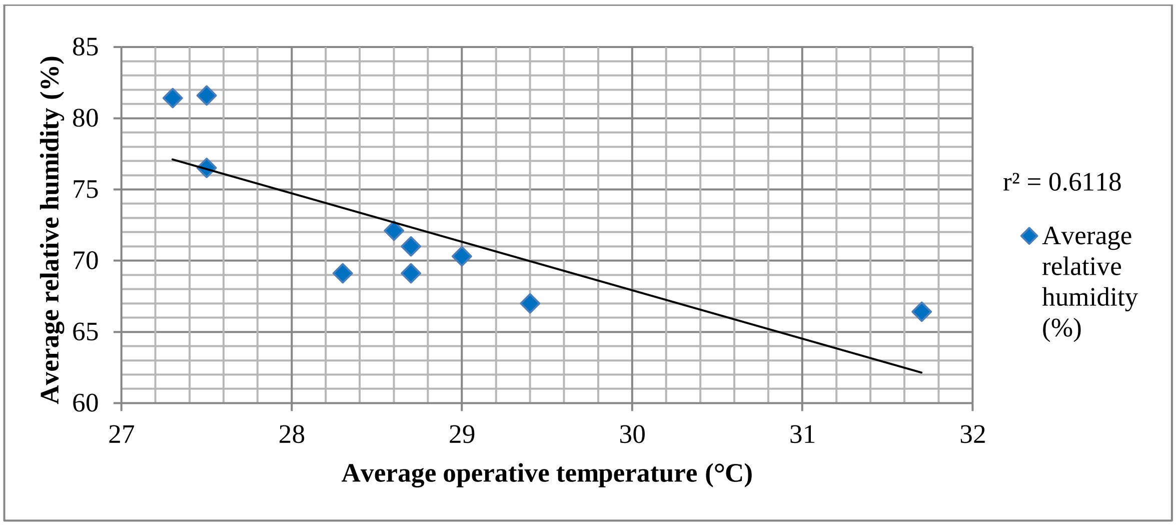

Figure 4.2: Average Relative Humidity vs Average Indoor Operative Temperature

The r^2 value of 0.6118 shows that this linear regression model is close to unity. This proves that the measurements data fit well to the model. Table 4.16 shows the average humidity level of each residential area and their average indoor operative temperature.

Table 4.16: Average Relative Humidity vs Average Indoor Operative Temperature

Residential area	Average relative humidity (%)	Average indoor operative temperature (°C)
1	66.4	31.7
2	76.5	27.5
3	69.1	28.3
4	72.1	28.6
5	69.1	28.7
6	67.0	29.4
7	70.3	29.0
8	71.0	28.7
9	81.4	27.3
10	81.6	27.5

4.2.5 Average Air Velocity vs Average Indoor Operative Temperature

By plotting the graph of average air velocity against average indoor operative temperature, the relationship between the two parameters can be observed. It was discovered that the average air velocity escalated with the increase of average indoor operative temperature. However, the r^2 value is relatively low which reveals that the data did not fit the model well.

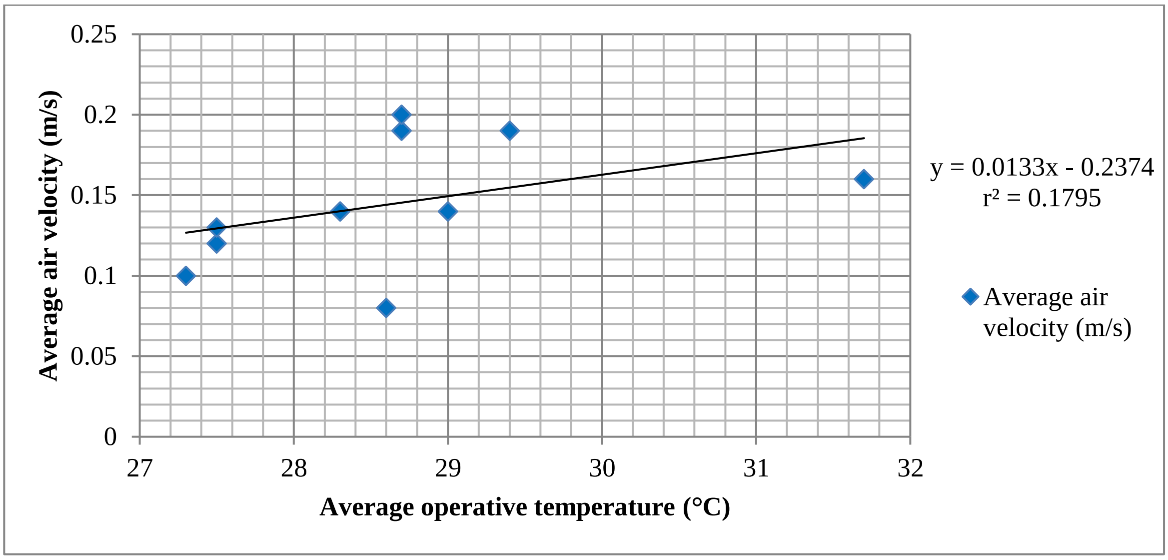

Figure 4.3: Average Air Velocity vs Average Indoor Operative Temperature

Figure 4.3 shows a positive slope which is similar to the findings of deDear [173] and Mui [19]. Findings of Chew [20] demonstrated a negative slope which opposed to the result shown in present study. This is because the thermal environment in Chew's study was controlled by a centralized cooling system that cannot be adjusted by the occupants. Meanwhile, residents of present study were allowed to have control on their cooling systems adaptively.

The linear regression between the average air velocity and average indoor operative temperature of this study is defined in Equation (4.1).

$$v_a = 0.0133\ T_{op} - 0.2374 \tag{4.1}$$

The model found by deDear [173] is written in Equation (4.2).

$$v_a = 0.03\ T_{op} - 0.56 \tag{4.2}$$

The model found by Mui [19] is shown in Equation (4.3).

$$v_a = 0.02\ T_{op} - 0.35 \tag{4.3}$$

Table 4.17: Average Air Velocity vs Average Indoor Operative Temperature

Residential area	Average air velocity (ms^{-1})	Average indoor operative temperature (°C)
1	0.16	31.7
2	0.12	27.5
3	0.14	28.3
4	0.08	28.6
5	0.19	28.7
6	0.19	29.4
7	0.14	29.0
8	0.20	28.7
9	0.10	27.3
10	0.13	27.5

4.2.6 Clothing Insulation vs Indoor Operative Temperature

By referring to Figure 4.4, the linear relationship between average clothing insulation and average indoor operative temperature is defined and written in Equation (4.4). The finding of this study is similar with the findings of Chew [20], deDear [173] and Mui [19]. Their models are presented in Equation (4.5), (4.6) and (4.7), respectively.

$$\text{Clothing insulation} = -0.0068\ T_{op} + 0.4438 \tag{4.4}$$

$$\text{Clothing insulation} = -0.0021\ T_{op} + 0.6866 \tag{4.5}$$

$$\text{Clothing insulation} = -0.04\ T_{op} + 1.73 \tag{4.6}$$

$$\text{Clothing insulation} = -0.04\ T_{op} + 1.76 \tag{4.7}$$

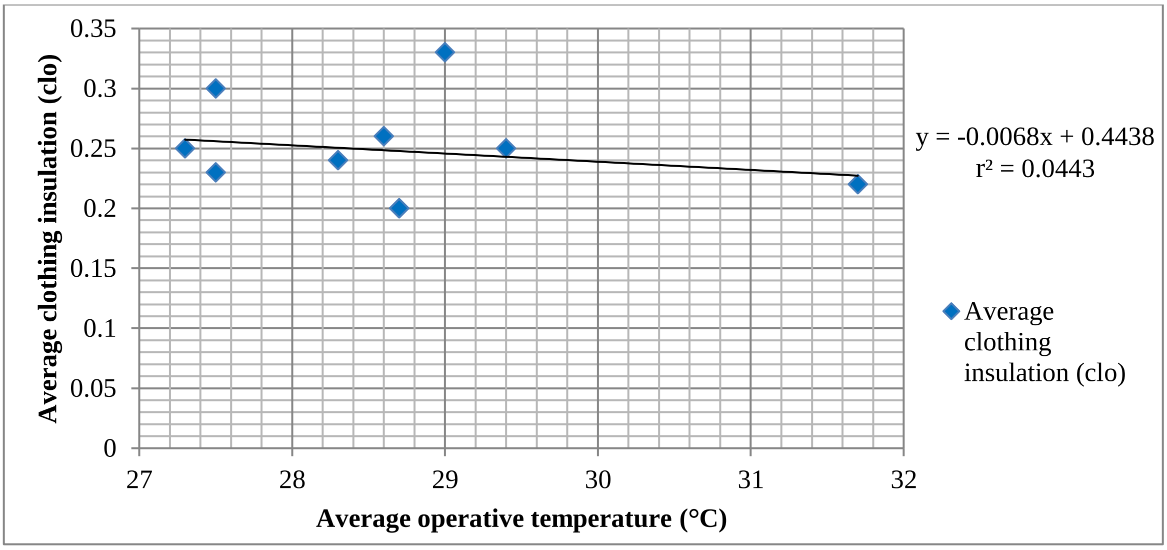

Figure 4.4: Average Clothing Insulation vs Average Indoor Operative Temperature

The r^2 value of this study was 0.0443 which is almost equal to 0. The r^2 value of Equation (4.5) was found to be 0 as well, which is identical to the r^2 value obtained from Equation (4.6) and (4.7). From these findings, it can be concluded that the clothing insulation of the residents is not dependent on their living indoor environment. This is attributed to the hot and humid climate experienced by the residents constantly throughout the year and they might have reached the minimum level on their clothing insulation. Therefore, there would be no further decrease in clothing insulation regardless of the increase in indoor operative temperature.

Table 4.18: Average Clothing Insulation vs Average Indoor Operative Temperature

Residential area	Average clothing insulation (clo)	Average indoor operative temperature (°C)
1	0.22	31.7
2	0.30	27.5
3	0.24	28.3
4	0.26	28.6
5	0.20	28.7
6	0.25	29.4
7	0.33	29.0
8	0.20	28.7
9	0.25	27.3
10	0.23	27.5

4.2.7 Activity Level vs Indoor Operative Temperature

Figure 4.5 shows that the linear model ran horizontally across the indoor operative temperature between 1.1 met and 1.4 met. The low r^2 value of 0.0022 indicates that there is no significant relationship between the activity level and its corresponding indoor operative temperature. This is reasonable since activity level should be depending on working nature rather than physical environments.

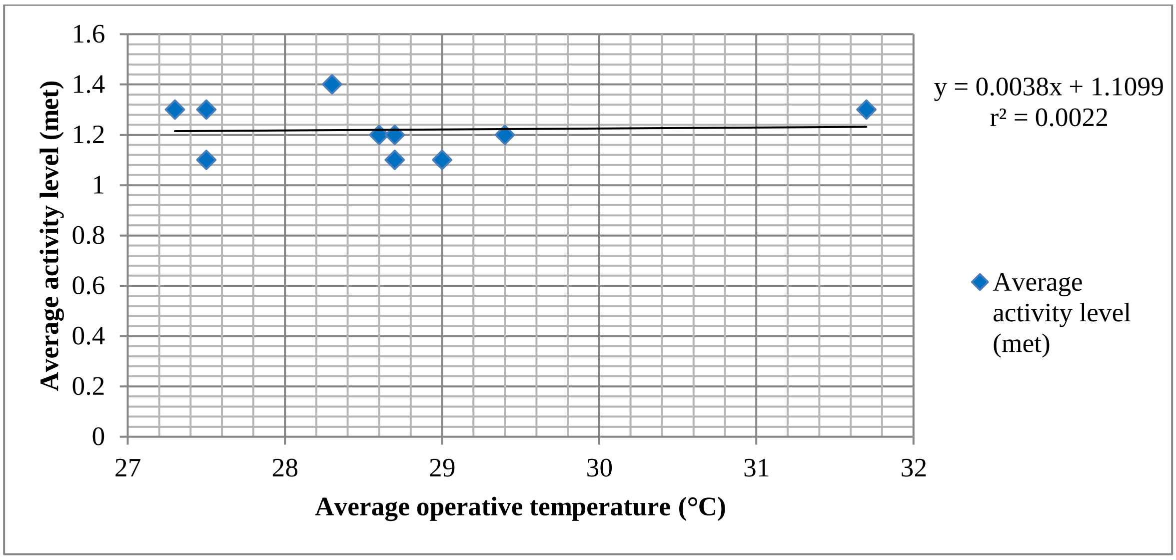

Figure 4.5: Average Activity Level vs Average Indoor Operative Temperature

The regression model produced from Figure 4.5 is written in Equation (4.8). Chew [20] and Mui [19] also showed similar results and their findings are written in Equation (4.9) and (4.10).

$$\text{Activity level} = 0.0038\ T_{op} + 1.1099 \tag{4.8}$$

$$\text{Activity level} = 0.006\ T_{op} + 0.906, \quad r^2 = 0.011 \tag{4.9}$$

$$\text{Activity level} = -0.0067\ T_{op} + 1.3513, \quad r^2 = 0.0179 \tag{4.10}$$

Table 4.19 shows the average activity level of each residential area with their respective average indoor operative temperature.

Table 4.19: Average Activity Level vs Average Indoor Operative Temperature

Residential area	**Average activity level (met)**	**Average indoor operative temperature (°C)**
1	1.3	31.7
2	1.3	27.5
3	1.4	28.3
4	1.2	28.6
5	1.2	28.7
6	1.2	29.4
7	1.1	29.0
8	1.1	28.7
9	1.3	27.3
10	1.1	27.5

4.3 Thermal Comfort Analysis

The thermal behavior of the residents was analyzed by using ASHRAE scale, Bedford scale, thermal acceptability scale and thermal preference scale.

4.3.1 Thermal Perception of Respondents on ASHRAE Scale

Figure 4.6 illustrates the relative frequency of the votes on ASHRAE scale. The distribution of the votes on each category is shown in Table 4.20.

73.8% of the thermal sensation votes were skewing to the right side from “neutral” (0) to “warm” (2) categories, which were consistent with the hot weather experienced by the respondents during the assessment period. The highest indoor operative temperature and outdoor temperature recorded was 32.6 °C and 37.5 °C, respectively.

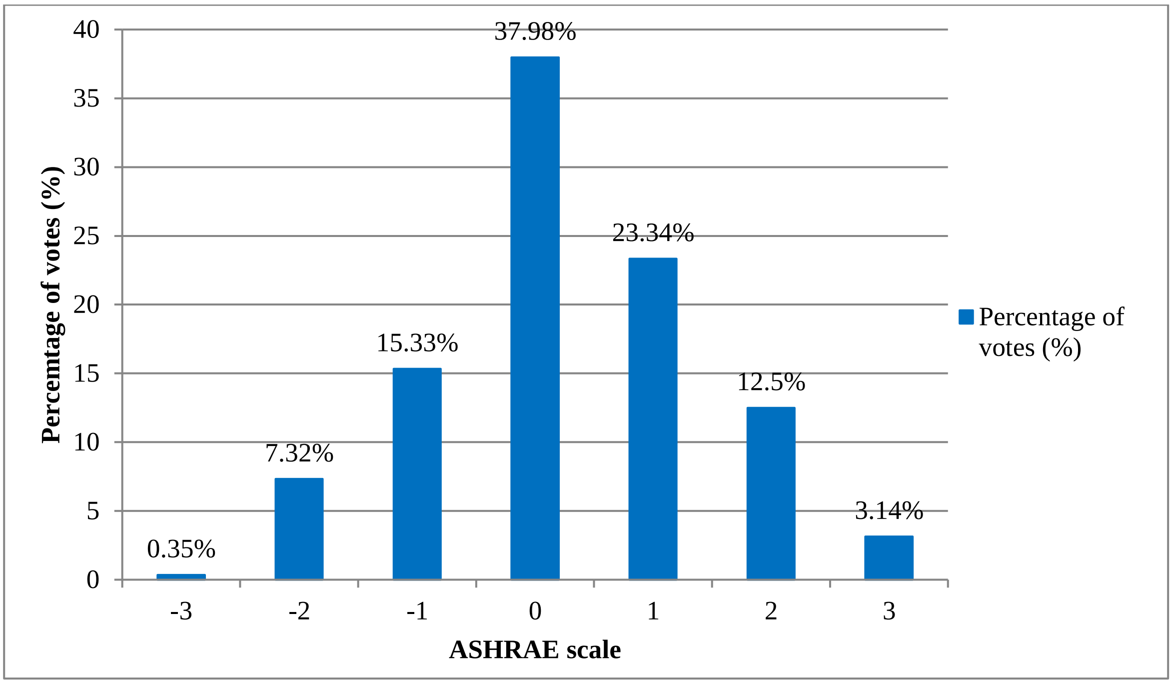

Figure 4.6: Distribution of Thermal Sensation Votes (TSV)

The “neutral” category had the highest portion of votes with 37.98% followed by “slightly warm” category with 23.34% and “slightly cool” category with 15.33%. Only minority of the respondents voted in “cold” and “hot” categories with 0.35% and 3.14%, respectively.

ASHRAE scale was applied with the assumption of people recognizing their thermal environment as acceptable or comfortable if they voted within the middle three classes of the scale. Based on the data obtained in this study, 76.65% of the respondents identified their thermal environment as acceptable.

Table 4.20: Distribution of Votes on ASHRAE Scale

ASHRAE scale	Number of votes and percentage of votes (%)
-3	1 (0.35)
-2	21 (7.32)
-1	44 (15.33)
0	109 (37.98)
1	67 (23.34)
2	36 (12.5)
3	9 (3.14)
Total	287 (100.0)

4.3.2 Thermal Perception of Respondents on Bedford Scale

The distribution of Bedford scales' votes in each category is shown in Figure 4.7 and Table 4.21. Majority of the votes were centralized in the middle class of the scale with 54.36% of the votes distributed in "comfortable" (0) category, 16.72% in "comfortably warm" category and 14.63% in "comfortably cool" category. These central three categories represented 85.68% of the total votes of the study.

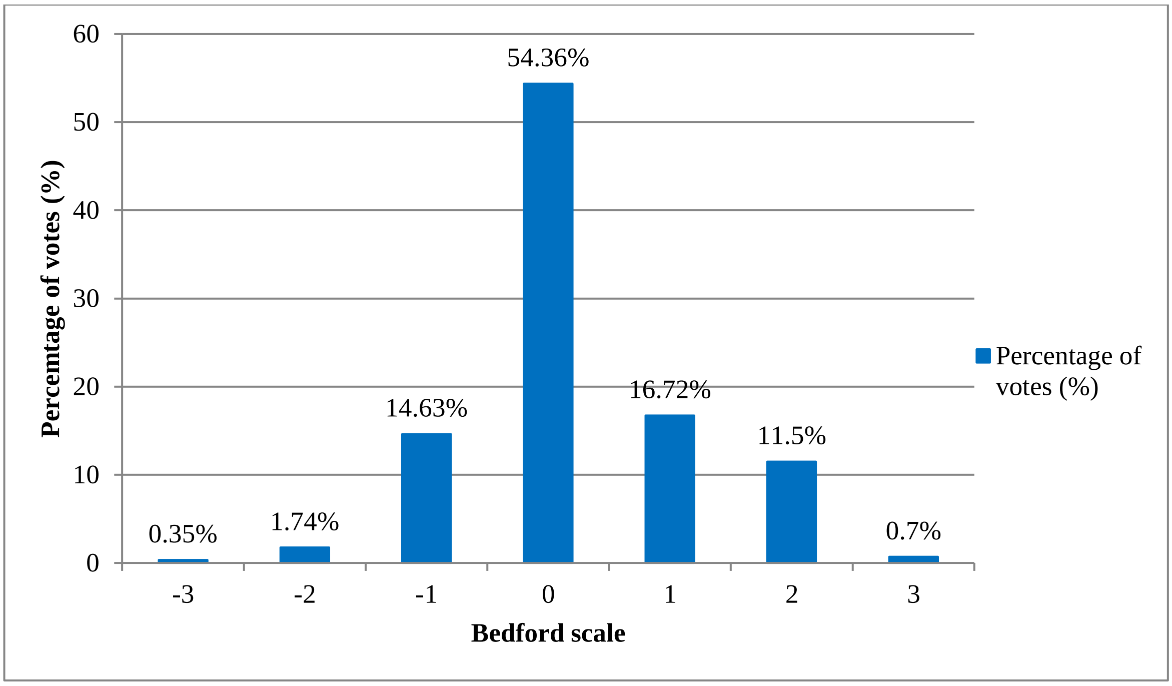

Figure 4.7: Distribution of Thermal Comfort Votes (TCV)

Meanwhile, 14.29% of the remaining respondents had voted in the extreme categories of Bedford scale, 0.35% for “much too cool” category, 1.74% for “too cool” category, 11.5% for “too warm” category and 0.7% for “much too warm” category. The voting trend of the respondents in Bedford scale is similar to the voting trend in ASHRAE scale where the votes were skewing to the warmer side of the scale.

Table 4.21: Distribution of Votes on Bedford Scale

Bedford scale	**Number of votes and percentage of votes (%)**
-3	1 (0.35)
-2	5 (1.74)
-1	42 (14.63)
0	156 (54.36)
1	48 (16.72)
2	33 (11.5)
3	2 (0.7)
Total	287 (100.0)

4.3.3 ASHRAE Scale vs Bedford Scale

Since Bedford scale and ASHRAE scale are both a seven-point scale, the votes’ distribution between these two scales was compared. Figure 4.8 demonstrates the distribution of votes on ASHRAE scale and Bedford scale.

The percentage of votes in the middle 3 categories of Bedford scale was 85.68% which was higher than ASHRAE scale with just 76.65%. This attests that respondents who voted outside the central three categories of ASHRAE scale still identified their environment as comfortable and acceptable.

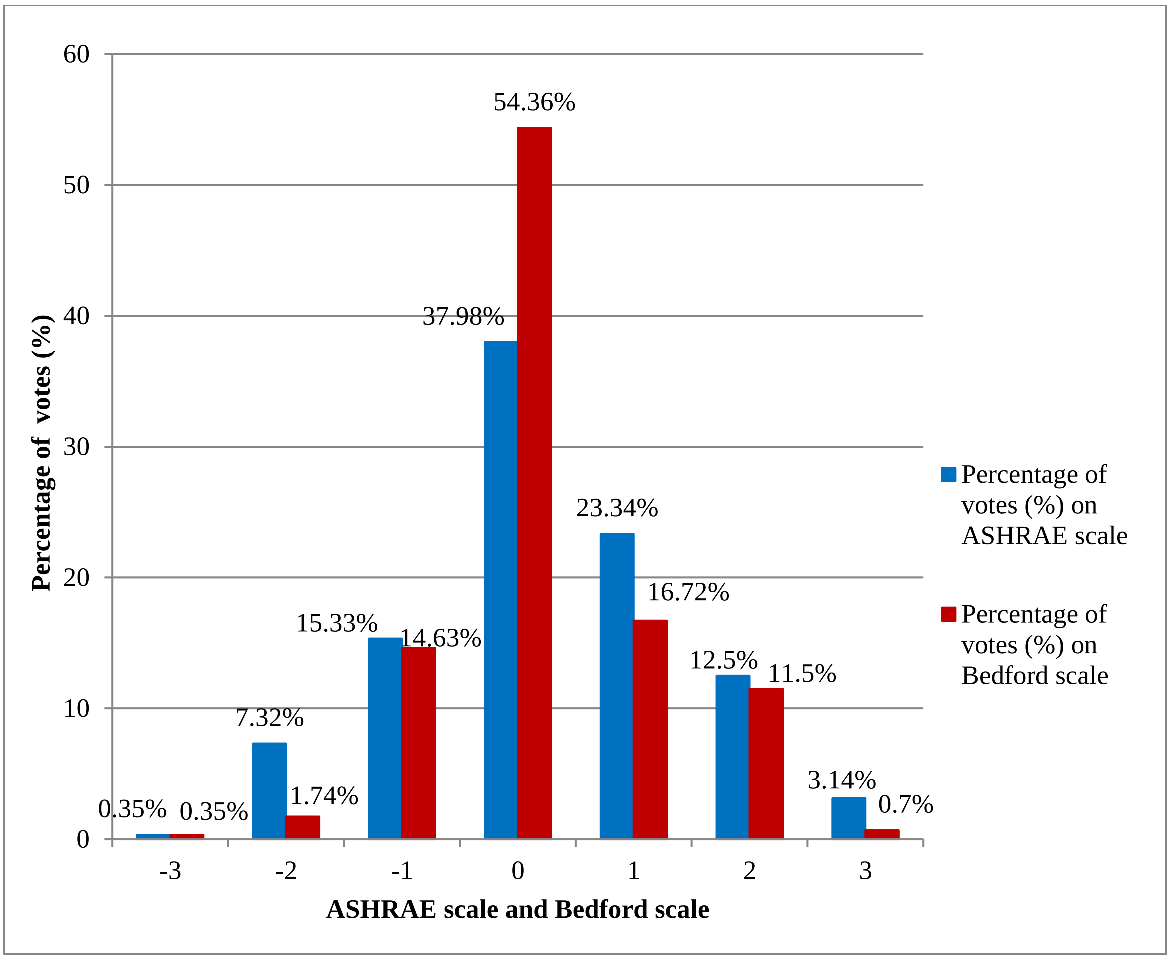

Figure 4.8: Distribution of Votes on ASHRAE Scale and Bedford scale

Table 4.22 shows the cross tabulation between thermal sensation votes and thermal comfort votes. 93.15% of the voters who voted in the central three categories of ASHRAE scale also voted in the central three categories of Bedford scale. 81.82% of the people who voted in the extreme categories (cool and cold) of ASHRAE scale still found themselves comfortable. This is due to the hot and humid context experienced by the local residents as those who live in tropical climate tend to prefer a cooler environment.

Around 41.3% of the respondents indicated that they were comfortable even though they voted in the warm and hot categories of ASHRAE scale. The reasons of this include personal preference and personal adaptations. These minority respondents might prefer a warmer ambience than a cooler environment due to their personal preference. Personal preference could be affected by their personal adaptations especially when they are adapted to a certain climate. People who have accustomed to a warmer climate would find themselves uncomfortable in a cooler environment and vice versa. This suggests that thermal discomfort does not necessary comply to everyone even if their thermal sensation state is deviated from the neutral point.

Therefore, a comfort scale such as Bedford scale might be a better measure to determine acceptability if compare to ASHRAE scale. Bedford scale emphasizes more on respondents' response on their comfortable state while ASHRAE scale focuses on thermal sensation only. A person who votes beyond the central three categories of ASHRAE scale could still find his or her environment acceptable and comfortable. By using Bedford scale, the deficiency of ASHRAE scale can be avoided.

Table 4.22: Cross-tabulation of Thermal Sensation Votes and Thermal Comfort Votes

Bedford scale	**Number and percentage of votes (%)**		
	ASHRAE scale		
	-3, -2	-1, 0, 1	2, 3
-3, -2	4 (18.18)	2 (0.91)	0 (0.0)
-1, 0, 1	18 (81.82)	204 (93.15)	19 (41.3)
2, 3	0 (0.0)	13 (5.94)	27 (58.7)
Total	22 (100.0)	219(100.0)	46 (100.0)

4.3.4 Thermal Acceptability Scale

The distribution of acceptability votes is illustrated in Figure 4.9 and tabulated in Table 4.23. Around 73.52% of the residents voted their thermal environment as acceptable with 26.48% of them opposing it.

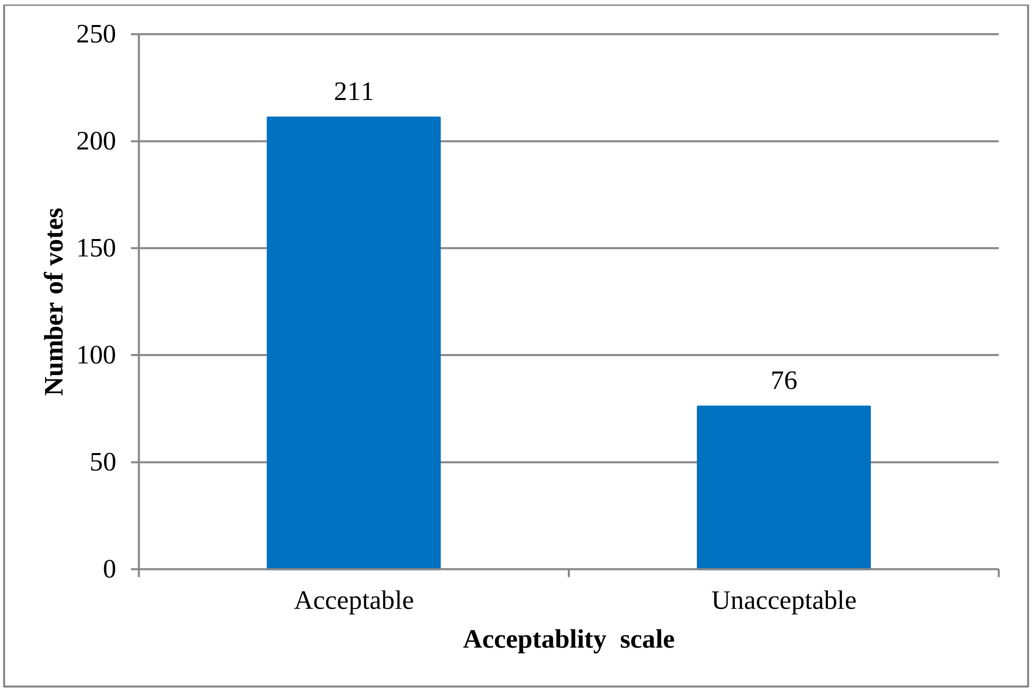

Figure 4.9: Distribution of Acceptability Votes

The acceptable percentage of thermal acceptability scale was discovered to be lower than the acceptable percentage of the votes in the central three categories of ASHRAE scale and Bedford scale. Both of these scales were having the acceptable percentage of 76.65% and 85.68%, respectively compared to 73.52% of thermal acceptability scale. This is ascribed to the residents' responses where some of them expressed their thermal conditions as not acceptable even though they had voted in the acceptable and comfortable categories of ASHRAE scale and Bedford scale.

Table 4.23: Votes on Thermal Acceptability Scale

Acceptability scale	**Number of votes and percentage of votes (%)**
Acceptable	211 (73.52)
Unacceptable	76 (26.48)
Total	287 (100.0)

4.3.5 Thermal Acceptability Scale vs ASHRAE scale

The comparison between thermal acceptability scale and ASHRAE scale is shown in Figure 4.10 and Table 4.24. It was observed that the acceptable percentage of the residents who voted in the extreme categories of “cool” and “cold” was higher than the percentage who voted in the warmer categories.

This extrapolates that the votes in extreme categories do not necessarily represent thermal discomfort. Residents might still find their thermal environment acceptable even though they are not experiencing neutral sensations.

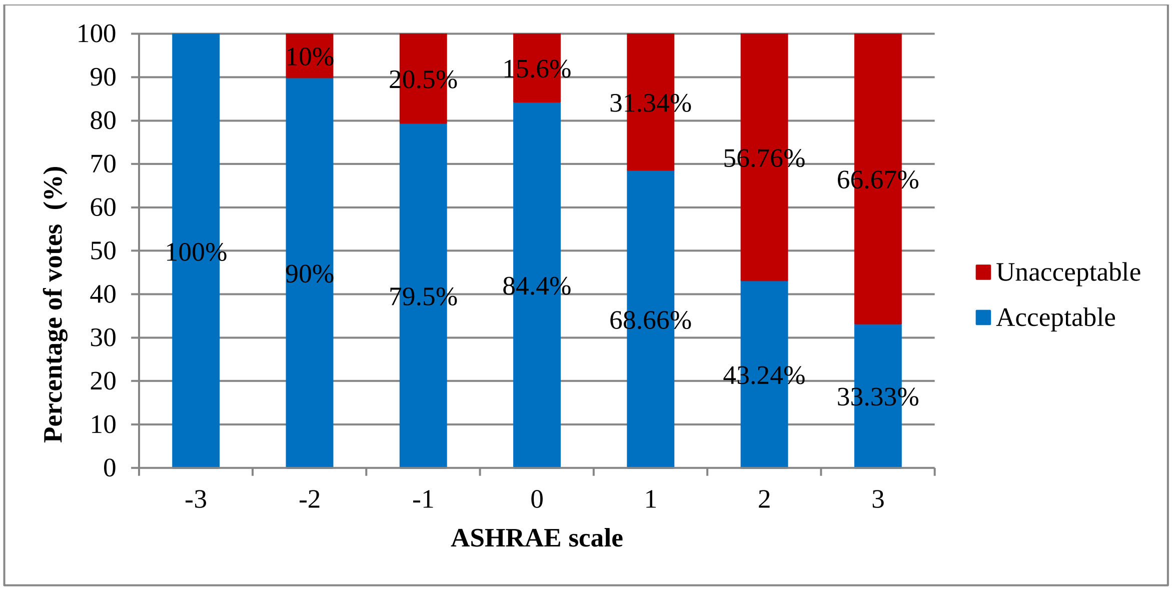

Figure 4.10: Thermal Acceptability Scale vs ASHRAE Scale

It was also discovered that only 78.64% of the respondents from the central three categories of ASHRAE scale who identified their thermal environment as acceptable. This proves that there is a portion of respondents who are not satisfied with their environment even though they had voted in the acceptable categories of ASHRAE scale.

Table 4.24: Percentage of Acceptable Votes on ASHRAE Scale

ASHRAE scale	**Number and percentage of votes (%)**	
	Acceptable	**Unacceptable**
-3	1 (100)	0 (0)
-2	18 (90)	2 (10)
-1	35 (79.5)	9 (20.5)
0	92 (84.4)	17 (15.6)
1	46 (68.66)	21 (31.34)
2	16 (43.24)	21 (56.76)
3	3 (33.33)	6 (66.67)
Total votes	211	76

4.3.6 Thermal Acceptability Scale vs Bedford Scale

Percentage of acceptability votes on Bedford scale is illustrated in Figure 4.11 and tabulated in Table 4.25. It can be noticed that the bar chart was skewing towards the cooler direction which is similar to the results in Section 4.3.5.

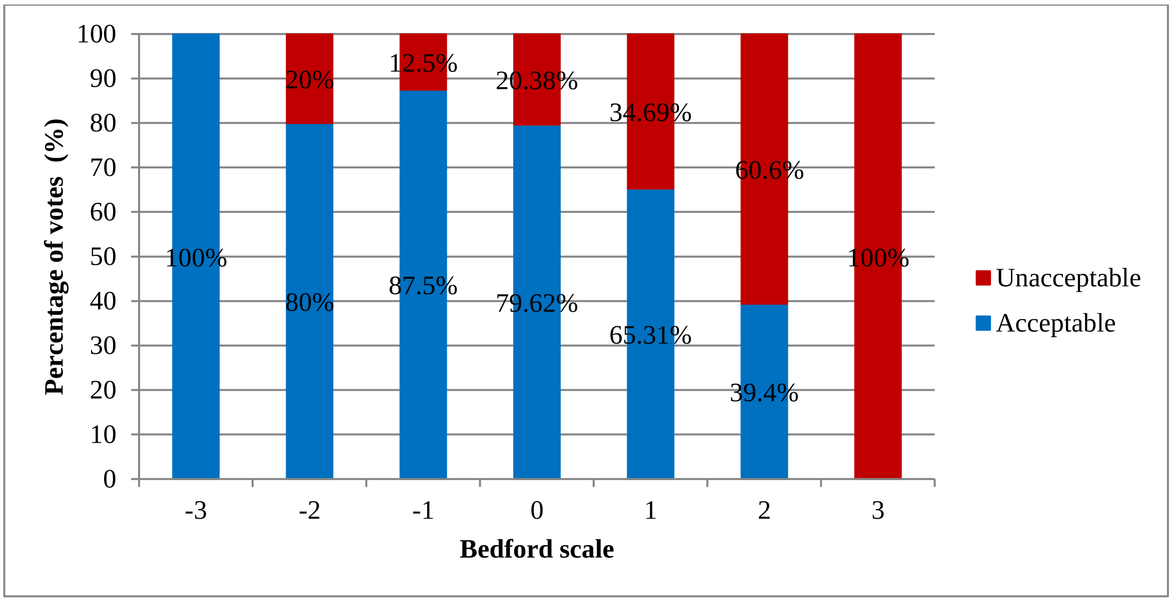

Figure 4.11: Thermal Acceptability Scale vs Bedford Scale

Percentage of acceptability on the cooler categories from -3 to -1 was relatively higher than its contrast percentage. In the “comfortably warm” category, respondents are supposed to be in an ideal state, but its acceptable percentage indicated otherwise where almost 35% of them implying dissatisfaction. This is due to weather factor which might influence their thermal responses during the assessment.

