ANALYSIS OF THE EFFECT AND RESPONSIVENESS OF PHYSIOLOGY FACTORS ON THERMAL COMFORT IN AN AIR-CONDITIONED ENVIRONMENT

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DEDICATION

Dedicated to my family for their love, support and motivation and who made everything possible.

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ABSTRAK

Persekitaran yang panas dan sejuk boleh mengganggu aktiviti manusia tidak boleh disangkalkan lagi. Ia memberi kesan kepada prestasi tugas yang dilakukan dan mempengaruhi produktiviti pekerja di dalam bangunan. Antara faktor yang boleh menyediakan keselesaan kepada pekerja dalam menjalankan tugas mereka adalah faktor-faktor persekitaran. Banyak kajian lepas menunjukkan bahawa tahap kualiti persekitaran yang rendah akan menyebabkan penurunan prestasi pekerja dan akan meningkatkan masalah kesihatan. Sehingga hari ini, banyak kajian telah dijalankan untuk menentukan tahap optimum terhadap faktor-faktor persekitran tetapi didapati kurang kajian seperti ini dijalankan di Malaysia. Tambahan pula, masih terdapat kekurangan kajian yang dijalankan untuk mengkaji hubungan antara faktor persekitaran terhadap pekerja di dalam bangunan, terutamanya dalam pengudaraan yang menggunakan penyaman udara. Dalam kajian ini mempunyai tiga objektif. Objectif pertama; untuk menyiasat hubungan keselesaan terma dan sensasi terhadap faktor-faktor fisiologi manusia (suhu kulit dan kadar deyutan jantung manusia) di bawah lima suhu bilik yang berbeza dengan tiga aktiviti tugas, kedua; untuk mendapatkan kesan korelasi kesan haba terhadap faktor-faktor fisiologi manusia (suhu kulit dan kadar deyutan jantung manusia) dan ketiga; mencadangan keadaan terma yang optimum berdasarkan faktor-faktor fisiologi manusia (suhu kulit dan kadar denyutan jantung manusia). Kajian ini dijalankan di dalam ruang persekitaran yang tertutup dan terkawal. Kajian ini telah dijalankan dengan tiga tugas aktiviti seperti berfikir, duduk dan menaip dan melakukan percetakan telah simulasikan seperti kerja-kerja pejabat di dalam sebuah bilik. Eksperimen ini diulangi dengan lima suhu bilik (19 ^{o}C, 21 ^{o}C, 23 ^{o}C, 26 ^{o}C dan 29 ^{o}C) di mana untuk mendapatkan satu suhu keselesaan bagi pekerja di pejabat dalam bangunan. Seramai lima belas orang telah terlibat dalam kajian ini. Tempoh eksperimen untuk setiap orang adalah 3 jam 20 minit. Semua parameter dan tugas aktiviti telah direkodkan dalam tempoh 10 minit untuk setiap data. Data faktor-faktor persekitaran dan fisiologi manusia yang diperolehi dianalisis dengan menggunakan analisis statistik dan simulasi. Kajian ini mendapati bahawa julat suhu bilik di antara 19 ^{o}C, 21 ^{o}C, 23 ^{o}C, 26 ^{o}C and 29 ^{o}C dan metabolisma yang berbeza memberikan kadar deyutan dan tahap keselesaan manusia yang berbeza. Analisis suhu kulit menunjukkan bahawa tahap suhu yang berbeza bergantung kepada bahagian badan dan subjek. Penemuan ini dapat mengenal pasti bahagian badan yang paling responsif dan menggunakan data suhu kulit subjek untuk meramalkan kesan haba terhadap subjek. Tambahan pula, penemuan ini menunjukkan bangunan yang menggunakan sistem mekanikal (penyaman udara) sebagai input untuk menjana suhu optimum supaya keselesaan pada subjek dapat dikekalkan pada tahap sekata dan dapat menghalang kesejukan dan panas yang melampau. Keadaan terma yang optimum berdasarkan fisiologi manusia ialah 23 ^{o}C. Pada suhu ini menunjukkan bahawa suhu kulit dan kadar deyutan jantung berada pada tahap yang selesa untuk melakukan tugas pejabat. Kajian ini meningkatkan pemahaman tentang kesan, model dan dalam meramalkan nilai keadaan terma yang optimum bagi mendapatkan suhu yang optimum di dalam pejabat di Malaysia.

ABSTRACT

There is no doubt that hot and cold environment can interfere with human activities, affect the task performance and influence productivity of worker in the building. Environmental factors can be utilized to provide the worker comfort while performing their tasks. Previous studies have indicated that the poor environment level decreased workers' performance and increased their health problems. Nowadays, various studies have been conducted to determine the optimal level of environmental factors. But in Malaysia, few studies were conducted involving the Malaysian workers. Furthermore, there are still lacking of studies conducted in finding the relationship between environmental factors and workers in the building, especially in air conditioning ventilation. This study has three objectives; first, to investigate the relationship of thermal comfort and sensation towards human physiology factors (skin temperatures and heart rate) under room temperatures with three task activities. The second objective is to obtain the significance correlation implication of thermal effect to the human physiology factors (skin temperatures and heart rate). And, the final objective is to propose the optimal thermal condition based on human physiological factors (skin temperatures and heart rate). This study was conducted in a closed and controlled environmental chamber. The experiments were carried out with the activities of thinking, sitting while typing and printing at 3.6 m x 2.4 m x 2.4 m of dimension a simulated office in the chamber. This experiment was repeated under the five room temperatures (19 ^{o}C, 21 ^{o}C, 23 ^{o}C, 26 ^{o}C and 29 ^{o}C) in order to identify the most comfortable temperature for office workers. Fifteen subjects were recruited in this study. The duration of the experiment for each subject is 3 hours 20 minutes. All the studies factors and activities were recorded at an interval of 10 minutes. All the environmental and physiological factors collected data was analyzed using statistical analysis and computer simulation. The study found that the different room temperatures and metabolic rate produced different level of heart rate. It indicates the level of comfort by subjects. Analysis of skin temperature showed that levels of temperatures vary, depending on the body segment considered and the subject. This finding is meaningful in showing the possibility of identifying the most responsive region and using the skin temperature data collected from that point to estimating a subject’s thermal sensation. Furthermore, this study shows the potential application of this finding for buildings that use mechanical systems (air conditioning ventilation) as an input to generate an optimal set-point temperature so that a subject’s thermal sensation could be maintained at the neutral level while preventing over cooling or over heating conditions. The optimal thermal condition based on human physiology is 23 ^{o}C. At this temperature, the skin temperature and heart rate level shown by each subject are at medium level. So, they are comfortable to do their office tasks and lead to increase in performance. The study contributes towards enhancing understanding of determining effects, modelling and predicting the optimal temperatures for office environments in Malaysia.

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LIST OF SYMBOLS

A_{cl}	Surface Area of the Clothed Body (m^2)
A_D	Surface Area of the Nude Body (m^2)
A_r	Effective Radiative Area of the Body (m^2)
C	Heat Transfer by Convection from Clothing Surface (Wm^2)
C_{Res}	Convection by Respiration
E	Evaporation (Wm^2)
E_d	Heat Loss by Water Vapor Diffusion through Skin
E_{re}	Latent Respiration Heat Loss
E_{Res}	Evaporative by Respiration (W/m^2)
$E_{rsw,req}$	Sweat Rate Required for Comfort (W/m^2)
E_{sk}	Evaporative Heat Loss from the Skin
E_{sw}	Heat Loss by Evaporation of Sweat from Skin Surface
f_{cl}	Clothing Area Factor
G	Heat Transfer by Conduction to Solid Substrates
H	Heat Loss
h	Combined Heat Transfer Coefficient (W/m^{2}K)

h_c	Convective Heat Transfer Coefficient (W/m^{2}K)
h_e	Evaporative Heat Transfer Coefficient (Wm^{-2}kPa^{-1})
h_r	Linear Radiative Heat Transfer Coefficient (W/m^{2}K)
I	Energy Input
J	Rate of Change of Heat Storage in the Body
K	Heat Transfer from Skin to Outer Surface of Clothing (Wm^2)
L	Dry Respiration Heat Loss
M	Metabolic Heat Generation Flux (W/m^2)
M_n	Net Flux Density of Metabolic Rate (W/m^2)
P_a	Partial Vapor Pressure (N/m^2)
P_{sa}	Saturated Water Vapor Pressure (N/m^2)
$P_{sk,s}$	Water Vapor Pressure at the Skin
S	Heat Storage (Wm^2)
T	Temperature (^{o}C)
T_a	Air Temperature (^{o}C)
T_{cr}	Core Body Temperature (^{o}C)

T_{eq}	Equivalent Temperature (^{o}C)
T_o	Operative Temperature (^{o}C)
T_r	Radiant Temperature (^{o}C)
T_{re}	Rectal Temperature (^{o}C)
T_{sk}	Skin Temperature (^{o}C)
T_u	Turbulence Intensity
T_w	Wet Bulb Temperature (°C)
t_{cl}	Mean Temperature Over the Clothed Body (^{o}C)
$t_{sk,req}$	Skin Temperature Required for Comfort (^{o}C)
v_a	Indoor Air Velocity (m/s)
R	Heat Transfer by Radiation from Clothing Surface
R_{cl}	Thermal Resistance of Clothing (m^{2}K/W)
$R_{e,cl}$	Evaporative Heat Transfer Resistance of the Clothing Layer (m^{2}kPa/W)
W	Mechanical work (W/m^{2})
w	Skin Wittedness

Greek Letters

$\emptyset$	Relative Humidity (%)
ε	Area Weighted Emissivity of the Clothing Body Surface
σ	Stefean-Boltzman Constant (W/m^2K^4)
σ_u	Standard Deviation of the Air Velocity
$\bar{u}$	Mean Air Velocity

LIST OF ABBREVIATIONS

3D	Three Dimensional
A_{DU}	Body Surface Area
A/D	Analog to Digital
ACMV	Air Conditioning and Mechanical Ventilation
ANOVA	Analysis of Variance
ASCII	American Standard Code for Information Interchange
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ASHVE	American Society of Heating and Ventilating Engineer
BMI	Body Mass Index
CET	Corrected Effective Temperature
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institute of Building Services Engineers
Clo	Clothing Insulation
CumDI	Cumulative Discomfort Index
DAQ	Data Acquisition System
DI	Discomfort Index
DR	Draught
ECG	Electrocardiography
ESI	Environmental Stress Index
ET	Effective Temperature
ET*	New Effective Temperature
h	Hour
HR	Heart Rate

HSI	Heat Stress Index
HVAC	Heating, Ventilation and Air Conditioning
ICOP	Industry Code of Practice
ISO	International Organization for Standardization
ISO DIS	International Organization for Standardization Draft International Standard
ISO/NP	International Organization for Standardization New Proposal
ISO TS	International Organization for Standardization Technical Specification
ITS	Index of Thermal Stress
Max	Maximum
MDI	Modified Discomfort Index
Met	Metabolic Rate
min	Minute
NIFT	Non-Contact Infrared Forehead Temperature
OSHA	Occupational Safety and Health
P4SR	Predicted 4-h Sweat Rate
PC	Personal Computer
PET	Physiological Equivalent Temperature
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
ppm	Parts per Million
RTU	Remote Terminal Unit
SBS	Sick Building Syndrome
SET	Standard Effective Temperature
TAR	Thermal Acceptance Ration

TSI	Thermal Strain Index
UTCI	Universal Thermal Climate Index
WBDT	Wet Bulb Dry Temperature
WBGT	Wet Bulb Globe Temperature
WES	Workplaces Ergonomics Simulator
WHO	World Health Organization

CHAPTER 1

INTRODUCTION

1.1 Introduction

Environmental and economic reasons increased the pressure to design, build and preserve more energy-efficient buildings, such as low energy houses, passive houses and nearly zero energy houses. Improving energy-efficiency will bring unavoidable changes in building service design and its practices. In energy-efficient buildings, the indoor surface temperatures will increase during heating period and this might be due to better building insulation. At the same time, the surface of temperatures tends to decrease because of heating demand decline. Dimensioning criteria of building and heating or cooling systems for future low energy buildings need to be reconsidered to ensure the proper of building service and increase the applicability of renewable low energy sources (for instance, low temperature heating and high temperature cooling). This new design and dimensioning criteria must also ensure the overall thermal comfort of the building occupant.

The increase in the number of buildings in Malaysia not only has a great impact on national development, but it also increases the energy demand (Ahmad et al., 2012). Pusat Tenaga Malaysia recorded that 94 % of electricity generated in the country are from fossil fuels and this figure is expected to remain unchanged until the next decade (UNFCCC, 2010). Mohammad et al. (2014) showed that buildings consumed up to 40 % and it is beyond of total world energy, particularly electricity. It releases up to 1/3 of global contamination/greenhouse gas (GHG) through fossil fuels burning in generating electricity.

Zakaria et al. (2012) highlighted that greenhouse gas emission in the Malaysian existing buildings and its communities had contributed to over 40 % carbon gases to the environment.

During the 1970's oil crisis, many energy efficiency measures were introduced to the Finnish buildings which resulted in occupant discomfort. The current EU 2020 policy aims at reducing drastically the energy use of the building (EU, 2010). Apart from major need for energy renovation measures, the new buildings were proposed to have more insulation than before. These increased insulation levels have been reported to cause overheating problems during the summer. Thus, this might be leading to installing an electricity consuming cooling system. More research is needed to better understand the behaviour of energy efficient building and its relationship to the indoor air quality, comfort, ventilation and energy consumption (Seppanen et al., 1999; Wargocki et al., 2000). There is a quantitative relationship between work performance and space air temperatures as indicated in the comfort zone (Seppanen et al., 2006). Since thermal issues seem likely to be the dominant cause of indoor environmental complaints, it is important to understand the true nature of human thermal sensation and comfort.

To estimate in advance the thermal comfort of a new or renovated building, a thermal comfort calculation method is needed. The widely used Fanger's *PMV* method (Fanger, 1970) is a heat balance model. It views the human being as a passive receiver of thermal stimuli, and assuming the effects of the surrounding environment are assumed and the physics of heat and mass exchanges between the body and the environment described the thermal comfort model.

1.2 Motivation

It is widely accepted that there are multiple factors influencing an occupant's thermal sensation. These environmental factors include variables such as air temperature, humidity, velocity, mean radiant temperature, and individually dependent factors such as metabolic rate and clothing level (ASHRAE 55, 1992). The physical relationships were developed through laboratory studies over the last 80 years (Hoppe, 1999). The thermal comfort is also thought as a process of satisfaction affected by circumstances beyond the physics of the body's heat balance, such as climatic setting, social conditioning, economic considerations and other contextual factors (Brager and de Dear, 1998).