Table 4.25: Percentage of Acceptable Votes on Bedford Scale

Bedford scale	**Number and percentage of votes (%)**	
	Acceptable	**Unacceptable**
-3	1 (100)	0 (0)
-2	4 (80)	1 (20)
-1	35 (87.5)	5 (12.5)
0	125 (79.62)	32 (20.38)
1	32 (65.31)	17 (34.69)
2	13 (39.4)	20 (60.6)
3	0 (0)	2 (100)
Total votes	210	77

4.3.7 Thermal Preference Scale

The distribution of preference votes is shown in Figure 4.12 and Table 4.26. It was discovered that most of the residents wanted their indoor environment to be cooler.

Meanwhile, 32.06% of them felt satisfied with their thermal conditions and no changes were needed to improve their thermal environment. Only 2.09% of the subjects preferred to have a warmer environment.

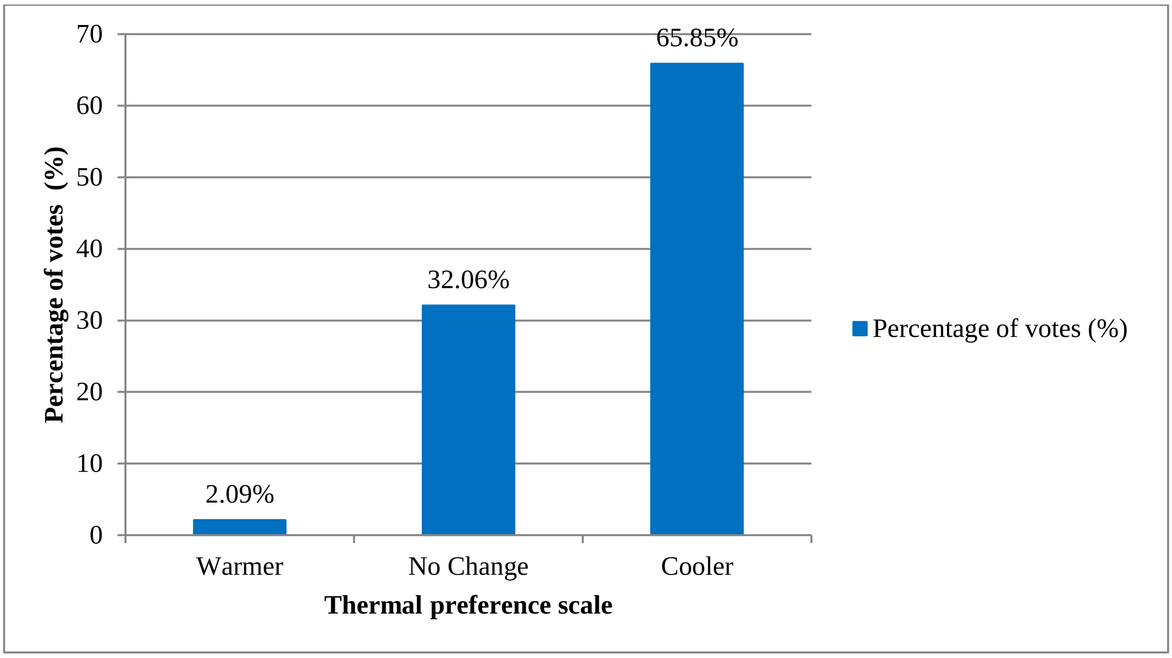

Figure 4.12: Distribution of Thermal Preference Votes

The large portion of votes in "wanted to be cooler" category shows that even though most of the residents accepted their indoor environment thermally, most of them still demanded their environment to be cooler. This is attributed by personal preference as most of the occupants who are living under a warmer climate would opt for a cooler ambient and vice versa.

Table 4.26: Thermal Preference Scale

Thermal preference	**Number of votes and percentage of votes (%)**
Warmer	6 (2.09)
No change	92 (32.06)
Cooler	189 (65.85)
Total	287 (100)

4.3.8 Thermal Preference Scale vs Thermal Acceptability Scale

The comparison of thermal preference scale and thermal acceptability scale is shown in Figure 4.13 and Table 4.27.

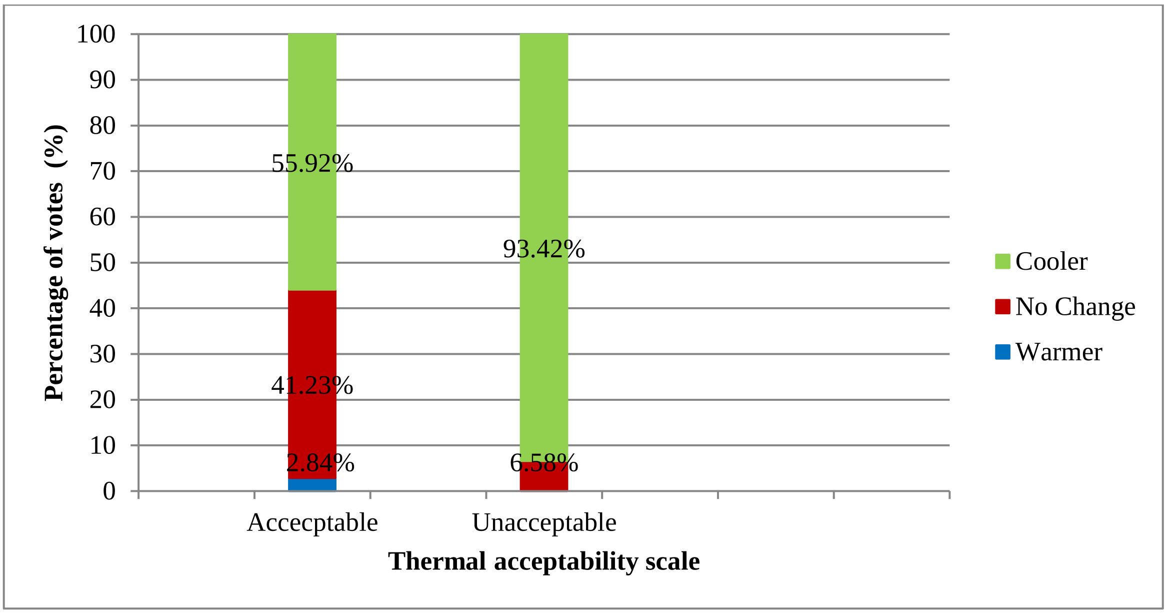

Figure 4.13: Thermal Preference Scale vs Thermal Acceptability

From the bar chart in Figure 4.13, it can be observed that 55.92% of the respondents who defined their thermal environment as acceptable still demanded for a cooler surrounding. Around 41.23% of them preferred to maintain their environmental state while only 2.84% of them wanted to feel warmer.

For the respondents who voted “unacceptable” in thermal acceptability scale, it was discovered that most of them wanted their living indoor environment to be cooler. This again shows that residents who live under a warmer climate will always prone towards a cooler environment.

Table 4.27: Thermal Preference Scale vs Thermal Acceptability Scale

Thermal preference	Number and percentage of votes (%)	
	Acceptable	**Unacceptable**
Warmer	6 (2.84)	0 (0)
No change	87 (41.23)	5 (6.58)
Cooler	118 (55.92)	71 (93.42)
Total	211 (100)	76 (100)

4.3.9 Thermal Preference Scale vs ASHRAE Scale

The thermal sensation votes of ASHRAE scale was further assessed by adding the preference aspect of thermal preference scale into the analysis. The assessment results are shown in Figure 4.14 and Table 4.28.

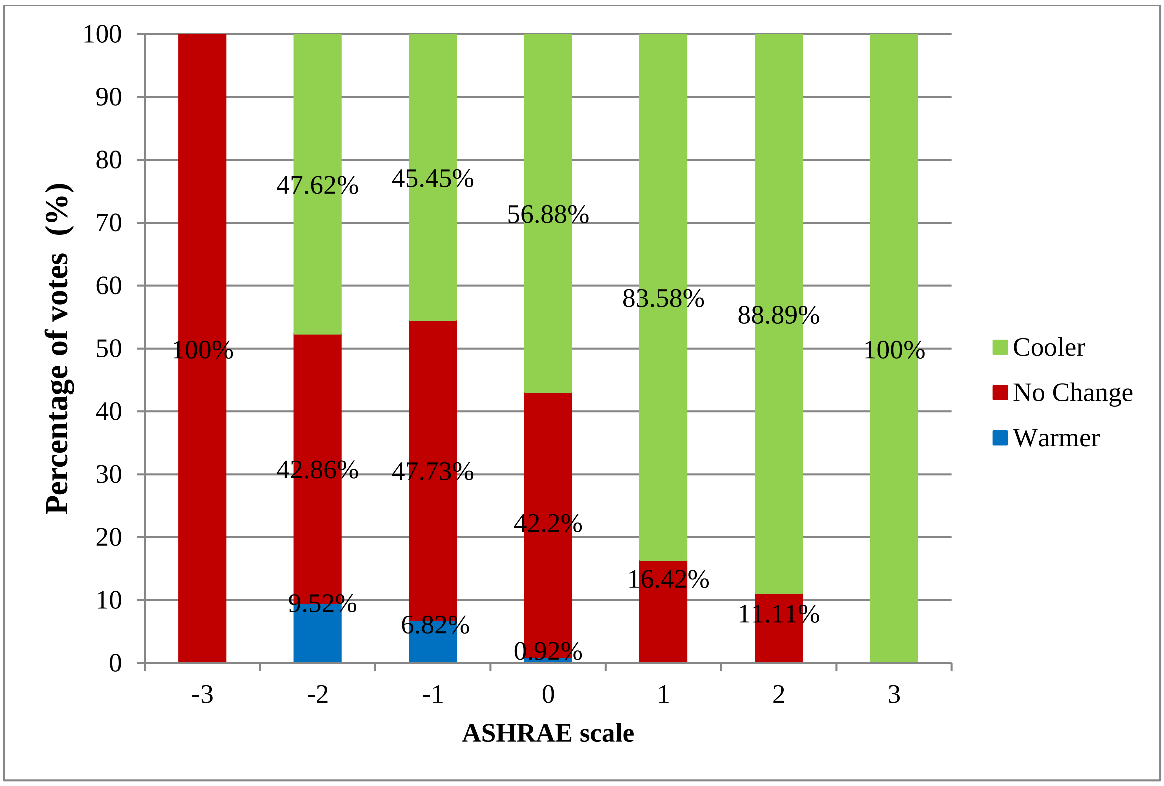

Figure 4.14: Thermal Preference Scale vs ASHRAE Scale

In the neutral category of 0, it was astonished to observe that only 42.2% of the residents wanted no change on their thermal environment. When they were exposed to cooler circumstances, most of them still wanted to feel cooler. This was proven in the “cool” category of -2 where 47.62% of the residents still demanded for a cooler environment even though they were at a cooler sensation state.

By assessing the central three categories of ASHRAE scale which was presumed to be acceptable for the residents, it was discovered that only 35.45% of them wanted to maintain their thermal condition state while 62.73% of them insisted to have a cooler indoor context. This shows that residents from tropical climate have identified cooler sensation as their ideal indoor condition rather than the postulated ideal state of ASHRAE scale.

Table 4.28: Thermal Preference Scale vs ASHRAE Scale

ASHRAE scale	**Number and percentage of votes (%)**		
	Warmer	**No Change**	**Cooler**
-3	0 (0)	1 (100)	0 (0)
-2	2 (9.52)	9 (42.86)	10 (47.62)
-1	3 (6.82)	21 (47.73)	20 (45.45)
0	1 (0.92)	46 (42.2)	62 (56.88)
1	0 (0)	11(16.42)	56 (83.58)
2	0 (0)	4 (11.11)	32 (88.89)
3	0 (0)	0 (0)	9 (100)
Total votes	6	92	189

4.3.10 Thermal Preference Scale vs Bedford Scale

The thermal responses of residents in Bedford scale was analyzed via thermal preference scale. The results are illustrated in Figure 4.15 and tabulated in Table 4.29.

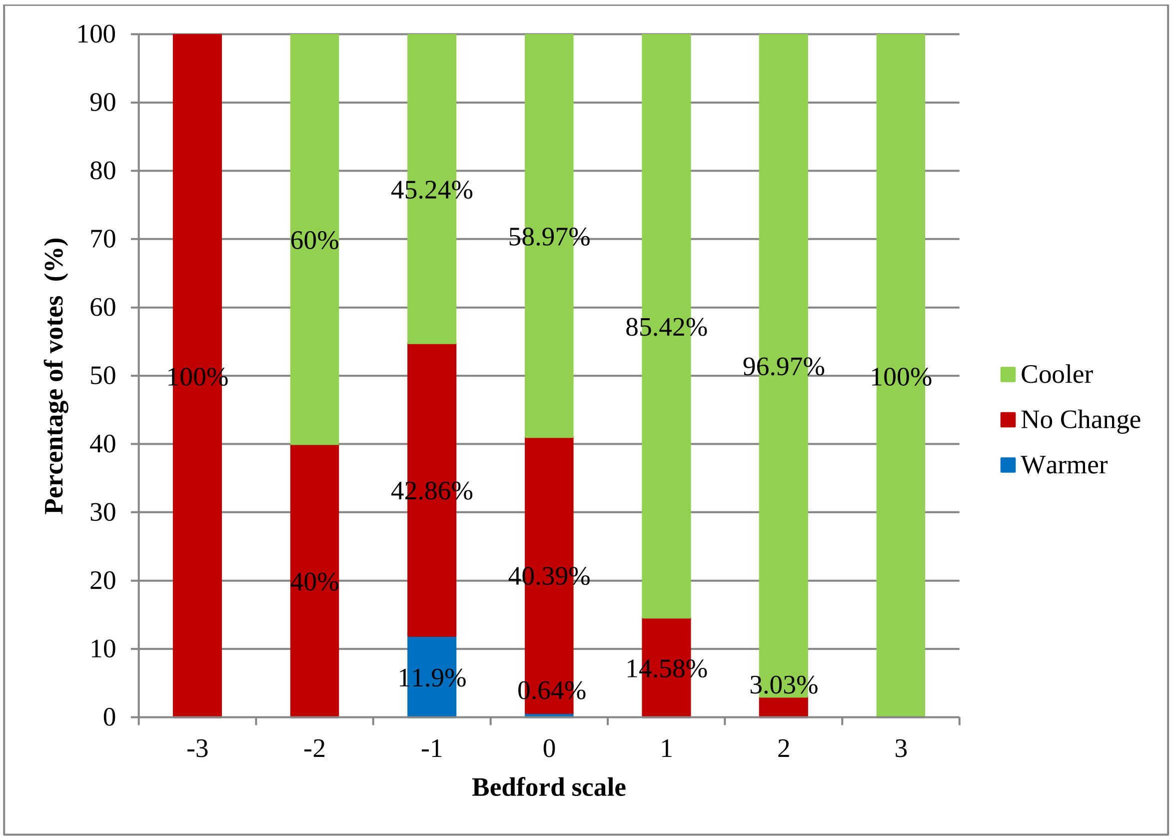

Figure 4.15: Thermal Preference Scale vs Bedford Scale

It can be observed that the results were biased towards the cooler preference side which was in contradictory with the warmer preference category. 45.24% of the respondents who voted in the “comfortably cool” category were supposed to feel satisfied and comfortable but in fact, they were still looking forward to a cooler indoor environment.

In the extreme categories of “too cool” and “much too cool”, it was shown that none of the respondents wanted to feel warmer but in contrast, all of them hoped to either maintain their thermal condition state or to feel even cooler.

By assessing the central three categories of Bedford scale which was assumed to be comfortable, it was found that only 35.77% of the residents wanted to preserve their thermal condition state. Meanwhile, 61.79% of them who were anticipated to feel comfortable still opted for a cooler environment. This finding is similar to the results evaluated in Section 4.3.9.

Thus, it can be concluded that the residents from hot and humid climate do prefer a cooler living atmosphere even though they have defined their existing thermal environment as acceptable and comfortable.

Table 4.29: Thermal Preference Scale vs Bedford Scale

Bedford scale	**Number and percentage of votes (%)**		
	Warmer	**No change**	**Cooler**
-3	0 (0)	1 (100)	0 (0)
-2	0 (0)	2 (40)	3 (60)
-1	5 (11.9)	18 (42.86)	19 (45.24)
0	1 (0.64)	63 (40.39)	92 (58.97)
1	0 (0)	7 (14.58)	41(85.42)
2	0 (0)	1 (3.03)	32 (96.97)
3	0 (0)	0 (0)	2 (100)
Total votes	6	92	189

4.3.11 Evaluation of Acceptability for Various Scales

Thermal comfort analysis of Section 4.3 is concluded in Figure 4.16 and Table 4.30 where the acceptability of various scales was assessed. It was obvious that different scales can produce different acceptability results.

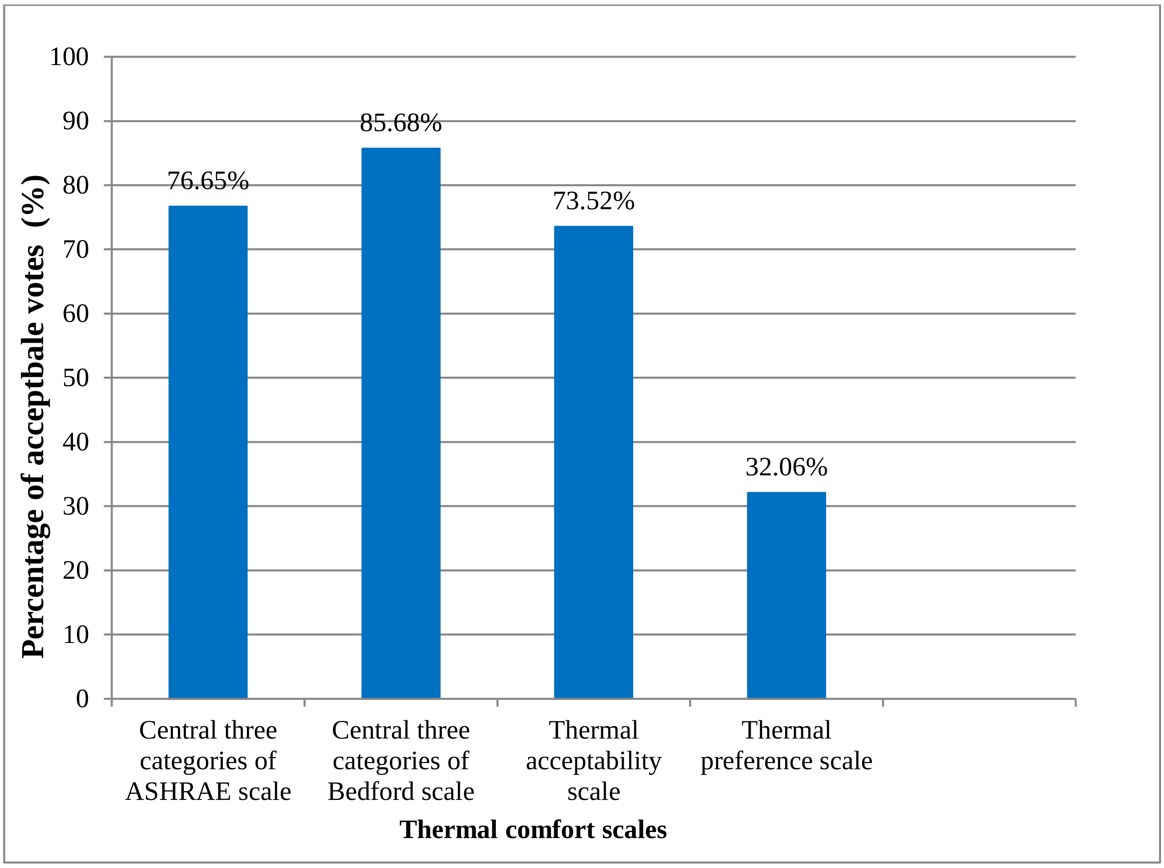

Figure 4.16: Percentage of Acceptable Votes for Various Scales

According to the bar chart as shown in Figure 4.16, Bedford scale possessed the highest acceptability votes with 85.68% followed by ASHRAE scale, 76.65% and thermal acceptability scale, 73.52%. The percentage of acceptable votes for thermal preference scale was recorded to be 32.06% which is relatively low if compared to other scales. This is because thermal preference scale assesses respondents based on their preferred comfortable state. Respondents might respond based on their personal preference rather than assessing their present thermal environment. Therefore, thermal preference scale is not a suitable scale to evaluate the thermal comfort perception of the respondents.

It was presumed that the central three categories of ASHRAE scale and Bedford scale can represent thermal satisfaction. However, the percentage obtained from Bedford scale was around 10% higher than the percentage of ASHRAE scale. This is because some of the residents who voted outside the central three categories of ASHRAE scale still found themselves comfortable. Thus, this indicates that extreme sensations of ASHRAE scale does not necessarily represent thermal discomfort.

Since the votes of central three categories of ASHRAE scale and Bedford scale were postulated to be acceptable and comfortable, thermal acceptability scale should demonstrate the highest acceptance level in terms of percentage. However, in this study, the acceptable percentage of thermal acceptability scale was lower than the percentage found on ASHRAE scale and Bedford scale. It is because there were residents who identified their thermal environment as not acceptable even though they had voted in the acceptable criteria of ASHRAE scale and Bedford scale.

Another reason which leads to this occasion is the information shortage on thermal acceptability scale. By asking residents to respond to either “acceptable” or “unacceptable”, it is difficult to evaluate their thermal responses accurately. Thus, ASHRAE scale and Bedford scale are better thermal comfort indicators since they carry weighted information of the respondents.

Table 4.30: Percentage of Acceptable Votes for Various Scales

Scales	Percentage of acceptable votes (%)
Central three categories of ASHRAE scale	76.65
Central three categories of Bedford scale	85.68
Thermal acceptability scale	73.52
Thermal preference scale	32.06

4.4 Comfort Temperature

Comfort temperature, T_c which can also be referred as neutral temperature, was determined by using ASHRAE scale, Bedford scale and Fanger's PMV model. The comfort temperature obtained from each scale was assessed.

4.4.1 Comfort Temperature Analysis based on ASHRAE scale

In order to determine the comfort temperature of the studied residential areas, the mean thermal sensation vote of each residential area was calculated. In this study, each residential area was assessed for five times on different periods to expand the range of measured parameters since the physical conditions of the environment were kept on varying throughout the study. The indoor operative temperature of each measurement was determined from Equation (3.3).

The mean thermal sensation vote for each indoor operative temperature is tabulated in Table 4.31. The graph of mean thermal sensation votes was plot against their respective indoor operative temperatures as indicated in Figure 4.17.

Table 4.31: Mean Thermal Sensation Votes

Residential area	**Operative temperature (ºC)**	**Mean thermal sensation vote (TSV)**
1	31.1	0.63
1	32.0	0.55
1	32.6	1.59
1	31.0	0.26
1	31.6	0.72
2	27.5	0.40
2	28.3	1.60
2	27.8	0.67
2	27.6	0.25
2	26.5	0.17
3	28.3	0.33
3	29.4	0.33
3	29.3	0.00
3	27.5	0.00
3	27.1	-1.00
4	28.2	-0.80
4	29.3	1.17
4	29.4	2.00
4	28.6	0.80
4	27.6	-0.25
5	30.2	1.00
5	30.9	1.00
5	28.1	0.80
5	27.4	0.67
5	27.0	-0.50
6	29.2	0.00
6	30.0	0.00
6	31.2	0.50
6	30.2	1.00
6	26.5	-0.33
7	28.2	0.50
7	30.2	1.00
7	30.1	0.14
7	29.2	-0.14
7	27.1	-0.29
8	28.5	0.00
8	28.4	0.33
8	30.1	0.75
8	29.2	0.22
8	27.3	0.00

Table 4.31 continued

9	26.4	0.00
9	28.6	0.67
9	27.2	0.00
9	27.2	-0.71
9	27.1	-0.33
10	28.1	0.75
10	27.2	-1.00
10	27.3	0.00
10	27.3	-0.50
10	27.4	-1.00

The comfort temperature was obtained when the linear regression line intercepted at the point where MTSV = 0. According to Figure 4.17, the comfort temperature based on ASHRAE scale was found to be 27.5 °C.

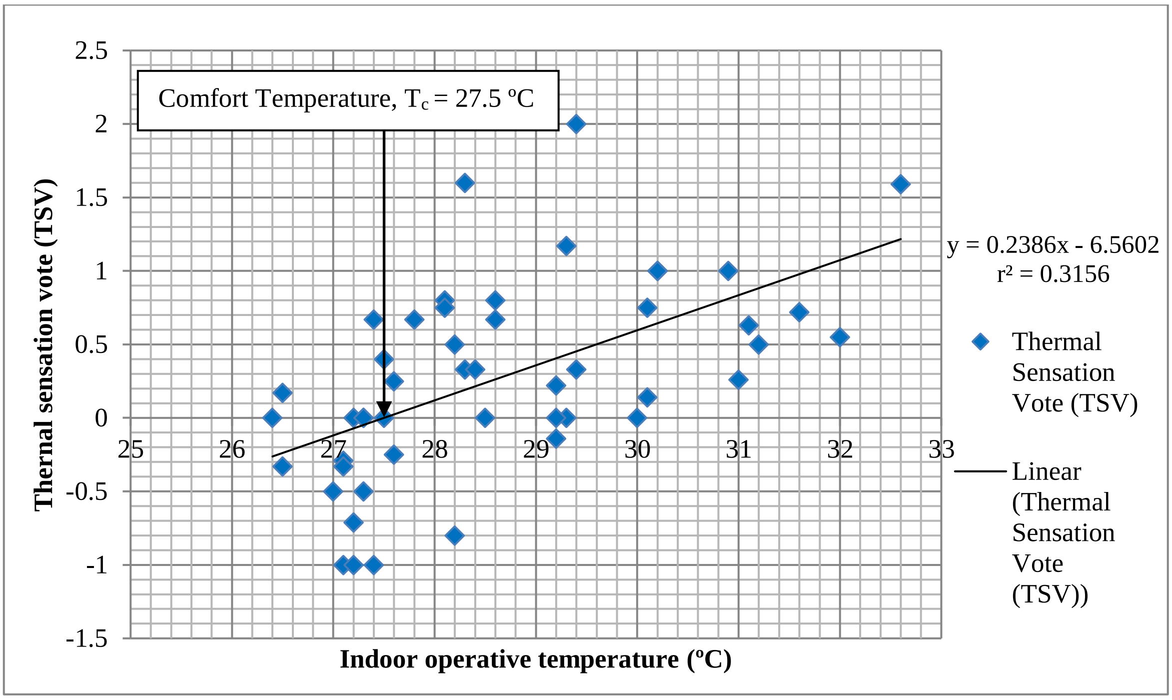

Figure 4.17: Thermal Sensation Votes against Indoor Operative Temperature

The comfort temperature of this study was 1.8 ºC higher than the findings discovered by Chew [20] where the comfort temperature was found to be 25.7 ºC. This is due to different environment context between the studies. Chew was conducting his assessment in air-conditioned lecture halls while current study was focusing on residential buildings which was naturally and mechanically ventilated.

The comfort temperature found by Feriadi [97] in naturally ventilated houses of Indonesia was 29.2 ºC, which was higher than the comfort temperature obtained from present study. By comparing to the residential houses which were naturally ventilated without the support of air conditioning systems, it is discovered that residents can adapt themselves to a higher comfort temperature.

The thermal comfort study conducted in Singapore also showed similar results [81]. The comfort temperature of classrooms which was ventilated by mechanical cooling fans was found to be 28.8 ºC [81]. This proves that different indoor contexts will result in different comfort temperatures. Occupants who implement simple ventilation systems can acclimatize themselves easily to a higher comfort temperature compare to those who rely on heavy cooling systems such as air-conditioners. Nevertheless, it can be concluded that the comfort temperature obtained from this study is in good agreement with the findings revealed by other researchers.

The liner regression model between thermal sensation votes and indoor operative temperatures is deduced from Figure 4.17 and written in Equation (4.11).

$$\text{TSV} = 0.2386\ T_{op} - 6.5602 \tag{4.11}$$

The gradient coefficient of 0.2386 of the model indicates that residents will experience one unit increase in their thermal sensation state for every 4.2 ºC change in their indoor operative temperature.

4.4.2 Comfort Temperature Analysis based on Bedford scale

The mean thermal comfort vote for each indoor operative temperature is tabulated in Table 4.32. The graph of mean thermal comfort votes against their indoor operative temperatures is illustrated in Figure 4.18.

Table 4.32: Mean Thermal Comfort Votes

Residential area	Operative temperature (ºC)	Mean thermal comfort vote (TCV)
1	31.1	0.42
1	32.0	0.55
1	32.6	1.29
1	31.0	0.21
1	31.6	0.61
2	27.5	0.00
2	28.3	0.60
2	27.8	0.00
2	27.6	0.00
2	26.5	-0.25
3	28.3	0.17
3	29.4	0.33
3	29.3	-0.33
3	27.5	-0.50
3	27.1	-0.25
4	28.2	-0.40
4	29.3	0.83
4	29.4	1.00
4	28.6	0.20
4	27.6	-0.50

Table 4.32 continued

5	30.2	1.80
5	30.9	1.33
5	28.1	1.00
5	27.4	0.00
5	27.0	-0.50
6	29.2	-0.25
6	30.0	0.00
6	31.2	0.50
6	30.2	0.00
6	26.5	-0.17
7	28.2	0.25
7	30.2	0.5
7	30.1	0.57
7	29.2	0.14
7	27.1	-0.43
8	28.5	0.00
8	28.4	0.33
8	30.1	0.75
8	29.2	0.33
8	27.3	-0.40
9	26.4	-0.67
9	28.6	0.33
9	27.2	0.00
9	27.2	-0.29
9	27.1	0.00
10	28.1	0.25
10	27.2	-0.33
10	27.3	0.25
10	27.3	-0.50
10	27.4	-1.33

The comfort temperature was obtained when the linear regression line intercepted at the point where MTCV = 0. According to Figure 4.18, the comfort temperature based on Bedford scale was found to be 28.1 ºC.

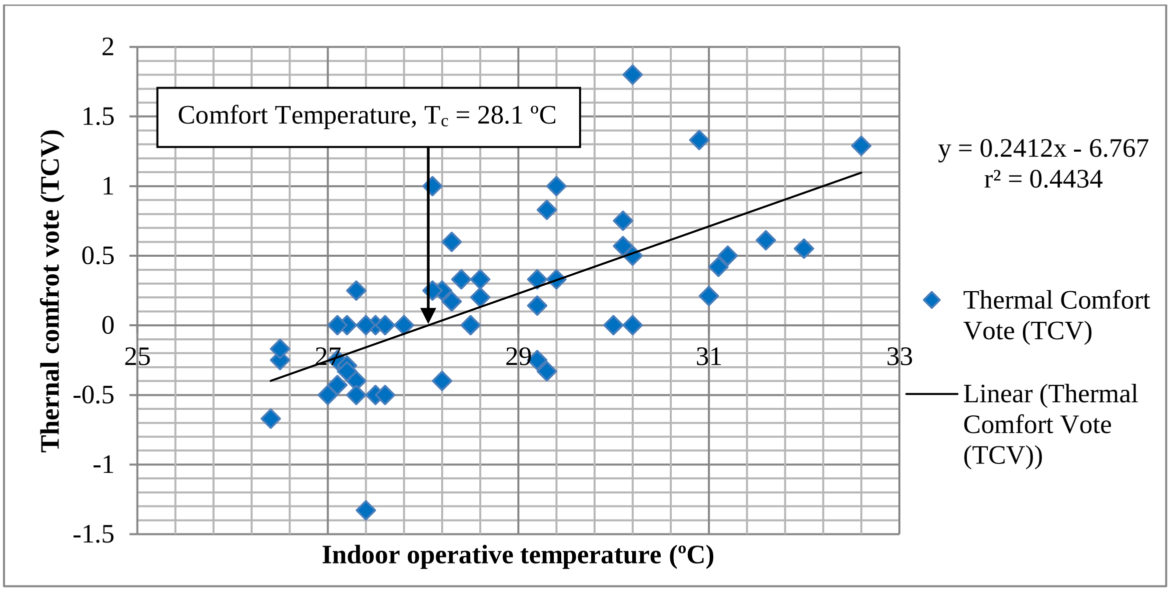

Figure 4.18: Thermal Comfort Votes against Indoor Operative Temperature

The liner regression model between thermal comfort votes and their indoor operative temperatures is obtained from Figure 4.18 and written in Equation (4.12).

$$TCV = 0.2412\ T_{op} - 6.767 \qquad (4.12)$$

The gradient coefficient of 0.2412 of the linear model implies that residents will experience one unit increase in their thermal comfort state for every 4.1 ºC change in their indoor operative temperature.

4.4.3 Comfort Temperature Analysis based on PMV Model

The predicted mean vote for each indoor operative temperature was calculated from Fanger’s model and tabulated in Table 4.33. The graph of predicted mean votes was plot against their indoor operative temperatures as shown in Figure 4.19.

Table 4.33: Predicted Mean Votes

Residential area	**Operative temperature (ºC)**	**Predicted mean vote (PMV)**
1	31.1	1.94
1	32.0	2.18
1	32.6	2.41
1	31.0	1.63
1	31.6	2.00
2	27.5	0.98
2	28.3	1.00
2	27.8	0.42
2	27.6	0.84
2	26.5	0.50
3	28.3	0.96
3	29.4	1.39
3	29.3	1.55
3	27.5	0.61
3	27.1	0.35
4	28.2	1.27
4	29.3	0.97
4	29.4	1.75
4	28.6	0.53
4	27.6	0.74
5	30.2	0.07
5	30.9	1.68
5	28.1	-0.36
5	27.4	1.38
5	27.0	0.19
6	29.2	1.58
6	30.0	0.05
6	31.2	2.02
6	30.2	1.49
6	26.5	-0.15
7	28.2	1.17
7	30.2	1.60
7	30.1	1.23
7	29.2	1.31
7	27.1	0.34
8	28.5	0.39
8	28.4	0.71
8	30.1	1.29
8	29.2	0.85
8	27.3	-0.71

Table 4.33 continued

9	26.4	-0.40
9	28.6	1.42
9	27.2	0.76
9	27.2	0.75
9	27.1	0.68
10	28.1	0.57
10	27.2	0.17
10	27.3	0.09
10	27.3	0.43
10	27.4	0.12

The comfort temperature was obtained when the linear regression line intercepted at the point where PMV = 0. Based on Figure 4.18, the comfort temperature was found to be 26.2 ºC.

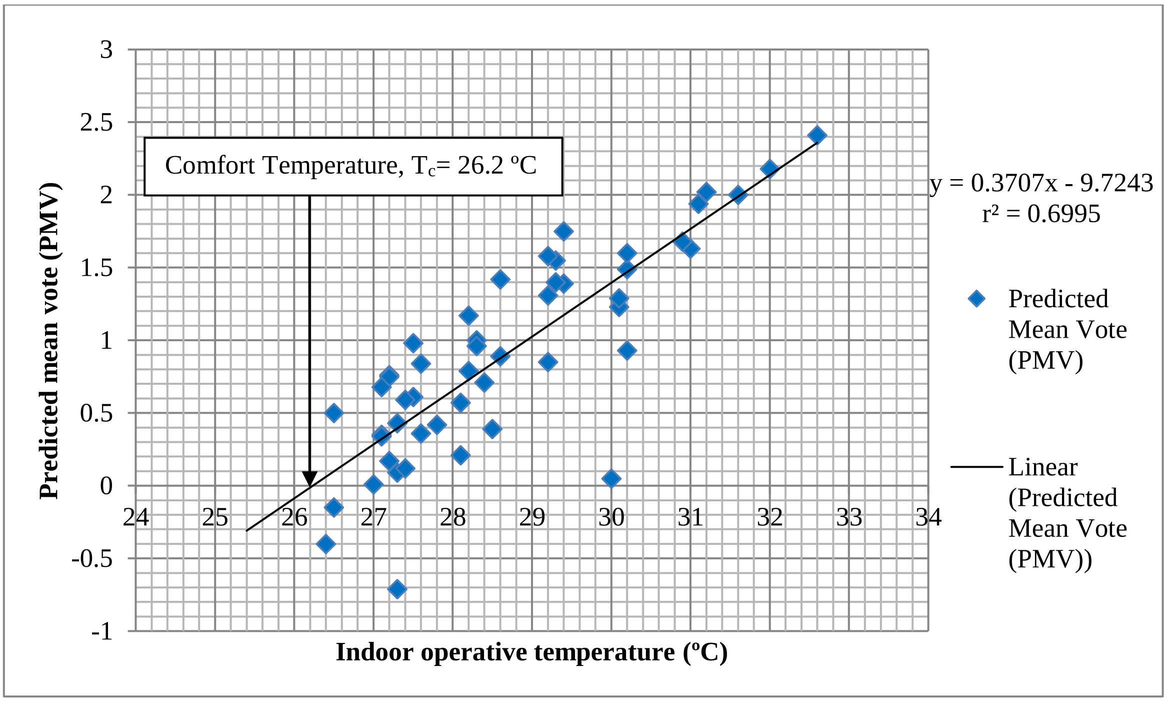

Figure 4.19: Predicted Mean Votes against Indoor Operative Temperature

The liner regression model between predicted mean votes and their corresponding indoor operative temperatures is obtained from Figure 4.19 and written in Equation (4.13).

$$PMV = 0.3707\ T_{op} - 9.7243 \qquad (4.13)$$

The gradient coefficient of 0.3707 in the liner model indicates that residents will experience one unit increase in their thermal state for every 2.7 ºC change in their indoor operative temperature.