Many researchers suggested that thermal conditions in commercial buildings are generally not favorable for occupants. Schiller et al. (1988) undertook a field investigation of buildings and found that 20 % of building occupants were dissatisfied with the thermal environments of their buildings. Federspiel (1998) analyzed complaint reports from 23,500 occupants in 690 buildings. The author found that 77 % of the respondents claimed that their buildings were either too hot or too cold. The results of the Center for the Built Environment Indoor Environmental Quality (CBE IEQ) survey database, from over 25,000 occupants of 150 US buildings up to November 2004 as illustrated in Figure 1.1. The environmental factors that featured the thermal comfort, indoor air quality, and acoustics make the three very dissatisfied scores. The thermal comfort has the lowest average score.

This result also stated that, a large amount of the nation's energy was used to produce indoor environmental conditions that are not highly appreciated by the inhabitants. Thermal dissatisfaction was most commonly related to human feeling that they did not have enough control over their environment. It is probably not desirable to increase the dissatisfaction rate through attempts to conserve energy.

Many researchers and designers have argued that reliance on ASHRAE Standard 55 has allowed important cultural, social and contextual factors to be ignored, leading to an exaggeration of the "need" for air conditioning. Others have argued that allowing people greater control of indoor environments, and allowing temperatures to more closely track patterns in the outdoor climate, could improve levels of occupant satisfaction with indoor environments and reduce energy consumption. Conversely, the low starting point provides room for improvement in comfort as a possible outcome of improved building operation for every conservator of building energy.

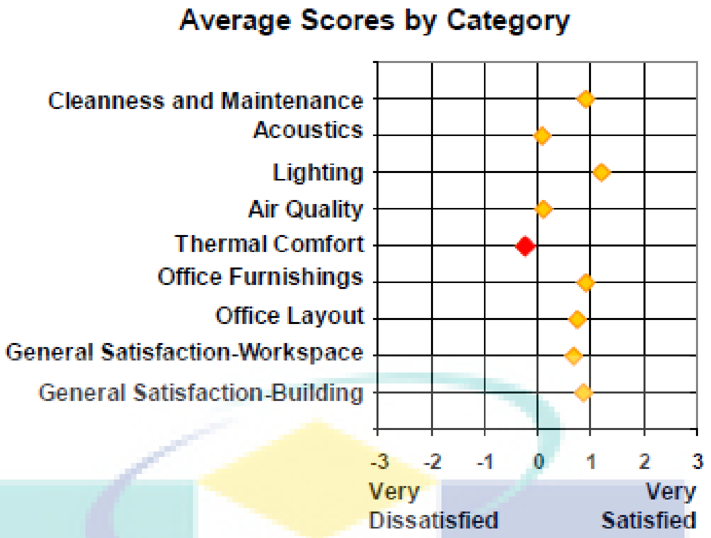


Figure 1.1 Survey Results (25,000 Occupants and 150 Buildings).

Source: CBE IEQ (2004)

1.3 Problem Statement

Malaysia is called to have hot and humid tropical weather conditions. These conditions influenced high temperature and low air flow which effect on comfortable indoor environment. Buildings are subject to the significant cooling requirements due to the high intensity of heat transient from the building envelope. Tropical building design principle can significantly decrease air temperature in the rooms and large energy savings can be achieved (CRC, 2011).

The thermal discomfort occurred when one felt. The body started to move to control this uncomfortable feeling and this produced sweat and that indicated humans are in a hot condition. A similar situation happened when one felt cold and start to rub their hands hoping can generate some heat to reduce cold. If the cold persists, human responded by shivering. These situations were faced by many people everyday. Due to this discomfort conditions, many researchers studied this phenomena and come out with the field study on thermal comfort. There are many thermal comfort studies that have been conducted in the previous years that covered the situation in industrial, school, collages and building sectors. Nowadays, Malaysia is one of the countries that pass through era globalization and modernization due to the rapid growth of industrialization.

The thermal studies that focused on industries and building have been reported by Ismail et al. (2010). Thus, thermal comfort in industrial building skewed to hot temperature but it is differentiated to the problem facing by those who work in the office building. Most modern buildings in Malaysia depend on air conditioning and ventilation system that provide a thermally acceptable working environment as well as for human comfort. It is expected that this resulted in higher productivity and less thermal dissatisfaction. Thus, the main problem is, until now, in Malaysia there is no standard for room temperature air conditioned setting. The most common guideline such as ASHRAE Standard 55 and ISO Standard 7730 do provide reference on thermal comfort and optimum temperature range for indoor environment. However, it is not a universal reference for all regions and types of building. A tropical country such as Malaysia, with hot and humid climate could have a different thermal comfortable range.

1.4 Objectives of the Study

The aim of this study is to illustrate how the outcome of thermal comfort changes under different circumstances and how the thermal comfort effects in regards to the changes in different parameters. In addition, there are three objectives of this study:

i. To investigate the relationship of human physiology factors to occupant comfort in office building (thermal sensation, skin temperatures and heart rate) under multiple temperatures through structured experimentation and computational simulation

ii. To obtain the correlation between thermal effect and human physiology factors

iii. To propose the optimal thermal condition based on human physiology factors

1.5 Scope of Study

The scope of the study is important in order to comply with the main objective with the boundaries of the research. The scopes of this study covered the following conditions:

i. Conduct the thermal comfort study on the physiological (skin temperature and heart rate) and environmental factors that affect human performance. There are six environmental factors which affect the thermal comfort; air temperature, air velocity, humidity, mean radiant temperature, metabolite rate and clo (thermal resistance). The experiments were carried out at the Workplaces Ergonomic Simulator Chamber (WES-103) in Universiti Malaysia Pahang (UMP). The measurement of arrangement accords with ISO 7726 and overall thermal comfort were reported by ASHRAE (ASHRAE Standard 55) 7-point continuous scale.
ii. Perform laboratory experiment that measured skin temperature and heart rate of respondents in a climate chamber.
iii. Chamber temperatures were set at 19 ^{o}C, 21 ^{o}C, 23 ^{o}C, 26 ^{o}C and 29 ^{o}C.
iv. Three types of tasks, namely thinking, sitting on the chair while typing and printing were conducted during the experiment.

Before the experiment start, several assumptions have to be made to obtain results and experimental data stable and uniform. There are:

i. The study was carried out in closed conditioned.
ii. There are no leaks from the ceiling that air can be entered into the chamber.
iii. The effected of wall and ceiling was ignored.
iv. Transferred by the heat from the wall and ceiling was ignored.
v. Another environmental factor such as vibration and noise was ignored.

The area of the study is limited to the assumption of dimension 3.6 m x 2.4 m x 2.4 m office area.

1.6 Significant of Study

Thermal comfort is defined in ASHRAE 55 (2004) as the condition of mind, which expresses satisfaction with the thermal environment. It is affected by heat transfer in the form of conduction, convection and radiation and is maintained when the generated body heat is the equilibrium condition with the surrounding thermal environment. Thermal comfort is determined by six variables: air temperature, mean radiant temperature, air velocity, and relative humidity as environmental factors, as well as clothing (insulation) and activity level (metabolic rate) as human factors (ASHRAE 55, 2004). The environmental and human factors caused heat to exchange between the human body and its surrounding and this lead to human maintaining his constant internal body temperature of 37 °C (Karakitsos and Karabinis, 2008). To sustain such heat balance, the human body uses thermoregulatory principles. When significant heat gain or heat loss occurred, individual thermoregulation may be insufficient to ensure this delicate equilibrium. As a result, thermal stress and thermal discomfort arise when situations were too warm or hot and too cool or cold.

Thermal discomfort is significantly related to individual physiological and psychological mechanisms. Discomfort is linked to thermal stress, which can affect work performance and individual health (Wyon, 1996; Hannula et al., 2000; Witterseh, 2001; Rowe, 2002). Since work performance and individual health's are directly linked to organizational success, to same extent company profits, maintaining the thermal comfort is critical.

The deterministic approach to thermal comfort accepts humans as the passive recipients of the external stimulus and humans evaluate the thermal environment based on expectations. Thermal comfort standards are the detailed versions of this deterministic approach to thermal comfort (de Dear, 2004). However, arguably the most important aspects of thermal comfort, for instance, the physiological and psychological drives that generate a subjective evaluation of the thermal environment. And also, this is not in the comfort standards. One objective of this study is to determine the relationship between the thermal comfort and the physiological signals. The practicality of using the physiological signals as indicators of thermal comfort and as input to thermal environment control is arguable. However, proposals (Mabuchi et al., 1996; Lv and Liu,

2005) for this type of systems were already made and with the advent of the technology, it will be possible to use psychophysiological signals as input to the environmental condition.

This study's objective of increasing set point temperatures while maintaining or improving the thermal comfort has a significant potential for energy savings. Changing of 1 ^{o}C in temperature set points can yield savings of 10 % in heating or cooling costs (Tanabe and Kimura, 1994). Zhao et al. (2004) pointed out that increasing the temperature set point by 3.5 ^{o}C and providing a dynamic airflow environment can save up to 39 % of the total energy in a typical urban office building. Moreover, the perception of the thermal environment has a significant relationship to human productivity (Kosonen and Tan, 2004; Tanabe et al., 2007; Tse and So, 2007). Increasing the thermal comfort by creating a dynamic environment can result in increased productivity. The dynamic environment can be defined relationship of the environment to occupant in the building. This result in a significant monetary gain since worker salaries far exceed the total cost of building energy, maintenance, construction and rental expenses (Woods, 1989; Kosonen and Tan, 2004). Seppanen et al. (2004) showed that better indoor climate conditions improved thermal comfort and workers' productivity, which led to monetary gains.

1.7 Outline of the Thesis

This thesis is constituted from five chapters. These chapters are described as follows:

The first chapter dwells on the topic introduction with a brief background, the objectives and significance of the study.

Chapter 2 presented the literature survey for various topics related to the thermal comfort. Literature survey is a critical discussion of the previous study based on the analyses presented in the following sections. Fundamental concepts of thermal comfort were also discussed including general aspects of thermal comfort, climatic and design dependent elements affecting thermal performance of buildings and recent thermal comfort studies in buildings.

Chapter 3 presented the material and method used to conduct this study. The methodology explained the experiment facility, human subject test design, test protocol and the thermal conditions that were utilized during the tests. This chapter also highlighted the equipment's for data collection, including sensors and the data acquisition (DAQ) system. In addition, it also presented data analysis by engaging statistical and Computational Fluid Dynamics (CFD) methods.

Chapter 4 comprised of data and analysis on the effects of environmental parameters and physiology factors towards respondents' comfort in their work area. The focus has been put on the effect metabolic rate on the different temperature condition. The study uses predicted mean vote (*PMV*) and Predicted Percentage Dissatisfaction (*PPD*) to incorporate the effect comfort in the work area. Physiological responses of thermal comfort including skin temperature and heart rate of respondents are reviewed. Effect of supply air temperature and metabolic rate are analyzed. All the experimental results are compared with *CFD* simulations. Different thermal comfort indices are employed to predict zone of comfort and discomfort.

Chapter 5 concluded the research by summarizing its finding, suggested future study directions and contribution in this study.

The appendices presented the supplemental information related to the design chamber, procedures and the environmental conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter explores the fundamental principles of human thermal comfort in the building, summarizes existing approaches and gives an overview of the key studies undertaken to date. The aim of this chapter is to review the theory thermal comfort and issues that affect health (skin temperature and heart rate) within the building.

2.2 History of Thermal Comfort

The first serious discussions and analyses of thermal comfort emerged during 19th in America. During this era, heating and ventilation systems proved problematic and created uncomfortable environments for occupants. In that era also, the American Society of Heating and Ventilating Engineer (ASHVE) was established in Pittsburgh (Leung, 2008). This organization focused its effort to study ways to create a better indoor thermal environment. The early scope of the research is focused on the working thermal conditions in the industries or hot environments. This happened because industries and countries were moving into an advanced technology status.

In the 1930, more commercial buildings were built and of course more workers were needed. The increasing complaints from these workers about the cold airflow within spaces began to occur. Houghton et al. (1938) investigated of the relationship between air temperature, air velocity and air cooling. Consequently, research studies were developed to establish residential buildings and other working area performance.

Thermal comfort, especially over cooling effect was still the main complaint of building occupants. Today, in Malaysia particularly in office condition still is facing the same problem.

During the last century, the thermal comfort model was developed because they quantitatively based on large surveys of people describe the ranges of conditions where people feel thermally comfortable in buildings. There are two outstanding thermal comfort models:

i. Comfort model as proposed by Fanger.
ii. The Adaptive Comfort Model which takes into account the adaptation to the prevailing climate of occupants of buildings.

From a physiological point of view, the early endeavor to understand the regulatory system of the human body temperature dated back to Blagden (1775). He used a thermometer in a heated room. His experiments were about human ability to endure high temperatures. Richet (1885) found the ideas of brain regulations in temperature understanding. In 1930s, Gagge started working on human heat exchange processes (Gagge, 1937; Winslow et al., 1936; Winslow et al., 1937; Gagge et al., 1941). American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) adopted the predicted thermal comfort model based on a thermal equilibrium approach in 1969 (Gagge et al., 1969).

The first idea of body heat transfer was introduced by Hill et al. (1897). In 1914, the authors made a thermometer which integrated the influence of mean radiant temperature, air temperature and air velocity. Later, Dufton (1929) defined the equivalent temperature (T_{eq}). This equivalent temperature, however, was no longer applied because environmental variables were not covered in the algorithms (Yongping and Jiuxian, 1999; Ouzi et al., 2001). However, ASHRAE proposed and used the effective temperature, ET, from 1919 till 1967 (Hanqing et al., 2006). In 1971, Gagge introduced ET* which was more accurate than ET because it covered simultaneously radiation, convection and evaporation. ET* defines the new effective temperature. Table 2.1 showed the development of indices related to the thermal comfort models.

Table 2.1 Chronological Development of Indices Related to Thermal Comfort

Year	Index	Author
1897	Theory of heat transfer	Hill et al. (1897)
1905	Wet bulb temperature (T_w)	Haldane (1905)
1914	Katathermometer	Hill (1916)
1923	Effective temperature (ET)	Houghton and Yaglou (1923)
1929	Equivalent temperature (T_{eq})	Dufton (1929)
1932	Corrected effective temperature (CET)	Vernon and Warner (1932)
1937	Operative temperature (T_o)	Winslow et al. (1937)
1945	Thermal acceptance ratio (TAR)	Robbinson et al. (1945)
1947	Predicted 4-h sweat rate (P4SR)	McArdle et al. (1947)
1948	Resultant temperature (RT)	Missenard (1948)
1955	Heat stress index (HSI)	Belding and Hatch (1955)
1957	Wet bulb globe temperature (WBGT)	Yaglou and Minard (1957)
1957	Oxford index (WD)	Lind and Hallon (1957)
1957	Discomfort index (DI)	Thom (1959)
1958	Thermal strain index (TSI)	Lee (1958)
1960	Cumulative discomfort index (CumDI)	Tennenbaum et al. (1961)
1962	Index of thermal stress (ITS)	Givoni (1962)
1966	Heat strain index (corrected) (HSI)	McKarns and Brief (1966)
1966	Prediction of heart rate (HR)	Fuller and Brouha (1966)
1970	Predicted mean vote (*PMV*)	Fanger (1970)
1971	New effective temperature (ET*)	Gagge et al. (1971)
1971	Wet globe temperature (WGT)	Botsford (1971)
1971	Humid operative temperature	Nishi and Gagge (1971)
1972	Predicted body core temperature	Givoni and Goldman (1972)
1972	Skin wettednes	Kerslake (1972)
1973	Standard effective temperature (SET)	Gonzalez et al. (1974)
1973	Predicted heart rate	Givoni and Goldman (1973)
1986	Predicted mean vote (modified) (PMV*)	Gagge et al. (1986)
1999	Modified discomfort index (MDI)	Morans et al. (1999)
1999	Physiological equivalent temperature (PET)	Hoppe (1999)
2001	Environmental stress index (ESI)	Moran et al. (2001)
2001	Universal thermal climate index (UTCI)	Jendritzky et al. (2001)
2005	Wet bulb dry temperature (WBDT)	Wallace et al. (2005)

Source: Taleghani et al. (2013)

The Predicted Mean Vote–Predicted Percentage of Dissatisfied (*PMV–PPD*) model developed by Fanger (1970) used six primary factors defining thermal comfort. Four of these factors were related to the environment, namely air temperature, radiant temperature, air speed and relative humidity. The other two individual factors were clothing insulation and metabolic activity.

The *PMV–PPD* model (Fanger, 1970) is based on a large sample of subjects recruited mostly from college age students. However, facing the increasing number of elderly people in the population, the question arises wheather the model is applicable for any subpopulation. The elderly do not perceive thermal comfort differently from their younger counterparts, when factors such as activity level or clothing were considered (Havenith, 2001; van Hoof and Hensen, 2006; DeGroot et al., 2006). However, the thermoregulation ability tends to decrease with the increasing age (Havenith, 2001). This implies that, even when the preferred temperature is the same for young and elderly, the deviations from the optimum condition affected the elderly to a greater extent.

A comprehensive literature review on gender differences in thermal comfort was presented by Karjalainen (2012). The females were generally more likely to express dissatisfaction with their thermal environment. Although no clear difference was revealed in terms of neutral temperature, women seem to be more sensitive to deviations from optimum leading to more complaints, especially in cooler conditions. This is in the line with the findings of Schellen et al. (2012) who reported that the hand skin temperature was highly important for overall thermal sensation in cooler conditions, especially for females.

The lower the tolerance of women compared to men is explained by an optimal temperature range. This is because, men have a smaller total and lean body mass, larger body surface and lower resting metabolic rate. However, due to their greater body fat content, this should allow them to tolerate lower ambient temperatures better (Kaciuba-Uscilko and Grucza, 2001). This is supported by the finding of Tikuisis et al. (2000) whom compared the thermoregulatory responses of men and women immersed in cold water. No significant differences occurred between the two genders, when the body fatness and the ratio of body surface area to size were taken into account.

Body fat is one of the most important thermophysiological differences between individuals. Both the conduction of heat transfer and blood flow were influenced by body fat. The complex interrelations between human morphology and thermoregulation make it difficult to isolate one component and describe its impact (Anderson, 1999).

People with a higher percentage of body fat generally have a higher level of activity, hence they preferred a lower temperature (Zhang et al., 2001).

Savastano (2009) studied the core, fingernail bed and abdominal skin temperature of obese and normal weight adults under thermoneutral conditions at rest. The abdominal subcutaneous fat depot was selected because it is the most homogeneous across all participants with regard to the absence of prominent surface vessels. The core temperature did not differ significantly between the obese and normal weight persons. However, infrared thermography-measured fingernail-bed temperature was significantly higher in obese subjects than in normal weight subject. Conversely, the abdominal skin temperature was significantly lower in obese subjects than in normal weight subjects (Savastano, 2009). Increasing the heat release of the hands may offset heat retention in areas of the body with greater fat percentage, thereby helping to maintain the normal temperature in obesity. This indicates that the heat loss through the hands of obese subjects increased to compensate for the lower heat loss through the body, where the subcutaneous fat is damming the heat losses. The lower heat loss by the insulation layer also explains why obese subjects preferred a lower temperature than normal weight persons. The body pursues a similar core temperature, whether a person is obese or of normal weight.

Another approach to thermal comfort, which has been incorporated in the ASHRAE Standard 55 (2004), is the adaptive model introduced by de Dear and Brager (1998). The adaptive model is an approach to comfort that starts with the behavioral adaptations rather than with the heat exchange theory. This adaptation is a two-way process. People adapt themselves to their thermal environment by changing their clothing insulation, their posture, or their activity. They also adapt the thermal environment to the current requirement by actions such as opening windows, adjusting blinds, and adjusting the heating or cooling. By these adaptations people are in dynamic equilibrium with their surroundings (Humphreys et al., 2013).

The partial and whole body thermal sensations of the human body are related to changing skin and core temperatures. Non-uniformities in environmental conditions (air temperature, air movement, radiation, and conduction to surfaces) affect the skin temperature of the body’s various parts, affecting a person's overall thermal sensation and comfort in complex ways. Even in spatially and temporally uniform environments, the body's skin temperatures are distributed non-uniformly (Huizenga et al., 2004).

In a uniform thermal environment, the overall thermal sensation follows the local one that is furthest from neutral, and the overall comfort follows the worst local discomfort votes (Arens et al., 2006). Thermal sensation and comfort correlate quite well in uniform environments. A neutral sensation correlates to the best comfort; warmer and cooler sensations correlate to reduced comfort. Generally, the head is the most sensitive area of the body in warm conditions and the feet, hands, and back in cool conditions (Arens et al., 2006).

Thermal environments created by personalized conditioning are often spatially non-uniform or transient. In a non-uniform environment, the influence of the individual body parts on the overall sensation varies greatly. The most influential group consists of the back, chest, and pelvis. Sensations from these body parts have a dominant impact on overall sensation. The least influential group includes the hand and foot at the end of the extremities where vasodilatation and vasoconstriction are strongest (Wang et al., 2007; Zhang, 2003). The meaning of vasodilatation refers to the widening of blood vessels while vasoconstriction referring to the narrowing of blood vessels (Guyton and Hall, 2006).

In non-uniform environments the relationship between sensation and comfort is more complex. The identical cool face sensation may be perceived as comfortable when the whole body is warm or uncomfortable when the whole body is cold. Therefore, non-uniform environments are not necessarily less desirable than thermal neutrality, but they can actually produce better comfort than a uniform neutral condition.

Zhang et al. (2010) found that the overall thermal comfort can be based on local comfort only, without any need to include local sensation information. Overall comfort is actually close to the two most uncomfortable votes, so the least comfortable local votes have the most significant influence. Averaging the two least comfortable votes gives the best prediction of the overall comfort. If the subject has some control over his/her thermal environment (e.g., controllable radiant panel) or the thermal conditions are transient, than overall comfort is the average of the two minimum votes and the maximum comfort vote. To keep the whole body comfortable, eliminating the most uncomfortable local votes has the highest priority. This suggests the use of task ambient systems.

As the individual differences based on age, gender or body fat content showed, thermal comfort is not only a simple function of the thermal environment, but it is also influenced by a whole set of individual factors. It is generally very complicated to capture all these influences on thermal comfort and nearly impossible to find an optimal thermal environment for a group of individuals. Thermal neutrality is considered to provide the best comfort, but this does not respect the individual preferences (van Hoof, 2008). Therefore, the thermal environment needs to become personalized in order to fit different preferences of each individual.

2.2.1 Overview of Thermal Comfort

Typically, senses or feeling comfortable relate to the definition comfort when human in a home or building. Hensen (1991) defined the thermal comfort as a state in which there are no driving impulses to correct the environment by the behavior. So, whatever the meaning of thermal comfort is, Djongyang et al. (2010) pointed out it will be influenced by personal differences in mood, culture and other individual organizational and social factor. There were studies that reported that emphasized the judgment of comfort is a cognitive process involving many inputs influenced by physical, physiological and psychological (Lin and Deng, 2008). Cena and Clark (1981) reviewed there categories of science that influenced the thermal comfort, namely:

i. Physics: How human regulates the thermal environment, including clothing

ii. Physiology: The mechanisms of thermoregulation and acclimatization and their variation with age and health

iii. Psychology: The perception of comfort and discomfort and its relation to other competing stimuli

Generally human's thermal sensation of feeling is different from each other even in a similar environment or place. Indeed, human staying in very similar spaces, subjected to the similar climate, and belonging to a common culture, differs in opinions on thermal comfort due to the combination of a large number of factors that affect the human perceptions. Hensen (1991) suggested that thermal discomfort is treated as a subjective condition while thermal sensation is an objective sensation. Ogbonna and Harris (2008) found that the satisfaction with the thermal environment is a complex subjective response to several interacting and less tangible variables. The comfort occurred when the body temperatures were held within narrow ranges, skin moisture is low, and the physiological effort of regulation is minimized. Comfort also depends on behavioral actions such as altering clothing, altering an activity, changing posture or location, changing the thermostat setting, opening a window, complaining, or leaving a space.

Figure 2.1 illustrated six factors that affecting thermal sensation. These factors are indoor air temperature, indoor air velocity, indoor humidity and mean radiant temperature, another two personal variables consists clothing insulation and activity level such as metabolic rate.

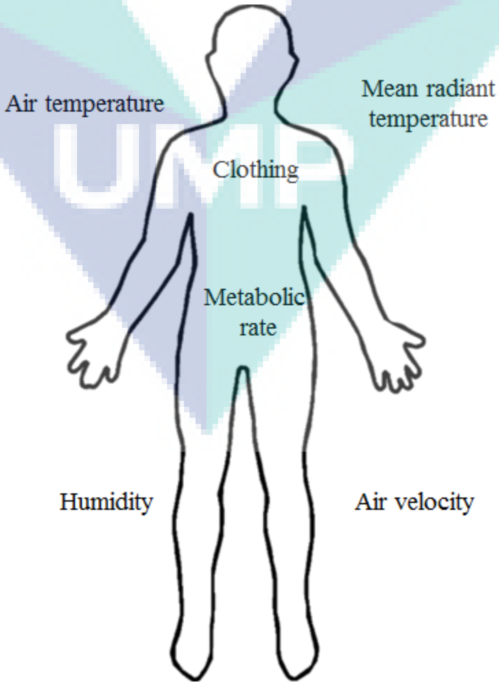


Figure 2.1 Parameters of Thermal Comfort.

Air Temperature, T_a

Parsons (2003) defined air temperature (T_a) is a measurement that determines how cold or hot the air is. More specifically, temperature describes the kinetic energy or enegy motion of the gases that make up air. As gas molecules move more quickly, air temperature increases. Alternatively, T_a is the dry bulb temperature, which is the most significant factor in determining the energy balance, comfort, discomfort, thermal sensation and perception of air quality. It can be measured by mercury in glass thermometer shielded from direct heat radiation and suspended in air (Moss, 1998).

The Workplace Health, Safety and Welfare Regulations (2013) stated that the temperature in the workplace should provide reasonable comfort without the need for special clothing (jacket). Previous research on thermal comfort in the workplace stated that an acceptable zone of thermal comfort for most people in the UK is between 13 °C and 30 °C, with acceptable temperatures for more strenuous work activities concentrated towards the bottom end of the range, and more sedentary activities towards the higher end. Additionally, the Guide A Environmental Design (Environmental Criteria for Design), suggested that for offices, the temperature range for comfort should be 21-23 ºC in winter and 22-24 ºC in summer. The World Health Organization (WHO) also recommended a similar maximum working temperature in building as 24 ^{o}C (WHO, 2011).

The comfortable feeling was very subjective in nature and cannot be defined objectively. Frequent changes in office space arrangement and the huge amount of the cables brought about by the extensive use of computers make the implementation of air conditioning office a necessity (Wan and Chao 2002). Naturally ventilated building designs can perform efficiently in a hot climate country like Malaysia because of their low evaporation rate, long hours of sunshine, high relative humidity and very overcast cloud. Dahlan et al. (2008) proposed that buildings are designed to enable natural ventilation with energy conservation and saving in mind.

Results of a study in Germany, which was conducted on workplace occupant satisfaction in 16 office buildings revealed that the occupant’s control of the indoor climate and moreover the perceived effect of their intervention strongly influences their satisfaction with the thermal indoor quality (Wagner et al., 2007). This finding points out that there is not even one standard or regulation for setting air-conditional in workplaces. Overall, the study on thermal comfort emphasize the importance of thermal comfort for office occupants and highlight that achieving thermal comfort in offices not only delivers more satisfaction for the occupants, but also improves their performance (Nazanin et al., 2008).

Seppanen and Fisk (2005) reported that the air temperature within 20-23 ^{o}C may improve work performance while any increase beyond this range may lead to negative productivity. This is consistent with a study in the Tropics climate, which revealed that office workers preferred a slightly cooler work environment within the range of 20-24 ^{o}C (Tham, 2004). Wyon and Wargocki (2005) postulated that the room air temperature seems to affect the office work by lowering arousal, elevating Sick Building Syndrome (SBS) symptoms and reducing manual dexterity (ability to use the hands to perform a difficult action skillfully and quickly so that it looks easy). The SBS used to describe a situation in which the occupants of a building experience acute health or comfort.

Ailu and Victor (2012) investigated on the prevalence of SBS symptoms and thermal comfort in Singapore. They found that the prevalence of individual SBS symptoms is lower than the similar studies in other geographic regions. Overcooling seems to be the domineering complaint in the local context and the occupants seem to prefer a higher indoor temperature. Hence, human behavioral adjustments such as adding clothing happen quite frequently. Moreover, the data suggested that cultural traits might skew the survey results, especially in certain subjective aspects regarding the satisfaction level and comfort.

Many local field studies have reported the phenomenon of overcooling in Air Conditioning and Mechanical Ventilation (ACMV) offices in recent years, but only little known about the occupant’s reactions to overcooling and the potential energy efficiency impact. Foo and Poon (1987) found that 60 % of the occupants worked in ACMV offices with air temperatures less than 24 ^{o}C. They suggested that an air temperature of 27 ^{o}C might be good enough to satisfy more than 80 % of the occupants. Dear et al. (2001) studied 235 respondents’ thermal comfort levels in ACMV offices.

Their results indicated that the mean thermal comfort vote was 0.34, which deviated slightly from neutrality on the cool side. Cheong et al. (2003) investigated thermal comfort of college students in an ACMV lecture theater. The results revealed that the occupants were slightly uncomfortable and dissatisfied with overcooling. All these studies mainly aimed to understand human thermal comfort states assuming that the subjects were 'passive sensors' of the thermal conditions. Nonetheless, Nicol and Humphreys (2002) suggested that people are active adaptors to environmental stimuli.

Air Velocity, v_a

Air velocity (v_a) is the air movement varies in time, space and direction (Parsons, 2003). The air velocity in combination with air temperature, will affect the rate at which warm air or vapor is 'taken' away from the body. Thus, affecting body temperature. A right value of air velocity might reduce the heat stress through the evaporation on the skin in a space of low relative humidity. High speed air velocity, however, causes discomfort due to dryness in the respiratory organs, ocular systems and skin (Moon, 2009). According to Moss (1998), the air velocity can be measured using anemometer, which detect air velocity all directions.