4.5 Results Comparison between TSV, TCV and PMV

The comfort temperature of 27.5 ºC, 28.1 ºC and 26.2 ºC were determined respectively from ASHRAE thermal sensation vote, Bedford thermal comfort vote and Fanger's predicted mean vote. Most of the studies are comparing the comfort temperature of ASHRAE scale and PMV model as there is always discrepancy found between these 2 scales. In this study, the difference of comfort temperature between ASHRAE scale and PMV model was found to be 1.3 ºC. This finding is significant because if the setting of indoor comfort temperature is prescribed wrongly, it could affect the total amount of energy consumed in building sectors, particularly on ventilation systems.

Table 4.34: Value Comparison between TSV, TCV and PMV

Residential area	Operative temperature (ºC)	Thermal sensation vote (TSV)	Thermal comfort vote (TCV)	Predicted mean vote (PMV)
1	31.1	0.63	0.42	1.94
2	27.6	0.25	0.00	0.84
3	27.1	-1.00	-0.25	0.35
4	28.2	-0.80	-0.40	0.79
5	27.4	0.67	0.00	0.59

Table 4.34 continued

6	31.2	0.50	0.50	2.02
7	28.2	0.50	0.25	1.17
8	28.4	0.33	0.33	0.71
9	28.6	0.67	0.33	1.42
10	27.3	-0.50	-0.50	0.43

PMV model often underestimates the thermal impression of the respondents and consequently overpredicts their thermal sensation state. This is proven in this study where most of the calculated PMV values were higher than the values of TSV and TCV. Some of the TSV, TCV and PMV values were selected from each residential area for comparison purposes and tabulated in Table 4.34.

It can be observed that there are slight differences between TSV and TCV values but their differences with PMV values are drastic. For example, in Residential Area 4, ASHRAE scale and Bedford scale categorized the thermal state of the residents under “slightly cool” and “comfortably cool” categories but PMV model predicted them to be in warm category. By comparing all the PMV values with TSV and TCV values in Table 4.34, it is discovered that most of the PMV values overpredicted the thermal state of the respondents. Therefore, PMV model is not suitable to be used in this study without some degrees of error.

In order to find out the strength of the correlation between thermal sensation votes and predicted mean votes of the study, linear regression analysis was performed by plotting the graph of TSV against PMV.

Based on the regression graph shown in Figure 4.20, the relationship between TSV and PMV is defined in Equation (4.14).

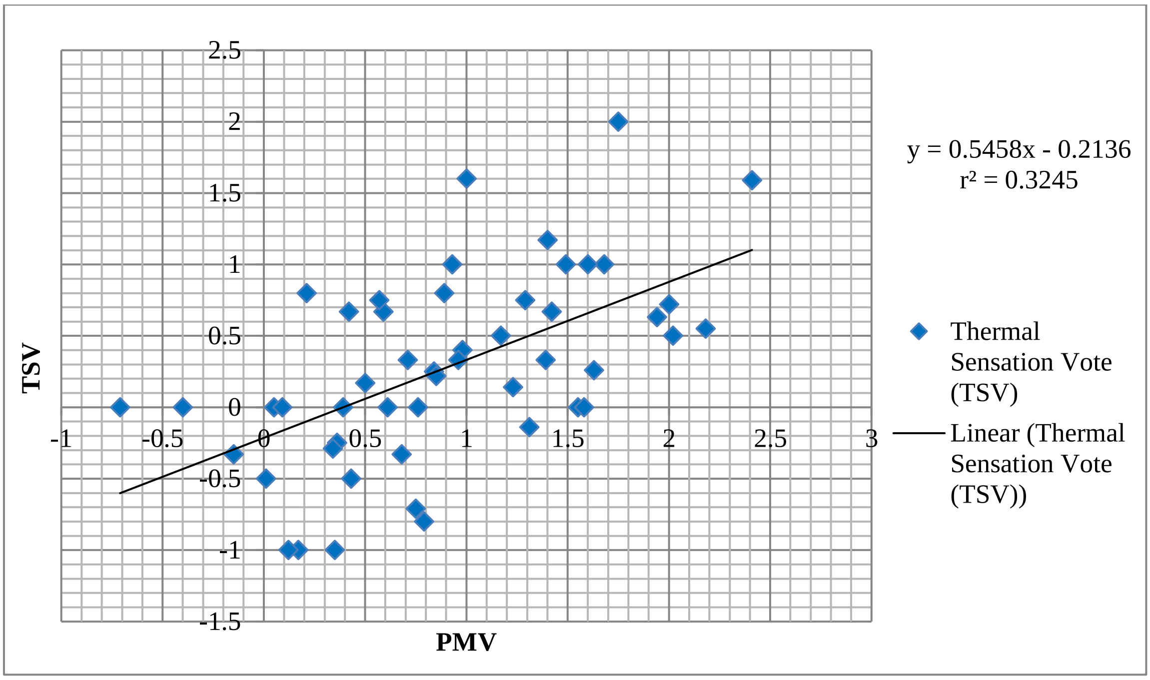

Figure 4.20: Regression Analysis between TSV and PMV

$$\text{TSV} = 0.5458\ \text{PMV} - 0.2136 \qquad (4.14)$$

From Equation (4.14), it can be calculated that when PMV is equal to zero (neutral sensation), the thermal sensation vote will demonstrate the value of – 0.2136 which is located in between “slightly cool” and “neutral” category. In other words, when people voted for neutral thermal sensation (TSV = 0), the PMV value will shift + 0.39 away from the neutral point towards the warmer side. Therefore, it can be concluded that PMV model predicted warmer than how the respondents actually felt in this study. The low r^2 value shown in Figure 4.20 also indicates that there is not much correlation between TSV and PMV.

As discussed in Section 4.3.3, the central three categories of Bedford scale had a higher acceptable percentage than the central three categories of ASHRAE scale. The results also showed that the respondents who voted in the warm and hot categories eventually still identified their thermal condition as comfortable. This is important in thermal comfort aspect since thermal comfort evaluation should be done according to the comfortable state experienced by the respondents rather than assessing them through their thermal sensation state. For example, people can still feel comfortable even though they are exposed to a warmer environment and vice versa. Therefore, Bedford scale should be a better measure for thermal comfort instead of ASHRAE scale.

In this study, the comfort temperature obtained from Bedford scale was 0.6 ºC higher than the one from ASHRAE scale. If this comfort temperature is used as a standard setting for indoor environment, more energy can be conserved while thermal comfort of the residents can be preserved concurrently.

The relationship between TCV and TSV is defined in Equation (4.15) and illustrated in Figure 4.21.

$$\mathrm{TCV} = 0.6663\ \mathrm{TSV} - 0.0371 \tag{4.15}$$

When TCV = – 1 and + 1, the calculated value of TSV is – 1.5 and + 1.6, respectively. This indicates that when TSV is at the cooler side, the thermal environment will be rated as “comfortably cool” at the cooler side of TCV as well. When TSV is at the warmer side, it will be rated as “comfortably warm” at the warmer side of TCV too. This shows that TSV and TCV correlate well with one another which is proven by the high r^2 value indicated in Figure 4.21.

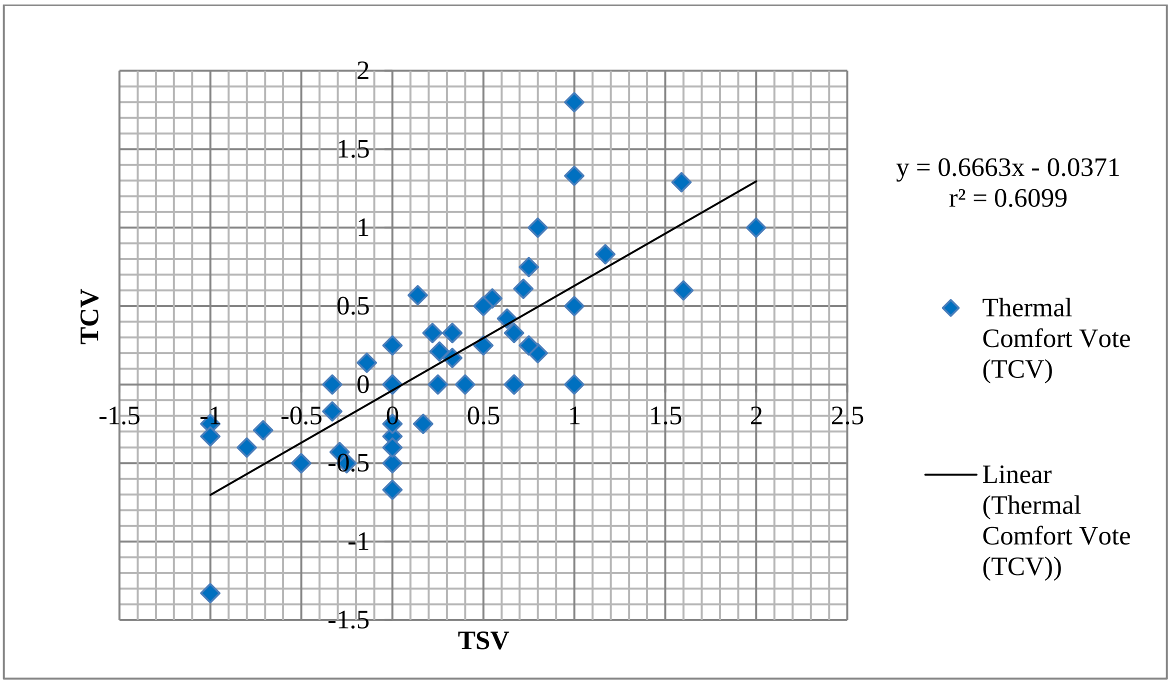

Figure 4.21: Regression Analysis between TCV and TSV

Linear regression analysis was performed on TCV and PMV as well to identify the relationship between them. The relationship between TCV and PMV is defined in Equation (4.16) according to the regression graph shown in Figure 4.22.

$$\text{TCV} = 0.479\ \text{PMV} - 0.2835 \qquad (4.16)$$

When TCV = – 0.5 and + 0.5, the calculated value of PMV is – 0.5 and + 1.6, respectively. This shows that when PMV is at the “neutral” to “slightly cool” category, TCV will evaluate the environment similarly on Bedford scale under the comfortable criteria. However, if PMV is at the warmer side of the scale, it is discovered that the environment will be rated in the comfortable category of Bedford scale.

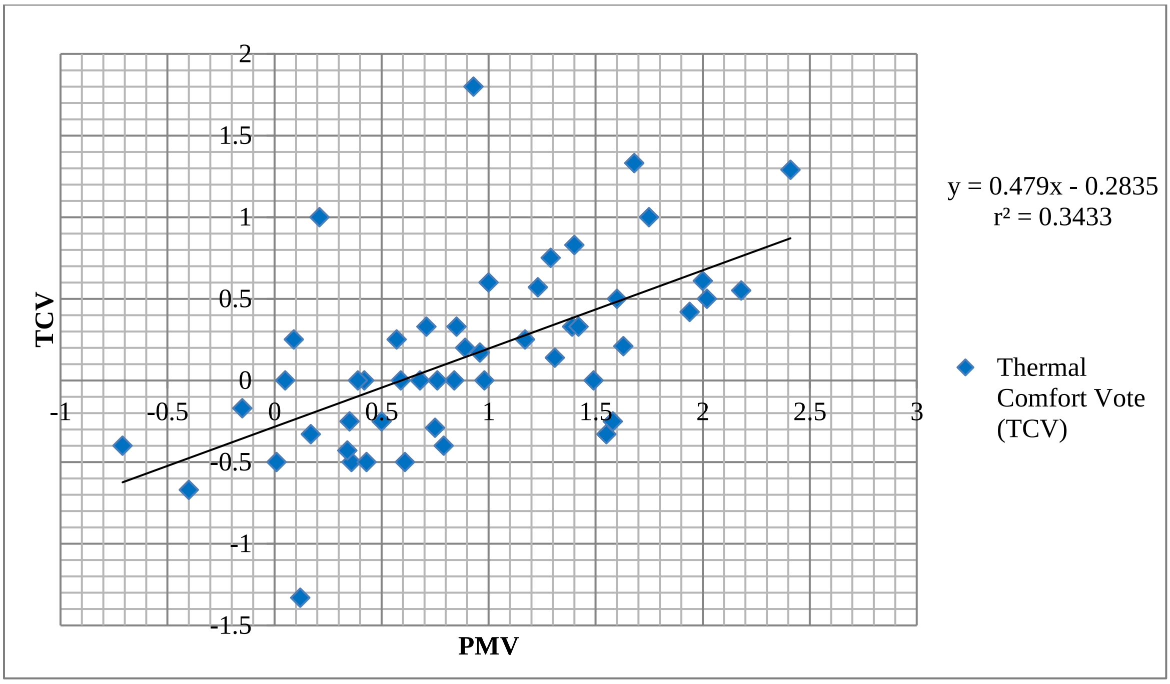

Figure 4.22: Regression Analysis between TCV and PMV

The PMV value will shift + 0.59 away from the neutral point of Bedford scale if people voted for neutral thermal comfort (TCV = 0). The deviation of PMV from Bedford scale in this study was higher than the deviation of PMV from ASHRAE scale. This ascertained that PMV had overpredicted the thermal perception of the respondents. The r^2 value between TCV and PMV is similar to the r^2 value between TSV and PMV which indicate that the correlation between TCV and PMV is relatively low as well.

4.6 Average Relative Humidity and Mean Relative Humidity Vote (RHV)

The average relative humidity of this study was in the range of 66.4% to 81.6% which is common among the hot and humid tropics [113]. This relative humidity range is similar to the study done by Feriadi [97] and Harimi [174] where the relative humidity range was reported to be 60% - 95% and 79.5% - 82.2%, respectively.

Since it is difficult to determine the effect of relative humidity [123], the scale of relative humidity was used in this study to analyze the response of occupants on their environment's humidity level. The scale indicator of relative humidity is shown in Table 3.8.

The humidity level experienced by the respondents was expressed in terms of numerical value which can also be referred as relative humidity vote (RHV). The negative value of the vote represents arid sensation while the positive value indicates humid sensation. The mean relative humidity vote for each residential area was calculated and tabulated in Table 4.35.

Table 4.35: Average Relative Humidity and Mean Relative Humidity Vote (RHV)

Residential area	Average relative humidity (%)	Mean relative humidity vote (RHV)
1	66.4	-0.67
2	76.5	0.12
3	69.1	-0.18
4	72.1	-0.30
5	69.1	-0.82
6	67.0	-0.03
7	70.2	0.34
8	71.0	-0.01
9	81.4	-0.06
10	81.6	0.10

The relationship between average relative humidity and mean relative humidity vote for each residential area is further illustrated in Figure 4.23.

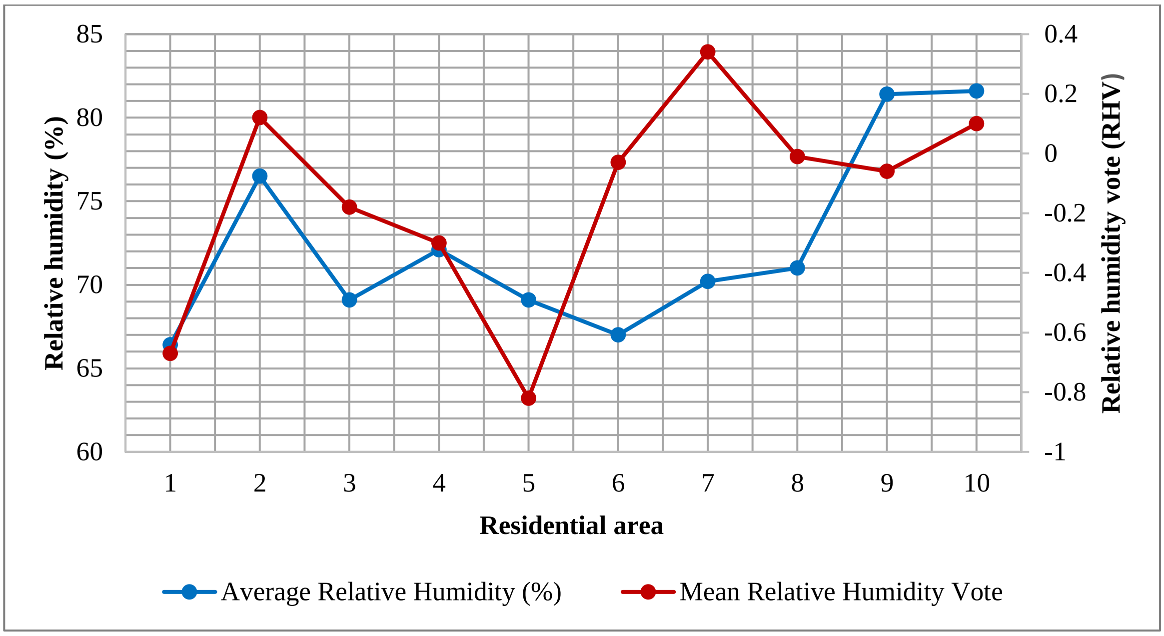

Figure 4.23: Average Relative Humidity vs Mean Relative Humidity Vote

It was presumed that the perception of respondents on their humidity sensation will be directly proportional to the humidity level of their corresponding environment. A high relative humidity percentage is supposed to be accorded with a positive value of humidity vote. However, Figure 4.23 shows that the presumption was only fulfilled partially. It is also discovered that at some points, the mean humidity votes responded inversely to their corresponding humidity level. For example, at Residential Areas 4 and 9, the calculated mean humidity votes were indicating dry sensation but in fact these respective environments were recorded with high humidity percentage.

Meanwhile at Residential Area 6, the mean relative humidity vote increased when its humidity level was eventually decreasing. This shows that the humidity perception experienced by the respondents varies from one person to another person due to different personal preferences, personal adaptations and personal perspectives towards their thermal environment.

The mean relative humidity vote was calculated to be 0.10 only for the highest average relative humidity (81.6%) recorded in the study. This indicates that the residents from hot and humid climate can withstand a higher range of humidity level in their environment and still found themselves at a relatively dry condition.

4.7 Average Air Speed vs Mean Air Speed Vote (ASV)

Air speed or air velocity is a highly variable parameter since it can be detected in multiple directions [79]. Therefore, this parameter is difficult to be measured accurately without a precise equipment [79, 171].

The average air speed of this study was in between 0.08 ms^{-1} and 0.20 ms^{-1} which fulfills the requirement of ISO 7730 standard [87] and Malaysian Standard, MS 1525: 2007 [94]. The minimum air speed set by these two standards are 0.10 ms^{-1} to 0.12 ms^{-1} and 0.15 ms^{-1} to 0.50 ms^{-1}, respectively.

The air speed scale used in this study is shown in Table 3.9. The responses of occupants on air speed for each residential area were converted into the value of air speed vote (ASV) and tabulated in Table 4.36. The positive value of air speed vote stands for windy condition whereas negative value denotes static condition. The correlation between average air speed and mean air speed vote for each residential area is illustrated in Figure 4.24.

Table 4.36: Average Air Speed and Mean Air Speed Vote (RHV)

Residential area	Average air speed (ms^{-1})	Mean air speed vote (ASV)
1	0.16	-0.60
2	0.12	-0.12
3	0.14	0.02
4	0.08	-0.23
5	0.19	-0.03
6	0.19	0.15
7	0.14	-0.54
8	0.20	-0.26
9	0.10	-0.25
10	0.13	0.03

Similar with relative humidity, it was assumed that the mean air speed vote will be directly proportional to the average air speed experienced by the respondents. Figure 4.24 shows that the aforementioned statement is valid as most of the calculated air speed votes correlated well with their respective air velocity.

There were only a few points where the value of air speed vote appeared to be decreasing at a higher air velocity reading and vice versa. This is caused by different perspective views of respondents towards their environment. When the air velocity cannot fulfill the thermal comfort demanded by the respondents, they would identify such air velocity as static or not breezy enough even though the air speed experienced by them is high. On the other hand, respondents would eventually recognize lower air speed as windy if they are feeling comfortable under their thermal condition.

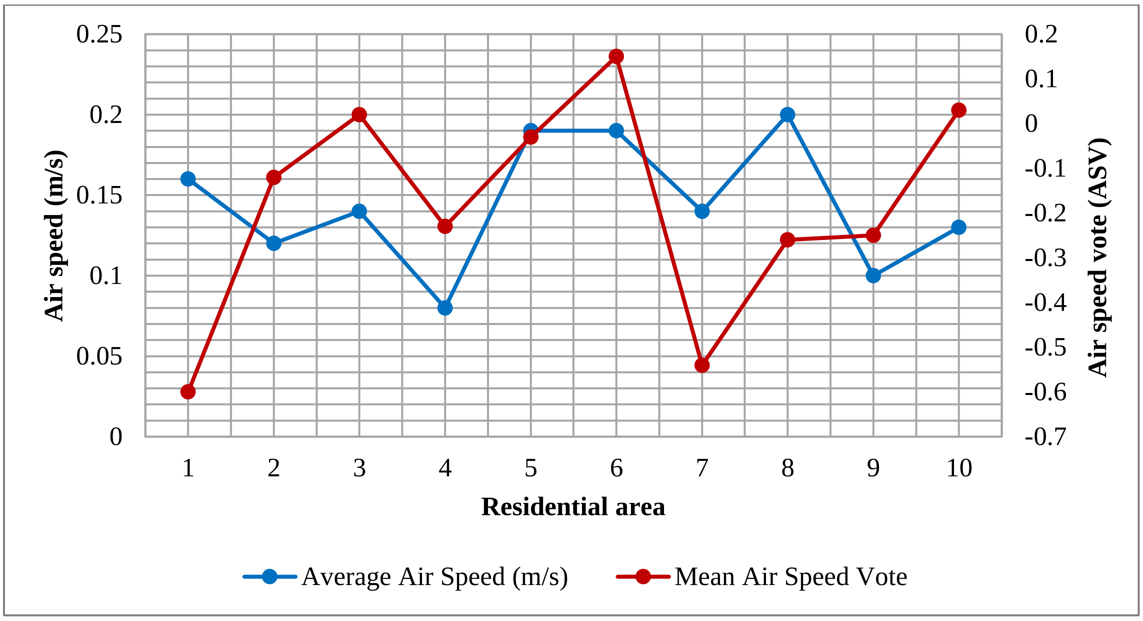

Figure 4.24: Average Air Speed vs Mean Air Speed Vote

The mean air speed votes of this study were mostly negative values ranging from -0.03 to -0.60. Only three residential areas showed positive values of 0.02, 0.03 and 0.15, which are comparatively low. This reveals that respondents from hot and humid climate do require a higher air velocity range in order to fulfill their thermal comfort expectation.

4.8 Proposed Adaptive Thermal Comfort Models

In order to develop an adaptive thermal comfort model for the residential buildings in this study, linear regression analysis was performed to determine the correlation between the comfort temperatures and their corresponding outdoor temperatures. The comfort temperature of each residential area and their respective average outdoor temperature was identified.

The upper and lower limit of the adaptive thermal comfort models were determined by using actual percentage dissatisfied (APD) extracted from thermal acceptability scale.

The APD was calculated and compared with the predicted percentage dissatisfied (PPD) calculated from PMV model.

In this study, two adaptive thermal comfort models were proposed, one from thermal sensation votes (TSV) of ASHRAE scale and another one from thermal comfort votes (TCV) of Bedford scale. The differences between these models were evaluated.

4.8.1 Thermal Neutrality and Outdoor Temperature for each Residential Area

The comfort temperatures of Residential Area 1 to Residential Area 10 were determined by using linear regression analysis which involved thermal sensation votes, thermal comfort votes and their respective indoor operative temperatures. The mean outdoor temperature for each residential area was also calculated.

4.8.1.1 Residential Area 1

The comfort temperature of Residential Area 1 based on TSV and TCV is shown in Figure 4.25 and Figure 4.26, which was 30.5 ºC and 30.6 ºC. The average outdoor temperature of 34.2 ºC was calculated from Table 4.37.

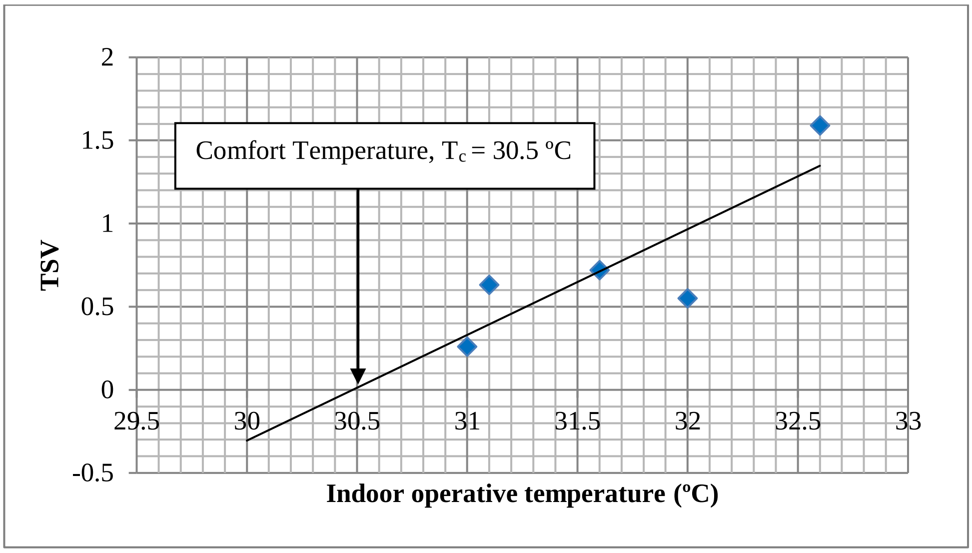

Figure 4.25: Regression Analysis between TSV and Indoor Operative Temperature for Residential Area 1

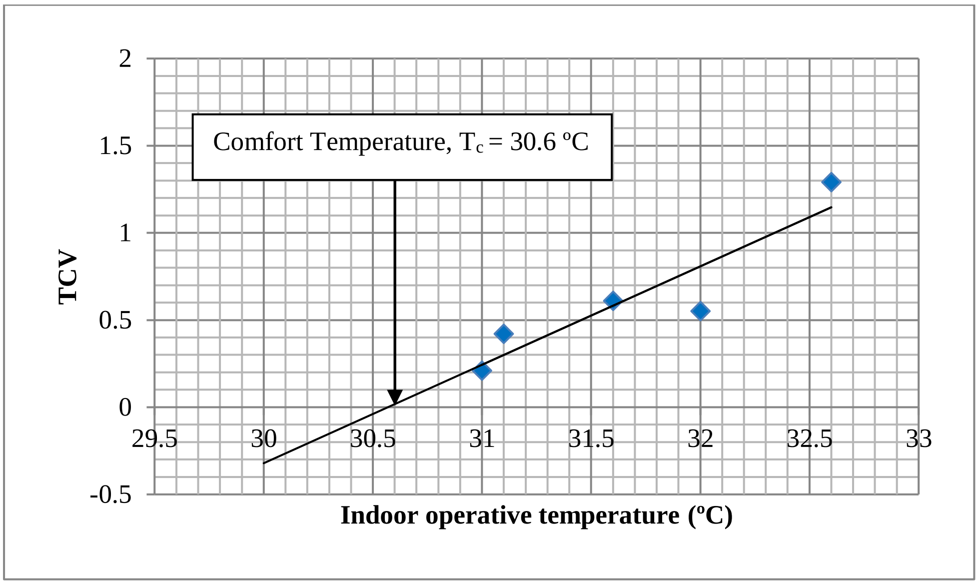

Figure 4.26: Regression Analysis between TCV and Indoor Operative Temperature for Residential Area 1

Table 4.37: TSV, TCV, Indoor Operative and Outdoor Temperature for Residential Area 1

Number of measurement	**TSV**	**TCV**	**Indoor operative temperature** (ºC)	**Outdoor temperature** (ºC)
1	0.63	0.42	31.1	33.3
2	0.55	0.55	32.0	34.5
3	1.59	1.29	32.6	34.9
4	0.26	0.21	31.0	34.0
5	0.72	0.61	31.6	34.1

4.8.1.2 Residential Area 2

The comfort temperature of Residential Area 2 based on TSV and TCV is shown in Figure 4.27 and Figure 4.28, which was 26.7 ºC and 27.4 ºC. The average outdoor temperature of 30.2 ºC was calculated from Table 4.38.

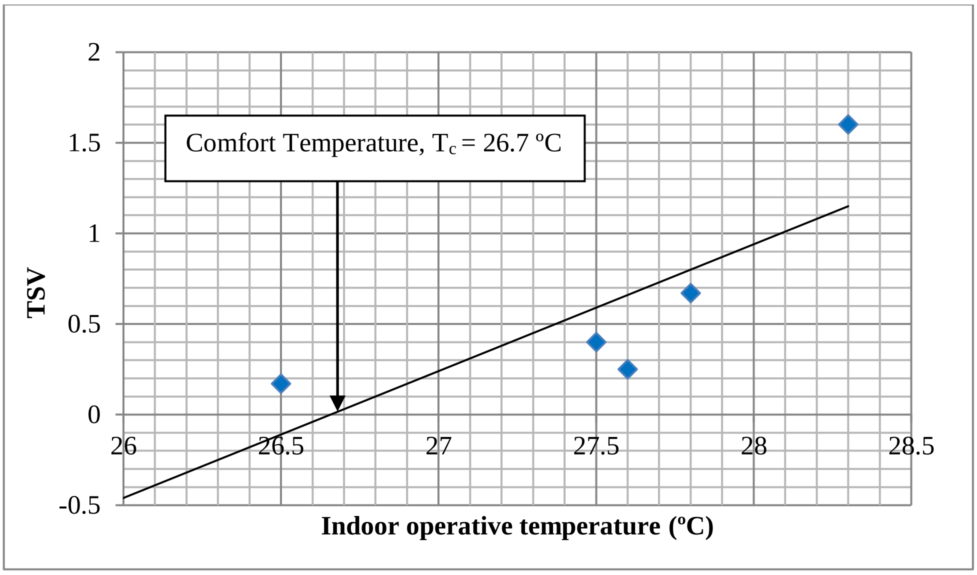

Figure 4.27: Regression Analysis between TSV and Indoor Operative Temperature for Residential Area 2

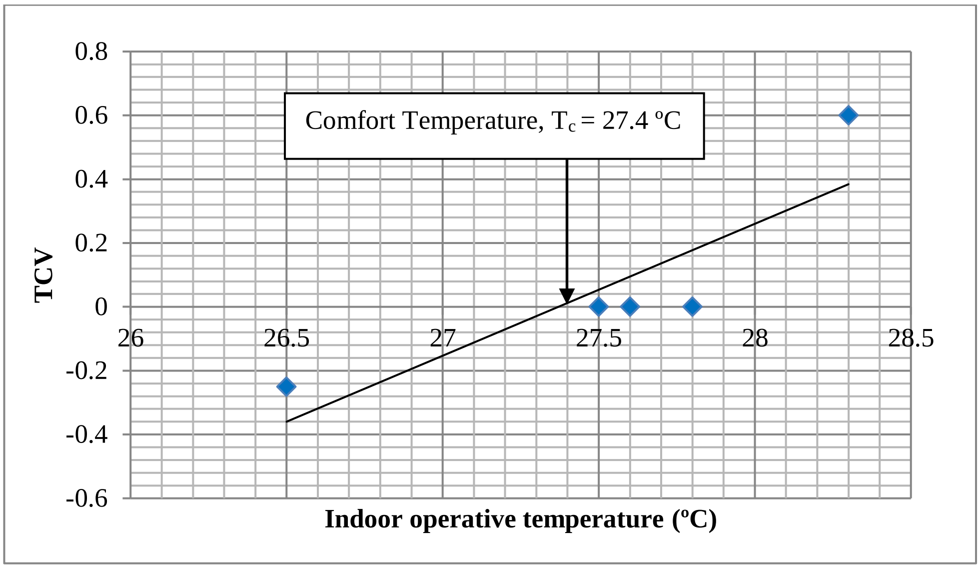

Figure 4.28: Regression Analysis between TCV and Indoor Operative Temperature for Residential Area 2

Table 4.38: TSV, TCV, Indoor Operative and Outdoor Temperature for Residential Area 2

Number of measurement	**TSV**	**TCV**	**Indoor operative temperature** (°C)	**outdoor temperature** (°C)
1	0.40	0.00	27.5	32.0
2	1.60	0.60	28.3	34.0
3	0.67	0.00	27.8	29.5
4	0.25	0.00	27.6	28.2
5	0.17	-0.25	26.5	27.5

4.8.1.3 Residential Area 3

The comfort temperature of Residential Area 3 based on TSV and TCV is shown in Figure 4.29 and Figure 4.30, which was 28.5 °C and 29 °C. The average outdoor temperature of 31.3 °C was calculated from Table 4.39.