Pursuant to Toftum (2004), the air velocity in ventilated spaces has a significant influence on occupant's thermal comfort. If a human feels from neutral (comfort) to cold, air velocity tends to be perceived as draught, an unwanted local cooling of the skin. On the other hand, if a person feels warm, then air velocity could generate the desired cooling, which moves their thermal assessment towards neutral (Xai et al., 2000). In warm conditions higher air speeds could be used to offset an increase in temperature (Arens et al., 1998), where acceptance of the increased v_a requires occupant control of the local air speed.

Xai et al. (2000) reported an annoying effect (dry eyes, tensioned skin and blocked breath) when high velocity was used to restore the neutral state at high temperature. They suggested that the definition of draught should be extended to cover both the cooling and the annoying effect. The cyclic air velocity has also been used to cool humans during hot conditions. Tanabe and Kimura (1987) found that the air velocity in a sinus wave pattern with a frequency of 0.016-0.1 Hz was perceived as cooler than a constant one. The air motion with a frequency of 0.3-0.5 Hz is most preferred when subjects are in the neutral to warm condition (Xai et al. 2000). This could be compared with the findings from Fanger and Pedersen (1977) whom suggested that the airflow with a frequency of 0.3-0.5 Hz caused most uncomfortable draught feelings when subjects are in a cool to neutral state.

Indoor Humidity

Parsons (2003) stated that if liquid such as water or sweat is heated by a human body, evaporates into a vapor and is lost to the surrounding environment, then the heat has been transferred from the body to the environment and the body is cooled. The ‘driving force’ for this vapor (or mass) transfer is the difference in mass per unit volume of moist air. It is the difference in absolute humidity (mass concentration or density of water vapor) between that at the skin surface and that in the environment. The ‘driving force’ for heat loss is considered to be the difference in partial vapor pressures between that of the skin and that in the environment. The absolute humidity, kg/m^3 and partial vapor pressure, P_a, kPa by the gas laws and temperature of the vapor, T (Kerslake, 1972):

$$Absolute\ humidity = 2.17\frac{P_a}{T} \tag{2.1}$$

The humidity of the environment is therefore a basic parameter. It can be expressed in a number of forms, however, two are commonly used which is relative humidity and partial vapor pressure. Relative humidity, $\emptyset$ (often given as a percentage) is the ratio of the prevailing partial pressure of water vapor to the saturated water vapor pressure:

$$\emptyset = \frac{P_a}{P_{sa}} \tag{2.2}$$

where the partial vapor pressure, P_a (N/m^2) is the prevailing partial pressure of water vapor in the air, while P_{sa} (N/m^2) is the saturation water vapor pressure.

Human comfort, productivity, and a sense of health and well-being are the positive outcome of a healthy indoor environment where the indoor air is fresh and free from odors, dust and other contaminants. Human comfort depends on a complex interaction of multiple variables with humidity being only one of them. However, optimizing both temperature and relative humidity satisfies the comfort requirements for a wider variety of occupants as opposed to regulating temperature only.

Alahmer and Omar (2013) stated that the low indoor air relative humidity results in human discomfort. Headache, irritated eyes, sore throat, and dry skin are all symptoms of a dry indoor environment. Dry air lowers the natural defense against airborne infections and makes human vulnerable to the attack of viruses and other micro-organisms. In addition to the problems associated with low humidity, too high humidity can also cause problems. These problems are related to the growth and spread of unhealthy biological pollutants and to the damaging effect of moisture on the construction materials.

VAISALA (2010) points out the typically humans are less sensitive to humidity than temperature. They generally fail to associate discomfort and potential health problems with variations in relative humidity. This is where a good technology can support the human senses. A reliable humidity measurement is the key to successful humidity control. The recommendations for indoor air relative humidity vary from country to country. The ASHRAE Standard 55 specifies that to decrease the possibility of discomfort due to low humidity, the dew point temperature should not be less than 2.8 °C. This equals to 30 % relative humidity in 21 °C. The upper dew point limit is specified to 16.7 °C, which equals to 76 % relative humidity in 21 °C.

Health and Safety Executive (2014) in the United Kingdom recommends a relative humidity in the range of 40 to 70 % in the workplace environment. At higher temperatures, the relative humidity should be at the lower end of this range. Similarly to Occupational Safety & Health Administration (OSHA) United States, recommends controlling indoor air humidity in the range of 20-60 %.

Radiant Temperature, T_r

Parson (2003) defined the radiant temperature (T_r) as the temperature of a uniform enclosure with which a small black sphere at the test point would have the same radiation exchange as it does with the real environment. While, the ISO 7726 (1998) defines the radiant temperature is the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure. Furthermore, the radiant temperature of the human body can be calculated from the temperature of surrounding surfaces and their orientation with respect to the human body. The equation is (McIntyre, 1980),

$$T_r = T_g + 2.44\sqrt{v_a}\left(T_g - T_a\right) \tag{2.3}$$

where,

T_g is globe temperature

Clothing

Clothing provides a thermal resistance between the human body and the environment. It is functional to maintain the body in an acceptable thermal state in a variety of environments. Hens (2011) reported that clothing helps in staying comfortable in environments that are too cold for the activities going on. It increased the thermal resistance of the skin, limit the heat loss and keep up the average skin temperature. Parson (2003) examined the thermal behavior of clothing on an active person and focused that it was complex and dynamic, not fully understood and was difficult to quantify. What is known is to date is mainly derived from theoretical and empirical research. There are factors affecting the thermal behavior of clothing, namely:

i. Dry thermal insulation

ii. Transfer of moisture and vapor through clothing (such as sweat, rain)

iii. Heat exchange with clothing (conduction, convection, radiation, evaporation and condensation)

iv. Compression (caused by high wind)

v. Pumping effects (caused by body movement)

vi. Air penetration (such as through fabrics, vents and openings)

vii. Subject posture

Nishi (1981) proposed the practical unit of clothing insulation and called *clo*. It represents the effective insulation provided by a normal business suit worn by a sedentary worker in comfortable indoor surroundings. The value of one unit *clo* is arbitrarily set at 0.155 m^2K/W.

Metabolic Rate

The metabolic rate refers to the rate at which energy is released from food into the body cells (Moss, 1998). It is affected by a person's size, body fat, sex, age, hormones and activity level. The *Met* is equal to the metabolic rate for a seated adult at rest and is equivalent to 58 W/m^2 of body surface. Table 2.2 represents a list of the metabolic rate in units of the Met and W/m^2 for different levels of activity.

Table 2.2 Metabolic Rate for Different Levels of Activity

Activity	**Metabolic Rate**	
	Met	**W/m^2**
Lying down	0.8	45
Seated quietly	1.0	58
Sedentary work-seated at work	1.2	70
Light activity-bodily movement on foot	1.6	93
Medium activity-bodily movement including carrying	2.0	117
High activity	3.0	175

Source: Parsons (2003)

Kroemer et al. (1997) stated that the human body maintains a balance (homeostasis) between energy input and output. The input is determined by the nutrients, from which chemically stored energy is liberated during the metabolic processes within the body. The output is mostly heat and work with work measured in terms of physically useful energy which is energy transmitted to outside objects. The amount of such external work performed strains individuals differently depending on their physique and activity.

Astrand and Rodahl (1986) used an analogy between the human body and an automobile. They said that the cylinder of the engine, an explosive combustion of a fuel air mixture transforms chemically stored energy into physical kinetic energy and heat. The energy moves the pistons of the engine and gears transfer their motion to the wheels of the car. The engine needs to be cooled to prevent overheating. Waste products are expelled. This whole process can work only in the presence of oxygen and when there is fuel in the tank. In the human machine, muscle fibers are both cylinders and pistons: bones and joints are the gears. Heat and metabolic by products are generated while the muscles work. Nutrients (mostly carbohydrates and fats) are the fuels that must be oxidized to yield energy.

The term metabolism includes all chemical processes in the living body. In a strict sense, here it is need to describe the (overall) energy yielding processes.

The balance between energy input, I and outputs can be expressed as (Kroemer et al., 1997):

$$I = M = H + W + S \tag{2.4}$$

where M is the metabolic energy generated which is the sum of the heat H that must be dispelled to the outside, the work W performed and the energy storage, S in the body (positive is increases, negative if it decreases).

Since the early 1970s, the work done by Fanger (1970) stipulates that being thermoneutral guarantees comfort because in this optimal case, no specific cold or warm sensation is expected in normal subjects. However this conclusion is, not accepted by everybody. On the contrary, the same work states that not being thermoneutral leads to discomfort. This point in under debate since many studies leads to the conclusion that being a little warm much better. The ISO 7730 is based on Fanger’s work, which also links the percentage of dissatisfied people to the thermal sensation symmetrically on either side of thermoneutrality.

2.2.2 Heat Balance of Human Body

Allen (1995) reported that the human body is in its most fundamental mechanical behavior, a heat engine. The fuel engine is derived from food in the form of proteins, carbohydrates and fats.

Rowe (2001) pointed out that human thermal comfort depends on a balance between the rate of production of metabolic heat and losses due to exchange with the surrounding environment. It is well established that the heat balance depends on physical variables and personal variables. The physical variables can be controlled by design procedures but the designers have no such control over the personal variables. According to Fanger (1970) and Djonyang et al. (2010), the static energy balance of the human body is the equation of metabolic rate, physical work performed and the heat loss of the body. In the state of static balance the energy balance should be zero.

According to Fanger (1970) the static energy balance of the human body is the equation of metabolic heat, physical work performed and the heat loss of the body. In the state of static balance the energy balance should be zero. Bartal et al. (2012) stated that the comfort sensation (thermal comfort) of an active person is agreeable (optimal) if the following criteria are met:

i. The static energy balance describing the thermal and mechanical connection between the human and his environment is zero, and the result of the heat produced and lost as well as the performed work is zero

ii. Human skin temperature remains within a narrow range.

iii. Perspiration remains within a given range.

According to the experiments skin temperature in the state of agreeable thermal comfort depends on metabolism only and heat loss through perspiration is similarly linked to metabolic heat in a defined statistical connection.

Equation 2.5 is an application of the First Law Thermodynamics which described the energy conservation and therefore satisfies the requirement that the sum of heat inputs, outputs and storage must be zero (Monteith, 1973; Campbell, 1977). For practical purposes the components of the heat balance are usually expressed in power per unit area of the external surface of the body. A convenient algebraic expression is given as in Eq. (2.5):

$$M_n + R + H + G + J = 0 \tag{2.5}$$

where,

M_n = The net flux density of metabolic heat, W/m^2
R = The net radiative energy exchange between the surface and its surrounding
H = The total heat transfer by convection with the surrounding medium
G = The heat transfer by conduction to solid substrates
J = The rate of change of heat storage in the body. The numerical value of J will therefore be negative when the body temperature is rising, for example when storage is contributing to heat dissipation

Because the environment is usually specified in terms of temperature and humidity, H is usually divided into convection, C and evaporation, E; both carried by convective processes, so that:

$$H = C + E \tag{2.6}$$

The most significant landmark in the thermal comfort research and practice was the publication of a thermal comfort book by Fanger (1970), which outlines the conditions necessary for the thermal comfort and methods and also principles for thermal environments evaluate and analyze with respect to the thermal comfort. It is the combination of the thermal effect of all the physical factors which determines the human thermal comfort and that a practical method was required which could predict conditions for ‘average thermal comfort’ and its consequences.

Fanger (1970) used a mathematical model based on a steady state energy balance to calculate Predicted Mean Vote (PMV). The author listed three conditions for a person to be in a state of thermal comfort, namely:

i. The body is in heat balance

ii. Sweat rate is within comfortable limits

iii. Mean skin temperature is within comfortable limits

The objective was to produce a comfort equation requiring input of only the six parameters and based on the above mentioned three conditions to calculate condition for thermal comfort. Fanger's original work was old in imperial unit. The SI version presented by Olesen (1982), ASHRAE (1993) and ISO 7730 (1994) and the expression presented as in Eq. (2.6):

$$H - E_d - E_{sw} - E_{re} - L = K = R + C \qquad (2.7$$

where,

H = Internal heat production in the human body
E_d = Heat loss by water vapor diffusion through skin
E_{sw} = Heat loss by evaporation of sweat from skin surface
E_{re} = Latent respiration heat loss
L = Dry respiration heat loss
K = Heat transfer from skin to outer surface of clothing
R = Heat transfer by radiation from clothing surface
C = Heat transfer by convection from clothing surface

Heat is generated in the body and lost in the skin and from the lungs. It is transferred through clothing where it is lost to the environment. Heat balance is a necessary but not a sufficient condition for comfort. The body can be in heat balance but uncomfortably hot due to sweating or uncomfortably cold due to vasoconstriction and low skin temperatures. Skin temperatures and sweat rates required for comfort $t_{sk,req}$

$E_{rsw,req}$, depend upon activity level. In 1971, Rohles and Nevins provided the related terms as expressed as in Eq. (2.8) and (2.9):

$$t_{sk,req} = 35.7 - 0.0275(M - W) \quad (2.8)$$

$$E_{rsw,req} = 0.42(M - W - 58.15) \quad (2.9)$$

where,

M = Metabolic rate
W = Mechanical work

According to Huynh (2001), the heat generation is equal to heat removal when humans are in thermal equilibrium with the environment. The heat generation is the internal heat production, which is the difference between the metabolic rate, M and the mechanical work, W as shown in Equation 2.10. However, mechanical work, W is commonly assumed to be zero for several reasons, namely:

i. The mechanical work produced is small compared to metabolic rate, especially for office activities

ii. Estimates for metabolic rate can often be inaccurate

iii. The assumption results in a more conservative estimate when designing air conditioning equipment

By substituting Eq. (2.8) and (2.9) into the heat balance equation, the methods of combination of the six basic parameters which produce thermal comfort are expressed as in Eq. (2.10):

$$\begin{aligned} H &= M - W \\ E_d &= -3.05[5.73 - 0.07(M - W) - P_a] \\ E_{sw} &= -0.42[(M - W) - 58.15] \\ E_{re} &= -0.0173M(5.87 - P_a) \\ L &= -0.0014M(34 - t_a) \\ R &= 3.96 \times 10^{-8} f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4] \\ C &= f_{cl} h_c (t_{cl} - t_a) \end{aligned} \quad (2.10)$$

where,

$$t_{cl} = 35.7 - 0.0275(M - W) - 0.155I_{cl}\,[(M - W) - 3.05(5.73 - 0.007(M - W) - P_a\,) - 0.42[(M - W) - 58.15] - 0.0173M(5.87 - P_a - 0.0014M(34 - t_a\,)) \tag{2.11}$$

$$h_c = \max(2.38(t_{cl} - t_a)^{0.25}\,, 12.1\sqrt{v} \tag{2.12}$$

$$\begin{aligned} f_{cl} &= 1.0 + 0.2I_{cl}\,for\ I_{cl}\ \leq 0.5 \\ &= 1.05 + 0.1I_{cl}\,for\ I_{cl}\ > 0.5 \end{aligned} \tag{2.13}$$

where,

t_{cl} = Average surface temperature of clothed body, ^{o}C

h_c = Convection heat transfer coefficient, W/m^{2}K

f_{cl} = Ratio of clothing surface area to DuBois surface area

In order to determine how these six parameters affect the human comfort, the thermal sensation scales were established. Fanger (1970) developed the Predicted Percentage of Dissatisfied (*PPD*), a method used to estimate unacceptable conditions for occupants. According to the *PPD* method, if 95 % of the occupants in the building are satisfied then the environment is classified as comfortable. However, *PPD* is based on the Predicted Mean Vote (*PMV*) which is used to predict an occupant's thermal sensation follow by the environmental parameters. Therefore, to obtain *PPD*, the *PMV* must calculate first. Table 2.3 represents the relationship between the thermal sensation scale and the *PMV* numerical values.

The numerical values of the scale in the Table 2.3 diminished. A scale is thus obtained which is easier to remember, as it is symmetrical around the zero point, so that a positive value corresponds to the warm side and a negative value to the cold side of neutral.

Fanger related *PMV* to an imbalance between the actual heat flow from the body in a given environment and the heat flow required for optimum comfort at a specific

Table 2.3 Standard Thermal Sensation Scale

Thermal Sensation	**Vote Number (*PMV*)**
Hot	+3
Warm	+2
Slightly Warm	+1
Neutral	0
Slightly Cool	-1
Cool	-2
Cold	-3

activity level. *PMV* can be expressed as a function of metabolic rate, *M* and thermal load on the body, which is the difference between the heat generation and the heat removal and is represented by *L*:

$$PMV = \quad [0.303e^{-0.036M} + 0.028]L \tag{2.14}$$

Furthermore, Fanger related *PMV* to *PPD* and expressed *PPD* as a function of *PMV* and given as:

$$PPD = \quad 100 - 95e^{[-(0.03353PMV^4+0.2179PMV^2)]} \tag{2.15}$$

Figure 2.2 showed the flow chart showing sensible and latent heat flows from the human body to the surrounding climate. Moss (1998) suggested the thermal criteria which trigger each mode of heat transfer. Heat balance can be drawn such as that the heat generated to maintain a core temperature of 37.2 ^{o}C is equal to the bodily heat loss to its surrounding. A practical approach is therefore to consider heat production (*H*) within the body ($M - W$), heat loss at the skin ($C + R + E_{sk}$) and the heat loss due to respiration ($C_{res} + E_{res}$) (Parson, 2003).

Sensible heat loss, $(R + C)$:

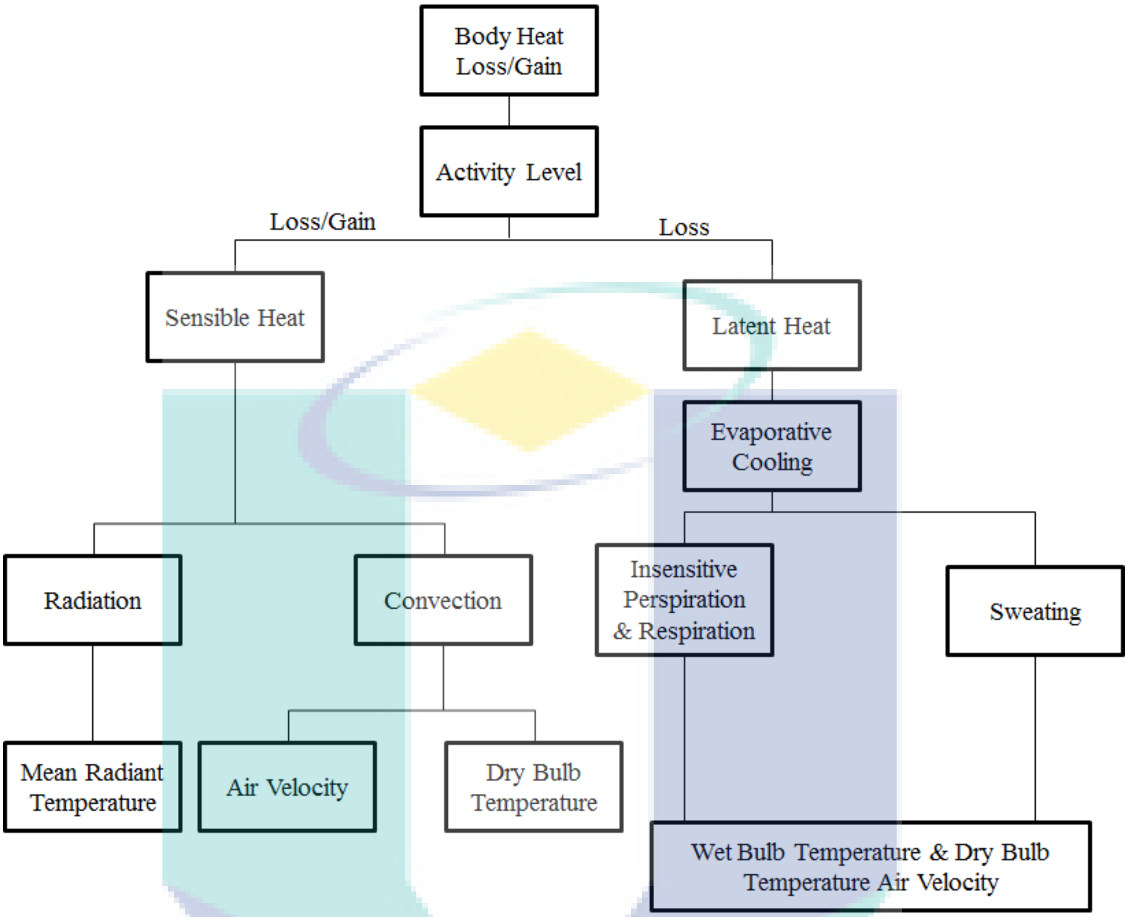


Figure 2.2 Heat Energy Flows Between the Human Body and the Surrounding Climate.

Source: Parson (2003)

ASHRAE (1997) listed the following Eq. (2.16):

$$\begin{aligned} C &= f_{cl}h_c(t_{cl} - T_a) \\ R &= f_{cl}h_r(t_{cl} - T_r) \\ C + R &= f_{cl}h(t_{cl} - T_o) \end{aligned} \tag{2.16}$$

where,

$$T_o = \frac{(h_rT_r + h_cT_a)}{h_r + h_c} \text{ and } h = h_r + h_c \tag{2.17}$$

where,

T_o = Operative temperature, °C
h_c = Convection heat transfer coefficient, W/m^{2}K
h_r = Radiant heat transfer coefficient, W/m^{2}K

The actual transfer of heat through clothing by conduction, convection and radiation modes can be combined into a single thermal resistance value, R_{cl}. Therefore, the $C + R$ can be represented as follows:

$$C + R = \frac{(T_{sk} - t_{cl})}{R_{cl}} \tag{2.18}$$

Combining Eq. (2.16) and (2.18) to remove t_{cl},

$$C + R = \frac{(T_{sk} - T_o)}{\left(R_{cl} + \frac{1}{f_{cl}h}\right)} \tag{2.19}$$

Parson (2003) stated that Air temperature (T_a), radiant temperature (T_r) and the thermal resistance of clothing (R_{cl}) are parameters which must be measured or estimate to define the environment. Mean skin temperature can be estimated as a constant value such as around 33 °C for comfort and 36 °C under heat stress or can predicted from a dynamic model of human thermoregulation. Mitchell (1974) defined the heat transfer coefficient for a seated person which is given below:

$h_c = 8.3{v_a}^{0.6}\ for\ 0.2 < v_a < 4.0$
$h_c = 3.1\ for\ 0 < v_a < 0.2$

The radiative heat transfer coefficient h_r can be given by Eq. (2.20),

$$h_r = 4\varepsilon\sigma\frac{A_r}{A_D}\left[273.2 + \frac{t_{cl} + T_r}{2}\right]^3 \tag{2.20}$$

where,

ε = The area weighted emissivity of the clothing body surface

σ= Stefan-Boltzmann constant, 5.67×10^{-8} W/m^{2}K^4

A_r = Effective radiative area of the body, m^2

A_D = The surface area of the nude body, m^2

ε is often assumed to be between 0.95 to 1.0, however A_r/A_D can be estimated as 0.70 for sitting person and 0.73 for a standing person (Fanger, 1967); T_r is a basic parameter and t_{cl} must be calculated using iteration techniques. ASHRAE (1997) suggested that a value of h_r= 4.7 W/m^{2}K is a reasonable approximate for ‘typical indoor conditions’.

Evaporative Heat Loss from the Skin (E_{sk})

In 1997, ASHRAE presented the evaporative heat loss from skin and written as,

$$E_{sk} = \frac{w(P_{sk,s}-P_a)}{\left[R_{e,cl}+\frac{1}{f_{cl}h_e}\right]} \tag{2.21}$$

where,

$$w = 0.06 + 0.94\frac{E_{rsw}}{E_{max}}$$

h_e is calculated using the Lewis Relation $h_e = LRh_c$. This is an important development in the establishment of the body heat balance equation allowing comparison and combination of dry and evaporative heat transfer.

Heat Loss from Respiration ($C_{res} + E_{res}$)

Heat loss from respiration is by ‘dry’ convective heat transfer due to cool air being inhaled, heated to core temperature in the lungs and heat transferred in exhaled air to the environment (C_{res}). In addition, inhaled air is moistened by the lungs. When exhaled, therefore there is a mass (heat) transfer from the body core to the outside environment (E_{res}). ASHRAE (1997) gives the following Eq. (2.21) for total respiratory heat loss,

$$C_{res} + R_{res} = [0.0014M(34 - T_a) + 0.0173M(5.87 - P_a)] \tag{2.22}$$

where,

P_a = Water vapor pressure in the ambient air (kPa)

Figure 2.3 shows the components of heat transfer indoor the building that affected the thermal comfort. Each surface area in the room will be in radiant exchange will all other surfaces and will be in convective heat exchange with the air within the space.

Figure 2.3 The Heat Affected of Thermal Comfort Indoor the Building.

Table 2.4 shows human and environment by the mode of influence heat transfer. Heat is lost by evaporation of moisture, both from skin and respiratory tract, accounting for at least a 20 % of the total heat loss (one-third of the respiratory tract and two thirds of the skin surface). Evaporative heat loss is of great importance as it is the only means of dissipation when the environmental temperature is greater than the body temperature. This occurs due to the ability to sweat and allows thermoregulation under a relatively large range of environmental conditions. (Hardy and Stolwijk, 1966).

Table 2.4 Factors Influencing each of the Heat Transfer Modes

Mode of Transfer	**Individual Characteristics**	**Environmental Characteristics**
Radiant	Mean radiant temperature of surface; effective radiating area; reflectivity and emissivity	Mean radiant temperature solar radiation and reflectivity of surroundings
Convective	Surface temperature; effective convective area; radius of curvature and surface type	Air temperature; air velocity and direction
Conductive	Surface temperature; effective contact area	Floor temperature; thermal conductivity and thermal capacity of solid material
Evaporative	Surface temperature; percentage wetted area; site of evaporation relative to skin surface	Humidity; air velocity and direction

Source: Ingram and Mount (1975)

2.2.3 Standard of Thermal Environment

The main purpose of the ASHRAE 55 standard is to specify the combinations of indoor thermal environmental parameters (temperature, thermal radiation, humidity, and air speed) and personal parameters (clothing insulation and metabolism rate) that will produce thermal environmental conditions acceptable to a majority of the occupants.

In the1990s, ASHRAE appointed de Dear and Brager (1997) to conduct a specific research project to collect information from a lot of different field studies performed in several countries, namely: Thailand, Indonesia, Singapore, Pakistan, Greece, UK, USA, Canada and Australia (see Figure 2.4).

The Malaysian Meteorological Department had characterized Malaysian climate as one with high humidity, harsh temperature and abundant rainfall. In Malaysia it is very rare to have a complete day with complete clear sky even during periods of dry weather. It is unusual to have a few days without sunshine (MOSTI, 2013). Figure 2.4 showed that Malaysia (in circle) is in the tropical climate religion. Malaysia is located in between latitude 4^{o} 12' N / 101^{o} 58' E. This makes Malaysia 8 hours ahead of Greenwich Mean Time (GMT). Due to its latitude and longitude position, it has a variation in temperature ranging from 32 °C in the day time, to 22 °C in the night, with little or no variation in temperature throughout the country (Brager and de Dear, 2001). Taufiq et al. (2007) stated that several studies indicated that ambient temperature plays a vital role in relation to energy consumption of air conditioning system. Figure 2.4 also stated that in different areas of the world, thermal comfort is based on climate.

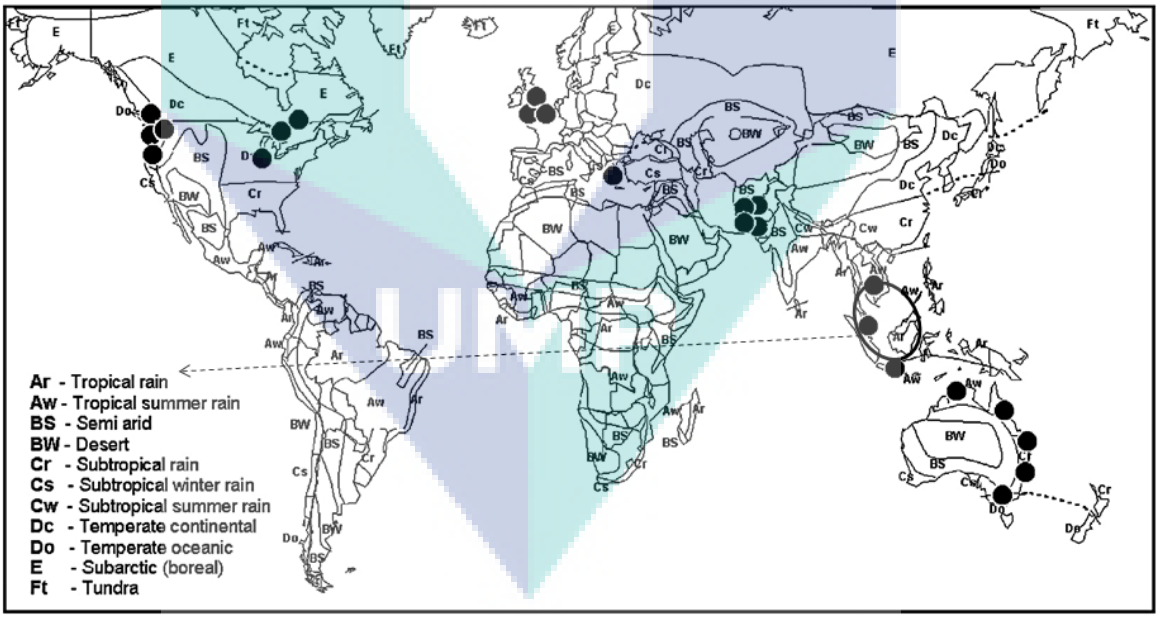


Figure 2.4 The Geographic Distribution Studies that Formed the Basis of the Adaptive Model and Adaptive Comfort Standard of ASHRAE.