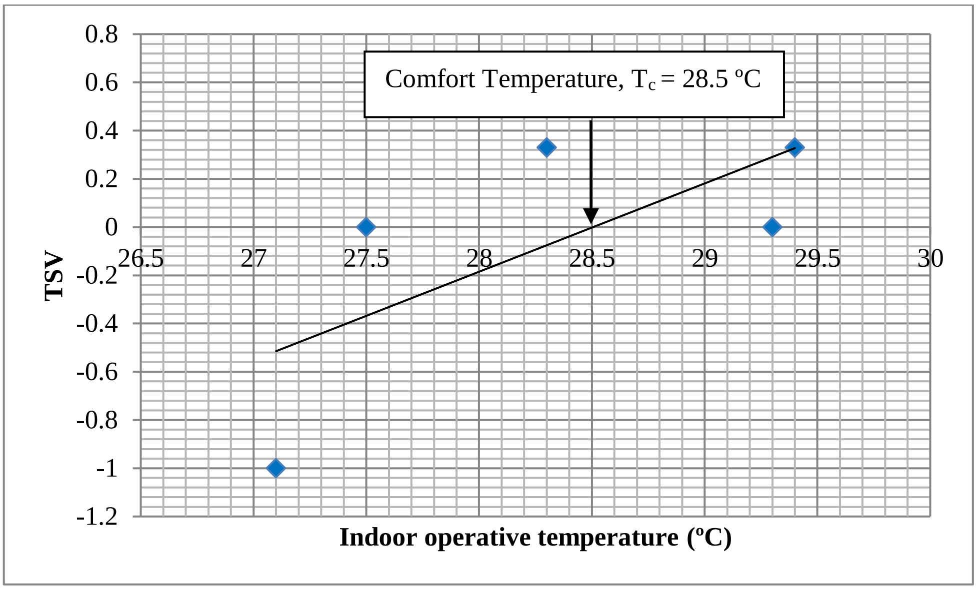

Figure 4.29: Regression Analysis between TSV and Indoor Operative Temperature for Residential Area 3

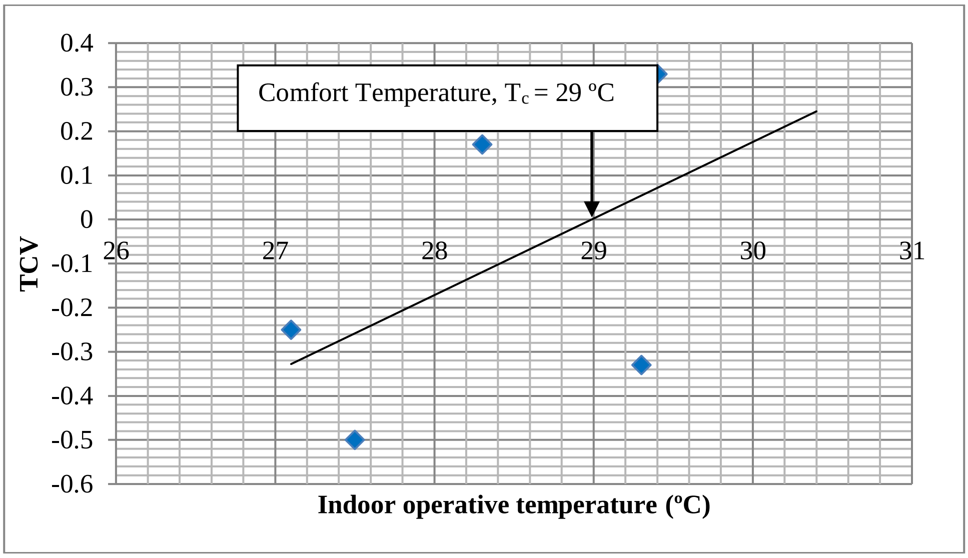

Figure 4.30: Regression Analysis between TCV and Indoor Operative Temperature for Residential Area 3

Table 4.39: TSV, TCV, Indoor Operative and Outdoor Temperature for Residential Area 3

Number of measurement	**TSV**	**TCV**	**Indoor operative temperature** (ºC)	**outdoor temperature** (ºC)
1	0.33	0.17	28.3	31.9
2	0.33	0.33	29.4	34.4
3	0.00	-0.33	29.3	36.4
4	0.00	-0.50	27.5	27.1
5	-1.00	-0.25	27.1	26.6

4.8.1.4 Residential Area 4

The comfort temperature of Residential Area 4 based on TSV and TCV is shown in Figure 4.31 and Figure 4.32, which was 28.2 ºC and 28.4 ºC. The average outdoor temperature of 31.9 ºC was calculated from Table 4.40.

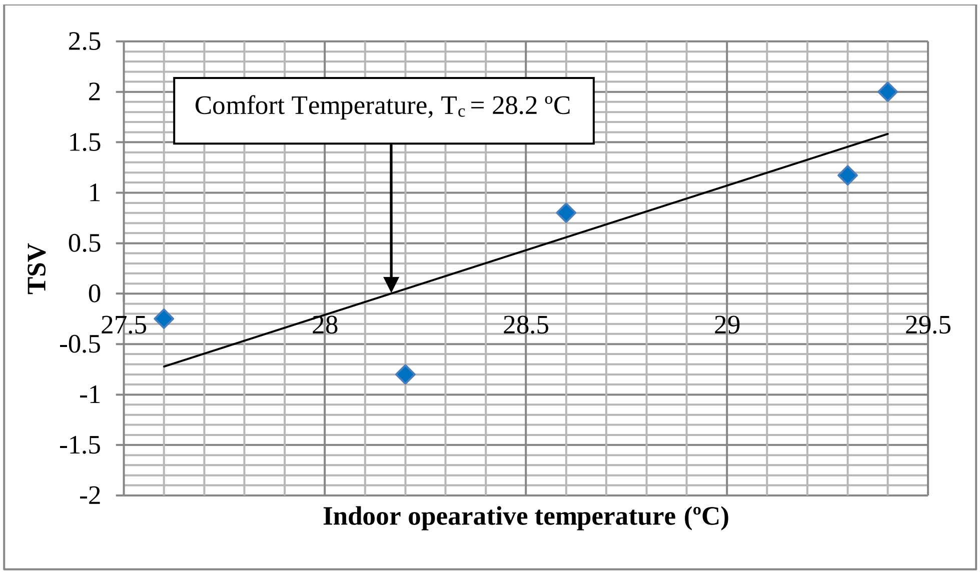

Figure 4.31: Regression Analysis between TSV and Indoor Operative Temperature for Residential Area 4

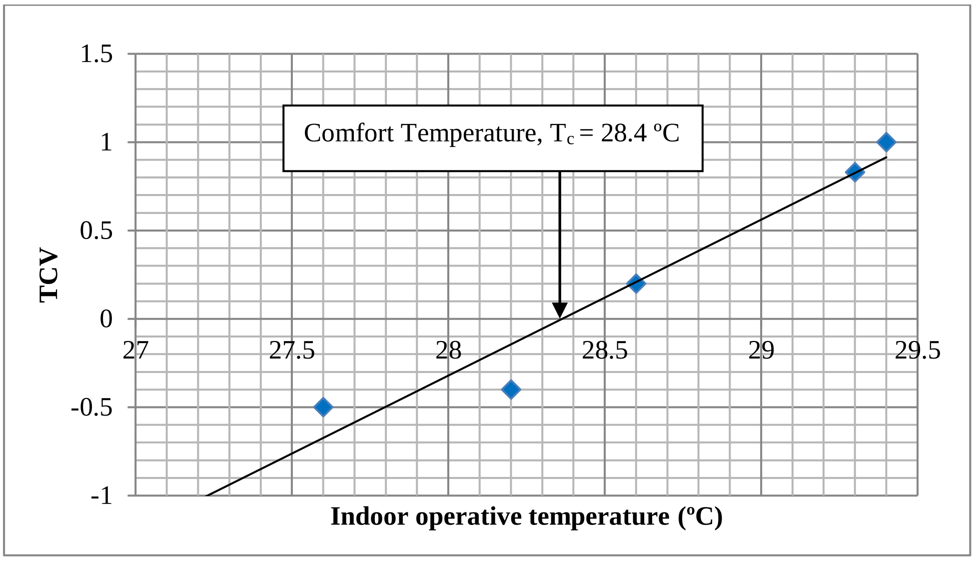

Figure 4.32: Regression Analysis between TCV and Indoor Operative Temperature for Residential Area 4

Table 4.40: TSV, TCV, Indoor Operative and Outdoor Temperature for Residential Area 4

Number of measurement	**TSV**	**TCV**	**Indoor operative temperature** (°C)	**Outdoor temperature** (°C)
1	-0.80	-0.40	28.2	31.6
2	1.17	0.83	29.3	33.8
3	2.00	1.00	29.4	32.9
4	0.80	0.20	28.6	32.6
5	-0.25	-0.50	27.6	28.7

4.8.1.5 Residential Area 5

The comfort temperature of Residential Area 5 based on TSV and TCV is shown in Figure 4.33 and Figure 4.34, which was 26.4 °C and 27.2 °C. The average outdoor temperature of 29.6 °C was calculated from Table 4.41.

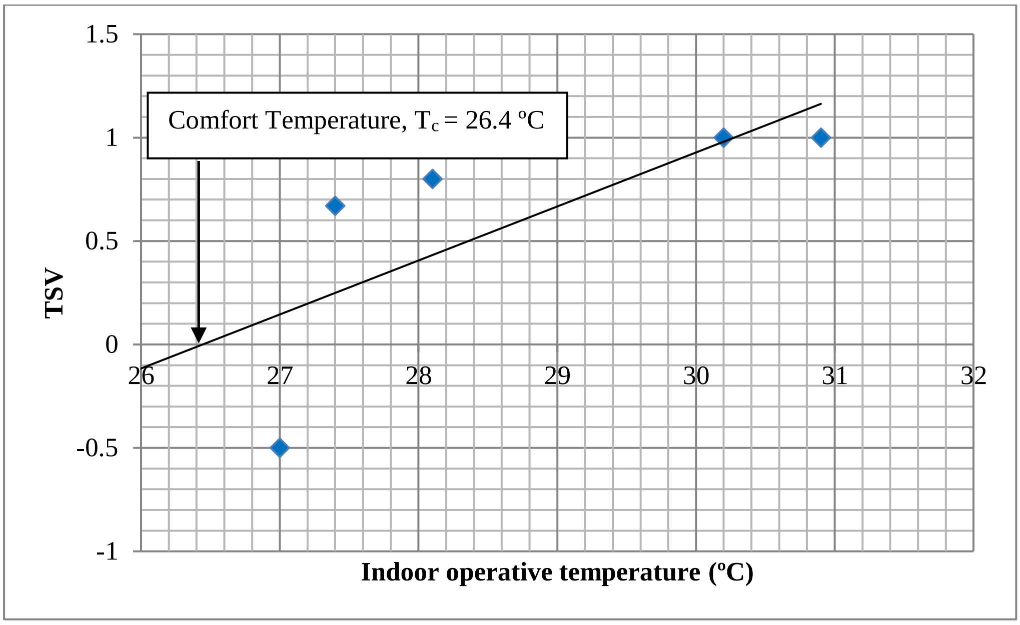

Figure 4.33: Regression Analysis between TSV and Indoor Operative Temperature for Residential Area 5

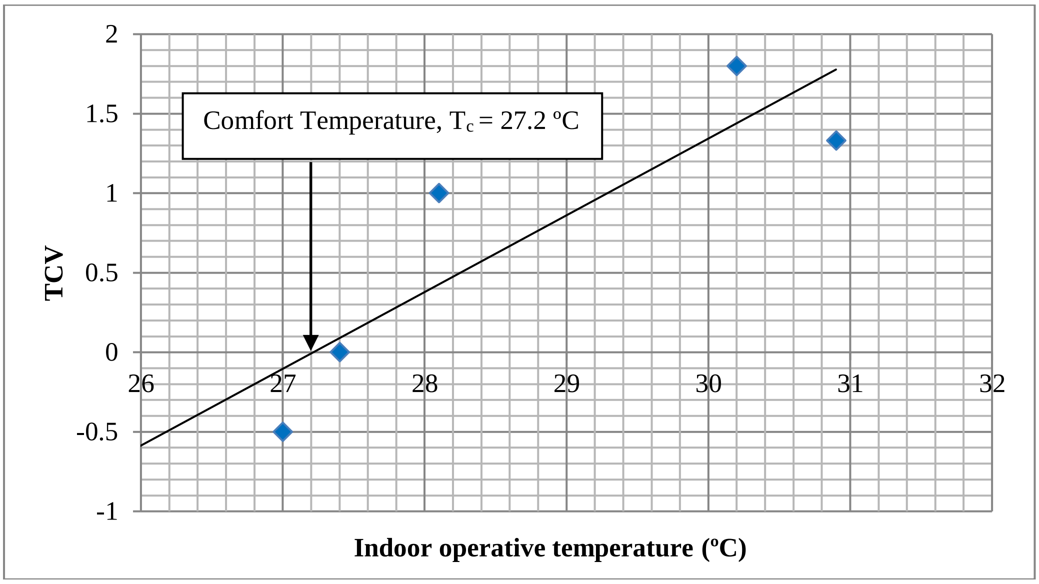

Figure 4.34: Regression Analysis between TCV and Indoor Operative Temperature for Residential Area 5

Table 4.41: TSV, TCV, Indoor Operative and Outdoor Temperature for Residential Area 5

Number of measurement	**TSV**	**TCV**	**Indoor operative temperature** (°C)	**Outdoor temperature** (°C)
1	1.00	1.80	30.2	33.1
2	1.00	1.33	30.9	34.5
3	0.80	1.00	28.1	27.3
4	0.67	0.00	27.4	26.6
5	-0.50	-0.50	27.0	26.6

4.8.1.6 Residential Area 6

The comfort temperature of Residential Area 6 based on TSV and TCV is shown in Figure 4.35 and Figure 4.36, which was 28.3 °C and 29.3 °C. The average outdoor temperature of 32.8 °C was calculated from Table 4.42.

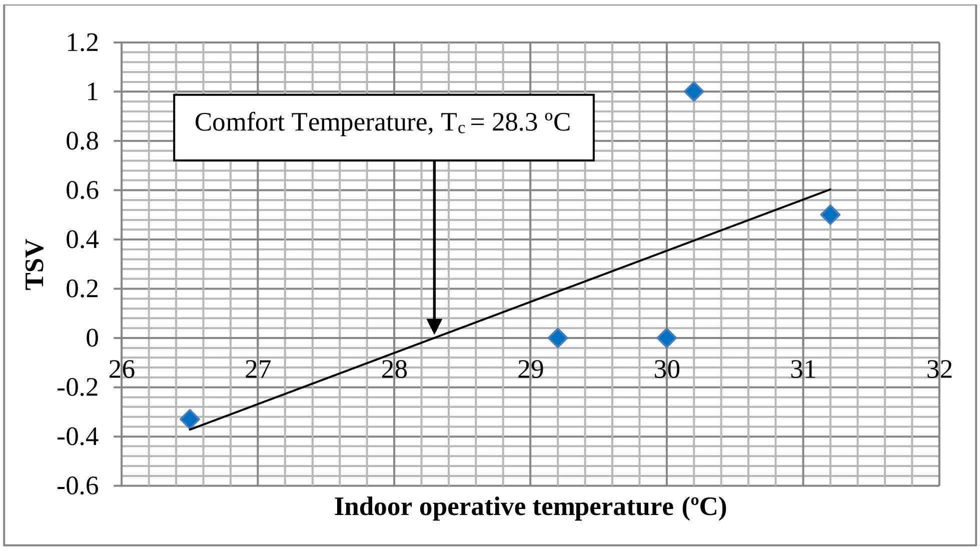

Figure 4.35: Regression Analysis between TSV and Indoor Operative Temperature for Residential Area 6

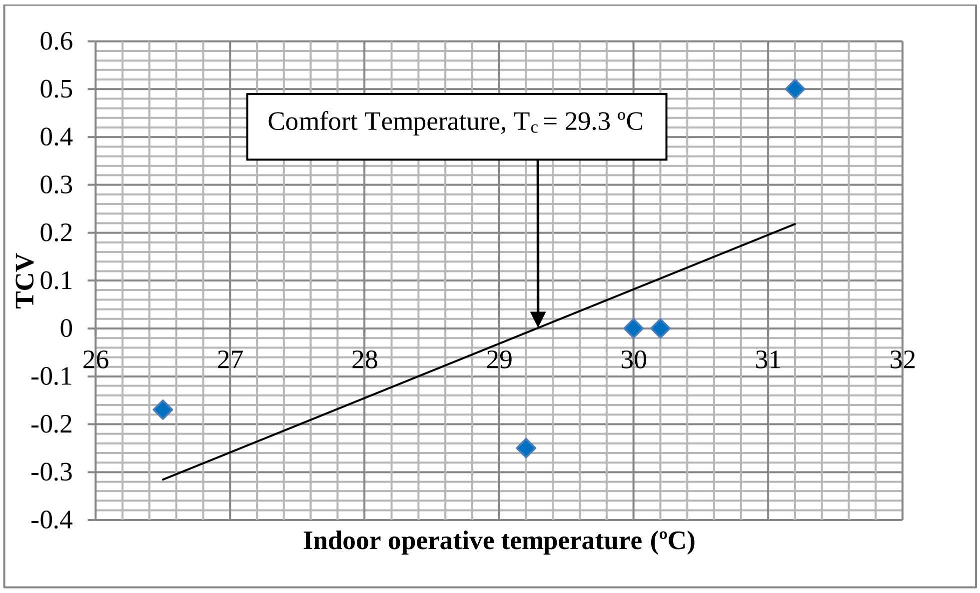

Figure 4.36: Regression Analysis between TCV and Indoor Operative Temperature for Residential Area 6

Table 4.42: TSV, TCV, Indoor Operative and Outdoor Temperature for Residential Area 6

Number of measurement	**TSV**	**TCV**	**Indoor operative temperature** (ºC)	**Outdoor temperature** (ºC)
1	0.00	-0.25	29.2	32.6
2	0.00	0.00	30.0	34.5
3	0.50	0.50	31.2	37.5
4	1.00	0.00	30.2	33.1
5	-0.33	-0.17	26.5	26.1

4.8.1.7 Residential Area 7

The comfort temperature of Residential Area 7 based on TSV and TCV is shown in Figure 4.37 and Figure 4.38, which was 27.9 ºC and 28.2 ºC. The average outdoor temperature of 31.5 ºC was calculated from Table 4.43.

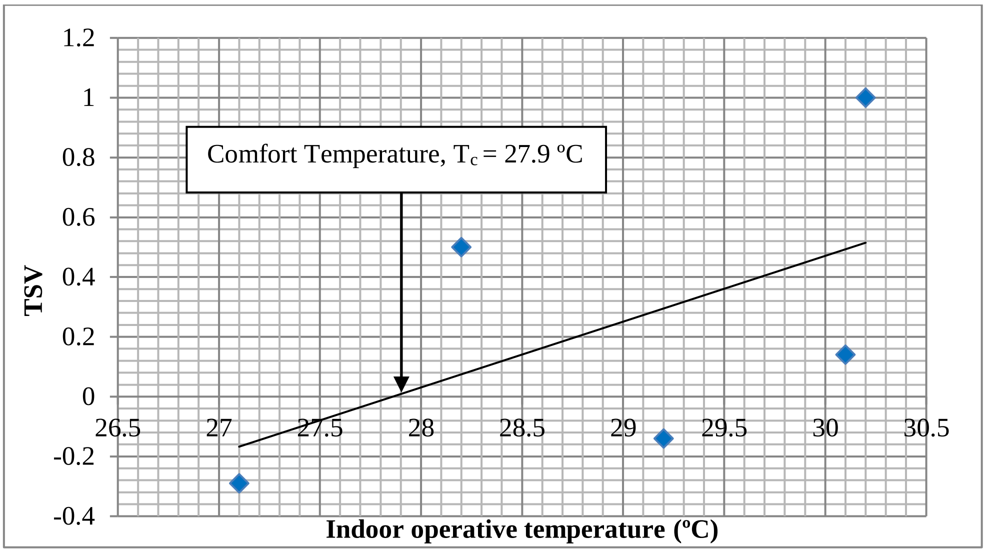

Figure 4.37: Regression Analysis between TSV and Indoor Operative Temperature for Residential Area 7

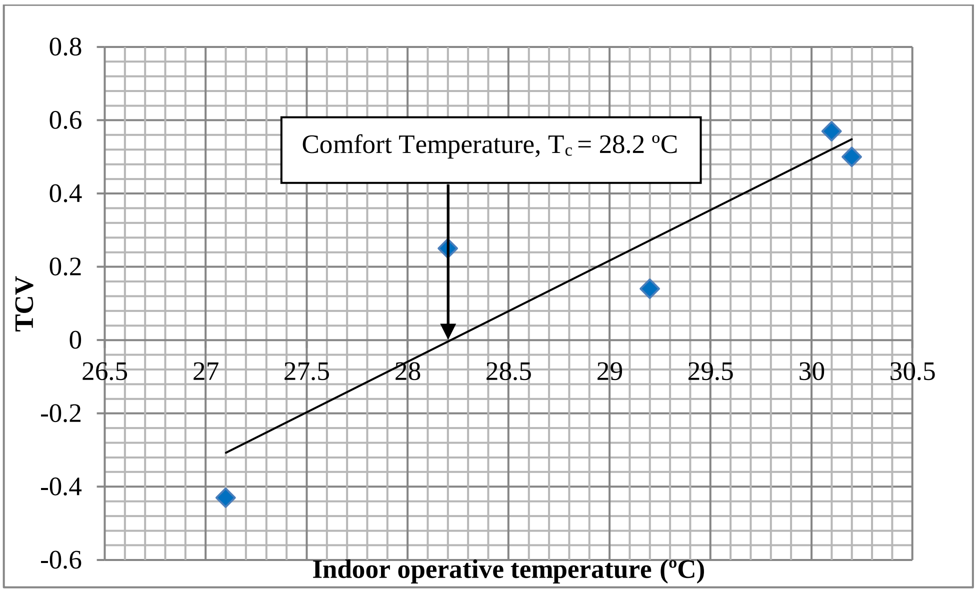

Figure 4.38: Regression Analysis between TCV and Indoor Operative Temperature for Residential Area 7

Table 4.43: TSV, TCV, Indoor Operative and Outdoor Temperature for Residential Area 7

Number of measurement	**TSV**	**TCV**	**Indoor operative temperature** (ºC)	**Outdoor temperature** (ºC)
1	0.50	0.25	28.2	31.6
2	1.00	0.50	30.2	33.6
3	0.14	0.57	30.1	34.2
4	-0.14	0.14	29.2	30.7
5	-0.29	-0.43	27.1	27.2

4.8.1.8 Residential Area 8

The comfort temperature of Residential Area 8 based on TSV and TCV is shown in Figure 4.39 and Figure 4.40, which was 27.6 ºC and 28.2 ºC. The average outdoor temperature of 31.9 ºC was calculated from Table 4.44.

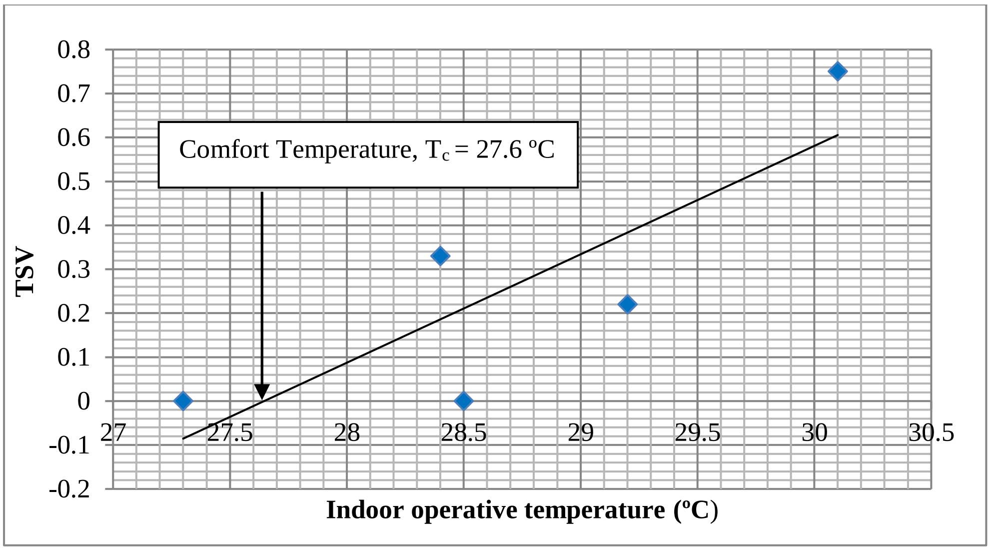

Figure 4.39: Regression Analysis between TSV and Indoor Operative Temperature for Residential Area 8

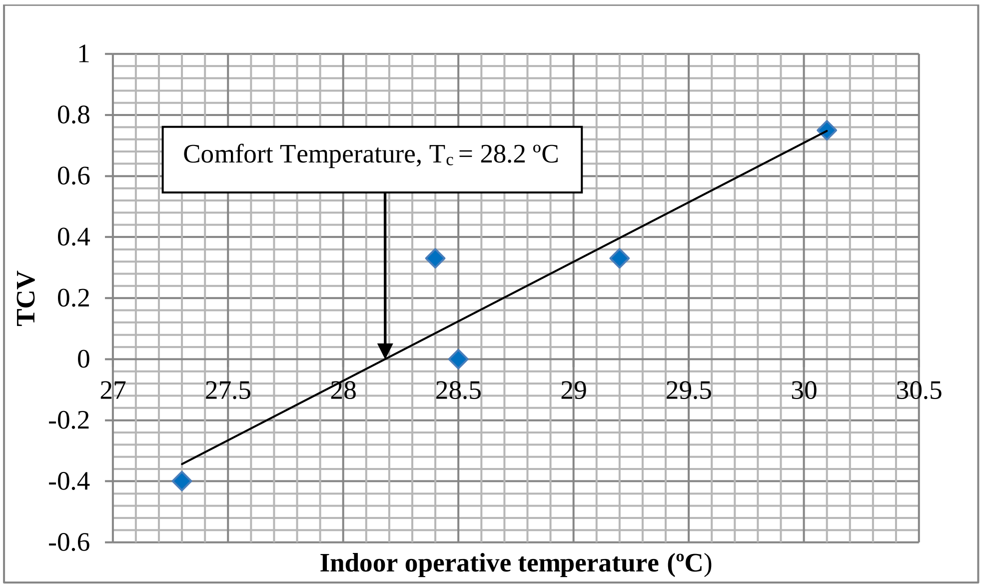

Figure 4.40: Regression Analysis between TCV and Indoor Operative Temperature for Residential Area 8

Table 4.44: TSV, TCV, Indoor Operative and Outdoor Temperature for Residential Area 8

Number of measurement	**TSV**	**TCV**	**Indoor operative temperature** (ºC)	**Outdoor temperature** (ºC)
1	0.00	0.00	28.5	32.6
2	0.33	0.33	28.4	32.9
3	0.75	0.75	30.1	35.4
4	0.22	0.33	29.2	30.7
5	0.00	-0.40	27.3	27.8

4.8.1.9 Residential Area 9

The comfort temperature of Residential Area 9 based on TSV and TCV is shown in Figure 4.41 and Figure 4.42, which was 27.5 ºC and 27.6 ºC. The average outdoor temperature of 29.2 ºC was calculated from Table 4.45.

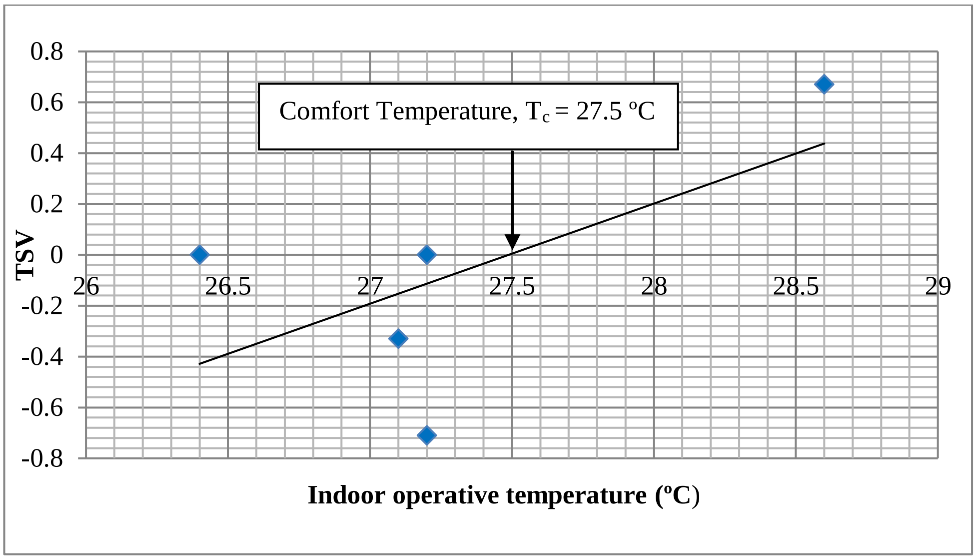

Figure 4.41: Regression Analysis between TSV and Indoor Operative Temperature for Residential Area 9

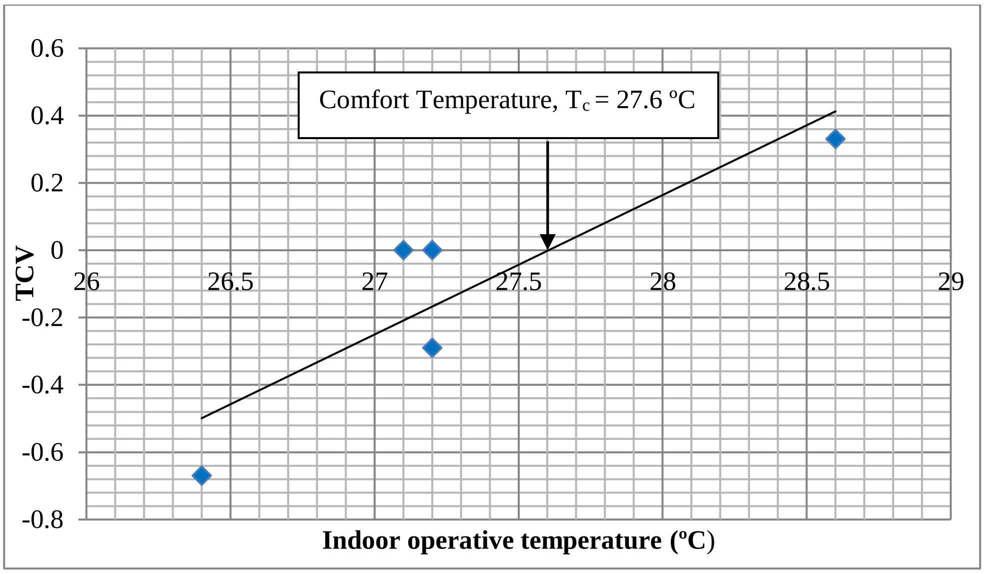

Figure 4.42: Regression Analysis between TCV and Indoor Operative Temperature for Residential Area 9

Table 4.45: TSV, TCV, Indoor Operative and Outdoor Temperature for Residential Area 9

Number of measurement	**TSV**	**TCV**	**Indoor operative temperature** (ºC)	**Outdoor temperature** (ºC)
1	0.00	-0.67	26.4	29.6
2	0.67	0.33	28.6	33.5
3	0.00	0.00	27.2	28.1
4	-0.71	-0.29	27.2	27.5
5	-0.33	0.00	27.1	27.2

4.8.1.10Residential Area 10

The comfort temperature of Residential Area 10 based on TSV and TCV is shown in Figure 4.43 and Figure 4.44, which was 27.7 ºC and 27.9 ºC. The average outdoor temperature of 29.1 ºC was calculated from Table 4.46.

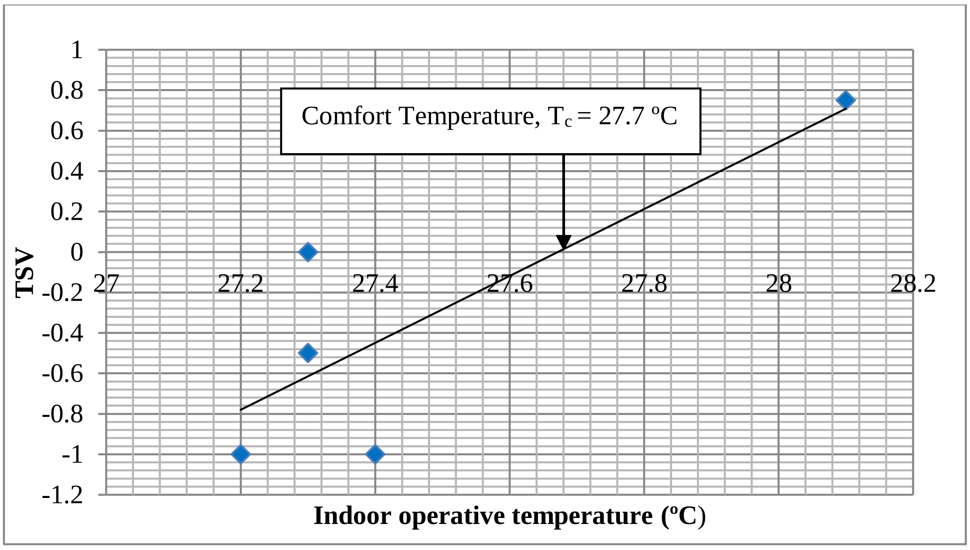

Figure 4.43: Regression Analysis between TSV and Indoor Operative Temperature for Residential Area 10

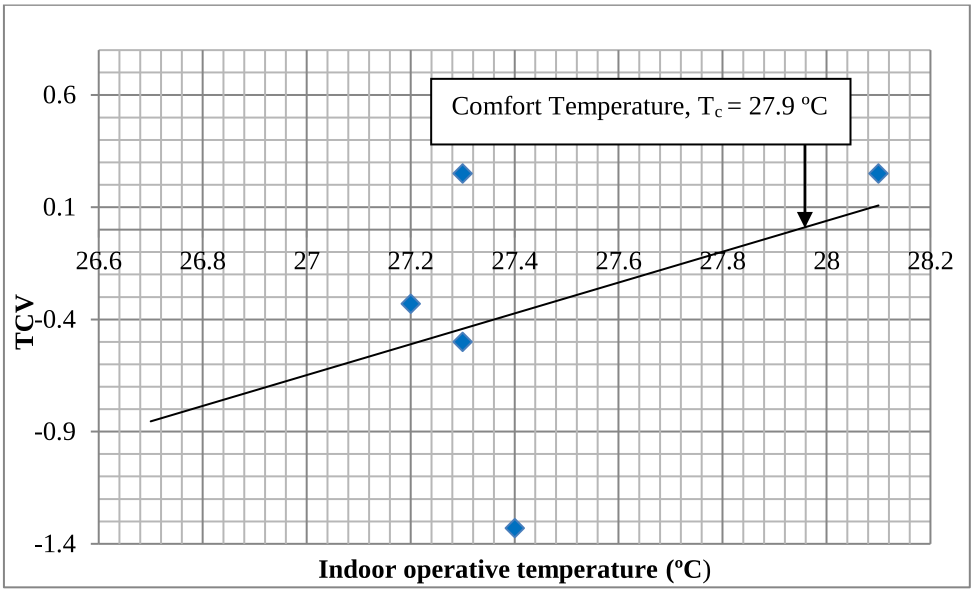

Figure 4.44: Regression Analysis between TCV and Indoor Operative Temperature for Residential Area 10

Table 4.46: TSV, TCV, Indoor Operative and Outdoor Temperature for Residential Area 10

Number of measurement	**TSV**	**TCV**	**Indoor operative temperature** (°C)	**Outdoor temperature** (°C)
1	0.75	0.25	28.1	34.0
2	-1.00	-0.33	27.2	27.5
3	0.00	0.25	27.3	27.9
4	-0.50	-0.50	27.3	28.1
5	-1.00	-1.33	27.4	27.8

4.8.2 Correlation of Average Relative Humidity with Comfort Temperature of TSV and TCV

The comfort temperature from ASHRAE scale and Bedford scale for each residential area is tabulated in Table 4.47 with their respective average relative humidity. The correlation between these two parameters is illustrated in Figure 4.45 and Figure 4.46.

Table 4.47: Comfort Temperature of ASHRAE Scale, Bedford Scale and Average Relative Humidity for each Residential Area

Residential area	**Comfort temperature from ASHRAE scale (ºC)**	**Comfort temperature from Bedford scale (ºC)**	**Average relative humidity (%)**
1	30.5	30.6	66.4
2	26.7	27.4	76.5
3	28.5	29.3	69.1
4	28.2	28.4	72.1
5	26.4	27.2	69.1
6	28.3	29.3	67.0
7	27.9	28.2	70.2
8	27.6	28.2	71.0
9	27.5	27.6	81.4
10	27.7	27.9	81.6

Different studies have shown that relative humidity does have an effect on comfort temperature, however the size of the effect is generally small [123, 146]. Under a hot environment where the heat loss of the body is achieved through the process of convection and radiation, a higher humidity level will reduce the heat dissipation process via evaporation which contributes to thermal discomfort.

It was also discovered that people will feel uncomfortable easily in a humid environment with a smaller change of temperature if compared to a dry environment [123]. Thus, the influence of relative humidity on comfort temperature cannot be neglected even though the effect is less significant.