Table 2.5 showed that an overview of the standards issued and documents for the ergonomics of the thermal environment. According to Olesen (2001), several of these standards may be used as a basic for the design and evaluation of buildings, HVAC (heating, ventilation and air conditioning) system, protective equipment (clothing) and optimization of work rest schedules. Light, noise, air quality and the thermal environment are all factors which will influence the acceptability and performance of the occupants.

Table 2.5 Development of International Standard of the Thermal Environment

Objective of the Standard	**Title of the Standard**	**Name of Standard**
General presentation of the set of standards in terms of principles and application	Ergonomics of the thermal environment: Principles and application of international standards	ISO EN 11399
Standardization of quantities, symbols and units used in the standards	Ergonomics of the thermal environment: Vocabulary and symbols	ISO 13731
Thermal stress evaluation in hotel environments -Analytical method	Hot environments: Analytical determination and interpretation of thermal stress using calculation of required sweat	ISO 7933 EN 12515
-Diagnostic method	Hot environments: Estimation of the heat stress on working man, based on the WBGT index (wet bulb globe temperature)	ISO EN 7243
Comfort evaluation in moderate environments	Moderate thermal environments: Determination of the PMV and PPD index and specification of the conditions for thermal comfort	ISO EN 7730
Thermal stress evaluation in cold environments	Evaluation of cold environments: Determination of required clothing insulation, I_{req}	ISOTRENV 11079
Data collection standards		
-Metabolic rate	Ergonomics: Determination of metabolic heat production	ISO 8996 EN 28996
-Requirements for measuring instruments	Thermal environments: Instruments for measuring physical quantities	ISO 7726
-Clothing insulation	Estimation of the thermal insulation and evaporative resistance of a clothing ensemble	ISO EN 9920
Evaluation of thermal strain using physiological measures	Evaluation of thermal strain by physiological measurements	ISO EN 9886

Table 2.5 Continued

Subjective assessment of the thermal environment	Assessment of the influence of the thermal environment using subjective judgment scales	ISO EN 10551
Selection of an appropriate system of medical supervision for different types of thermal exposure	Ergonomics of the thermal environment: Medical supervision of individuals exposed to hot or cold environments	ISO DIS 12894
Contact with hot, moderate and cold surfaces	Ergonomics of the thermal environment: Methods for assessment of human responses to contact with surfaces	ISO TS 13732
Vehicle environments	Evaluation of the thermal environments in vehicles	ISO/NP 14505
People with special requirements	Ergonomics of the thermal environment: the application of international standards for people with special requirements	ISO 14415
Assessment of risk in moderate, hot and cold environments	Risk assessment strategy for the prevention of stress or discomfort in thermal working conditions	ISO 15265
Work practice in cold environments	Risk assessment and management	ISO 15743

Ha (2008) reviewed the thermal comfort work by the global institutions such as ASHRAE, the Chartered Institute of Building Services Engineers (CIBSE), the ISO as well as the European Committee for Standardization. These organizations have produced standards concerning on thermal comfort in one way or another.

2.2.4 Indoor Environment

Thermal comfort is an important way that occupants experience the indoor environment, and it can have large impacts on their health and productivity. Several factors can affect the thermal comfort, but only the air velocity, humidity, air temperature, and mean radiant temperature can be predicted and controlled by architects and engineers through the design of a building and mechanical systems.

One could argue that the main objective of a building is to provide an environment which is acceptable to the building users. Whether or not the indoor climate is acceptable, it depends mainly on the tasks which have to be performed in case of commercial buildings, whereas in domestic buildings acceptability is more related to user expectation.

As illustrated in Figure 2.5, a building's indoor climate is determined by a number of sources acting via various heat and mass transfer paths. These sources are (Hensen, 1991):

i. The outdoor climate of which - in the present context - the main variables are: air temperature, radiant temperature, humidity, solar radiation, wind speed, and wind direction
ii. Occupants who cause casual heat gains by their metabolism, usage of various household or office appliances, lighting, etc.
iii. Auxiliary system which may perform heating, cooling, and/or ventilating duties.

The mode of heat and mass transfer processes that influenced the indoor climate are as follows:

i. Conduction through the building envelope and partition wall radiation in the form of solar transmission through transparent parts of the building envelope, and in the form of long wave radiation exchange between surfaces
ii. Convection causing heat exchange between surfaces and the air, and for instance heat exchange inside plant components
iii. Air flow through the building envelope, inside the building, and within the heating, cooling, and/or ventilating system
iv. Flow of fluids encapsulated within the plant system.

The indoor climate may be controlled by the occupants basically via two mechanisms. These are terms as human and mechanical control:

i. By human control, one can alter the building envelope or inner partitions by opening doors, windows, or vents, or by closing curtains, lowering blinds, etc.

ii. Scheduling or adjusting the set point of some controller device is a form of mechanical control which may act upon the auxiliary system or the building by automating the tasks.

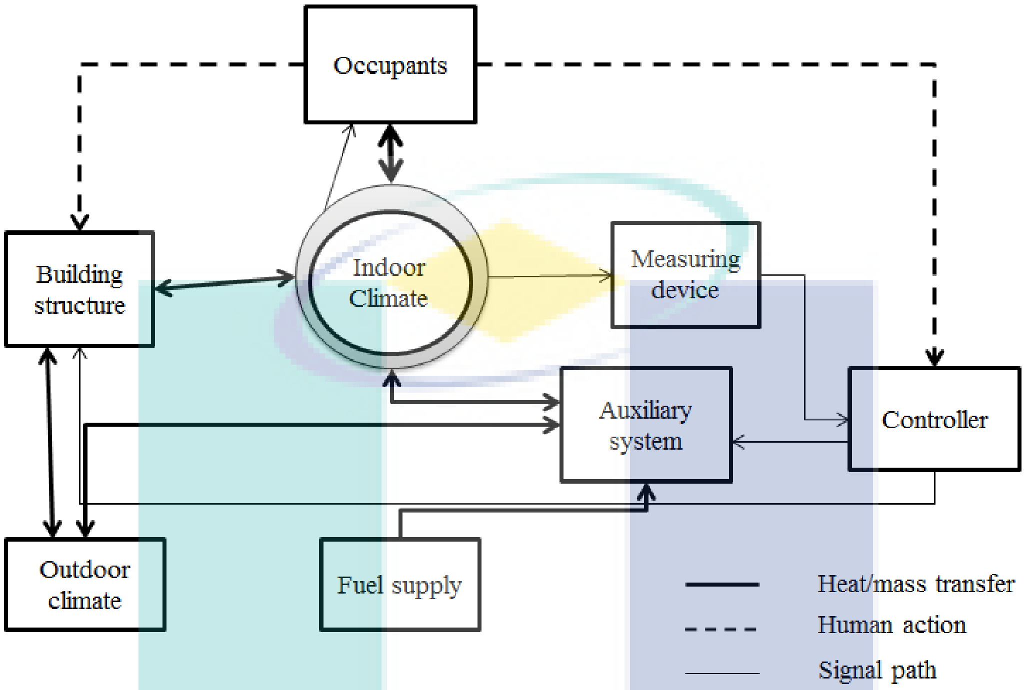


Figure 2.5 Diagrammatic Representations of Building and Plant.

Source: Hensen (1991)

Thermal environment refers to the circumstances comprising of several physical factors such as air temperature and humidity, air velocity and the surface temperature of the surrounding objects. The indoor thermal environment is affected by the ambient conditions through the external and internal heat exchanges of a building. A building's thermal process has a dynamic status during the day and varies from season to season according to the external climate fluctuations. Passive environmental systems such as building envelope insulation, passive solar radiation, shading devices, natural ventilation and thermal mass, in conjunction with night ventilation, will play the role of regulator in achieving a comfortable indoor thermal environment. However, in some poor weather conditions, normally in both summer and winter, passive systems are not capable of achieving a thermally comfortable environment. As a result, a mechanical system such as heating and cooling is required. Good passive building designs can ‘produce’ the indoor thermal environment according to variations in the outdoor climate, meanwhile, it can prevent heat losses in winter and heat gains in summer thus reducing the burden on mechanical systems as far as possible. Liu et al. (2012) stated that in China, during the spring and autumn seasons, many buildings are free-running (not heated or cooled). Occupants interact with environmental systems in order to achieve thermal comfort through adaptations (physiological, psychological and behavioral). The mechanism of achieving thermal comfort involves ‘creation’ and ‘adaptation’ behaviors from both environmental systems and people, is shown in Figure 2.6.

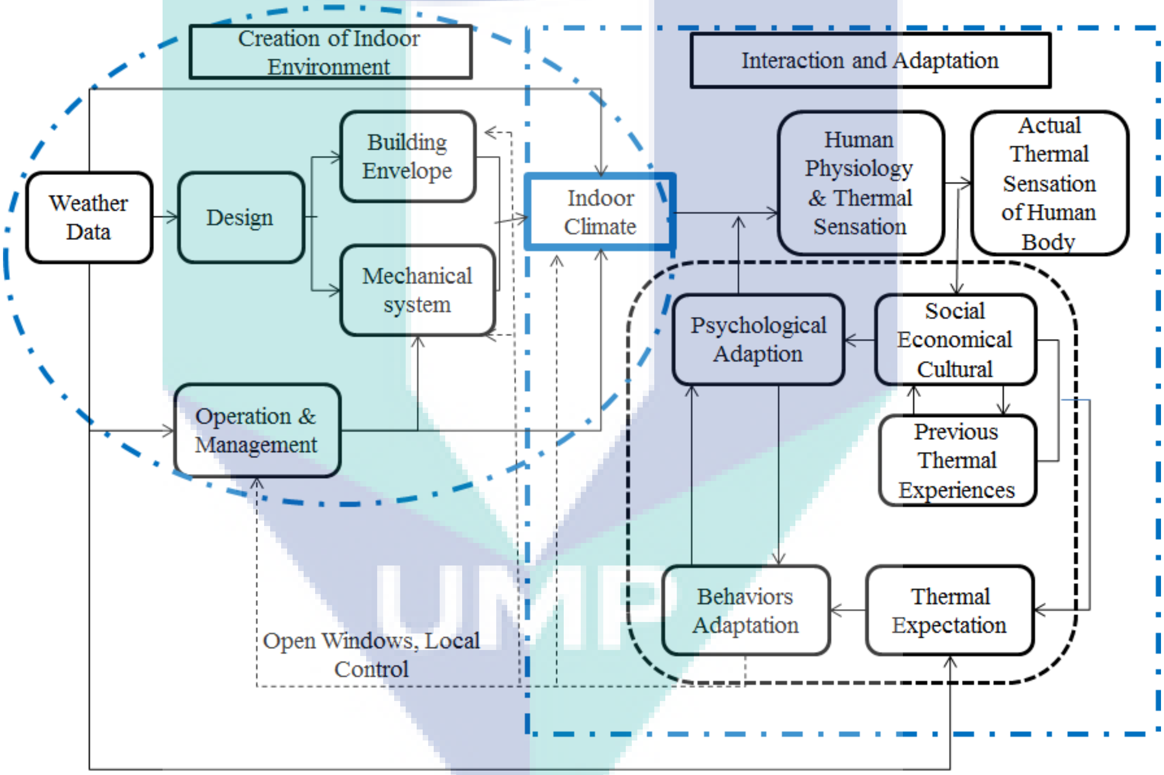


Figure 2.6 Mechanism of Adaptive Thermal Comfort.

Source: Li et al. (2014)

The principle of adaptive thermal comfort is defined as if change occurs, such as to produce discomfort, people react in ways which tend to restore their comfort (Nicol and Humphreys 2002). Recent research (Liu et al., 2012) carried out in free-running buildings in China demonstrates that occupants are active players in environmental control and their adaptive responses are driven strongly by ambient thermal stimuli and vary from season to season and from time to time, even on the same day. Thermal adaptation is a dynamic process of behaviors involving technological, personal, and psychological adaptations in response to varied thermal conditions.

2.3 Factors of Body Temperature and Thermoregulation

Thermal comfort is strongly related to the thermal balance of the body. This balance is influenced by heat exchange between body and environment, human body measurement and variable individual characteristics.

2.3.1 Environmental Conditions

The dependency of the heat exchange between body and environment with the ambient temperature is widely acknowledged with its corresponding effect on skin temperature (Nielsen and Nielsen, 1984; Kaynakli and Kilic, 2004; Nagano et al., 2005; Yanagisawa et al., 2007). This can be easily observed by exposing the subjects to a step change in temperature. A sudden change in the room temperature can be in the form of either positive (from lower to higher temperature) or negative (from higher to lower temperature). For a positive (negative) step the surface temperatures increase (reduce) both at naked skin and clothed areas, until it reaches to the optimal temperature for the environment. Once it reaches the optimal temperature, it is kept reasonably constant with few fluctuations due to the human regulatory system (Tortora and Grabowski, 2002). The relation between the mean skin temperature and the environmental conditions is given by Houdas et al. (1972). Thermal conductivity and blood flow of the skin has also changed with the environmental temperature. Thermal conductivity at different room temperatures was given by Burton and Edhlom (1955) and Werner and Reents (1980). Basal and maximum skin blood flow was measured for different room temperatures by Werner and Reents (1980).

Physiological parameter such as tympanic, rectal and mean skin temperature, metabolic rate and evaporative heat loss depends on the current and previous environmental temperature. This is because of the different time response of the physiological parameters to environmental changes, skin temperature and evaporative heat loss being the fastest (Hardy and Stolwijk, 1966). Also small, rapid ambient temperature swings about the ideal temperature seem to increase the skin temperature without increasing the variance of skin temperature with time, showing that the time constant of skin temperature response to heat and cold is different (Wyon et al., 1973). In the opposite case, Wyon et al. (1973) observed that larger, slower temperature swings about the ideal temperature increase the variance with time of skin temperature, without altering the average skin temperature.

2.3.2 Anthropometric Characteristics

In order to investigate thermal conditions in the building, some kind of human body measurement is necessary. Human body measurement must have an appropriated geometry in order to both influences the environment and have the heat transfer. In this section, the anthropometric characteristics that discus are age, gender and *BMI*.

Age

The effect of age on the thermoregulatory response of subjects when exposed to cold or heat is controversial, partially difficult of separating chronological age from other factors which change in concert with the biological aging process (Inoue et al., 1992; Havenith et al., 1995). Inoue et al. and Havenith et al. studied the relative influence of age by fixing other anthropometric parameters such as on body fatness and surface area: mass ratio. Inoue et al. observed that the heart rate, blood flow, rectal and mean skin temperature were not significantly different during equilibrium (T_a =28 ºC) (air temperature). However, when exposed to cold, the decrease in T_{re} (body core temperature) and $\bar{t}_{sk}$ (mean skin temperature) and the increase of blood flow was significantly greater for the older men. There was no mark different in the heart rate. With respect to the exposures to warm humid environment, Havenith et al. observed that chronological age affects the cardiovascular effector’s responses such as heart rate, arterial blood pressure, forearm blood flow and vascular conductance. However, the effect on body temperature, sweating, heat storage and heat loss was negligible. Park et al. (1997) observed that the blood flow statistically decreases with the age of the subjects, being a 32 % lower for elders compared to teenagers. Hodges et al. (2010) observed that cutaneous and forearm peak vasodilator capacity decrease non-linearly with the age, and so does the resting value at forearm, being males more severely affected than females. Inoue et al. concluded that old age has a limiting factor for the development of both cold and heat tolerances, perhaps suggesting a reduced adaptive temperature range.

Gender

The thermoregulatory control in women has been experimentally proved to be different due to the reproductive hormones (Charkoudian et al., 1999) and vary with the phase of the menstrual cycle (Webb, 1993). The decay of cutaneous and forearm peak vasodilator capacity is greater for males than females (Hodges et al., 2010). The gender loses its relevance in variance of the heat storage, body core and skin temperature, heart rate, blood pressure and skin blood flow when the maximal oxygen intake or other anthropometric data are included in the prediction equation (Havenith and van Middendorp, 1990).

Physical Fitness or fat

The constitution of a person can be partially characterized by his/her percentage of body fat, assessed in different ways (Durnin and Womersley, 1974; Webb, 1992), the surface area to mass ratio or the Body Mass Index (*BMI*).

BMI is the most widely used tools to identify obesity problems as it is calculated based on the ratio of weight and height of a person (Eq. 2.22). This index is used to measure the obesity level of the human (see Table 2.6) by assessing how much the weight departs from what is normal for a human a specific height. However, *BMI* does not consider the factors such as frame size and muscularity. Hence, the defined categories should not be used in special cases such as athletes, children, and elderly. In case of children and teenagers (2 to 18 years old) the thresholds are dynamic and defined in relation to the distribution of *BMI* values of the same age population. In Malaysia, the National Health and Morbidity Survey (2010) reported that in adult males, 15.1% were overweight and 2.9% obese while in adult females, 17.9% were overweight and 5.7% obese. As Malaysia proceeds rapidly towards developed economy status, there is a need to develop a national strategy to tackle both dietary and activity contributes to the excess weight gain of the population. *BMI* is defined as a person's weight in kilograms (kg) divided by his or her height (m^2). *BMI* is given by Eq. (2.22).

$$BMI = \frac{weight}{height^2} \tag{2.22}$$

Table 2.6 *BMI* Categories

Category	***BMI* Range (kg/m^2)**
Severely underweight/anorexic	$BMI < 16.5$
Underweight	$16.5 \leq BMI < 18.5$
Normal	$18.5 \leq BMI < 25.0$
Overweight	$25.0 \leq BMI < 30.0$
Obese class I	$30.0 \leq BMI < 35.0$
Obese class II	$35.0 \leq BMI < 40.0$
Severely obese	$40.0 \leq BMI < 45.0$
Morbidly obese	$45.0 \leq BMI < 50.0$
Super obese	$50.0 \leq BMI < 60.0$
Hyper obese	$BMI > 60.0$

Source: World Health Organization (2011)

2.3.3 Variable Individual Characteristics

In this study, there are at least four individual characteristics need to be understood. These variables are into related to some extent and the metabolic rate is the variable being considered in the experimental work.

Metabolic Rate or Activity

Metabolic rate is a major component on the thermoregulation. It rules the total heat loss and heat stored in the body in a given ambient conditions (Mairiaux et al., 1987). There is a significant time lag between metabolic rate and heat loss and core temperature, but still, the rectal temperature is related to the activity level of sleep (50 W) to hard sustained exercise (600 W), increasing with the activity level from 36 to 39 ºC for the extreme cases (Webb, 1993). The relation between core temperature and metabolic rate also exists in cooled subjects (Hayward et al., 1977).

The distribution of the skin temperature and its mean responds to the type of activity and its intensity (Nielsen and Nielsen, 1984; Mairiaux et al., 1987; Havenith et al, 1995a). In cold or neutral conditions, a change on the activity from rest to exercise causes the skin temperature to drop and subsequent by and progressively increase as exercise continues (Saltin et al., 1968). However, discrepancies appear in warm environments, where some believe the skin temperature increase with the metabolic rate (Givoni, 1963), and others believe them to be independent (Missenard, 1973).

These apparent discrepancies reflect the complex interactions between core and skin temperature (Mairiaux et al., 1987). Movements of limbs or body, typical of sports or working conditions, produce convective cooling (Nielsen and Nielsen, 1984). Hence, different activities of equivalent metabolic rate might induce different skin temperatures (Mairiaux et al., 1987; Adams, 1977). In the case of inability of moving the extremities, a lower mean skin temperature is observed by Svedberg et al. (2005). They detected temperature on the hand palm and on the foot dorsal in non-walking children to be around 0.85 and 1.1 °C, lower than healthy children, respectively. This is almost twice the standard deviation of the temperature distributions. In cold environments (around 16 and 19 ºC), muscular movement of the extremities promotes blood circulation and hence increasing skin temperature (Huizenga et al., 2004).

Kondo et al. (2010) studied the effects of exercise and its intensity. Exercise increases the threshold for cutaneous vasodilatation, however it does not seems affect the threshold for the onset of sweating. On the other hand, higher exercise intensities decrease the sensitivity of the skin blood flow and increase the sensitivity to the body temperature of the sweating response.

Clothing

Clothing affects the distribution of skin temperature by increasing the thermal insulation of the covered parts of the body, and thus decreasing the heat exchange between the body surfaces and the environment (Nielsen and Nielsen, 1984). It also affects the level of acclimation of human to the cold environment situation (Li et al., 2009). Hence, it ought to be taken into account in the predictive model (Mairiauxet et al., 1987). The level of thermal insulation and evaporative resistance of a garment or an ensemble provides depends on the type of clothing (material, thickness, number of layers), as tabulated by Standard 9920 (2007).

Table 2.7 Clothing Insulation Values for a Clothing Ensemble (ISO 9920)

Garment	**No.**	**Type**	**Weight (g)**	I_{chi} (***clo***)	$\mathbf{m^{2}\,{}^{o}CW^{-1\,a}}$
Underpants	80	briefs	80	0.04	0.006
Undershirt	31	T-shirt	180	0.10	0.016
Coverall	120	work	890	0.51	0.079
Overtrouser	191	Heat protective felt	1300	0.33	0.051
Over jacket	193	Heat protective felt	1620	0.42	0.065
Socks	254	Ankle length	61	0.02	0.003
Shoes	255	Suede, rubber soles	499	0.02	0.003
Total ensemble	489	Heat protective clothing	4630	1.55 (I_{cl})	0.240

Source: ISO 9920

The difference in the clothing has little effect over the skin temperature at normal room temperature while it becomes significant at higher stress levels (increased activity and/or air temperature) (Holmer et al., 1992). In cool environments, clothing may be associated with an increase on skin temperature (Vogt et al., 1983) while it has a marked cooling effect in warm environments as the unevaporated sweat may accumulate and wet the clothing, creating a microclimate (Craig, 1972; Mairiaux et al., 1987).

Hair and the ‘dead air’ (air enclosed in a very narrow space like between skin and clothing) can be treated as clothing. Long hair decreases the heat transfer coefficients for the head and neck due its insulative properties (de Dear et al., 1997) while ‘dead air’ provides a great thermal insulation, estimated to be 1.85 *clo* units (Burton and Edhlom, 1955), which is comparable to the best-insulating fur of animals (ISO 9920, 2007).

Emotions

Emotions such as fear, sadness, anger, frustration, amusement or boredom are known to affect some of the physiological signal of the body, like skin temperature, galvanic skin response and heart rate (Kreibig et al., 2007; Lisetti and Nasoz, 2004; Nasoz et al., 2010). Also mental arithmetic, mental testing, pain, noise and emotional stimuli affect sweating at palm and forearm (Ogawa, 1975). Finding unique physiological patterns for the recognition of emotions would lead to a more friendly and sympathetic human-machine interaction.

Acclimation

Long term exposures to heat stress causes behavioural, morphological and physiological changes on the individuals, i.e. decrease the metabolic rate (Bligh, 1976) or increase the volume of sweat-double after 20 days (Edholm, 1978) and lower its concentration (Ingram and Mount, 1975). This affects the mean skin temperature, which lower for acclimatized subjects (Candas, 1980). Hence, acclimatization factor should be included in mean skin temperature prediction formulas (Mairiaux et al., 1987).

2.3.4 Core Temperature

The core body temperature refers to the temperature of all tissues located at a sufficient depth so they are not affected by a temperature gradient through surface tissues (ISO 9886, 2004). It is considered an important indicator of the health status (Dollberg et al., 1993). It is also used to detect and prevent heat-related illnesses (Hoppe, 2002) such as heat exhaustion or heat stroke in athletes during long exercise (Newsham et al., 2002). Core body temperature remains within a narrow physiological range (Stolwijk and Hardy, 1966).

Core temperature is a concept and not practically measurable. Several approximation methods are proposed (Togawa, 1985; ISO 9886, 2004) such as oesophageal temperature, intra-abdominal temperature, oral temperature, auditory canal temperature, urine temperature, rectal temperature, or tympanic temperature. However, these authors only observed the mean temperature of the body mass or temperature of the blood supplied to the brain and therefore influencing the thermoregulation centers in the hypothalamus.

2.3.5 Skin Temperature

Skin temperature distribution is a physiological response that combines the effect of thermal environments, clothing and type of activity. It is the parameter of interest for the evaluation of thermal balance and cold stress (Nielsen and Nielsen, 1984; Mitchell and Wyndham, 1969) and the thermal comfort (Hoppe, 2002). Skin temperature provides fast information to central circuits, which promptly initiate corrective action even before the hypothalamus temperature is affected, such as shivering or sweating (Rosenzweig and Leiman, 1989), and rules the amount of heat exchanged between a person and the environment (Mitchell and Wyndham, 1969).

Local skin temperature is measured on the basis of environmental conditions (temperature and humidity), personal circumstances (clothing and activity) and personal characteristics (gender and constitution) (Werner and Reents, 1980; Houdas and Ring, 1982; Webb, 1992; Huizenga et al., 2004; Munir et al., 2009; Burton and Edhlom, 1955; Olesen and Fanger, 1973). However, local skin temperature map with self-clothed adults undertaking low level activities while sitting in mild environmental temperatures has not been investigated sufficiently when it represents a great percentage of population’s everyday life, working in offices, travelling, or while in theatres or cinemas.

2.3.6 Relation of Core and Surface Temperature in Human Body

The mean skin temperature was observed to be related to the rectal temperature (Mairiaux et al., 1987; Houdas et al., 1972), but others differ (Saltin et al., 1968). Core and skin temperature were also proved to relate linearly at the onset of vasoconstriction and shivering (Cheng et al., 1995). If interested in the relation of core and local skin temperatures, forehead is the most obvious choice. The forehead is typically exposed, hence thermal clothing insulation does not need to be considered and its temperature is easily measured. The use of forehead temperature for the estimation of core temperature is controversial although it does perform quite well for the detection of fever (Togawa, 1985). Ng et al. (2005) studied the agreement of non-contact infrared forehead temperature (NIFT) measurements and tympanic temperatures for children aged between 1 month and 18 years. They studied with a reasonable accuracy beside a difference of 2.34 °C between both temperatures, and could establish a cut-off point of forehead temperature for fever detection at 35.1 °C. However, the false-positive rate of fever screening is high Ng et al. (2005) also studied the feasibility and effectiveness of infrared (IR) systems measuring frontal and side profiles of face temperature for fever detection in mass blind screening. They believe this system is non-invasive, speedy, cost effective and fairly accurate, hence a useful tool in situations where public health is under concern due to a widespread infection. A different approach to estimate core temperature throughout skin temperature measurements would be the use of liquid crystal tape at abdomen, like done with infants by Togawa (1985).

2.4 Heart Rate

Skin temperature is not the only physiology factor that related to human thermal comfort. It is a common proposition that in different environments, their thermal comfort sensations root in the complicated changes of many physiological factors in a body besides the skin temperature. Therefore, this study was focused another physiological factors that are potentially related to thermal comfort which is a heart rate.

Kroemer et al. (1997) defines the heart as a hollow muscle that produces, through contraction and with the aid of valves, the desired blood flow. Each half of the heart has an antechamber (atrium) and chamber (ventricle), the pump properly. The atria receive blood from the veins, which then flows through open valves into the ventricle. The valve is closed while the ventricle is compressed by its surrounding musculature.

The mechanisms of excitation and contraction of the heart muscle are quite similar to those of skeletal muscle; however, specialized cardiac cells in the atrium (the sinoatrial nodes) serves as “peacemakers,” which do not need external nervous impulses to function. They determine the frequency of contractions by propagating stimuli to other cells in the ventricle, which make the ventricular muscles contract.

The heart's own intrinsic control system operates, without external influences, at rest with (individually different) 50-70 beats per minute (bpm). Changes in heart action stem from the central nervous system, which influences the heart through the sympathetic and the parasympathetic subsets of the autonomic system. Stimulation toward increase of heart action comes through the sympathetic system, mostly by increasing the heart rate, the strength of cardiac contraction and the blood flow through the coronary blood vessels supplying the heart muscle.

Heart rate generally follows oxygen consumption and hence energy production of the dynamically working muscle in a linear fashion moderate to rather heavy work. However, the heart rate at a given oxygen intake is higher when the work is performed with the arms than with the legs. This reflects the use of different muscles and muscle masses with different lever arms to perform the work. Smaller muscles doing the same external work as larger muscles are more strained and require more oxygen.

There are close interaction between the circulatory and metabolic processes. For proper functioning, nutrients and oxygen must be brought to the muscle or other metabolizing organs and metabolic by products removed from it. Therefore, heart rate as a primary indicator of circulatory functions and oxygen consumption, representing the metabolic conversion taking place in the body, have a linear and reliable relationship in the range between light and heavy work as shown in Figure 2.7. This relationship may change within one person with training and it differs from one individual to another. Given this relationship, heart rate measurements can simply be substituted for measurement of metabolic processes particularly for oxygen consumption.

The regression line in the Figure 2.7 relating heart rate of oxygen uptake (energy production) is different in slope and intersects from person to person and from task to task. In addition, the scatter of the data around the regression line, indicated by the coefficient of correlation. The correlation is low at light loads, where the heart rate is barely elevated and circulatory functions can be influenced by psychological (excitement, fear, etc.) which may be unrelated to the task. With heavy work, the oxygen-HR relation may also fall apart, for instance, when cardiovascular capacity is exhausted before metabolic or muscular limits are reached. The presence of heat load also influences the oxygen-HR relationship.