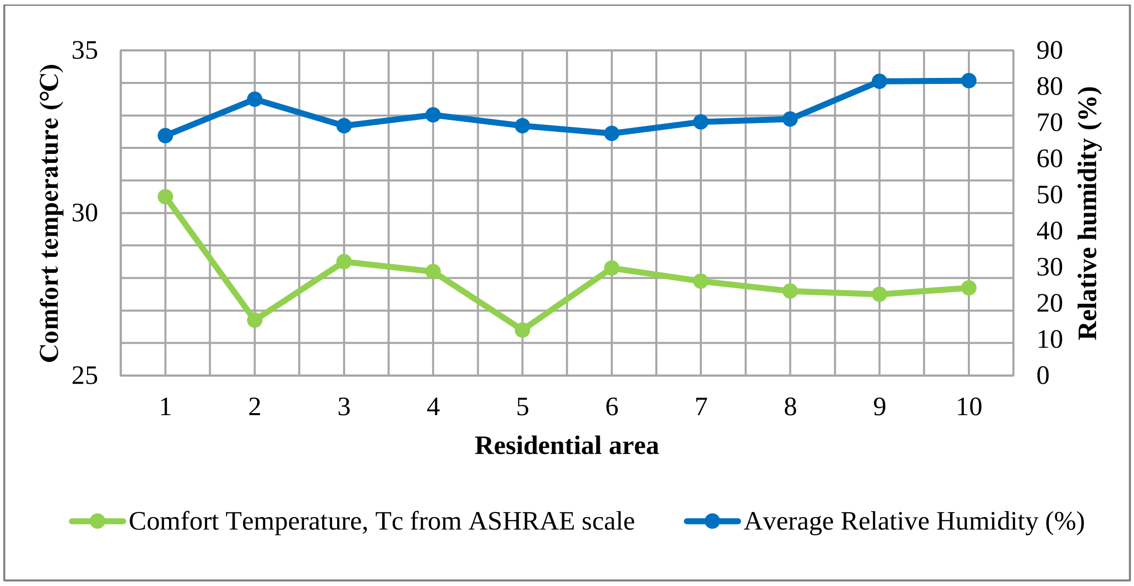

Figure 4.45: Comfort Temperature of ASHRAE Scale vs Average Relative Humidity

Figure 4.45 and Figure 4.46 show similar graphical illustration due to the same relative humidity level experienced. However, these two figures can be distinguished by the difference between the comfort temperatures obtained from ASHRAE scale and Bedford scale.

The results from Figure 4.45 and Figure 4.46 show that the respondents of this study can withstand a higher comfort temperature when the humidity level of their thermal environment was discovered to be less humid. In contrast, when the humidity level of the environment increased, the acceptable value for comfort temperature will decrease. The outcome of this result is in good agreement with the research work done in [175] which proved that the comfort temperature will be higher if the occupants feel “less humid”. Nicol also suggested that people will require a lower temperature to achieve thermal comfort if they are experiencing difficulties on evaporative heat loss caused by high humidity level [123].

All of the points in Figure 4.45 and Figure 4.46 correlated well apart from the point on Residential Area 5. The comfort temperature value for Residential Area 5 was supposed to be higher since there was a drop in humidity level. However, the result showed another way round. This is because the comfort temperature can also be affected by other factors such as air velocity. Based on the negative air speed vote determined from Residential Area 5, it can be concluded that there was not much air movement encountered within its indoor environment. Thus, the low comfort temperature value found on Residential Area 5 is due to inadequate amount of air velocity even though the humidity level was low.

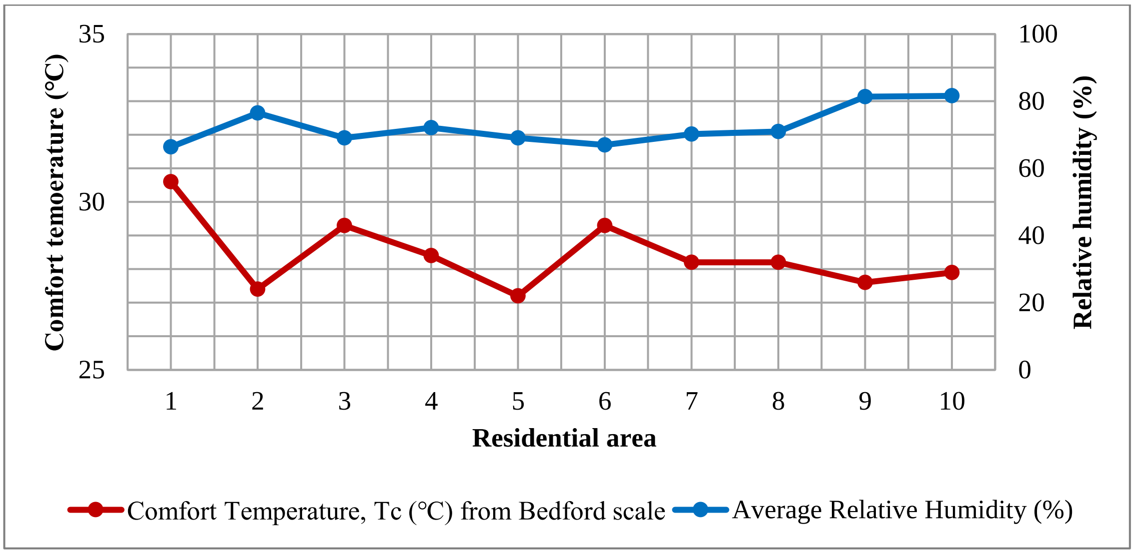

Figure 4.46: Comfort Temperature of Bedford Scale vs Average Relative Humidity

4.8.3 Correlation of Average Air Velocity with Comfort Temperature of TSV and TCV

The comfort temperature determined from ASHRAE scale and Bedford scale for each residential area is tabulated in Table 4.48 together with their corresponding average air velocity. The relationship between comfort temperature and average air velocity is further illustrated in Figure 4.47 and Figure 4.48.

Table 4.48: Comfort Temperature of ASHRAE Scale, Bedford Scale and Average Air Speed for each Residential Area

Residential Area	**Comfort temperature from ASHRAE scale (ºC)**	**Comfort temperature from Bedford scale (ºC)**	**Average air velocity (ms^{-1})**
1	30.5	30.6	0.16
2	26.7	27.4	0.12
3	28.5	29.3	0.14
4	28.2	28.4	0.08
5	26.4	27.2	0.19
6	28.3	29.3	0.19
7	27.9	28.2	0.14
8	27.6	28.2	0.20
9	27.5	27.6	0.10
10	27.7	27.9	0.13

In addition to relative humidity, indoor air velocity would affect the comfort temperature as well. It was postulated that the increase of air velocity within the indoor environment could accommodate a higher comfort temperature [176]. This was proven in the results illustrated in Figure 4.47 and Figure 4.48. Research done by Damiati also showed similar outcome where the comfort temperature was found to be higher when the air speed within the office buildings increased [175].

It was also not surprised to discover that the comfort temperature trends of ASHRAE scale and Bedford scale showed similar graphical pattern in this study since they were experiencing the same average air velocity values, only with different comfort temperature readings.

It can be observed that there were two points each in Figure 4.47 and Figure 4.48 which did not correlate well with their parameters. The comfort temperature of Residential Areas 5 and 8 supposed to increase when the average air speed increased. However, it was discovered that the comfort temperature decreased even though the average air speed was escalating. This is due to the expectation difference among the residents in this study. It is obvious that the respondents from Residential Areas 5 and 8 had a higher expectation on indoor air velocity. Based on the negative mean air speed vote of -0.03 and -0.26 obtained from Table 4.36, it can be concluded that the respondents had identified their indoor air movement as not breezy enough although the air velocity recorded was comparatively high with 0.19 ms^{-1} and 0.20 ms^{-1}, respectively. Therefore, the comfort temperature of Residential Areas 5 and 8 decreased even though the air velocity was increasing.

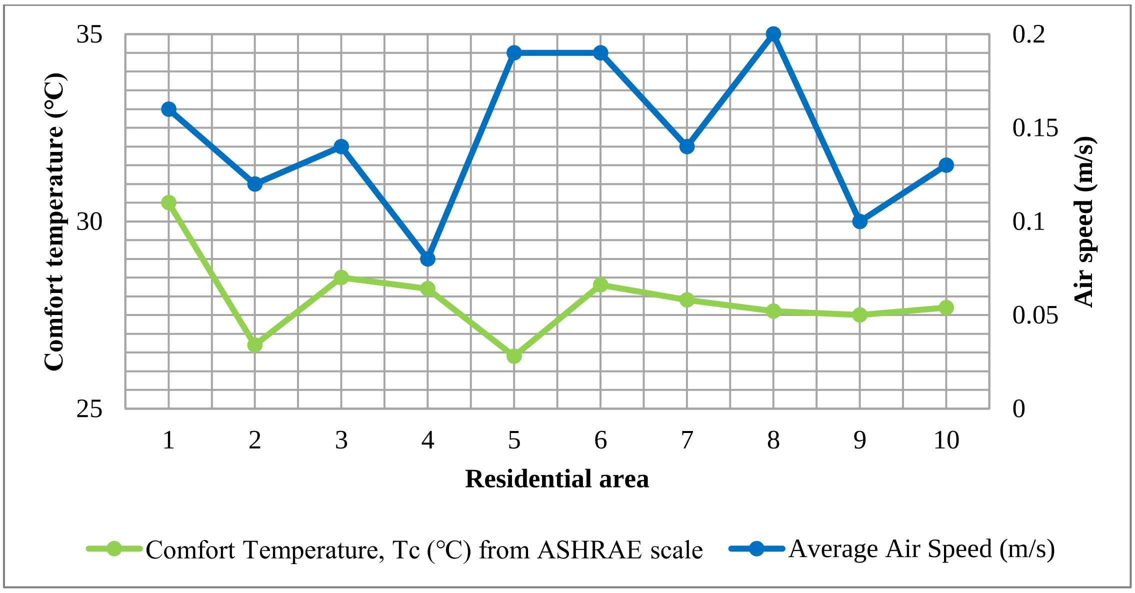

Figure 4.47: Comfort Temperature of ASHRAE Scale vs Average Air Speed

Another minor flaw can be detected on Residential Area 4. The comfort temperature of Residential Area 4 supposed to be lower than the temperature value shown in Figure 4.47 and Figure 4.48 since the air speed recorded was only 0.08 ms^{-1}, the lowest average air speed value among all the residential areas. This is due to the effect of relative humidity. The average relative humidity of Residential Area 4 was 72.1% which was considered to be less humid. As a result, the comfort temperature will increase due to the low humidity level. This explains the phenomenon occurred at Residential Area 4 where the comfort temperature did not decrease much even though the air velocity was considered to be low. It is because the low humidity level had reduced the effect of air velocity on the comfort temperature.

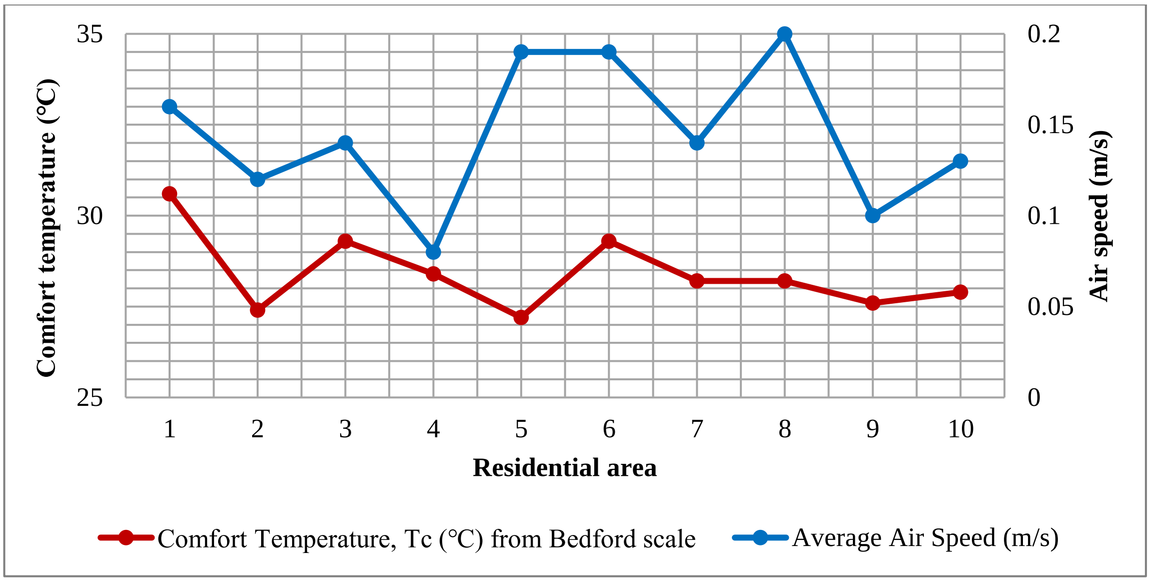

Figure 4.48: Comfort Temperature of Bedford scale vs Average Air Speed

4.8.4 Regression Analysis between Thermal Neutrality and Average Outdoor Temperature of each Residential Area

The comfort temperature of each residential area based on ASHRAE scale and Bedford scale and their respective average outdoor temperature is tabulated in Table 4.49.

Linear regression analysis was performed on both of these scales to determine the relationship between the indoor thermal neutrality and their average outdoor temperature.

Table 4.49: Comfort Temperature from ASHARAE Scale and Bedford Scale and Average Outdoor Temperature

Residential area	**Comfort temperature, T_c from ASHRAE scale (°C)**	**Comfort temperature, T_c from Bedford scale (°C)**	**Outdoor temperature, T_{out} (°C)**
1	30.5	30.6	34.2
2	26.7	27.4	30.2
3	28.5	29.3	31.3
4	28.2	28.4	31.9
5	26.4	27.2	29.6
6	28.3	29.3	32.8
7	27.9	28.2	31.5
8	27.6	28.2	31.9
9	27.5	27.6	29.2
10	27.7	27.9	29.1

The regressed linear adaptive thermal comfort model established from ASHRAE scale is written in Equation (4.17) and illustrated in Figure 4.49.

$$T_c = 0.5418\ T_{out} + 11.042, \quad r^2 = 0.6368 \tag{4.17}$$

Equation (4.17) is in good agreement with the findings of Mui [19] and Chew [20] where their r^2 values were discovered to be 0.5928 and 0.7204, respectively compared to the r^2 value of 0.6368 found in this study, which is close to unity. Thus, it was proven that the proposed adaptive model is acceptable to be used. The thermal comfort models proposed by Mui and Chew are shown in Equation (2.13) and Equation (2.16), respectively.

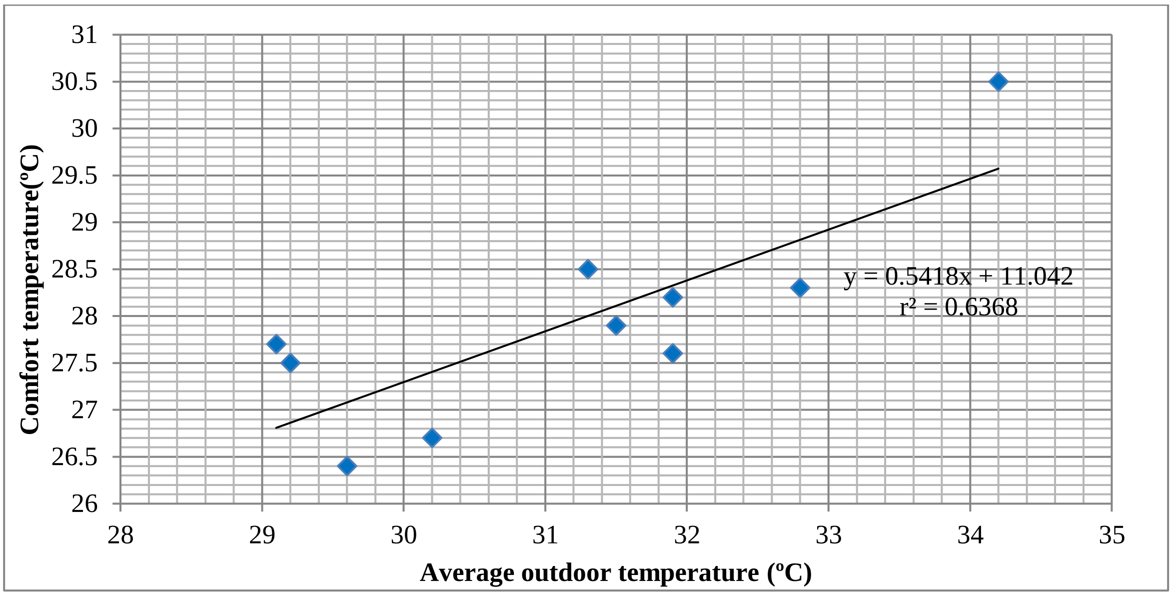

Figure 4.49: Adaptive Thermal Comfort Model based on ASHRAE Scale

The slope of the proposed adaptive model indicates that the indoor comfort temperature will increase by 1 ºC for the increment of 1.9 ºC on the outdoor temperature. This increment was lower than the findings of Mui [19] and Chew [20].

In Chew's study, it was discovered that the indoor thermal neutrality will only increase by 1 ºC for every 3.6 ºC increased of outdoor temperature [20]. This is due to the difference of thermal environment between the studies. Chew's research was carried out in a fixed air-conditioned indoor environment whereas the present study was focusing on residential buildings which were naturally ventilated with minimum usage of mechanical ventilation systems. Therefore, the later respondents will be more sensitive thermally towards their thermal environment compared to the subjects who were staying in an air-conditioned building. Eventually, they can only experience the changes in thermal neutrality once there is a significant increase on outdoor temperature.

The slope of the model proposed by Mui [19] indicates that the comfort temperature will increase by 1 ºC for every 6 ºC increased of outdoor temperature. This increment was much higher than the increment found by Chew [20] even though both of these studies were conducted in air-conditioned buildings. This shows that climate difference will also affect the outcome of the model since Mui's research was done in a cooler climate while Chew's work was carried out under a hot and humid climate.

The adaptive thermal comfort model established from Bedford scale is written in Equation (4.18) and illustrated in Figure 4.50.

$$T_c = 0.5489\ T_{out} + 11.301, \quad r^2 = 0.751 \tag{4.18}$$

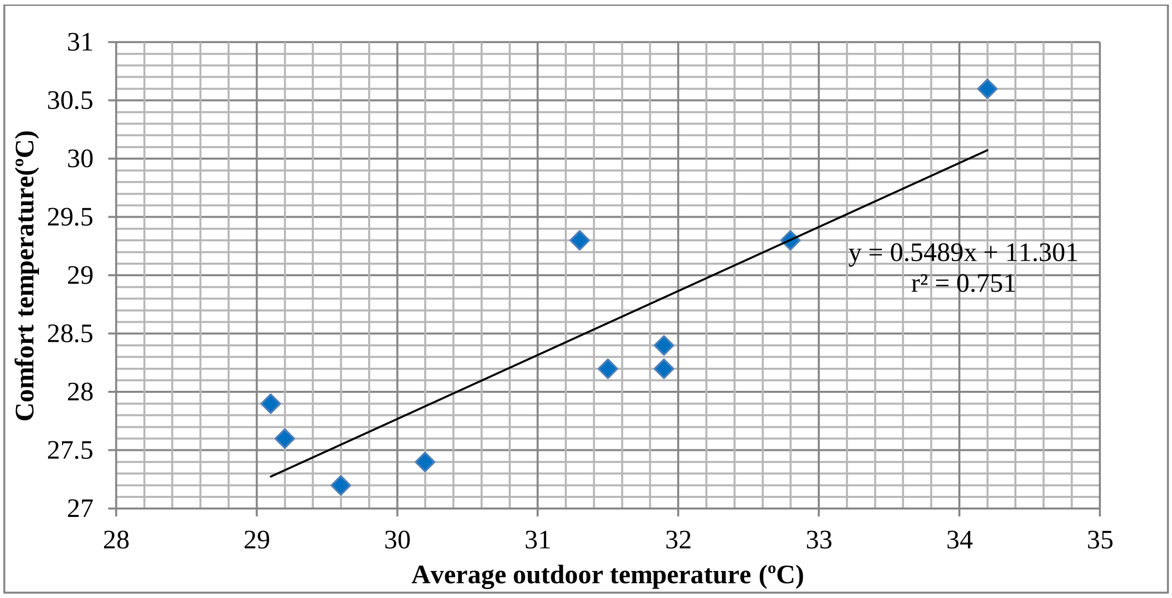

Figure 4.50: Adaptive Thermal Comfort Model based on Bedford Scale

It was observed that an increment of 1.8 ºC on outdoor temperature is needed to increase the indoor comfort temperature by 1 ºC. The slope of this model is similar to the model proposed in Equation (4.17). However, the thermal comfort model proposed by Bedford scale showed a higher r^2 value (0.751) than the model proposed by ASHRAE scale (0.6368). This reveals that the model proposed by Bedford scale can fit the field assessments' data more accurately than the model proposed by ASHRAE scale.

Furthermore, based on the thermal comfort evaluations done in Section 4.3, it has been concluded that Bedford scale was a better measure of comfort than ASHRAE scale. Thus, the adaptive thermal comfort model proposed by Bedford scale is more recommended to be used in thermal comfort study.

4.8.5 Upper and Lower Limit of the Adaptive Models

The upper and lower limit of the adaptive models which included indoor operative temperature, relative humidity and air velocity were determined by using actual percentage dissatisfied, APD and predicted percentage dissatisfied, PPD below 20%. The difference between APD and PPD was evaluated.

4.8.5.1 Operative Temperature

The actual percentage dissatisfied, APD and predicted percentage dissatisfied, PPD of each indoor operative temperature was calculated and tabulated in Table 4.50. Actual percentage dissatisfied was determined from thermal acceptability scale while PMV model was implemented to calculate the predicted percentage dissatisfied of each indoor operative temperature. The correlation between APD and operative temperatures, PPD and operative temperatures are shown in Figure 4.51 and Figure 4.52.

Table 4.50: Actual Percentage Dissatisfied, Predicted Percentage Dissatisfied for each Operative Temperature

Residential area	**Operative temperature (℃)**	**Actual percentage dissatisfied, APD (%)**	**Predicted percentage dissatisfied, PPD (%)**
1	31.1	21.1	74.0
1	32.0	45.5	84.0
1	32.6	70.6	91.0
1	31.0	31.6	58.0
1	31.6	27.8	77.0
2	27.5	0.0	25.0
2	28.3	0.0	26.0
2	27.8	0.0	9.0
2	27.6	0.0	20.0
2	26.5	33.3	10.0
3	28.3	50.0	24.0
3	29.4	0.0	45.0
3	29.3	66.7	54.0
3	27.5	0.0	13.0
3	27.1	0.0	8.0
4	28.2	20.0	18.0
4	29.3	33.3	46.0
4	29.4	0.0	65.0
4	28.6	60.0	22.0
4	27.6	25.0	8.0
5	30.2	0.0	23.0
5	30.9	100.0	61.0
5	28.1	40.0	6.0
5	27.4	66.7	12.0
5	27.0	0.0	5.0
6	29.2	0.0	55.0
6	30.0	0.0	5.0
6	31.2	0.0	77.0
6	30.2	66.7	51.0
6	26.5	83.3	5.0

Table 4.50 continued

7	28.2	0.0	34.0
7	30.2	0.0	56.0
7	30.1	0.0	37.0
7	29.2	0.0	41.0
7	27.1	14.3	7.0
8	28.5	0.0	8.0
8	28.4	0.0	16.0
8	30.1	25.0	40.0
8	29.2	11.1	20.0
8	27.3	100.0	16.0
9	26.4	0.0	8.0
9	28.6	100.0	46.0
9	27.2	16.7	17.0
9	27.2	28.6	17.0
9	27.1	0.0	15.0
10	28.1	0.0	12.0
10	27.2	0.0	6.0
10	27.3	0.0	5.0
10	27.3	0.0	9.0
10	27.4	0.0	5.0

In order to achieve 80% thermal satisfaction [173], actual percentage dissatisfied and predicted percentage dissatisfied below 20% was used to obtain the acceptable indoor operative temperature range.

From Figure 4.51, the acceptable temperature range of actual percentage dissatisfied below 20% was between 27.3 ºC and 29.6 ºC. The temperature range to keep the predicted percentage dissatisfied below 20% was between 26.4 ºC and 28.1 ºC as indicated in Figure 4.52.

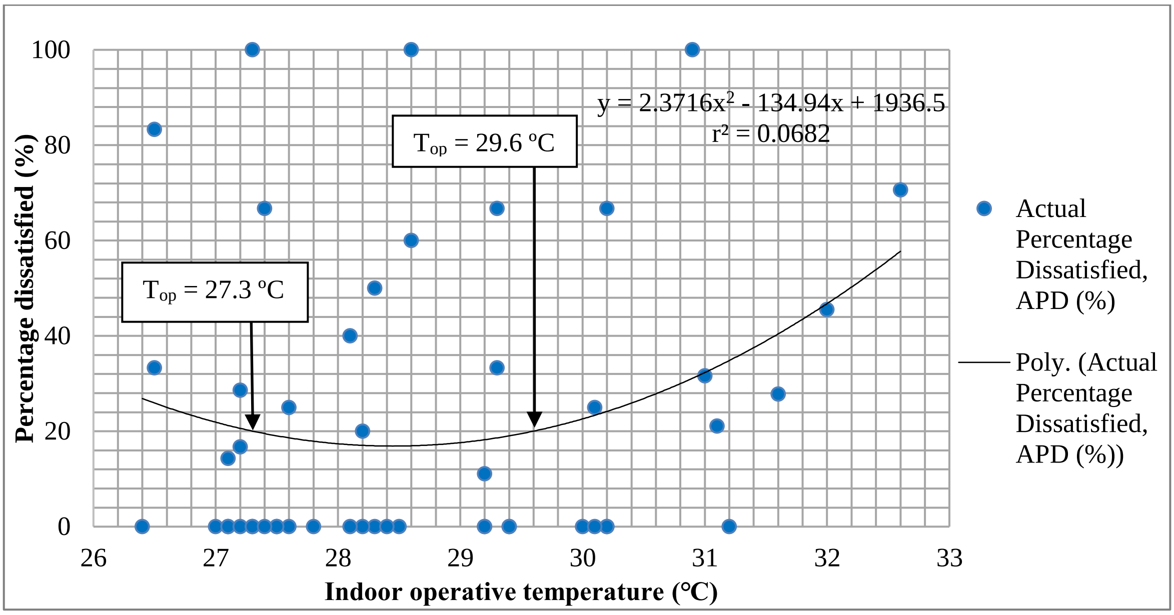

Figure 4.51: Actual Percentage Dissatisfied against Operative Temperature

By comparing Figure 4.51 and Figure 4.52, it is observed that the actual percentage dissatisfied below 20% covered a wider temperature range than the predicted percentage dissatisfied. This indicates that thermal acceptability scale predicted higher human adaptation ability towards their thermal environment. In contrast, PMV model overpredicted the thermal sensation of the people, thus, its PPD value was also affected.

In this study, the maximum acceptable temperature suggested by PPD was 28.1 ºC but in fact, the subjects still found the temperature of 29.6 ºC acceptable. PPD also predicted that subjects will only feel comfortable at the temperature of 26.4 ºC but it was discovered that subjects were already feeling comfortable at 27.3 ºC. Therefore, it can be concluded that PMV model underestimated thermal sensation at a higher temperature and overestimated thermal perception at a lower temperature.

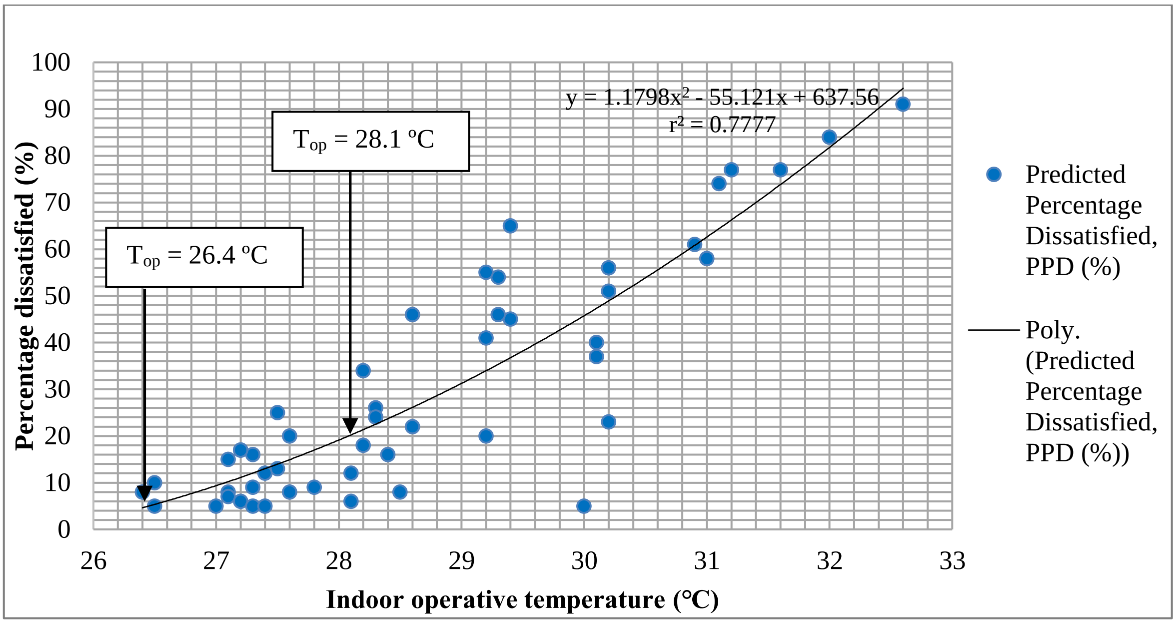

Figure 4.52: Predicted Percentage Dissatisfied against Operative Temperature

According to actual percentage dissatisfied below 20%, the acceptable indoor comfortable temperature range was from 27.3 °C to 29.6 °C. If this acceptable temperature range is used on adaptive thermal comfort model of ASHRAE scale, then the calculated outdoor temperature range is between 30.0 °C and 34.3 °C. This indicates that if the outdoor temperature is lower than 30.0 °C, the recommended indoor comfort temperature will be constant at 27.3 °C, if the outdoor temperature is higher than 34.3 °C, then the maximum recommended indoor temperature will be at 29.6 °C.

If the acceptable indoor temperature range of 27.3 °C to 29.6 °C is used on adaptive thermal comfort model of Bedford scale, then the calculated outdoor temperature range is in between 29.1 °C and 33.3 °C. This indicates that if the outdoor temperature is lower than 29.1 °C, the recommended indoor comfort temperature will have to be set constant at 27.3 °C, if the outdoor temperature is higher than 33.3 °C, then the maximum recommended indoor temperature will be 29.6 °C.

4.8.5.2 Relative Humidity

The actual percentage dissatisfied, APD and predicted percentage dissatisfied, PPD for every humidity level is tabulated in Table 4.51. The upper and lower limit of humidity level were determined by plotting the graph of APD and PPD against their relative humidity. The results are illustrated in Figure 4.53 and Figure 4.54.

Table 4.51: Actual Percentage Dissatisfied, Predicted Percentage Dissatisfied for each Relative Humidity

Residential area	Relative humidity (%)	Actual percentage dissatisfied, APD (%)	Predicted percentage dissatisfied, PPD (%)
1	71.6	21.1	74.0
1	67.9	45.5	84.0
1	63	70.6	91.0
1	66.9	31.6	58.0
1	62.6	27.8	77.0
2	76.6	0.0	25.0
2	75.3	0.0	26.0
2	75.5	0.0	9.0
2	76.3	0.0	20.0
2	78.9	33.3	10.0
3	67.1	50.0	24.0
3	65.8	0.0	45.0
3	67.8	66.7	54.0
3	71.4	0.0	13.0
3	73.2	0.0	8.0
4	68.0	20.0	18.0
4	71.2	33.3	46.0
4	68.3	0.0	65.0
4	82.5	60.0	22.0
4	70.5	25.0	8.0

Table 4.51 continued

5	73.3	0.0	23.0
5	56.7	100.0	61.0
5	80.5	40.0	6.0
5	64.2	66.7	12.0
5	71.0	0.0	5.0
6	70.3	0.0	55.0
6	61.0	0.0	5.0
6	56.6	0.0	77.0
6	65.3	66.7	51.0
6	81.8	83.3	5.0
7	73.7	0.0	34.0
7	57.7	0.0	56.0
7	70.2	0.0	37.0
7	71.4	0.0	41.0
7	78.2	14.3	7.0
8	73.0	0.0	8.0
8	71.8	0.0	16.0
8	66.6	25.0	40.0
8	68.6	11.1	20.0
8	74.8	100.0	16.0
9	80.5	0.0	8.0
9	72.8	100.0	46.0
9	85.2	16.7	17.0
9	84.2	28.6	17.0
9	84.5	0.0	15.0
10	73.4	0.0	12.0
10	84.5	0.0	6.0
10	82.2	0.0	5.0
10	83.8	0.0	9.0
10	84.0	0.0	5.0

Actual percentage dissatisfied and predicted percentage dissatisfied below 20% was used to determine the acceptable range for relative humidity. From Figure 4.53, the acceptable humidity range of actual percentage dissatisfied was discovered to be in between 74.0% and 92.0%. This relative humidity range is similar to the range discovered in Singapore [81] and Indonesia [97] which are experiencing the same climate context as Malaysia.

However, this is opposed to the humidity range suggested by ISO 7730 standard [87]. Based on this standard, the relative humidity recommended is ranging from 30% to 70% where 50% is regarded as the most comfortable humidity level for a thermal environment.

By referring to Table 4.51, it can be observed that most of the respondents were satisfied with their environmental condition even though the humidity level recorded was beyond the range suggested by ISO 7730 standard. This indicates that regulated standards are not necessary applicable to every context since thermal comfort is a subjective parameter.

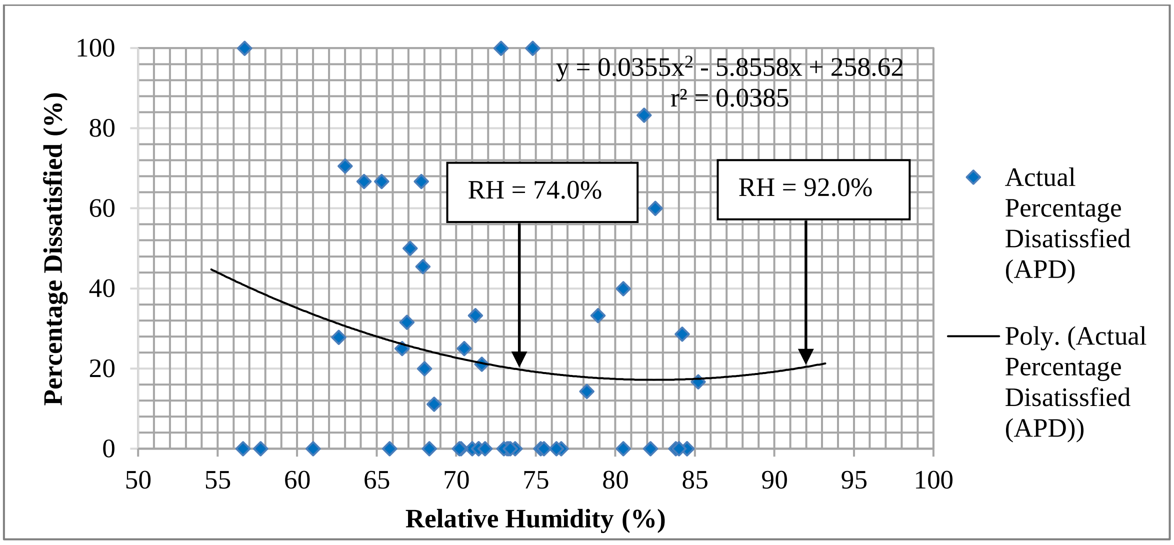

Figure 4.53: Actual Percentage Dissatisfied against Relative Humidity

The relative humidity range obtained from actual percentage dissatisfied was slightly higher than the humidity range of predicted percentage dissatisfied which was found to be in between 77.0% and 90.0% as indicated in Figure 4.54. This shows that PPD of PMV model had overpredicted the thermal expectation of the respondents. Therefore, actual percentage dissatisfied is more recommended to be used in this study since it can cover the adaptiveness of the respondents to a wider extent.

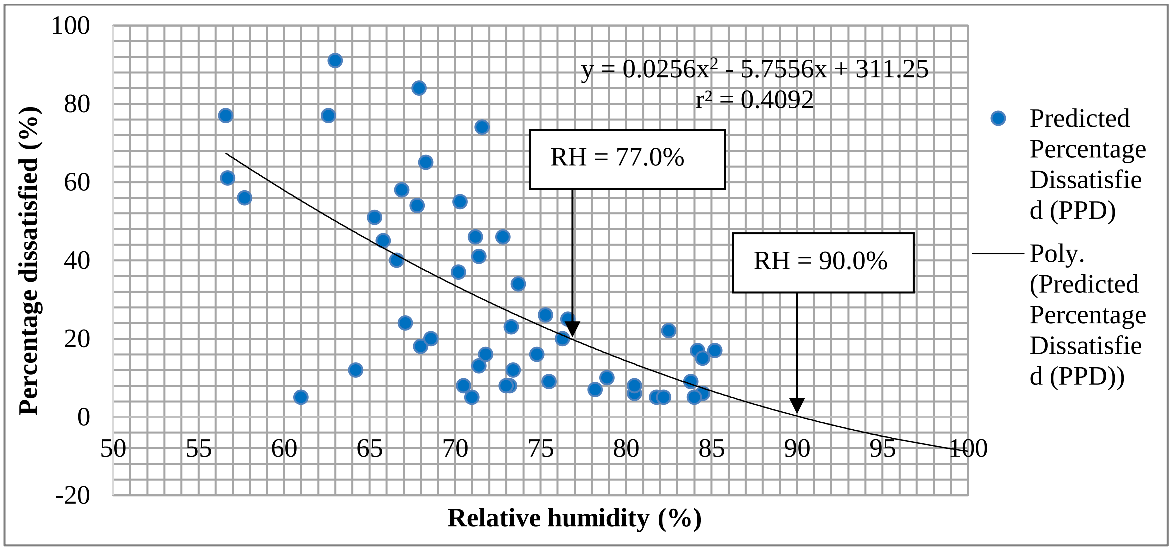

Figure 4.54: Predicted Percentage Dissatisfied against Relative Humidity

4.8.5.3 Air Velocity

The actual percentage dissatisfied, APD and predicted percentage dissatisfied, PPD for each air velocity is tabulated in Table 4.52. The correlation of APD and PPD with their corresponding air velocity are illustrated in Figure 4.55 and Figure 4.56.

Table 4.52: Actual Percentage Dissatisfied, Predicted Percentage Dissatisfied for each Air Velocity

Residential area	Air velocity (ms^{-1})	Actual percentage dissatisfied, APD	Predicted percentage dissatisfied, PPD
1	0.16	21.1	74.0
1	0.15	45.5	84.0
1	0.15	70.6	91.0
1	0.19	31.6	58.0
1	0.15	27.8	77.0
2	0.07	0.0	25.0
2	0.09	0.0	26.0
2	0.14	0.0	9.0
2	0.19	0.0	20.0
2	0.11	33.3	10.0
3	0.12	50.0	24.0
3	0.08	0.0	45.0
3	0.11	66.7	54.0
3	0.20	0.0	13.0
3	0.17	0.0	8.0
4	0.10	20.0	18.0
4	0.15	33.3	46.0
4	0.06	0.0	65.0
4	0.04	60.0	22.0
4	0.06	25.0	8.0
5	0.19	0.0	23.0
5	0.13	100.0	61.0
5	0.23	40.0	6.0
5	0.20	66.7	12.0
5	0.20	0.0	5.0
6	0.14	0.0	55.0
6	0.48	0.0	5.0
6	0.14	0.0	77.0
6	0.14	66.7	51.0
6	0.06	83.3	5.0
7	0.09	0.0	34.0
7	0.13	0.0	56.0
7	0.19	0.0	37.0
7	0.14	0.0	41.0
7	0.16	14.3	7.0

Table 4.52 continued

8	0.20	0.0	8.0
8	0.21	0.0	16.0
8	0.17	25.0	40.0
8	0.17	11.1	20.0
8	0.27	100.0	16.0
9	0.12	0.0	8.0
9	0.05	100.0	46.0
9	0.11	16.7	17.0
9	0.10	28.6	17.0
9	0.14	0.0	15.0
10	0.05	0.0	12.0
10	0.21	0.0	6.0
10	0.09	0.0	5.0
10	0.11	0.0	9.0
10	0.20	0.0	5.0

Based on the predicted percentage dissatisfied illustrated in Figure 4.56, the acceptable air velocity range required by the respondents to achieve thermal comfort was 0.32 ms^{-1} to 0.46 ms^{-1}. The minimum air velocity of 0.32 ms^{-1} is relatively high if compared to the value determined from actual percentage dissatisfied. According to APD in Figure 4.55, respondents were eventually feeling comfortable under the air velocity of 0.18 ms^{-1} which was about half of the value determined by PPD.

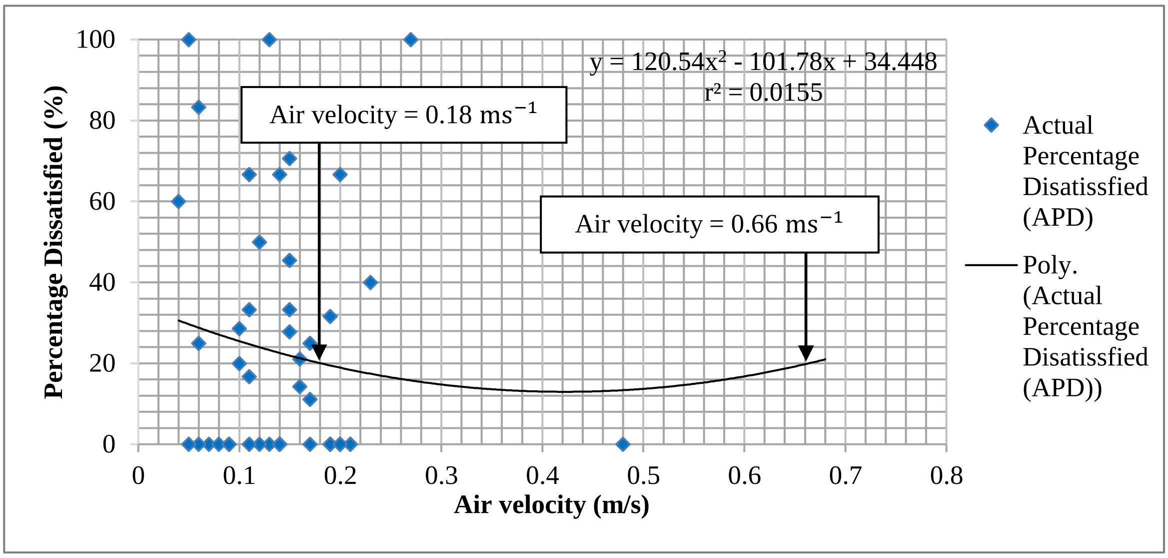

Figure 4.55: Actual Percentage Dissatisfied against Air Velocity

For the upper limit of the air velocity, PPD had underestimated the air velocity demanded by the respondents. The maximum air velocity required to achieve 80% satisfaction based on APD was found to be 0.66 ms^{-1}, which was 0.20 ms^{-1} higher than the air velocity predicted by PPD.

The comfortable air velocity range standardized by ISO 7730 standard [87] and Malaysian Standard, MS 1525: 2007 [94] are 0.21 ms^{-1} to 0.24 ms^{-1} and 0.15 ms^{-1} to 0.50 ms^{-1}, respectively. By comparing these standardized air velocity range to the air velocity range of this study, it is discovered that the demanded air velocity range had exceeded the range recommended by the standards.

This indicates that residents indeed required a higher air velocity range to accommodate themselves to a hot and humid context where the outdoor temperature was recorded to be as high as 37.5 °C. Studies done in other hot and humid countries also proved that wider air velocity range is needed to sustain the thermal comfort level of the indoor environment [96, 98, 99].

Due to the limitation of PMV model, actual percentage dissatisfied, APD was chosen over PPD in this study since it can cover a wider range of air velocity which was proven to be significant in thermal comfort study. Thus, the acceptable air velocity range of 0.18 ms^{-1} to 0.66 ms^{-1} of APD was selected ahead of 0.32 ms^{-1} to 0.46 ms^{-1} determined by PPD.

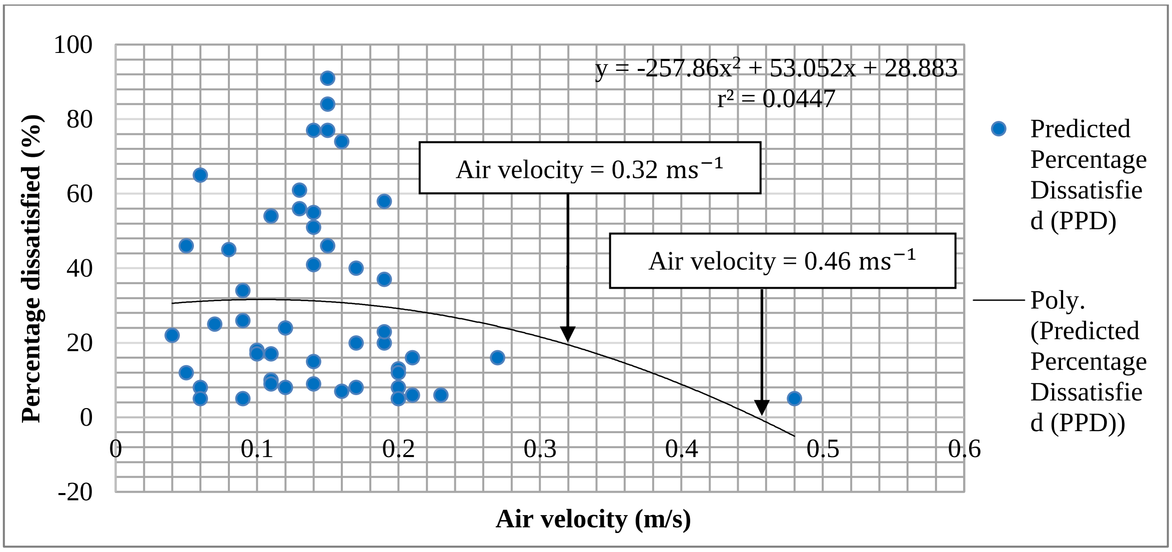

Figure 4.56: Predicted Percentage Dissatisfied against Air Velocity

4.9 Validation of the Adaptive Thermal Comfort Models

Another experiment was carried out at different residential areas in order to verify the adaptive thermal comfort models proposed in Section 4.8.4. The residential areas chosen for this validation study was located in between 7th mile and 10th mile of Kuching city, Sarawak. 31 residents which consisted of 15 females and 16 males had participated in this study. The photos of different types of residential buildings involved are attached in Appendix D.

Similar with Section 4.2, the field measurements were divided into physical measurements and subjective assessments. The field measurements were carried out for six different periods of time and all the parameters collected were evaluated and attached in Appendix E.

4.9.1 Thermal Comfort Analysis

ASHRAE scale, Bedford scale, thermal acceptability scale and thermal preference scale were used to evaluate the thermal responses of the residents via subjective assessments.

Table 4.53 and Table 4.54 show the distribution of votes on ASHRAE scale and Bedford scale, respectively. It can be observed that 96.77% of the votes were allocated within the central three categories of ASHRAE scale which was postulated to be acceptable. Only minority of the residents voted beyond the acceptable categories of this scale.

Table 4.53: Distribution of Votes on ASHRAE Scale

ASHRAE scale	Number of votes and percentage of votes (%)
-3	0 (0.0)
-2	1 (3.23)
-1	7 (22.58)
0	10 (32.26)

Table 4.53 continued

1	13 (41.94)
2	0 (0.0)
3	0 (0.0)
Total	31 (100.0)

On the other hand, all of the votes were distributed within the central three categories of Bedford scale with 61.29% of them voted under the “comfortable” category while the remaining votes were divided equally among “comfortably cool” and “comfortably warm” categories. This shows that respondents were eventually feeling very comfortable under their environment.

Table 4.54: Distribution of Votes on Bedford Scale

Bedford scale	**Number of votes and percentage of votes (%)**
-3	0 (0.0)
-2	0 (0.0)
-1	6 (19.36)
0	19 (61.29)
1	6 (19.36)
2	0 (0.0)
3	0 (0.0)
Total	31 (100.0)

The distribution of votes on ASHRAE scale and Bedford scale are illustrated in Figure 4.57. It can be observed that the percentage of votes in the middle three categories of Bedford scale was slightly higher than the percentage of ASHRAE scale. This indicates that the respondents who voted in the unacceptable categories of ASHRAE scale was eventually feeling satisfied and comfortable with their environment.

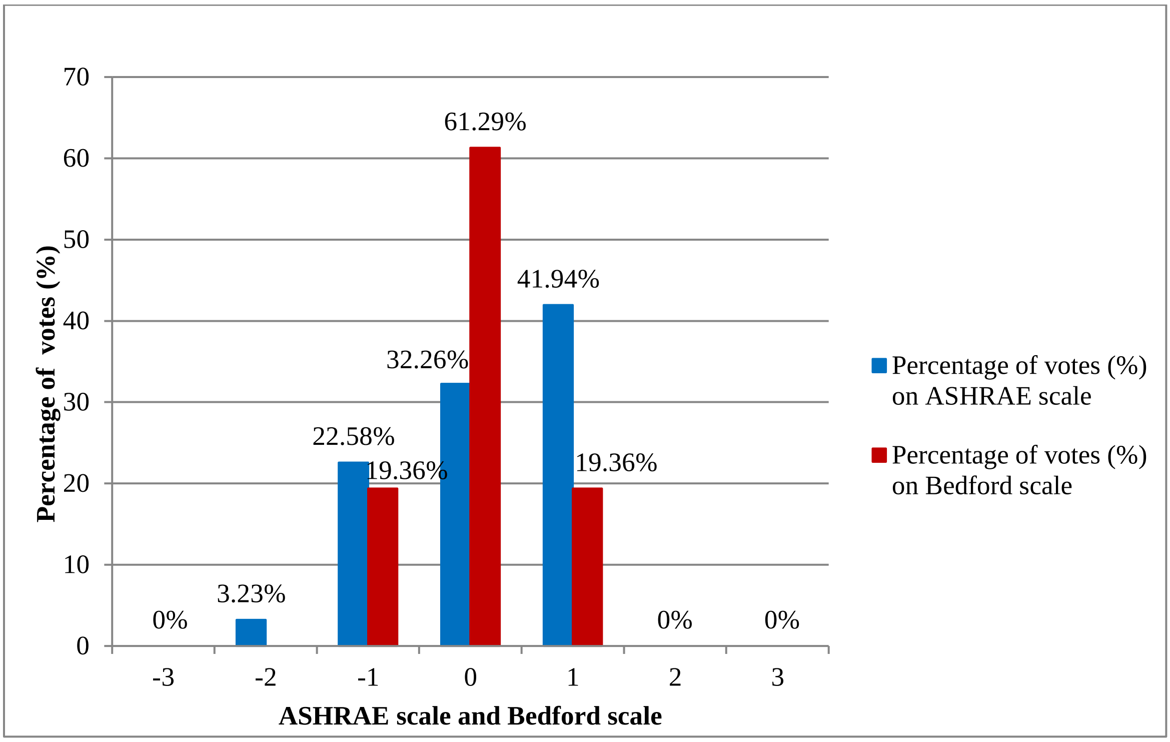

Figure 4.57: Distribution of Votes on ASHRAE Scale and Bedford Scale

Table 4.55 shows the cross tabulation between the votes from ASHRAE scale and the votes from Bedford scale. In this study, all of the voters who voted in the middle three categories of ASHRAE scale also voted in the middle three categories of Bedford scale.

Table 4.55: Cross-tabulation of Thermal Sensation Votes and Thermal Comfort Votes

Bedford scale	**Number and percentage of votes (%)**		
	ASHRAE scale		
	-3, -2	-1, 0, 1	2, 3
-3, -2	0 (0.0)	0 (0.0)	0 (0.0)
-1, 0, 1	1 (100.0)	30 (100.0)	0 (0.0)
2,3	0 (0.0)	0 (0.0)	0 (0.0)
Total	1 (100.0)	30 (100.0)	0 (100.0)

According to Table 4.55, it was proven that the minority voters who voted in the “cool” and “cold” categories of ASHRAE scale had recognized their thermal environment as comfortable. This is due to personal preference as most of the people who are living under the hot and humid climate would prefer a cooler environment. This finding is similar to the outcome discussed in Section 4.3.3.

The percentage of acceptable votes for ASHRAE scale, Bedford scale, thermal acceptability scale and thermal preference scale are tabulated and illustrated in Table 4.56 and Figure 4.58, respectively. Based on the bar chart shown in Figure 4.58, it is discovered that Bedford scale possessed a full percentage of acceptability votes. This was followed by ASHRAE scale and thermal acceptability scale with both of their acceptability percentage exceeding 90%. Thermal preference scale was recorded with the lowest acceptability percentage of 45.16%.

Table 4.56: Percentage of Acceptable Votes for Various Scales

Scales	Percentage of acceptable votes
Central three categories of ASHRAE scale	96.77
Central three categories of Bedford scale	100.0
Thermal acceptability scale	90.32
Thermal preference scale	45.16

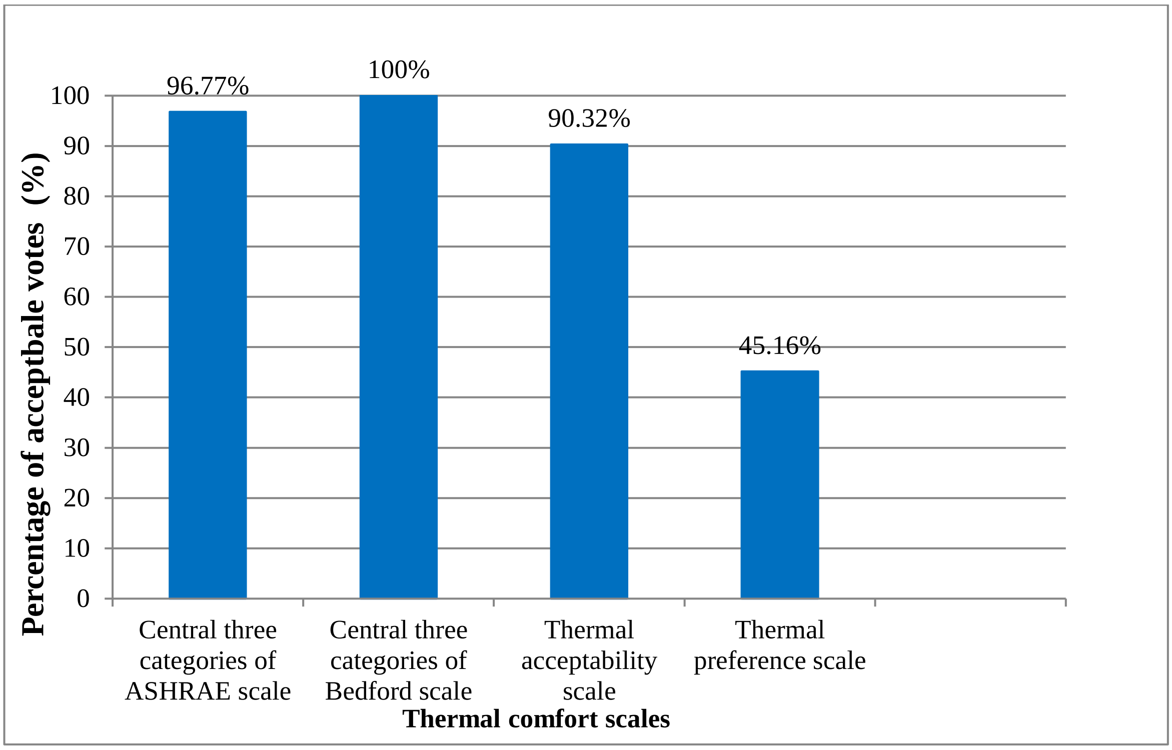

Figure 4.58: Percentage of Acceptable Votes for Various Scales

Thermal acceptability scale should demonstrate the highest acceptability percentage if the central three categories of ASHRAE scale and Bedford scale were presumed to be an ideal criteria. It is because people who voted in the ideal categories were expected to identify their thermal environment as acceptable. However, the thermal acceptability scale of this study yielded a percentage lower than the percentage showed on ASHRAE scale and Bedford scale. This indicates that there were respondents who did not satisfied with their environment even though they had voted in the ideal categories of these scales. Another explanation for this phenomenon is due to the low credibility of thermal acceptability scale. It is inaccurate to assess the thermal perception of the respondents based on two options only, either acceptable or unacceptable.

On the other hand, thermal preference scale is also not a good method to evaluate thermal comfort since its evaluation is based on respondents' preferred condition rather than their actual environmental state. Therefore, ASHRAE scale and Bedford scale are better options to evaluate thermal comfort as these scales can extract more information from the respondents.

The acceptable percentage of Bedford scale was 3.23% higher than the percentage obtained from ASHRAE scale. While this percentage might look less significant if compared to the 10% obtained from Section 4.3.11 due to the smaller sample size of current verification study, it did prove that people who voted beyond the central three categories of ASHRAE scale still found themselves comfortable. This indicates that the extreme categories of ASHRAE scale do not necessary represent thermal discomfort even though the thermal sensation state of the respondents is deviated from its neutral point. This again proved the discussion discussed earlier in Section 4.3.3 and Section 4.3.11 that the Bedford scale was actually a better scale to determine thermal comfort in terms of acceptability since it is a comfort scale.

4.9.2 Discrepancy between Comfort Temperature Values

The parameters of indoor operative temperatures, thermal sensation votes (TSV), thermal comfort votes (TCV), predicted mean votes (PMV) and outdoor temperatures collected from the field measurements were summarized and tabulated in Table 4.57.

Table 4.57: Measurements for the Validation Study

Time	**Indoor operative temperature (°C)**	**Thermal sensation vote (TSV)**	**Thermal comfort vote (TCV)**	**Predicted mean vote (PMV)**	**Outdoor temperature (°C)**
11.00 am	28.3	0.00	-0.17	0.62	35.3
12.15 pm	29.1	0.67	0.67	0.93	33.0
2.00 pm	28.4	1.00	0.00	1.00	33.1
3.00 pm	28.2	0.00	0.00	1.16	30.5
4.30 pm	28.1	-0.14	-0.14	0.42	30.7
6.30 pm	27.4	-0.33	-0.33	0.74	27.1

For this validation study, the comfort temperature of ASHRAE scale, Bedford scale and PMV model were determined by plotting the graph of thermal sensation votes, thermal comfort votes and predicted mean votes against their indoor operative temperatures, respectively. The graph of each plot is shown in Figure 4.59, Figure 4.60 and Figure 4.61.

From Figure 4.59, Figure 4.60 and Figure 4.61, the comfort temperature of ASHRAE scale, Bedford scale and PMV model were discovered to be 28.0 °C, 28.2 °C and 22.8 °C, respectively. The comfort temperature obtained from PMV model was relatively low if compared with the comfort temperature of ASHRAE scale and Bedford scale. Since PMV model does not consider human adaptive behaviors in its model, the thermal sensation state of the respondents would either be underpredicted or overpredicted, leading to the deviation of comfort temperature. According to Table 4.57, it can be observed that most of the PMV values were higher than the values of thermal sensation vote and thermal comfort vote. Respondents were predicted to feel warmer under PMV model but in fact, they were feeling comfortable. This indicates that PMV model had overpredicted the thermal state of the respondents. Thus, PMV model is not recommended to be used in this study which was also proven in Section 4.5.

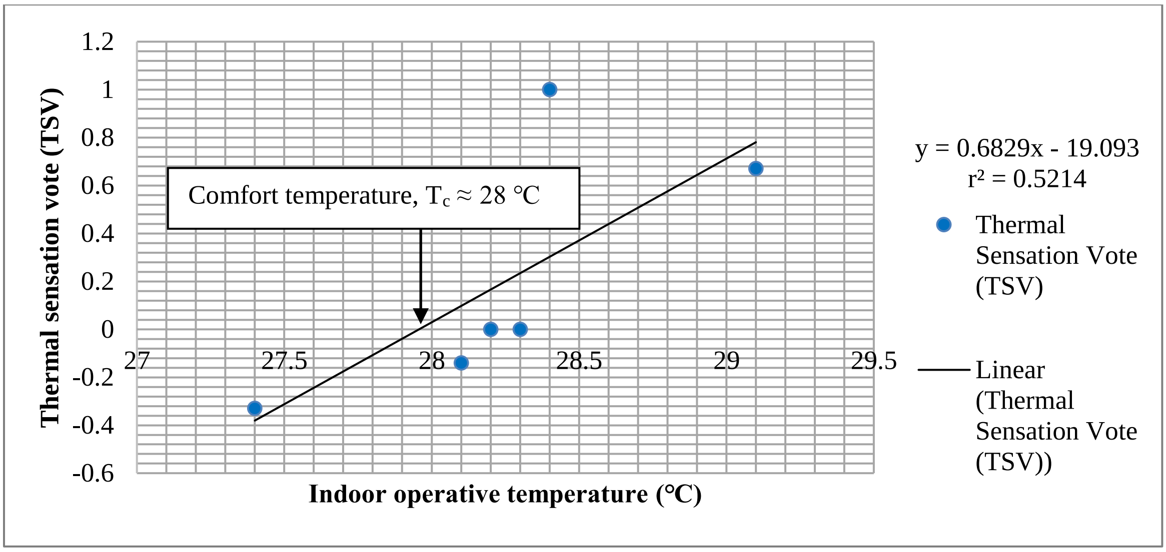

Figure 4.59: Thermal Sensation Votes vs Indoor Operative Temperature

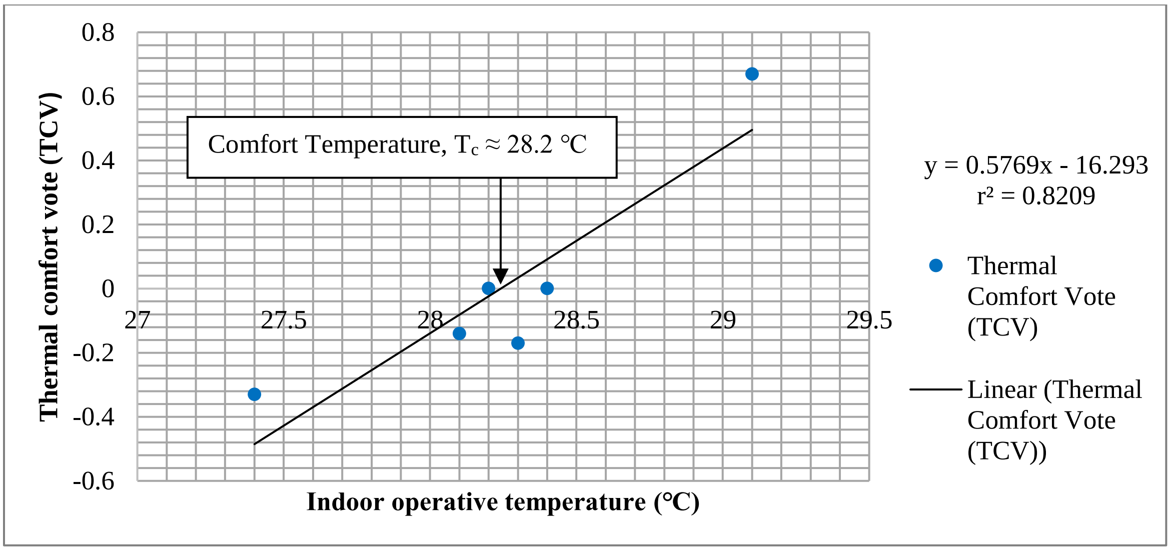

Figure 4.60: Thermal Comfort Votes vs Indoor Operative Temperature

The comfort temperature of Bedford scale was 0.2 °C higher than the comfort temperature of ASHRAE scale. This result is similar to the findings in Section 4.4.1 and Section 4.4.2 where the comfort temperature of Bedford scale was also discovered to be higher than the comfort temperature of ASHRAE scale. This shows that the comfort temperature of Bedford scale can cover a wider temperature range which in turn can help to conserve the amount of energy consumed in building sector. If the comfort temperature of Bedford scale is used as a guideline for the setting of indoor environment, the outcome of the study should be encouraging since Bedford scale was proven to be more accurate than ASHRAE scale.

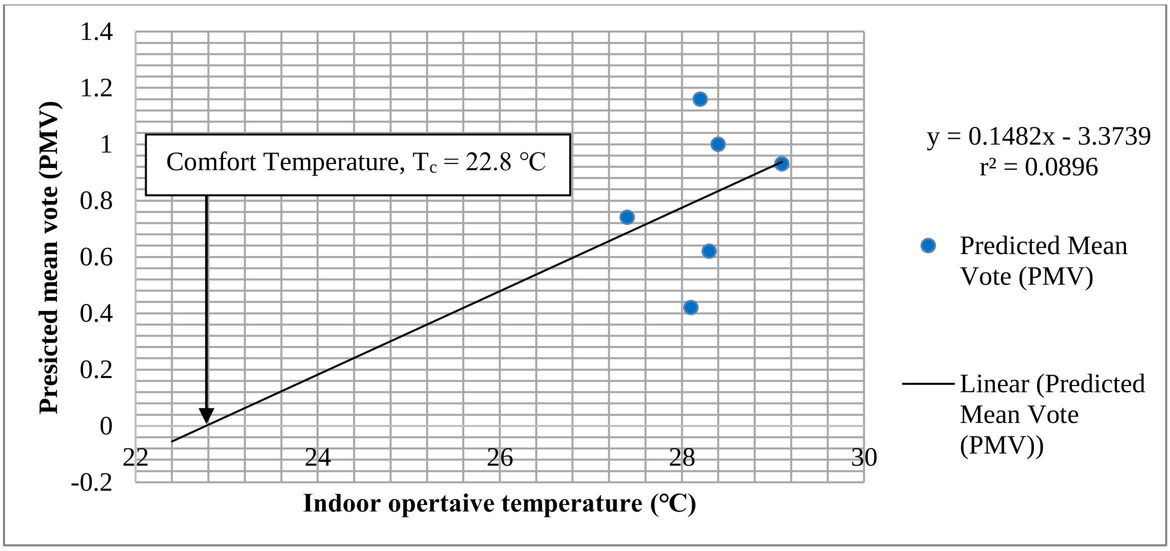

Figure 4.61: Predicted Mean Votes vs Indoor Operative Temperature

The average outdoor temperature of validation study was 31.6 °C. By substituting this value into the adaptive thermal comfort models proposed in Equation (4.17) and Equation (4.18), the comfort temperature of ASHRAE scale and Bedford scale were calculated to be 28.2 °C and 28.7 °C, respectively. The difference between the comfort temperatures calculated from the adaptive models and the comfort temperatures obtained from the validation study was 0.2 ℃ for ASHRAE scale and 0.5 ℃ for Bedford scale which can also be written as 0.71% and 1.74% in terms of error percentage. This discrepancy is due to the difference of clothing insulation values and the outdoor conditions between the validation study and the experiment done earlier.

The average clothing insulation for the experiment was 0.25 clo which was higher than the clothing insulation of 0.23 clo found on the validation study. Furthermore, the outdoor temperature for the validation study appeared to be higher than the average outdoor temperature obtained from the experiment, each with 31.6 ℃ and 31.2 ℃. This implies that different outdoor conditions and different clothing insulations will affect the thermal perspective of the respondents.

Comfort temperatures determined from the experiment, validation test and experimental models are tabulated in Table 4.58. Since the discrepancy percentage was only 0.71% and 1.74% which is in good agreement with the findings of Chew [20], the adaptive thermal comfort models proposed in this study are valid to be used on the residential buildings in the urban areas of Sarawak, Malaysia.

Table 4.58: Comfort Temperature from Experiment, Validation Test and Experimental Models

	Comfort temperature (℃)	
	ASHRAE scale	**Bedford scale**
Experiment	27.5	28.1
Validation test	28.0	28.2
Experimental model	28.2	28.7

4.10 Chapter Summary

Based on the information collected from the field measurements which included physical measurements and subjective assessments, the thermal behavior of the subjects from different residential areas were evaluated based on ASHRAE scale, Bedford scale, thermal acceptability scale and thermal preference scale. PMV model was also used to predict the thermal responses of the residents. The correlation between thermal sensation vote TSV, thermal comfort vote TCV and predicted mean vote PMV was assessed. The thermal neutrality was determined from ASHRAE scale, Bedford scale and PMV model. Finally, two adaptive thermal comfort models were proposed, one based on the parameters of ASHRAE scale while another one based on Bedford scale. The upper and lower limit of the models were determined by using actual percentage dissatisfied APD by following the 80% acceptability standard. The validity of the models was also verified.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The field measurements were successfully carried out and thermal comfort analysis was done to evaluate the thermal responses of the respondents. The major findings of the study are shown as follows:

i. Different thermal comfort scales showed different evaluation outcomes. In this study, ASHRAE thermal sensation scale, Bedford thermal comfort scale, thermal acceptability scale, thermal preference scale and predicted mean vote of Fanger’s model were used to determine the thermal responses of the residents. The thermal behaviors of the respondents were assessed in terms of indoor operative temperature, relative humidity and also air velocity. A total of 10 residential areas were involved in the study.

ii. The bias uncertainty of the parameters implicated in this study were less than 10%. This indicates that all the data were valid to be used for analysis. The bias uncertainty of air velocity was the only parameter which exceeded 10% due to the big fluctuation change of air velocity during the field measurements. However, the air velocity of this study was still acceptable to be used since its average bias uncertainty percentage was only slightly above 10%.

iii. It was discovered that 76.65% of the residents defined their thermal environment as acceptable based on ASHRAE thermal sensation scale. A higher acceptable percentage was spotted on Bedford scale with 85.68% of the respondents identified their thermal environment as comfortable. Around 41.3% of the residents who voted in the extreme categories of ASHRAE scale indicated that they were actually feeling satisfied with their environment. This shows that even though their thermal sensation state was deviating from the acceptable categories of ASHRAE scale, it did not necessarily represent thermal discomfort. The acceptable percentage of thermal acceptability scale was found to be 73.52% which was lower than the percentage of ASHRAE scale and Bedford scale. This indicates that there were residents who still found their living environment not acceptable even though they had voted in the acceptable and comfortable criteria of ASHRAE scale and Bedford scale. The thermal preference scale showed the least acceptable percentage level with only 32.06% of the respondents wanted to preserve their thermal ambience while 65.85% of them wanted their environment to be cooler. In this study, Bedford scale covered a higher acceptable percentage than ASHRAE scale. Thus, it can be concluded that Bedford scale is a better measure of thermal comfort since it emphasizes on the comfortable state of the subjects.

iv. The comfort temperature of 27.5 ºC was obtained by analyzing the thermal sensation votes of ASHRAE scale, 28.1 ºC for the thermal comfort votes of Bedford scale and 26.2 ºC for the predicted mean votes of Fanger’s model. This is an important finding as these comfort temperatures can be used as a guideline for the setting of indoor comfort conditions. The comfort temperature defined from Bedford scale is recommended to be used since it can cover a wider temperature range. This consequently will conserve the amount of energy used on ventilation systems and fulfil the thermal comfort state of the residents simultaneously.

v. The correlation between thermal sensation votes, thermal comfort votes and predicted mean vote are analyzed as follows:

$$\text{TSV} = 0.5458\ \text{PMV} - 0.2136, \quad r^2 = 0.3245$$

$$\text{TCV} = 0.6663\ \text{TSV} - 0.0371, \quad r^2 = 0.6099$$

$$\text{TCV} = 0.479\ \text{PMV} - 0.2835, \quad r^2 = 0.3433$$

vi. Comfort temperature will be affected by relative humidity and air velocity. Respondents can accept a higher comfort temperature when the relative humidity of the environment is low and vice versa. The increase of air velocity will facilitate air circulation and improve the thermal comfort level of the environment, thus, people can accommodate themselves to a warmer environment.

vii. The adaptive thermal comfort models were proposed from thermal sensation votes (ASHRAE scale) and thermal comfort votes (Bedford scale) by using linear regression analysis as shown as follows:

$$T_c = 0.5418\ T_{out} + 11.042, \quad r^2 = 0.6368, \text{ from TSV}$$

$$T_c = 0.5489\ T_{out} + 11.301, \quad r^2 = 0.751, \text{ from TCV}$$

The upper and lower limit of the models were determined by using actual percentage dissatisfied, APD below 20%. The acceptable range for indoor operative temperature, relative humidity and air velocity of this study were 27.3 ℃ to 29.6 ℃, 74.0% to 92.0 % and 0.18 ms^{-1} to 0.66 ms^{-1}, respectively.

viii. Another field study was carried out to validate the adaptive thermal comfort models proposed from the study. The comfort temperature determined from the validation study was compared with the comfort temperature calculated from the adaptive models proposed. Since the error percentage was only 0.71% for the model proposed by ASHRAE scale and 1.74% for the model proposed by Bedford scale, it can be concluded that the adaptive thermal comfort models proposed from this study are valid to be used on the residential buildings in the urban areas of Sarawak, Malaysia.

ix. The adaptive thermal comfort models developed from this study are expected to produce positive impact to the overall energy consumption on building sector upon its application since the acceptable indoor comfort temperature range of this study was discovered to be in between 27.3 ℃ and 29.6 ℃. This temperature range was much higher than the indoor comfortable temperature range set by Malaysian Standard 1525 which are ranged from 23 ℃ to 26 ℃ [94]. Besides, Bedford scale was proven to be more accurate in defining thermal comfort, thus, the adoption of its comfort model and its defined comfortable parameters (as mentioned in vii) are expected to succeed in reducing the amount of energy used in buildings without neglecting thermal comfort.

5.2 Recommendations

There are several aspects which can be improved in this research. The thermal comfort analysis done in this study was restricted to certain residential areas only due to the time constraint. It is recommended that more residential areas which consist of different types of building designs should be included in the study.

In this study, only 5 measuring points were selected for each residential area. In order to obtain a precise set of physical data which can represent the thermal characters of the environment, more measurements should be taken at each measuring point to improve its accuracy. Apart from that, there were 287 respondents involved in this study which is similar to the sample size used in most of the thermal comfort studies. However, a bigger sample size is recommended for future works so that the evaluation done will be more accurate as more thermal perspective views can be included in the study.

In this research, the study was performed on the residential buildings which were naturally and mechanically ventilated. Studies can be done on these two types of ventilation systems separately to determine the thermal reactions of the residents.

The adaptive thermal comfort models proposed in this study should be implemented practically on different types of residential buildings to evaluate its performance in terms of energy conservation and also its impact on overall energy consumption. If it shows positive results in real time applications, then the proposed thermal comfort models can be used in the future as a guideline for the settings of indoor comfort conditions.

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APPENDICES

Appendix A: Survey Form for Thermal Comfort

Nama/*Name*:
Umur/*Age*:

< 10	11-20	21-30	31-40	41-50	51-60	61-70	>70

Jantina/Gender:

Lelaki/Male	**Perempuan**/Female

Kawasan kediaman/*Residential area*:

Apakah jenis kerja rumah / aktiviti yang anda terlibat sebelum mengisi borang ini/
What type of housework/work are you involved with before filling this form

Aktiviti/*Activity*	**Tanda (√) / *Tick* (√)**
Duduk rehat/*Seated relaxed*	
Berdiri rehat/*Standing relaxed*	
Aktiviti sedentary (duduk rehat dengan acktiviti ringan)/*Sedentary activity (seated relaxed with light activity)*	
Berdiri, Aktiviti ringan/*Standing, light activity*	
Berdiri, Activity sederhana/*Standing, medium activity*	
Lain-lain (Sila nyata)/*Others (please mention)*	

Apakah jenis pakaian yang anda pakai sekarang/
What type of attire are you wearing now

Baju/*Shirt*	**Tanda (√) / *Tick* (√)**
Lengan pendek/*Short sleeve*	
Baju ringan dengan lengan panjang/*Light shirt with long sleeve*	

Baju biasa dengan lengan panjang/*Normal shirt with long sleeve*	
Dress ringan tanpa lengan/*Light dress sleeveless*	
Dress lengan panjang/*Dress long sleeves*	
Lain-lain (Sila nyata)/*Others (please mention)*	
Seluar/*Trousers*	**Tanda (√) / *Tick* (√)**
Seluar pendek/*Shorts*	
Seluar ringan/*Light trousers*	
Seluar biasa/*Normal trousers*	
Skirt atas lutut/*Skirt above knee*	
Skirt di bawah lutut/ *Skirt below knee*	
Lain-lain (Sila nyata)/*Others (please mention)*	
Pakaian kaki/*footwear*	**Tanda (√) / *Tick* (√)**
Sarung kaki/*Socks*	
Sarung kaki tebal dan panjang/*Thick long socks*	
Selipar/Slippers	
Kasut tapak nipis/*Thin soled shoes*	
Kasut tapak tebal/*Thick soled shoes*	
Lain-lain (Sila nyata)/*Others (please mention)*	

Apakah sistem pengudaraan yang anda gunakan semasa mengisi borang ini/
What is the cooling system that you are using when filling this form

Sistem Penyejukkan/*Cooling System*	**Tanda (√) / *Tick* (√)**
Tiada/*No*	
Kipas/*Fan*	
Penghawa dingin/*Air conditioner*	

Lain-lain (Sila nyata)/*Others (please mention)*	

Sila tanda (√) di atas pilihan anda/*Please tick (√)on your selection*

1. **Bagaimanakah perasaan anda tentang suhu di dalam rumah ini sekarang?**
   How do you feel about the temperature in this house at the moment?

Sangat sejuk/ *Cold*	Sejuk/ *Cool*	Sedikit sejuk/ *Slightly cool*	Neutral/ *Neutral*	Sedikit panas/ *Slightly warm*	Panas/ *Warm*	Sangat panas/*Hot*

2. **Adakah anda berasa selesa sekarang?**
   Do you feel comfortable now?

Terlalu dingin/ *Much too cool*	Dingin/ *Too cool*	Dingin selesa/ *Comfortably cool*	Selesa/ *Comfortable*	Hangat selesa/ *Comfortably warm*	Hangat/ *Too warm*	Terlalu hangat/ *Much too warm*

3. **Adakah anda ingin..**
   Would you like to be…

Lebih sejuk/*Cooler*	Tiada perubahan/*No change*	Lebih panas/*Warmer*

4. **Bagaimanakah penerimaan keseluruhan anda terhadap suhu pada masa ini?**
   How would you rate the overall acceptability of the temperature at this moment?

Diterima/*Acceptable*	Tidak dapat diterima/*Not acceptable*

5. **Bagaimanakah perasaan anda dari segi kelembapan sekarang**?
How do you feel at this moment in terms of humidity?

Terlalu kering/ *Much too dry*	Kering/ *Too dry*	Sedikit kering/ *Slightly dry*	Normal/ *Just right*	Sedikit lembap/ *Slightly humid*	Lembap/ *Too humid*	Terlalu lembap/ *Much too humid*

6. **Bagaimanakah perasaan anda tentang aliran udara pada masa ini?**
How do you feel about the air flow at this moment?

Sangat tenang/ *Much too still*	Tenang/ *Too still*	Sedikit tenang/ *Slightly still*	Normal/ *Just right*	Sedikit berangin/ *Slightly breezy*	Berangin/ *Too breezy*	Sangat berangin/ *Much too breezy*

7. **Pendapat/komen anda tentang soalan penyelidikan ini /** *Your opinion/comment about this questionnaire?*

____

____

____

Appendix B: Residential Areas of the Study

Figure B – 1(a): Residential Area 1

Figure B – 1(b): Residential Area 1

Figure B – 2(a): Residential Area 2

Figure B – 2(b): Residential Area 2

Figure B – 3(a): Residential Area 3

Figure B – 3(b): Residential Area 3

Figure B – 4(a): Residential Area 4

Figure B – 4(b): Residential Area 4

Figure B – 5(a): Residential Area 5

Figure B – 5(b): Residential Area 5

Figure B – 6(a): Residential Area 6

Figure B – 6(b): Residential Area 6

Figure B – 7(a): Residential Area 7

Figure B – 7(b): Residential Area 7

Figure B – 8(a): Residential Area 8

Figure B – 8(b): Residential Area 8

Figure B – 8(c): Residential Area 8

Figure B – 8(d): Residential Area 8

Figure B – 9(a): Residential Area 9

Figure B – 9(b): Residential Area 9

Figure B – 9(c): Residential Area 9

Figure B – 9(d): Residential Area 9

Figure B – 10(a): Residential Area 10

Figure B – 10(b): Residential Area 10

Appendix C: Environment Parameters and Personal Parameters

Table C – 1(a): Environmental Parameters for Residential Area 1

Residential Area	**Air Temperature (ºC)**	**Relative Humidity, RH (%)**	**Air Velocity (ms^{-1})**			**Wet Bulb Temperature (ºC)**	**Globe Temperature (ºC)**	**Mean Radiant Temperature (ºC)**	**Operative Temperature (ºC)**	**Outdoor Temperature (ºC)**
			Max	**Min**	**Average**					
1 (10.40 am)	31.2	71.6	0.26	0.06	0.16	27.5	31.0	30.9	31.1	33.3
1 (12.45 pm)	32.0	67.9	0.25	0.05	0.15	27.5	32.0	32.0	32	34.5
1 (3.00pm)	32.7	63.0	0.24	0.05	0.15	27.5	32.5	32.4	32.6	34.9
1 (12.30pm)	30.7	66.9	0.33	0.05	0.19	26.0	31.0	31.3	31	34.0
1 (1.15pm)	31.7	62.6	0.25	0.05	0.15	26.5	31.5	31.4	31.6	34.1

Table C – 1(b): Personal Parameters for Residential Area 1

Residential Area	**Operative Temperature (ºC)**	**Thermal Sensation Vote (TSV)**							**Thermal Preference Vote**			**Thermal acceptability vote**		**Total votes**
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**	**Warmer**	**No change**	**Cooler**	**Acceptable**	**Unacceptable**	
1 (10.40 am)	31.1	0	1	2	6	5	4	1	0	11	8	15	4	19
1 (12.45 pm)	32	0	0	0	6	4	1	0	0	0	11	6	5	11
1 (3.00pm)	32.6	0	1	1	0	4	7	4	0	1	16	5	12	` 17
1 (12.30pm)	31	0	1	3	8	4	3	0	0	7	12	13	6	19
1 (1.15pm)	31.6	0	0	0	10	4	3	1	0	4	14	13	5	18

Table C – 1(c): Personal Parameters for Residential Area 1

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Mean TSV/ Actual Mean Vote (AMV)	Totals	Percentage of votes beyond three central categories of ASHRAE scale (%)	Percentage of unacceptable votes (%)
		-3	-2	-1	0	1	2	3				
1 (10.40 am)	31.1	0	1	2	6	5	4	1	0.63	19	31.6	21.1
1 (12.45 pm)	32	0	0	0	6	4	1	0	0.55	11	9.1	45.5
1 (3.00pm)	32.6	0	1	1	0	4	7	4	1.59	` 17	70.6	70.6
1 (12.30pm)	31	0	1	3	8	4	3	0	0.26	19	21.1	31.6
1 (1.15pm)	31.6	0	0	0	10	4	3	1	0.72	18	22.2	27.8

Table C – 1(d): Personal Parameters for Residential Area 1

Residential Area	Operative Temperature (ºC)	Thermal Comfort Vote (TCV)							Mean TCV/ Actual Mean Vote (AMV)	Totals	Percentage of votes beyond three central categories of Bedford scale (%)	Percentage of unacceptable votes (%)
		-3	-2	-1	0	1	2	3				
1 (10.40 am)	31.1	0	0	2	11	2	4	0	0.42	19	21.1	21.1
1 (12.45 pm)	32.0	0	0	0	7	2	2	0	0.55	11	18.2	45.5
1 (3.00pm)	32.6	0	0	1	4	3	7	2	1.29	17	52.9	70.6
1 (12.30pm)	31.0	0	0	5	7	5	2	0	0.21	19	10.5	31.6
1 (1.15pm)	31.6	0	0	0	10	5	3	0	0.61	18	16.7	27.8

Table C – 1(e): Personal Parameters for Residential Area 1

Residential Area	Operative Temperature (ºC)	Relative Humidity (RH)	Relative Humidity Vote (RHV)							Mean RHV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
1 (10.40 am)	31.1	71.6	-	1	3	7	5	-	2	0.26	19
1 (12.45 pm)	32	67.9	2	-	4	3	1	1	-	-0.64	11
1 (3.00pm)	32.6	63.0	3	9	4	1	-	-	-	-1.82	` 17
1 (12.30pm)	31	66.9	1	2	4	10	2	-	-	-0.47	19
1 (1.15pm)	31.6	62.6	-	3	7	7	1	-	-	-0.67	18

Table C – 1(f): Personal Parameters for Residential Area 1

Residential Area	Operative Temperature (ºC)	Air Speed (ms^{-1})	Air Speed Vote (ASV)							Mean ASV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
1 (10.40 am)	31.1	0.16	-	3	8	7	1	-	-	-0.68	19
1 (12.45 pm)	32	0.15	3	-	2	6	-	-	-	-1.00	11
1 (3.00pm)	32.6	0.15	1	5	5	5	1	-	-	-1.00	` 17
1 (12.30pm)	31	0.19	-	-	5	13	1	-	-	-0.21	19
1 (1.15pm)	31.6	0.15	-	2	2	11	2	1	-	-0.11	18

Table C – 1(g): Environmental Parameters and Personal Parameters for Residential Area 1

Residential Area	Average Activity level (Met)	Average Clothing insulation (Clo)	Thermal Sensational Vote , TSV (ASHRAE scale)	Thermal Sensational Vote , TCV (Bedford scale)	Predicted Mean Vote, PMV	Predicted Percentage of Dissatisfied, PPD (%)	Actual Percentage Dissatisfied, APD (%)
1 (10.40 am)	1.4	0.26	0.63	0.42	1.94	74	21.1
1 (12.45 pm)	1.3	0.16	0.55	0.55	2.18	84	45.5
1 (3.00pm)	1.1	0.22	1.59	1.29	2.41	91	70.6
1 (12.30pm)	1.3	0.22	0.26	0.21	1.63	58	31.6
1 (1.15pm)	1.2	0.23	0.72	0.61	2.00	77	27.8

Table C – 2(a): Environmental Parameters for Residential Area 2

Residential Area	Air Temperature (ºC)	Relative Humidity, RH (%)	Air Velocity (ms^{-1})			Wet Bulb Temperature (ºC)	Globe Temperature (ºC)	Mean Radiant Temperature (ºC)	Operative Temperature (ºC)	Outdoor Temperature (ºC)
			Max	Min	Average					
2 (1.15 pm)	28.8	76.6	0.14	0.00	0.07	27.0	27.0	26.2	27.5	32.0
2 (4.30 pm)	29.4	75.3	0.18`	0.00	0.09	27.5	28.0	27.2	28.3	34.0
2 (6.45 pm)	29.3	75.5	0.27	0.00	0.14	26.5	27.5	26.2	27.8	29.5
2 (9.15 pm)	28.7	76.3	0.37	0.00	0.19	27.0	27.5	26.5	27.6	28.2
2 (11.00 pm)	28.6	78.9	0.22	0.00	0.11	27.0	26.0	24.4	26.5	27.5

Table C – 2(b): Personal Parameters for Residential Area 2

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Thermal Preference Vote			Thermal acceptability vote		Total votes
		-3	-2	-1	0	1	2	3	Warmer	No change	Cooler	Acceptable	Unacceptable	
2 (1.15 pm)	27.5	0	0	0	3	2	0	0	0	1	4	5	0	5
2 (4.30 pm)	28.3	0	0	0	1	1	2	1	0	4	1	5	0	5
2 (6.45 pm)	27.8	0	0	0	1	2	0	0	0	2	1	3	0	3
2 (9.15 pm)	27.6	0	0	0	3	1	0	0	0	0	4	4	0	4
2 (11.00 pm)	26.5	0	3	2	2	1	3	1	1	2	9	8	4	12

Table C – 2(c): Personal Parameters for Residential Area 2

Residential Area	**Operative Temperature (ºC)**	**Thermal Sensation Vote (TSV)**							**Mean TSV/ Actual Mean Vote (AMV)**	**Totals**	**Percentage of votes beyond three central categories of ASHRAE scale (%)**	**Percentage of unacceptable votes (%)**
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
2 (1.15 pm)	27.5	0	0	0	3	2	0	0	0.40	5	0.0	0.0
2 (4.30 pm)	28.3	0	0	0	1	1	2	1	1.60	5	60.0	0.0
2 (6.45 pm)	27.8	0	0	0	1	2	0	0	0.67	3	0.0	0.0
2 (9.15 pm)	27.6	0	0	0	3	1	0	0	0.25	4	0.0	0.0
2 (11.00 pm)	26.5	0	3	2	2	1	3	1	0.17	12	58.3	33.3

Table C – 2(d): Personal Parameters for Residential Area 2

Residential Area	**Operative Temperature (ºC)**	**Thermal Comfort Vote (TCV)**							**Mean TCV/ Actual Mean Vote (AMV)**	**Totals**	**Percentage of votes beyond three central categories of Bedford scale (%)**	**Percentage of unacceptable votes (%)**
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
2 (1.15 pm)	27.5	0	0	1	3	1	0	0	0.00	5	0.0	0
2 (4.30 pm)	28.3	0	0	0	2	3	0	0	0.60	5	0.0	0.0
2 (6.45 pm)	27.8	0	0	0	3	0	0	0	0.00	3	0.0	0.0
2 (9.15 pm)	27.6	0	0	1	2	1	0	0	0.00	4	0.0	0.0
2 (11.00 pm)	26.5	0	1	6	0	5	0	0	-0.25	12	8.3	33.3

Table C – 2(e): Personal Parameters for Residential Area 2

Residential Area	Operative Temperature (ºC)	Relative Humidity (RH)	Relative Humidity Vote (RHV)							Mean RHV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
2 (1.15 pm)	27.5	76.6	0	0	2	2	0	1	0	0.00	5
2 (4.30 pm)	28.3	75.3	0	0	0	5	0	0	0	0.00	5
2 (6.45 pm)	27.8	75.5	0	0	1	1	0	0	1	0.67	3
2 (9.15 pm)	27.6	76.3	0	0	0	3	1	0	0	0.25	4
2 (11.00 pm)	26.5	78.9	0	0	4	8	0	0	0	-0.33	12

Table C – 2(f): Personal Parameters for Residential Area 2

Residential Area	Operative Temperature (ºC)	Air Speed (ms^{-1})	Air Speed Vote (ASV)							Mean ASV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
2 (1.15 pm)	27.5	0.07	0	0	1	2	2	0	0	0.20	5
2 (4.30 pm)	28.3	0.09	0	0	0	2	2	1	0	0.80	5
2 (6.45 pm)	27.8	0.14	0	0	3	0	0	0	0	-1.00	3
2 (9.15 pm)	27.6	0.19	0	0	1	3	0	0	0	-0.25	4
2 (11.00 pm)	26.5	0.11	0	1	3	7	1	0	0	-0.33	12

Table C – 2(g): Environmental Parameters and Personal Parameters for Residential Area 2

Residential Area	Average Activity level (Met)	Average Clothing insulation (Clo)	Thermal Sensational Vote , TSV (ASHRAE scale)	Thermal Sensational Vote , TCV (Bedford scale)	Predicted Mean Vote, PMV	Predicted Percentage of Dissatisfied, PPD (%)	Actual Percentage Dissatisfied, APD (%)
2 (1.15 pm)	1.4	0.24	0.40	0.00	0.98	25.0	0.0
2 (4.30 pm)	1.2	0.25	1.60	0.60	1.00	26.0	0.0
2 (6.45 pm)	1.1	0.17	0.67	0.00	0.42	9.0	0.0
2 (9.15 pm)	1.3	0.41	0.25	0.00	0.84	20.0	0.0
2 (11.00 pm)	1.5	0.44	0.17	-0.25	0.50	10.0	33.3

Table C – 3(a): Environmental Parameters for Residential Area 3

Residential Area	Air Temperature (ºC)	Relative Humidity, RH (%)	Air Velocity (ms^{-1})			Wet Bulb Temperature (ºC)	Globe Temperature (ºC)	Mean Radiant Temperature (ºC)	Operative Temperature (ºC)	Outdoor Temperature (ºC)
			Max	Min	Average					
3 (11.30 am)	29.7	67.1	0.23	0.00	0.12	26.5	28.0	26.9	28.3	31.9
3 (1.15 pm)	30.3	65.8	0.16	0.00	0.08	27.0	29.0	28.4	29.4	34.4
3 (3.40 pm)	30.6	67.8	0.21	0.00	0.11	27.0	29.0	28.0	29.3	36.4
3 (6.15 pm)	28.9	71.4	0.39	0.00	0.20	26.0	27.0	25.3	27.5	27.1
3 (8.45 pm)	28.2	73.0	0.33	0.00	0.17	26.0	27.0	26.0	27.1	26.6

Table C – 3(b): Personal Parameters for Residential Area 3

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Thermal Preference Vote			Thermal acceptability vote		Total votes
		-3	-2	-1	0	1	2	3	Warmer	No change	Cooler	Acceptable	Unacceptable	
3 (11.30 am)	28.3	0	0	1	3	1	1	0	0	2	4	3	3	6
3 (1.15 pm)	29.4	0	0	0	2	1	0	0	0	1	2	3	0	3
3 (3.40 pm)	29.3	0	0	1	1	1	0	0	0	0	3	1	2	3
3 (6.15 pm)	27.5	0	0	0	4	0	0	0	0	2	2	4	0	4
3 (8.45 pm)	27.1	0	0	4	0	0	0	0	0	4	0	4	0	4

Table C – 3(c): Personal Parameters for Residential Area 3

Residential Area	**Operative Temperature (ºC)**	**Thermal Sensation Vote (TSV)**							**Mean TSV/ Actual Mean Vote (AMV)**	**Totals**	**Percentage of votes beyond three central categories of ASHRAE scale (%)**	**Percentage of unacceptable votes (%)**
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
3 (11.30 am)	28.3	0	0	1	3	1	1	0	0.33	6	16.7	50.0
3 (1.15 pm)	29.4	0	0	0	2	1	0	0	0.33	3	0.0	0.0
3 (3.40 pm)	29.3	0	0	1	1	1	0	0	0.00	3	0.0	66.7
3 (6.15 pm)	27.5	0	0	0	4	0	0	0	0.00	4	0.0	0.0
3 (8.45 pm)	27.1	0	0	4	0	0	0	0	-1.00	4	0.0	0.0

Table C – 3(d): Personal Parameters for Residential Area 3

Residential Area	**Operative Temperature (ºC)**	**Thermal Comfort Vote (TCV)**							**Mean TCV/ Actual Mean Vote (AMV)**	**Totals**	**Percentage of votes beyond three central categories of Bedford scale (%)**	**Percentage of unacceptable votes (%)**
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
3 (11.30 am)	28.3	0	0	0	5	1	0	0	0.17	6	0.0	50.0
3 (1.15 pm)	29.4	0	0	0	2	1	0	0	0.33	3	0.0	0.0
3 (3.40 pm)	29.3	0	0	1	2	0	0	0	-0.33	3	0.0	66.7
3 (6.15 pm)	27.5	0	0	2	2	0	0	0	-0.50	4	0.0	0.0
3 (8.45 pm)	27.1	0	0	1	3	0	0	0	-0.25	4	0.0	0.0

Table C – 3(e): Personal Parameters for Residential Area 3

Residential Area	Operative Temperature (ºC)	Relative Humidity (RH)	Relative Humidity Vote (RHV)							Mean RHV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
3 (11.30 am)	28.3	67.1	0	1	1	4	0	0	0	-0.50	6
3 (1.15 pm)	29.4	65.8	0	0	0	3	0	0	0	0.00	3
3 (3.40 pm)	29.3	67.8	0	0	2	1	0	0	0	-0.67	3
3 (6.15 pm)	27.5	71.4	0	0	1	2	1	0	0	0.00	4
3 (8.45 pm)	27.1	73.2	0	0	0	3	1	0	0	0.25	4

Table C – 3(f): Personal Parameters for Residential Area 3

Residential Area	Operative Temperature (ºC)	Air Speed (ms^{-1})	Air Speed Vote (ASV)							Mean ASV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
3 (11.30 am)	28.3	0.12	0	1	1	4	0	0	0	-0.50	6
3 (1.15 pm)	29.4	0.08	0	0	0	2	1	0	0	0.33	3
3 (3.40 pm)	29.3	0.11	0	0	0	3	0	0	0	0.00	3
3 (6.15 pm)	27.5	0.20	0	0	1	3	0	0	0	-0.25	4
3 (8.45 pm)	27.1	0.17	0	0	0	2	2	0	0	0.50	4

Table C – 3(g): Environmental Parameters and Personal Parameters for Residential Area 3

Residential Area	**Average Activity level (Met)**	**Average Clothing insulation (Clo)**	**Thermal Sensational Vote , TSV (ASHRAE scale)**	**Thermal Sensational Vote , TCV (Bedford scale)**	**Predicted Mean Vote, PMV**	**Predicted Percentage of Dissatisfied, PPD (%)**	**Actual Percentage Dissatisfied, APD (%)**
3 (11.30 am)	1.2	0.29	0.33	0.17	0.96	24.0	50.0
3 (1.15 pm)	1.3	0.21	0.33	0.33	1.39	45.0	0.0
3 (3.40 pm)	1.5	0.29	0.00	-0.33	1.55	54.0	66.7
3 (6.15 pm)	1.5	0.20	0.00	-0.50	0.61	13.0	0.0
3 (8.45 pm)	1.3	0.19	-1.00	-0.25	0.35	8.0	0.0

Table C – 4(a): Environmental Parameters for Residential Area 4

Residential Area	Air Temperature (ºC)	Relative Humidity, RH (%)	Air Velocity (ms^{-1})			Wet Bulb Temperature (ºC)	Globe Temperature (ºC)	Mean Radiant Temperature (ºC)	Operative Temperature (ºC)	Outdoor Temperature (ºC)
			Max	Min	Average					
4 (12.15 pm)	30.1	68.0	0.20	0.00	0.10	27.0	29.0	28.4	29.3	33.8
4 (2.00 pm)	29.3	71.2	0.29	0.00	0.15	26.5	28.0	27.0	28.2	31.6
4 (3.00 pm)	30.4	68.3	0.12	0.00	0.06	26.5	29.0	28.4	29.4	32.9
4 (4.15 pm)	28.8	82.5	0.08	0.00	0.04	27.0	27.0	26.4	27.6	28.7
4 (10.30 pm)	30.0	70.5	0.11	0.00	0.06	27.0	28.0	27.2	28.6	32.6

Table C – 4(b): Personal Parameters for Residential Area 4

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Thermal Preference Vote			Thermal acceptability vote		Total votes
		-3	-2	-1	0	1	2	3	Warmer	No change	Cooler	Acceptable	Unacceptable	
4 (12.15 pm)	29.3	0	0	0	1	3	2	0	0	2	4	4	2	6
4 (2.00 pm)	28.2	0	3	0	1	0	1	0	1	1	3	4	1	5
4 (3.00 pm)	29.4	0	0	0	0	0	2	0	0	0	2	2	0	2
4 (4.15 pm)	27.6	0	2	0	0	1	1	0	0	2	2	3	1	4
4 (10.30 pm)	28.6	0	0	0	2	2	1	0	0	2	3	2	3	5

Table C – 4(c): Personal Parameters for Residential Area 4

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Mean TSV/ Actual Mean Vote (AMV)	Totals	Percentage of votes beyond three central categories of ASHRAE scale (%)	Percentage of unacceptable votes (%)
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
4 (12.15 pm)	29.3	0	0	0	1	3	2	0	1.17	6	33.3	33.3
4 (2.00 pm)	28.2	0	3	0	1	0	1	0	-0.80	5	80.0	20.0
4 (3.00 pm)	29.4	0	0	0	0	0	2	0	2.00	2	100.0	0.0
4 (4.15 pm)	27.6	0	2	0	0	1	1	0	-0.25	4	75.0	25.0
4 (10.30 pm)	28.6	0	0	0	2	2	1	0	0.80	5	20.0	60.0

Table C – 4(d): Personal Parameters for Residential Area 4

Residential Area	Operative Temperature (ºC)	Thermal Comfort Vote (TCV)							Mean TCV/ Actual Mean Vote (AMV)	Totals	Percentage of votes beyond three central categories of Bedford scale (%)	Percentage of unacceptable votes (%)
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
4 (12.15 pm)	29.3	0	0	1	1	2	2	0	0.83	6	33.3	33.3
4 (2.00 pm)	28.2	0	0	3	1	1	0	0	-0.40	5	0.0	20.0
4 (3.00 pm)	29.4	0	0	0	0	2	0	0	1.00	2	0.0	0.0
4 (4.15 pm)	27.6	0	1	1	1	1	0	0	-0.50	4	20.0	25.0
4 (10.30 pm)	28.6	0	0	0	4	1	0	0	0.20	5	0.0	60.0

Table C – 4(e): Personal Parameters for Residential Area 4

Residential Area	Operative Temperature (ºC)	Relative Humidity (RH)	Relative Humidity Vote (RHV)							Mean RHV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
4 (12.15 pm)	29.3	68.0	0	0	0	2	3	1	0	0.83	6
4 (2.00 pm)	28.2	71.2	0	2	0	3	0	0	0	-0.80	5
4 (3.00 pm)	29.4	68.3	0	0	2	0	0	0	0	-1.00	2
4 (4.15 pm)	27.6	82.5	0	1	1	2	0	0	0	-0.75	4
4 (10.30 pm)	28.6	70.5	0	0	1	3	0	1	0	0.20	5

Table C – 4(f): Personal Parameters for Residential Area 4

Residential Area	Operative Temperature (ºC)	Air Speed (ms^{-1})	Air Speed Vote (ASV)							Mean ASV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
4 (12.15 pm)	29.3	0.10	0	0	1	4	1	0	0	0.00	6
4 (2.00 pm)	28.2	0.15	0	0	1	3	1	0	0	0.00	5
4 (3.00 pm)	29.4	0.06	0	2	0	0	0	0	0	-2.00	2
4 (4.15 pm)	27.6	0.04	0	1	1	2	0	0	0	-0.75	4
4 (10.30 pm)	28.6	0.06	0	0	0	1	1	2	1	1.60	5

Table C – 4(g): Environmental Parameters and Personal Parameters for Residential Area 4

Residential Area	Average Activity level (Met)	Average Clothing insulation (Clo)	Thermal Sensational Vote , TSV (ASHRAE scale)	Thermal Sensational Vote , TCV (Bedford scale)	Predicted Mean Vote, PMV	Predicted Percentage of Dissatisfied, PPD (%)	Actual Percentage Dissatisfied, APD (%)
4 (12.15 pm)	1.2	0.35	1.17	0.83	1.40	46.0	33.3
4 (2.00 pm)	1.1	0.32	-0.80	-0.40	0.79	18.0	20.0
4 (3.00 pm)	1.8	0.15	2.00	1.00	1.75	65.0	0.0
4 (4.15 pm)	1.0	0.21	-0.25	-0.50	0.36	8.0	25.0
4 (10.30 pm)	1.0	0.28	0.80	0.20	0.89	22.0	60.0

Table C – 5(a): Environmental Parameters for Residential Area 5

Residential Area	Air Temperature (ºC)	Relative Humidity, RH (%)	Air Velocity (ms^{-1})			Wet Bulb Temperature (ºC)	Globe Temperature (ºC)	Mean Radiant Temperature (ºC)	Operative Temperature (ºC)	Outdoor Temperature (ºC)
			Max	Min	Average					
5 (12.45 pm)	28.8	71.0	0.39	0.00	0.20	26.0	27.0	25.4	27.4	26.6
5 (2.40 pm)	32.8	56.7	0.25	0.00	0.13	27.0	30.5	29.0	30.9	34.5
5 (4.50 pm)	30.8	64.2	0.39	0.00	0.20	27.0	30.0	29.3	30.2	33.1
5 (8.00 pm)	27.8	80.5	0.46	0.00	0.23	26.0	26.8	25.8	27.0	26.6
5 (11.20 pm)	28.7	73.3	0.34	0.03	0.19	26.2	28.0	27.4	28.1	27.3

Table C – 5(b): Personal Parameters for Residential Area 5

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Thermal Preference Vote			Thermal acceptability vote		Total votes
		-3	-2	-1	0	1	2	3	Warmer	No change	Cooler	Acceptable	Unacceptable	
5 (12.45 pm)	27.4	0	0	0	1	2	0	0	0	0	3	1	2	3
5 (2.40 pm)	30.9	0	0	0	0	3	0	0	0	0	3	0	3	3
5 (4.50 pm)	30.2	0	0	0	0	5	0	0	0	0	5	5	0	5
5 (8.00 pm)	27.0	0	0	3	3	0	0	0	0	1	5	6	0	6
5 (11.20 pm)	28.1	0	0	1	1	1	2	0	0	0	5	3	2	5

Table C – 5(c): Personal Parameters for Residential Area 5

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Mean TSV/ Actual Mean Vote (AMV)	Totals	Percentage of votes beyond three central categories of ASHRAE scale (%)	Percentage of unacceptable votes (%)
		-3	-2	-1	0	1	2	3				
5 (12.45 pm)	27.4	0	0	0	1	2	0	0	0.67	3	0.0	66.7
5 (2.40 pm)	30.9	0	0	0	0	3	0	0	1.00	3	0.0	100.0
5 (4.50 pm)	30.2	0	0	0	0	5	0	0	1.00	5	0.0	0.0
5 (8.00 pm)	27.0	0	0	3	3	0	0	0	-0.50	6	0.0	0.0
5 (11.20 pm)	28.1	0	0	1	1	1	2	0	0.80	5	40.0	40.0

Table C – 5(d): Personal Parameters for Residential Area 5

Residential Area	Operative Temperature (ºC)	Thermal Comfort Vote (TCV)							Mean TCV/ Actual Mean Vote (AMV)	Totals	Percentage of votes beyond three central categories of Bedford scale (%)	Percentage of unacceptable votes (%)
		-3	-2	-1	0	1	2	3				
5 (12.45 pm)	27.4	0	0	0	3	0	0	0	0.00	3	0.0	66.7
5 (2.40 pm)	30.9	0	0	0	1	0	2	0	1.33	3	66.7	100.0
5 (4.50 pm)	30.2	0	0	0	0	1	4	0	1.80	5	80.0	0.0
5 (8.00 pm)	27.0	0	1	1	4	0	0	0	-0.50	6	16.7	0.0
5 (11.20 pm)	28.1	0	0	0	2	1	2	0	1.00	5	40.0	40.0

Table C – 5(e): Personal Parameters for Residential Area 5

Residential Area	Operative Temperature (ºC)	Relative Humidity (RH)	Relative Humidity Vote (RHV)							Mean RHV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
5 (12.45 pm)	27.4	71.0	0	2	1	0	0	0	0	-1.70	3
5 (2.40 pm)	30.9	56.7	0	3	0	0	0	0	0	-2.00	3
5 (4.50 pm)	30.2	64.2	0	1	3	1	0	0	0	-1.00	5
5 (8.00 pm)	27.0	80.5	0	0	0	6	0	0	0	0.00	6
5 (11.20 pm)	28.1	73.3	0	0	0	2	3	0	0	0.60	5

Table C – 5(f): Personal Parameters for Residential Area 5

Residential Area	Operative Temperature (ºC)	Air Speed (ms^{-1})	Air Speed Vote (ASV)							Mean ASV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
5 (12.45 pm)	27.4	0.20	0	0	0	1	2	0	0	0.67	3
5 (2.40 pm)	30.9	0.13	0	0	0	0	3	0	0	1.00	3
5 (4.50 pm)	30.2	0.20	0	1	3	1	0	0	0	-1.00	5
5 (8.00 pm)	27.0	0.23	0	0	0	6	0	0	0	0.00	6
5 (11.20 pm)	28.1	0.19	0	0	4	1	0	0	0	-0.80	5

Table C – 5(g): Environmental Parameters and Personal Parameters for Residential Area 5

Residential Area	Average Activity level (Met)	Average Clothing insulation (Clo)	Thermal Sensational Vote , TSV (ASHRAE scale)	Thermal Sensational Vote , TCV (Bedford scale)	Predicted Mean Vote, PMV	Predicted Percentage of Dissatisfied, PPD (%)	Actual Percentage Dissatisfied, APD (%)
5 (12.45 pm)	1.5	0.21	0.67	0.00	0.59	12.0	66.7
5 (2.40 pm)	1.0	0.27	1.00	1.33	1.68	61.0	100.0
5 (4.50 pm)	1.0	0.18	1.00	1.80	0.93	23.0	0.0
5 (8.00 pm)	1.2	0.21	-0.50	-0.50	0.01	5.0	0.0
5 (11.20 pm)	1.1	0.15	0.80	1.00	0.21	6.0	40.0

Table C – 6(a): Environmental Parameters for Residential Area 6

Residential Area	Air Temperature (ºC)	Relative Humidity, RH (%)	Air Velocity (ms^{-1})			Wet Bulb Temperature (ºC)	Globe Temperature (ºC)	Mean Radiant Temperature (ºC)	Operative Temperature (ºC)	Outdoor Temperature (ºC)
			Max	Min	Average					
6 (12.15 pm)	30.0	70.3	0.27	0.00	0.14	26.5	29.0	28.3	29.2	32.6
6 (1.45 pm)	31.6	61.0	0.88	0.07	0.48	27.0	30.0	27.7	30.0	34.5
6 (3.15 pm)	32.4	56.6	0.28	0.00	0.14	27.0	31.0	30.0	31.2	37.5
6 (5.00 pm)	31.4	65.3	0.26	0.01	0.14	27.0	30.0	29.0	30.2	33.1
6 (11.15 pm)	27.6	81.8	0.11	0.00	0.06	26.0	26.0	25.3	26.5	26.1

Table C – 6(b): Personal Parameters for Residential Area 6

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Thermal Preference Vote			Thermal acceptability vote		Total votes
		-3	-2	-1	0	1	2	3	Warmer	No change	Cooler	Acceptable	Unacceptable	
6 (12.15 pm)	29.2	0	0	1	2	1	0	0	1	1	2	4	0	4
6 (1.45 pm)	30.0	0	0	0	2	0	0	0	0	1	1	2	0	2
6 (3.15 pm)	31.2	0	0	0	1	1	0	0	0	0	2	2	0	2
6 (5.00 pm)	30.2	0	0	0	0	3	0	0	0	0	3	1	2	3
6 (11.15 pm)	26.5	0	0	3	2	1	0	0	0	0	6	1	5	6

Table C – 6(c): Personal Parameters for Residential Area 6

Residential Area	**Operative Temperature (ºC)**	**Thermal Sensation Vote (TSV)**							**Mean TSV/ Actual Mean Vote (AMV)**	**Totals**	**Percentage of votes beyond three central categories of ASHRAE scale (%)**	**Percentage of unacceptable votes (%)**
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
6 (12.15 pm)	29.2	0	0	1	2	1	0	0	0.00	4	0.0	0.0
6 (1.45 pm)	30.0	0	0	0	2	0	0	0	0.00	2	0.0	0.0
6 (3.15 pm)	31.2	0	0	0	1	1	0	0	0.50	2	0.0	0.0
6 (5.00 pm)	30.2	0	0	0	0	3	0	0	1.00	3	0.0	66.7
6 (11.15 pm)	26.5	0	0	3	2	1	0	0	-0.33	6	0.0	83.3

Table C – 6(d): Personal Parameters for Residential Area 6

Residential Area	**Operative Temperature (ºC)**	**Thermal Comfort Vote (TCV)**							**Mean TCV/ Actual Mean Vote (AMV)**	**Totals**	**Percentage of votes beyond three central categories of Bedford scale (%)**	**Percentage of unacceptable votes (%)**
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
6 (12.15 pm)	29.2	0	0	1	3	0	0	0	-0.25	4	0.0	0.0
6 (1.45 pm)	30.0	0	0	1	0	1	0	0	0.00	2	0.0	0.0
6 (3.15 pm)	31.2	0	0	0	1	1	0	0	0.50	2	0.0	0.0
6 (5.00 pm)	30.2	0	0	0	3	0	0	0	0.00	3	0.0	66.7
6 (11.15 pm)	26.5	0	0	1	5	0	0	0	-0.17	6	0.0	83.3

Table C – 6(e): Personal Parameters for Residential Area 6

Residential Area	**Operative Temperature (ºC)**	**Relative Humidity (RH)**	**Relative Humidity Vote (RHV)**							**Mean RHV/ Actual Mean Vote (AMV)**	**Totals**
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
6 (12.15 pm)	29.2	70.3	0	0	0	3	0	1	0	0.50	4
6 (1.45 pm)	30.0	61.0	0	0	2	0	0	0	0	-1.00	2
6 (3.15 pm)	31.2	56.6	0	0	1	1	0	0	0	-0.50	2
6 (5.00 pm)	30.2	65.3	0	0	0	3	0	0	0	0.00	3
6 (11.15 pm)	26.5	81.8	0	0	1	2	0	3	0	0.83	6

Table C – 6(f): Personal Parameters for Residential Area 6

Residential Area	**Operative Temperature (ºC)**	**Air Speed (ms^{-1})**	**Air Speed Vote (ASV)**							**Mean ASV/ Actual Mean Vote (AMV)**	**Totals**
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
6 (12.15 pm)	29.2	0.14	1	0	1	1	1	0	0	-0.75	4
6 (1.45 pm)	30.0	0.48	0	0	1	1	0	0	0	-0.50	2
6 (3.15 pm)	31.2	0.14	0	0	0	0	2	0	0	1.00	2
6 (5.00 pm)	30.2	0.14	0	0	0	3	0	0	0	0.00	3
6 (11.15 pm)	26.5	0.06	0	0	1	2	0	2	1	1.00	6

Table C – 6(g): Environmental Parameters and Personal Parameters for Residential Area 6

Residential Area	Average Activity level (Met)	Average Clothing insulation (Clo)	Thermal Sensational Vote , TSV (ASHRAE scale)	Thermal Sensational Vote , TCV (Bedford scale)	Predicted Mean Vote, PMV	Predicted Percentage of Dissatisfied, PPD (%)	Actual Percentage Dissatisfied, APD (%)
6 (12.15 pm)	1.6	0.27	0.00	-0.25	1.58	55.0	0.0
6 (1.45 pm)	1.0	0.18	0.00	0.00	0.05	5.0	0.0
6 (3.15 pm)	1.6	0.24	0.50	0.50	2.02	77.0	0.0
6 (5.00 pm)	1.0	0.31	1.00	0.00	1.49	51.0	66.7
6 (11.15 pm)	1.0	0.23	-0.33	-0.17	-0.15	5.0	83.3

Table C – 7(a): Environmental Parameters for Residential Area 7

Residential Area	Air Temperature (ºC)	Relative Humidity, RH (%)	Air Velocity (ms^{-1})			Wet Bulb Temperature (ºC)	Globe Temperature (ºC)	Mean Radiant Temperature (ºC)	Operative Temperature (ºC)	Outdoor Temperature (ºC)
			Max	Min	Average					
7 (12.00 pm)	28.9	73.7	0.18	0.00	0.09	26.4	28.0	27.5	28.2	31.6
7 (1.30 pm)	31.1	57.7	0.25	0.00	0.13	26.4	30.0	29.3	30.2	33.6
7 (4.00 pm)	31.0	70.2	0.34	0.04	0.19	27.5	30.0	29.2	30.1	34.2
7 (6.15 pm)	30.2	71.4	0.27	0.00	0.14	27.0	29.0	28.2	29.2	30.7
7 (11.30 pm)	27.5	78.2	0.31	0.00	0.16	26.0	27.0	26.6	27.1	27.2

Table C – 7(b): Personal Parameters for Residential Area 7

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Thermal Preference Vote			Thermal acceptability vote		Total votes
		-3	-2	-1	0	1	2	3	Warmer	No change	Cooler	Acceptable	Unacceptable	
7 (12.00 pm)	28.2	0	1	0	1	0	2	0	0	2	2	4	0	4
7 (1.30 pm)	30.2	0	0	0	1	2	1	0	0	1	3	4	0	4
7 (4.00 pm)	30.1	0	1	0	4	1	1	0	0	0	7	7	0	7
7 (6.15 pm)	29.2	0	1	1	4	0	1	0	0	5	2	7	0	7
7 (11.30 pm)	27.1	0	0	2	5	0	0	0	0	7	0	6	1	7

Table C – 7(c): Personal Parameters for Residential Area 7

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Mean TSV/ Actual Mean Vote (AMV)	Totals	Percentage of votes beyond three central categories of ASHRAE scale (%)	Percentage of unacceptable votes (%)
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
7 (12.00 pm)	28.2	0	1	0	1	0	2	0	0.50	4	75.0	0.0
7 (1.30 pm)	30.2	0	0	0	1	2	1	0	1.00	4	20.0	0.0
7 (4.00 pm)	30.1	0	1	0	4	1	1	0	0.14	7	28.6	0.0
7 (6.15 pm)	29.2	0	1	1	4	0	1	0	-0.14	7	28.6	0.0
7 (11.30 pm)	27.1	0	0	2	5	0	0	0	-0.29	7	0.0	14.3

Table C – 7(d): Personal Parameters for Residential Area 7

Residential Area	Operative Temperature (ºC)	Thermal Comfort Vote (TCV)							Mean TCV/ Actual Mean Vote (AMV)	Totals	Percentage of votes beyond three central categories of Bedford scale (%)	Percentage of unacceptable votes (%)
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
7 (12.00 pm)	28.2	0	0	1	1	2	0	0	0.25	4	0.0	0.0
7 (1.30 pm)	30.2	0	0	0	3	0	1	0	0.50	4	20.0	0.0
7 (4.00 pm)	30.1	0	0	0	4	2	1	0	0.57	7	14.3	0.0
7 (6.15 pm)	29.2	0	0	1	5	0	1	0	0.14	7	14.3	0.0
7 (11.30 pm)	27.1	0	1	1	5	0	0	0	-0.43	7	14.3	14.3

Table C – 7(e): Personal Parameters for Residential Area 7

Residential Area	Operative Temperature (ºC)	Relative Humidity (RH)	Relative Humidity Vote (RHV)							Mean RHV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
7 (12.00 pm)	28.2	73.7	0	0	1	1	0	2	0	0.75	4
7 (1.30 pm)	30.2	57.7	0	0	1	1	2	0	0	0.25	4
7 (4.00 pm)	30.1	70.2	0	0	1	3	2	1	0	0.43	7
7 (6.15 pm)	29.2	71.4	0	0	1	5	0	1	0	0.14	7
7 (11.30 pm)	27.1	78.2	0	0	0	6	1	0	0	0.14	7

Table C – 7(f): Personal Parameters for Residential Area 7

Residential Area	Operative Temperature (ºC)	Air Speed (ms^{-1})	Air Speed Vote (ASV)							Mean ASV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
7 (12.00 pm)	28.2	0.09	0	3	0	1	0	0	0	-1.50	4
7 (1.30 pm)	30.2	0.13	0	0	3	1	0	0	0	-0.75	4
7 (4.00 pm)	30.1	0.19	0	0	2	3	2	0	0	0.00	7
7 (6.15 pm)	29.2	0.14	0	0	1	6	0	0	0	-0.14	7
7 (11.30 pm)	27.1	0.16	0	1	1	4	1	0	0	-0.29	7

Table C – 7(g): Environmental Parameters and Personal Parameters for Residential Area 7

Residential Area	Average Activity level (Met)	Average Clothing insulation (Clo)	Thermal Sensational Vote , TSV (ASHRAE scale)	Thermal Sensational Vote , TCV (Bedford scale)	Predicted Mean Vote, PMV	Predicted Percentage of Dissatisfied, PPD (%)	Actual Percentage Dissatisfied, APD (%)
7 (12.00 pm)	1.3	0.33	0.50	0.25	1.17	34.0	0.0
7 (1.30 pm)	1.2	0.33	1.00	0.50	1.60	56.0	0.0
7 (4.00 pm)	1.0	0.31	0.14	0.57	1.23	37.0	0.0
7 (6.15 pm)	1.2	0.29	-0.14	0.14	1.31	41.0	0.0
7 (11.30 pm)	1.0	0.40	-0.29	-0.43	0.34	7.0	14.3

Table C – 8(a): Environmental Parameters for Residential Area 8

Residential Area	Air Temperature (ºC)	Relative Humidity, RH (%)	Air Velocity (ms^{-1})			Wet Bulb Temperature (ºC)	Globe Temperature (ºC)	Mean Radiant Temperature (ºC)	Operative Temperature (ºC)	Outdoor Temperature (ºC)
			Max	Min	Average					
8 (12.45 pm)	29.9	73.0	0.40	0.00	0.20	27.0	28.0	26.3	28.5	32.6
8 (2.30 pm)	29.7	71.8	0.41	0.00	0.21	26.6	28.0	26.5	28.4	32.9
8 (5.00 pm)	30.7	66.6	0.33	0.00	0.17	27.0	30.0	29.5	30.1	35.4
8 (6.30 pm)	30.4	68.6	0.34	0.00	0.17	27.0	29.0	27.9	29.2	30.7
8 (10.45 pm)	28.8	74.8	0.52	0.02	0.27	26.2	27.0	25.1	27.3	27.8

Table C – 8(b): Personal Parameters for Residential Area 8

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Thermal Preference Vote			Thermal acceptability vote		Total votes
		-3	-2	-1	0	1	2	3	Warmer	No change	Cooler	Acceptable	Unacceptable	
8 (12.45 pm)	28.5	0	0	0	3	0	0	0	0	2	1	3	0	3
8 (2.30 pm)	28.4	0	0	0	2	1	0	0	0	1	2	3	0	3
8 (5.00 pm)	30.1	0	0	0	1	3	0	0	0	1	3	3	1	4
8 (6.30 pm)	29.2	0	0	1	6	1	1	0	0	4	5	8	1	9
8 (10.45 pm)	27.3	0	1	0	2	2	0	0	0	0	5	0	5	5

Table C – 8(c): Personal Parameters for Residential Area 8

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Mean TSV/ Actual Mean Vote (AMV)	Totals	Percentage of votes beyond three central categories of ASHRAE scale (%)	Percentage of unacceptable votes (%)
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
8 (12.45 pm)	28.5	0	0	0	3	0	0	0	0.00	3	0.0	0.0
8 (2.30 pm)	28.4	0	0	0	2	1	0	0	0.33	3	0.0	0.0
8 (5.00 pm)	30.1	0	0	0	1	3	0	0	0.75	4	0.0	25.0
8 (6.30 pm)	29.2	0	0	1	6	1	1	0	0.22	9	11.1	11.1
8 (10.45 pm)	27.3	0	1	0	2	2	0	0	0.00	5	20.0	100.0

Table C – 8(d): Personal Parameters for Residential Area 8

Residential Area	Operative Temperature (ºC)	Thermal Comfort Vote (TCV)							Mean TCV/ Actual Mean Vote (AMV)	Totals	Percentage of votes beyond three central categories of Bedford scale (%)	Percentage of unacceptable votes (%)
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
8 (12.45 pm)	28.5	0	0	0	3	0	0	0	0.00	3	0.0	0.0
8 (2.30 pm)	28.4	0	0	0	2	1	0	0	0.33	3	0.0	0.0
8 (5.00 pm)	30.1	0	0	0	1	3	0	0	0.75	4	0.0	25.0
8 (6.30 pm)	29.2	0	0	0	7	1	1	0	0.33	9	11.1	11.1
8 (10.45 pm)	27.3	0	1	0	4	0	0	0	-0.40	5	20.0	100.0

Table C – 8(e): Personal Parameters for Residential Area 8

Residential Area	Operative Temperature (ºC)	Relative Humidity (RH)	Relative Humidity Vote (RHV)							Mean RHV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
8 (12.45 pm)	28.5	73.0	0	0	0	1	2	0	0	0.67	3
8 (2.30 pm)	28.4	71.8	0	0	0	1	2	0	0	0.67	3
8 (5.00 pm)	30.1	66.6	0	0	1	3	0	0	0	-0.25	4
8 (6.30 pm)	29.2	68.6	0	1	1	7	0	0	0	-0.33	9
8 (10.45 pm)	27.3	74.8	0	1	2	2	0	0	0	-0.80	5

Table C – 8(f): Personal Parameters for Residential Area 8

Residential Area	Operative Temperature (ºC)	Air Speed (ms^{-1})	Air Speed Vote (ASV)							Mean ASV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
8 (12.45 pm)	28.5	0.20	0	0	1	2	0	0	0	-0.33	3
8 (2.30 pm)	28.4	0.21	0	0	1	2	0	0	0	-0.33	3
8 (5.00 pm)	30.1	0.17	0	0	1	2	1	0	0	0.00	4
8 (6.30 pm)	29.2	0.17	0	1	2	6	0	0	0	-0.44	9
8 (10.45 pm)	27.3	0.27	0	0	2	2	1	0	0	-0.20	5

Table C – 8(g): Environmental Parameters and Personal Parameters for Residential Area 7

Residential Area	Average Activity level (Met)	Average Clothing insulation (Clo)	Thermal Sensational Vote , TSV (ASHRAE scale)	Thermal Sensational Vote , TCV (Bedford scale)	Predicted Mean Vote, PMV	Predicted Percentage of Dissatisfied, PPD (%)	Actual Percentage Dissatisfied, APD (%)
8 (12.45 pm)	1.0	0.25	0.00	0.00	0.39	8.0	0.0
8 (2.30 pm)	1.4	0.18	0.33	0.33	0.71	16.0	0.0
8 (5.00 pm)	1.1	0.25	0.75	0.75	1.29	40.0	25.0
8 (6.30 pm)	1.1	0.20	0.22	0.33	0.85	20.0	11.1
8 (10.45 pm)	1.0	0.14	0.00	-0.40	-0.71	16.0	100.0

Table C – 9(a): Environmental Parameters for Residential Area 9

Residential Area	Air Temperature (ºC)	Relative Humidity, RH (%)	Air Velocity (ms^{-1})			Wet Bulb Temperature (ºC)	Globe Temperature (ºC)	Mean Radiant Temperature (ºC)	Operative Temperature (ºC)	Outdoor Temperature (ºC)
			Max	Min	Average					
9 (9.00 am)	27.9	80.5	0.24	0.00	0.12	26.5	26.0	24.8	26.4	29.6
9 (1.20 pm)	29.9	72.8	0.10	0.00	0.05	27.0	28.0	27.3	28.6	33.5
9 (7.30 pm)	27.9	85.2	0.22	0.00	0.11	27.0	27.0	26.4	27.2	28.1
9 (10.00 pm)	27.8	84.2	0.20	0.00	0.10	27.0	27.0	26.5	27.2	27.5
9 (11.00 pm)	27.7	84.5	0.27	0.00	0.14	27.0	27.0	26.5	27.1	27.2

Table C – 9(b): Personal Parameters for Residential Area 9

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Thermal Preference Vote			Thermal acceptability vote		Total votes
		-3	-2	-1	0	1	2	3	Warmer	No change	Cooler	Acceptable	Unacceptable	
9 (9.00 am)	26.4	0	0	0	3	0	0	0	0	0	3	3	0	3
9 (1.20 pm)	28.6	0	0	1	1	0	0	1	0	0	3	0	3	3
9 (7.30 pm)	27.2	0	0	3	2	0	0	1	2	3	1	5	1	6
9 (10.00 pm)	27.2	0	1	3	3	0	0	0	1	3	3	5	2	7
9 (11.00 pm)	27.1	0	0	1	2	0	0	0	0	1	2	3	0	3

Table C – 9(c): Personal Parameters for Residential Area 9

Residential Area	**Operative Temperature (ºC)**	**Thermal Sensation Vote (TSV)**							**Mean TSV/ Actual Mean Vote (AMV)**	**Totals**	**Percentage of votes beyond three central categories of ASHRAE scale (%)**	**Percentage of unacceptable votes (%)**
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
9 (9.00 am)	26.4	0	0	0	3	0	0	0	0.00	3	0.0	0.0
9 (1.20 pm)	28.6	0	0	1	1	0	0	1	0.67	3	33.3	100.0
9 (7.30 pm)	27.2	0	0	3	2	0	0	1	0.00	6	16.7	16.7
9 (10.00 pm)	27.2	0	1	3	3	0	0	0	-0.71	7	14.3	28.6
9 (11.00 pm)	27.1	0	0	1	2	0	0	0	-0.33	3	0.0	0.0

Table C – 9(d): Personal Parameters for Residential Area 9

Residential Area	**Operative Temperature (ºC)**	**Thermal Comfort Vote (TCV)**							**Mean TCV/ Actual Mean Vote (AMV)**	**Totals**	**Percentage of votes beyond three central categories of Bedford scale (%)**	**Percentage of unacceptable votes (%)**
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
9 (9.00 am)	26.4	0	0	2	1	0	0	0	-0.67	3	0.0	0.0
9 (1.20 pm)	28.6	0	0	0	2	1	0	0	0.33	3	0.0	100.0
9 (7.30 pm)	27.2	0	0	2	3	0	1	0	0.00	6	16.7	16.7
9 (10.00 pm)	27.2	0	0	2	5	0	0	0	-0.29	7	0.0	28.6
9 (11.00 pm)	27.1	0	0	0	3	0	0	0	0.00	3	0.0	0.0

Table C – 9(e): Personal Parameters for Residential Area 9

Residential Area	Operative Temperature (ºC)	Relative Humidity (RH)	Relative Humidity Vote (RHV)							Mean RHV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
9 (9.00 am)	26.4	80.5	0	0	0	2	1	0	0	0.33	3
9 (1.20 pm)	28.6	72.8	0	0	2	0	0	1	0	0.00	3
9 (7.30 pm)	27.2	85.2	0	0	2	3	1	0	0	-0.17	6
9 (10.00 pm)	27.2	84.2	0	0	1	6	0	0	0	-0.14	7
9 (11.00 pm)	27.1	84.5	0	0	1	2	0	0	0	-0.33	3

Table C – 9(f): Personal Parameters for Residential Area 9

Residential Area	Operative Temperature (ºC)	Air Speed (ms^{-1})	Air Speed Vote (ASV)							Mean ASV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
9 (9.00 am)	26.4	0.12	0	0	0	3	0	0	0	0.00	3
9 (1.20 pm)	28.6	0.05	0	0	2	1	0	0	0	-0.67	3
9 (7.30 pm)	27.2	0.11	0	1	2	2	1	0	0	-0.50	6
9 (10.00 pm)	27.2	0.10	0	0	3	4	0	0	0	-0.43	7
9 (11.00 pm)	27.1	0.14	0	0	0	2	1	0	0	0.33	3

Table C – 9(g): Environmental Parameters and Personal Parameters for Residential Area 9

Residential Area	Average Activity level (Met)	Average Clothing insulation (Clo)	Thermal Sensational Vote , TSV (ASHRAE scale)	Thermal Sensational Vote , TCV (Bedford scale)	Predicted Mean Vote, PMV	Predicted Percentage of Dissatisfied, PPD (%)	Actual Percentage Dissatisfied, APD (%)
9 (9.00 am)	1.0	0.18	0.00	-0.67	-0.40	8.0	0.0
9 (1.20 pm)	1.6	0.18	0.67	0.33	1.42	46.0	100.0
9 (7.30 pm)	1.2	0.32	0.00	0.00	0.76	17.0	16.7
9 (10.00 pm)	1.2	0.32	-0.71	-0.29	0.75	17.0	28.6
9 (11.00 pm)	1.3	0.23	-0.33	0.00	0.68	15.0	0.0

Table C – 10(a): Environmental Parameters for Residential Area 10

Residential Area	Air Temperature (ºC)	Relative Humidity, RH (%)	Air Velocity (ms^{-1})			Wet Bulb Temperature (ºC)	Globe Temperature (ºC)	Mean Radiant Temperature (ºC)	Operative Temperature (ºC)	Outdoor Temperature (ºC)
			Max	Min	Average					
10 (11.40 am)	29.3	73.4	0.10	0.00	0.05	27.0	27.5	26.8	28.1	34.0
10 (3.10 pm)	27.6	84.5	0.42	0.00	0.21	27.0	27.0	26.5	27.2	27.5
10 (8.00 pm)	28.1	82.2	0.18	0.00	0.09	27.0	27.0	26.4	27.3	27.9
10 (10.30 pm)	28.3	83.8	0.22	0.00	0.11	27.0	27.0	26.2	27.3	27.1
10 (11.30 pm)	28.5	84.0	0.40	0.00	0.20	26.5	27.0	25.7	27.4	27.8

Table C – 10(b): Personal Parameters for Residential Area 10

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Thermal Preference Vote			Thermal acceptability vote		Total votes
		-3	-2	-1	0	1	2	3	Warmer	No change	Cooler	Acceptable	Unacceptable	
10 (11.40 am)	28.1	0	0	0	1	3	0	0	0	3	1	4	0	4
10 (3.10 pm)	27.2	0	1	1	1	0	0	0	0	2	1	3	0	3
10 (8.00 pm)	27.3	0	0	1	2	1	0	0	0	2	2	4	0	4
10 (10.30 pm)	27.3	0	0	2	2	0	0	0	0	2	2	4	0	4
10 (11.30 pm)	27.4	1	0	1	0	1	0	0	0	2	1	3	0	3

Table C – 10(c): Personal Parameters for Residential Area 10

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Mean TSV/ Actual Mean Vote (AMV)	Totals	Percentage of votes beyond three central categories of ASHRAE scale (%)	Percentage of unacceptable votes (%)
		-3	-2	-1	0	1	2	3				
10 (11.40 am)	28.1	0	0	0	1	3	0	0	0.75	4	0.0	0.0
10 (3.10 pm)	27.2	0	1	1	1	0	0	0	-1.00	3	33.3	0.0
10 (8.00 pm)	27.3	0	0	1	2	1	0	0	0.00	4	0.0	0.0
10 (10.30 pm)	27.3	0	0	2	2	0	0	0	-0.50	4	0.0	0.0
10 (11.30 pm)	27.4	1	0	1	0	1	0	0	-1.00	3	33.3	0.0

Table C – 10(d): Personal Parameters for Residential Area 10

Residential Area	Operative Temperature (ºC)	Thermal Comfort Vote (TCV)							Mean TCV/ Actual Mean Vote (AMV)	Totals	Percentage of votes beyond three central categories of Bedford scale (%)	Percentage of unacceptable votes (%)
		-3	-2	-1	0	1	2	3				
10 (11.40 am)	28.1	0	0	0	3	1	0	0	0.25	4	0.0	0.0
10 (3.10 pm)	27.2	0	0	1	2	0	0	0	-0.33	3	0.0	0.0
10 (8.00 pm)	27.3	0	0	0	3	1	0	0	0.25	4	0.0	0.0
10 (10.30 pm)	27.3	0	0	2	2	0	0	0	-0.50	4	0.0	0.0
10 (11.30 pm)	27.4	1	0	1	1	0	0	0	-1.33	3	33.3	0.0

Table C – 10(e): Personal Parameters for Residential Area 10

Residential Area	Operative Temperature (ºC)	Relative Humidity (RH)	Relative Humidity Vote (RHV)							Mean RHV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
10 (11.40 am)	28.1	73.4	0	0	2	2	0	0	0	-0.50	4
10 (3.10 pm)	27.2	84.5	0	0	0	1	2	0	0	0.67	3
10 (8.00 pm)	27.3	82.2	0	0	1	2	1	0	0	0.00	4
10 (10.30 pm)	27.3	83.8	0	0	2	1	0	1	0	0.00	4
10 (11.30 pm)	27.4	84.0	0	0	0	2	1	0	0	0.33	3

Table C – 10(f): Personal Parameters for Residential Area 10

Residential Area	Operative Temperature (ºC)	Air Speed (ms^{-1})	Air Speed Vote (ASV)							Mean ASV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
10 (11.40 am)	28.1	0.05	0	0	2	1	1	0	0	-0.25	4
10 (3.10 pm)	27.2	0.21	0	0	0	3	0	0	0	0.00	3
10 (8.00 pm)	27.3	0.09	0	1	0	3	0	0	0	-0.50	4
10 (10.30 pm)	27.3	0.11	0	0	1	1	2	0	0	0.25	4
10 (11.30 pm)	27.4	0.20	0	0	0	1	2	0	0	0.67	3

Table C – 10(g): Environmental Parameters and Personal Parameters for Residential Area 10

Residential Area	Average Activity level (Met)	Average Clothing insulation (Clo)	Thermal Sensational Vote , TSV (ASHRAE scale)	Thermal Sensational Vote , TCV (Bedford scale)	Predicted Mean Vote, PMV	Predicted Percentage of Dissatisfied, PPD (%)	Actual Percentage Dissatisfied, APD (%)
10 (11.40 am)	1.0	0.23	0.75	0.25	0.57	12.0	0.0
10 (3.10 pm)	1.2	0.20	-1.00	-0.33	0.17	6.0	0.0
10 (8.00 pm)	1.0	0.17	0.00	0.25	0.09	5.0	0.0
10 (10.30 pm)	1.0	0.32	-0.50	-0.50	0.43	9.0	0.0
10 (11.30 pm)	1.1	0.21	-1.00	-1.33	0.12	5.0	0.0

Appendix D: Residential Areas of the Validation Study

Figure D – 1(a): Residential Area

Figure D – 1(b): Residential Area

Figure D – 1(c): Residential Area

Figure D – 1(d): Residential Area

Figure D – 1(e): Residential Area

Figure D – 1(f): Residential Area

Appendix E: Environment Parameters and Personal Parameters of Validation Study

Table E – 1(a): Environmental Parameters

Time	Air Temperature (ºC)	Relative Humidity, RH (%)	Air Velocity (ms^{-1})			Globe Temperature (ºC)	Mean Radiant Temperature (ºC)	Operative Temperature (ºC)	Outdoor Temperature (ºC)
			Max	Min	Average				
Validation Study (11.00 am)	29.5	75.1	0.00	0.22	0.11	28.0	27.1	28.3	35.3
Validation Study (12.15 pm)	29.8	71.9	0.00	0.36	0.18	29.0	28.4	29.1	33.0
Validation Study (2.00 pm)	29.9	75.8	0.00	0.24	0.12	28.0	26.8	28.4	33.1
Validation Study (3.00 pm)	29.6	77.4	0.00	0.34	0.17	28.0	26.7	28.2	30.5
Validation Study (4.30 pm)	29.4	75.6	0.00	0.37	0.19	28.0	26.8	28.1	30.7
Validation Study (6.30 pm)	29.0	76.0	0.00	0.19	0.10	27.0	25.8	27.4	27.1

Table E – 1(b): Personal Parameters

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Thermal Preference Vote			Thermal acceptability vote		Total votes
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**	**Warmer**	**No change**	**Cooler**	**Acceptable**	**Unacceptable**	
Validation Study (11.00 am)	28.3	0	0	2	2	2	0	0	0	2	4	6	0	6
Validation Study (12.15 pm)	29.1	0	0	1	0	5	0	0	0	1	5	6	0	6
Validation Study (2.00 pm)	28.4	0	0	0	0	3	0	0	0	0	3	1	2	3
Validation Study (3.00 pm)	28.2	0	0	0	3	0	0	0	0	3	0	3	0	3
Validation Study (4.30 pm)	28.1	0	0	3	2	2	0	0	0	3	4	7	0	7
Validation Study (6.30 pm)	27.4	0	1	1	3	1	0	0	0	5	1	5	1	6

Table E – 1(c): Personal Parameters

Residential Area	Operative Temperature (ºC)	Thermal Sensation Vote (TSV)							Mean TSV/ Actual Mean Vote (AMV)	Totals	Percentage of votes beyond three central categories of ASHRAE scale (%)	Percentage of unacceptable votes (%)
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
Validation Study (11.00 am)	28.3	0	0	2	2	2	0	0	0.00	6	0.0	0.0
Validation Study (12.15 pm)	29.1	0	0	1	0	5	0	0	0.67	6	0.0	0.0
Validation Study (2.00 pm)	28.4	0	0	0	0	3	0	0	1.00	3	0.0	66.7
Validation Study (3.00 pm)	28.2	0	0	0	3	0	0	0	0.00	3	0.0	0.0
Validation Study (4.30 pm)	28.1	0	0	3	2	2	0	0	-0.14	7	0.0	0.0
Validation Study (6.30 pm)	27.4	0	1	1	3	1	0	0	-0.33	6	16.7	16.7

Table E – 1(d): Personal Parameters

Residential Area	**Operative Temperature (ºC)**	**Thermal Comfort Vote (TCV)**							**Mean TCV/ Actual Mean Vote (AMV)**	**Totals**	**Percentage of votes beyond three central categories of Bedford scale (%)**	**Percentage of unacceptable votes (%)**
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**				
Validation Study (11.00 am)	28.3	0	0	2	3	1	0	0	-0.17	6	0.0	0.0
Validation Study (12.15 pm)	29.1	0	0	0	2	4	0	0	0.67	6	0.0	0.0
Validation Study (2.00 pm)	28.4	0	0	0	3	0	0	0	0.00	3	0.0	66.7
Validation Study (3.00 pm)	28.2	0	0	0	3	0	0	0	0.00	3	0.0	0.0
Validation Study (4.30 pm)	28.1	0	0	2	4	1	0	0	-0.14	7	0.0	0.0
Validation Study (6.30 pm)	27.4	0	0	2	4	0	0	0	-0.33	6	16.7	16.7

Table E – 1(e): Personal Parameters

Residential Area	Operative Temperature (ºC)	Relative Humidity (RH)	Relative Humidity Vote (RHV)							Mean RHV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
Validation Study (11.00 am)	28.3	75.1	0	0	0	6	0	0	0	0.00	6
Validation Study (12.15 pm)	29.1	71.9	0	0	0	2	4	0	0	0.67	6
Validation Study (2.00 pm)	28.4	75.8	0	0	0	3	0	0	0	0.00	3
Validation Study (3.00 pm)	28.2	77.4	0	0	0	2	0	1	0	0.67	3
Validation Study (4.30 pm)	28.1	75.6	0	0	0	6	1	0	0	0.14	7
Validation Study (6.30 pm)	27.4	76.0	0	0	0	5	1	0	0	0.17	6

Table E – 1(f): Personal Parameters

Residential Area	Operative Temperature (ºC)	Air Speed (ms^{-1})	Air Speed Vote (ASV)							Mean ASV/ Actual Mean Vote (AMV)	Totals
			-3	**-2**	**-1**	**0**	**1**	**2**	**3**		
Validation Study (11.00 am)	28.3	0.11	0	0	0	6	0	0	0	0.00	6
Validation Study (12.15 pm)	29.1	0.18	0	1	0	4	1	0	0	-0.17	6
Validation Study (2.00 pm)	28.4	0.12	0	0	1	1	1	0	0	0.00	3
Validation Study (3.00 pm)	28.2	0.17	0	0	0	3	0	0	0	0.00	3
Validation Study (4.30 pm)	28.1	0.19	0	0	0	7	0	0	0	0.00	7
Validation Study (6.30 pm)	27.4	0.10	0	0	1	3	2	0	0	0.17	6

Table E – 1(g): Environmental Parameters and Personal Parameters

Residential Area	Average Activity level (Met)	Average Clothing insulation (Clo)	Thermal Sensational Vote , TSV (ASHRAE scale)	Thermal Sensational Vote , TCV (Bedford scale)	Predicted Mean Vote, PMV	Predicted Percentage of Dissatisfied, PPD (%)	Actual Percentage Dissatisfied, APD (%)
Validation Study (11.00 am)	1.1	0.15	0.00	-0.17	0.62	13.0	0.0
Validation Study (12.15 pm)	1.1	0.28	0.67	0.67	0.93	23.0	0.0
Validation Study (2.00 pm)	1.3	0.17	1.00	0.00	1.00	26.0	66.7
Validation Study (3.00 pm)	1.5	0.31	0.00	0.00	1.16	33.0	0.0
Validation Study (4.30 pm)	1.1	0.23	-0.14	-0.14	0.42	9.0	0.0
Validation Study (6.30 pm)	1.3	0.23	-0.33	-0.33	0.74	17.0	16.7

Appendix F: Publications

Article F – 1: Journal Publications

[1] T. Y. E. John, W. A. W. Z. Abidin, A. Baharun and T. Masri, (2014). A Review of Technological Developments in Cooling System for Different Climates. Middle-East Journal of Scientific Research, 21(9), 1503-1511.

Article F – 2: Conference Papers

[1] T. Y. E. John, W. A. W. Z. Abidin, A. Baharun and T. Masri, (2014). Conceptual Framework of Energy Efficient Home Cooling System Design. Postgraduate Colloquium 2014, Curtin University.

[2] T. Y. E. John, W. A. W. Z. Abidin, A. Baharun and T. Masri, (2013). Thermal Performance of Low-Cost House with Retrofit Solutions. EnCon 2013, 6th Engineering Conference, “Energy and Environment”, 2nd – 4th July 2013.

[3] T. Y. E. John, W. A. W. Z. Abidin, A. Baharun and T. Masri, (2013). Cooling System Design Technologies in Buildings. 2nd Faculty of Engineering Postgraduate Colloquium (FEPC) 2013, Universiti Malaysia Sarawak (UNIMAS).

[4] T. Y. E. John, W. A. W. Z. Abidin, A. Baharun and A. K. Othman and T. Masri, (2012). Progress in the Energy Efficient Home Cooling System Design. EnCon 2012, 5th Engineering Conference, “Engineering Towards Change – Empowering Green Solutions”, 10th -12th July 2012, 422-427.

[5] T. Y. E. John, W. A. W. Z. Abidin, A. Baharun, A. K. Othman and T. Masri, (2012). Adaptive Solar Energy System for Low-Cost Home Cooling System: Conceptual

Design. EnCon 2012, 5th Engineering Conference, “Engineering Towards Change – Empowering Green Solutions”, 10th – 12th July 2012, 428-433.