2.5 Summary of Background Study

The development of an adaptive predictive model of thermal comfort should combine features of both the static and adaptive theories, and that these various feedback loops should be described in terms of how they affect the more traditional linear relationships.

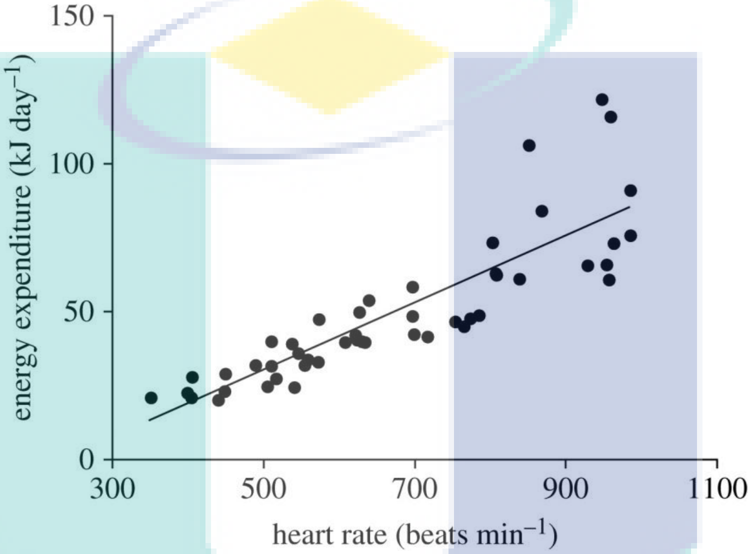


Figure 2.7 The Relationship Between Oxygen Uptake (Expressed as Energy Expenditure) and Heart Rate.

Source: Kroemer et al. (1997)

The deterministic underpin heat balance comfort models:

Physics → Physiology →Subjective Discomfort

Behavioral adjustment of the body’s heat balance probably offers the greatest opportunity for people to play an active role in maintaining their own comfort. The extent to which building occupants can, or do, behaviorally interact with their indoor climate depends a great deal on contextual factors. This is very important in both the development and application of an adaptive model, and deserves further elaboration.

Behavioral adjustment represents the most immediate feedback link to the thermal environment as shown in Figure 2.8. Stated simply, if a person is uncomfortable, or expects to become most probably, he is found to take corrective action. What might have previously been regarded as the final consequence in the static heat balance model (the conscious sensation of thermal discomfort), becomes the starting point of this feedback in the adaptation model.

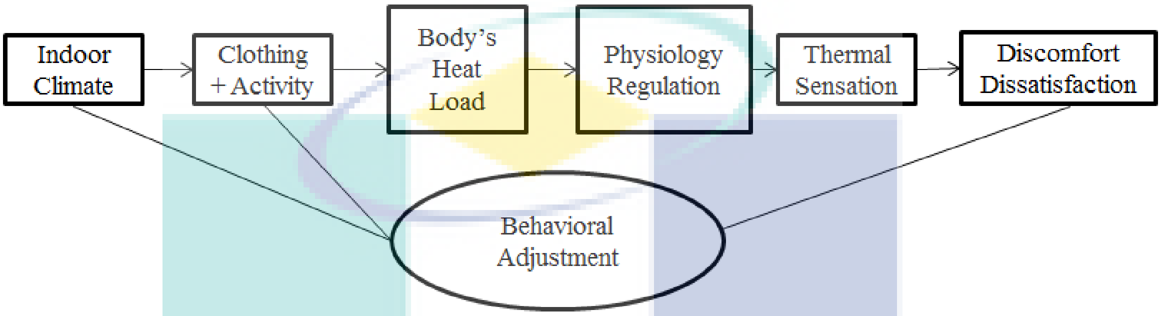


Figure 2.8 Behavioral Feedback Loop.

Source: de Dear and Brager (1997)

Acclimatization is an unconscious feedback loop mediated by the autonomic nervous system, which directly affects our physiological thermoregulation set points. Like behavioral adjustment depicted earlier, the physiological feedback process of acclimatization can also be depicted schematically as illustrated in Figure 2.9.

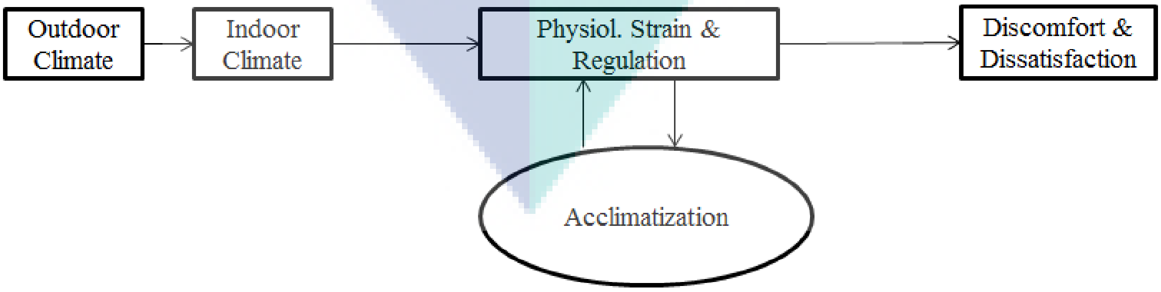


Figure 2.9 Physiological Feedback Loop.

Source: de Dear and Brager (1997)

In terms of a feedback loop that can be incorporated into the conceptual model of adaptation, expectation and habituation are influenced by one's current thermal experience or one's longer history of experiences with both the indoor and outdoor climate. This in turn directly affects our thermal sensation and cognitive assessments of thermal acceptability as described in Figure 2.10.

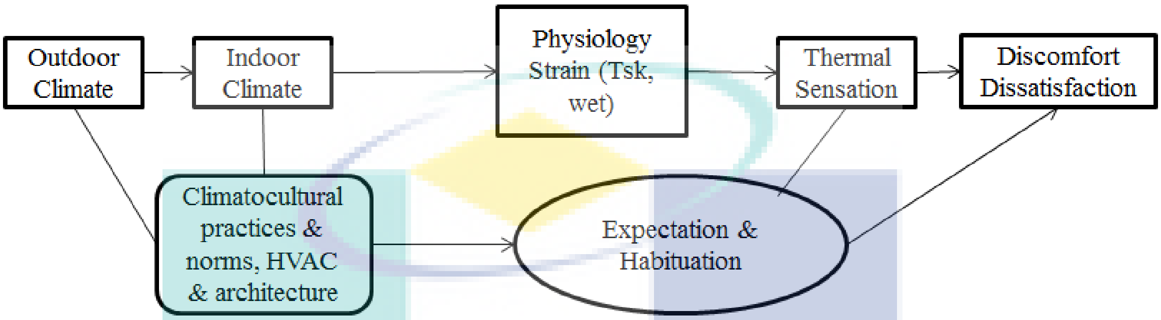


Figure 2.10 Psychological Feedback Loop.

Source: de Dear and Brager (1997)

Table 2.8 highlighted the previous study regarding the human thermal comfort in the building. There are four types of experiments to evaluate thermal comfort which is human subject or field study, using a thermal manikin, simulations and physical measurement. In this study review, the smallest number of subjects or respondents engaged in the experiment was eight subjects air conditioning system with controlled simulation.

In this study experiment were conducted in chamber (laboratory study) and design similar office work design. The methods applied in this study include human subjects or field study, physical measurements and simulation.

Table 2.8 Impact of Personalized Conditioning on Thermal Comfort

Authors	**Functions of the system**			**Type of experiments/evaluation**			
	Heating	Cooling	Ventilation	Human subject/field study (number of subjects)	Thermal manikin	Simulations	Physical measurements
Foda and Siren (2012)	√				√		
Kaczmarczyk et al. (2010)	√		√	√ (32)			
Zhang et al. (2007)	√	√		√ (24)			
Amai et al. (2007)	√	√	√	√ (24)			
Bauman et al. (1998)	√	√	√	√			
Melikov and Knudsen (2007)	√	√	√	√ (48)			
Watanabe et al. (2010)	√	√	√		√		
Zhang et al. (2010)	√	√	√	√ (18)			
Akimoto et al. (2010)		√	√	√			
Chen et al. (2012)		√	√	√ (64)			
Conceicao et al. (2010)		√	√		√	√	
Gong et al. (2006)		√	√	√ (24)			
Halvonova and Melikov (2010)		√	√		√		
Halvonova and Melikov (2010)		√	√		√		
Halvonova and Melikov (2010)		√	√		√		
Kaczmarczyk et al. (2006)		√	√	√ (30)			
Kaczmarczyk et al. (2004)		√	√	√ (60)			
Kalmar and Kalmar (2013)		√	√	√ (19)			
Li et al. (2010)		√	√	√ (30)			
Melikov et al. (2002)		√	√			√	√

Table 2.8 Continued

Makhoul et al. (2013)	√	√	√ (10)		√	
Melikov et al. (2012)	√	√	√ (35)			
Melikov et al. (2013)	√	√	√ (30)			
Niu et al. (2007)	√	√	√ (12)	√		
Sekhar et al. (2005)	√	√	√ (11)			
Yang et al. (2010)	√	√	√ (32)			
Arens et al. (1998)	√		√ (119)			
Chakroun et al. (2011)	√				√	√
Ghaddar et al. (2013)	√		√ (8)		√	
Sun et al. (2012)	√		√ (32)			
Zhai et al. (2013)	√		√ (16)			

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this study a methodology of this research work is described. The study consists of the case study of chamber; data collected and the data loggers used to collect the environmental parameters and physiology parameters of human data. The collections data are evaluated and using procedures as presented in the methodology.

3.2 Experiment Procedure

Figure 3.1 illustrated the research flow in this study. The environmental data and physiological parameters responses were measured through human subject experiments. These data were analyzed to investigate the relationship between the overall thermal sensation and physiological parameter's responses.

The second phase was developed to design of the experiment. At the beginning, the experimental procedure was planned. Before starting the collecting process data in the study, all the equipment must be calibrated. This is important to obtain the accuracy of the data during the experiment. The process of calibration was carried out using a computer. After calibrated, the device was ready to be used for taking readings in the study. After data collection is complete, the device will be re-calibrated to maintain the quality and simplify the process of data collection in the future.

The last phase (phase three) was developed to analyze the human body and the surrounding environment. The analysis was performed in two stages with the body

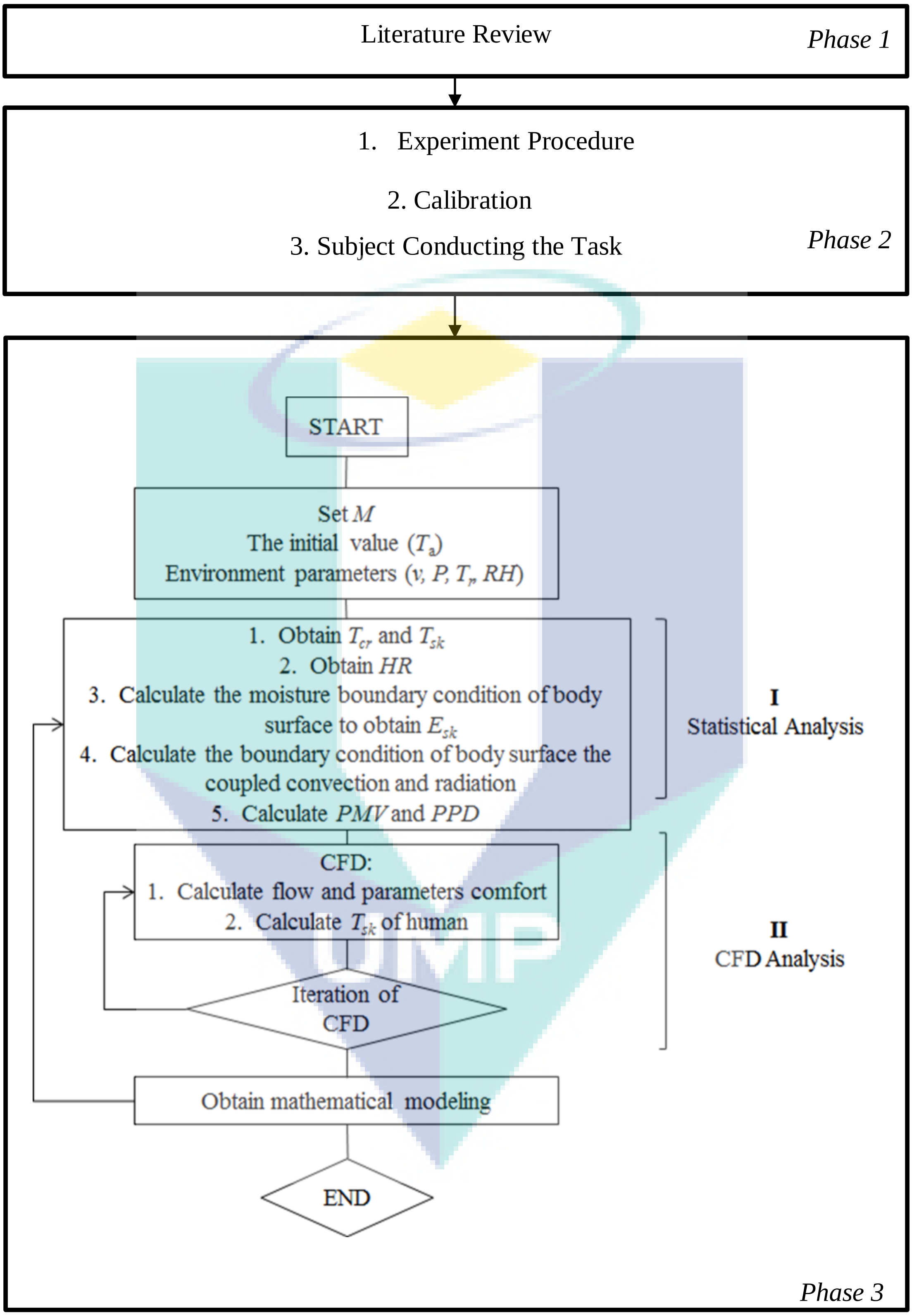


Figure 3.1 Research Flow.

skin surface being the interface between the body core and the surrounding air. In the first stage, the heat transfer inside the human body was calculated based on a human thermal physiological model. A micro climate (comfort parameters) around the body was first guessed and the two-node human body energy transport model is implemented to yield skin surface boundary conditions for sensible heat flux and water vapor concentration (ASHRAE, 1997). The second stage was a simulation analysis. The analysis involved skin temperature of the simulation and flow through the chamber with human and without human.

3.3 Experimental Facility

Thermal comfort research has divided into deterministic engineering and holistic architectural approaches (Ugursal, 2010; de Dear 2004). The deterministic engineering approach is based on environmental chamber studies, which led to the development of thermal comfort standards (Ugursal, 2010).

The shortcoming of this approach is that it is impossible to determine how multiple sources are combined to create dissatisfaction. An architectural approach is based on the holistic person environment systems and led to the development of field studies. The shortcoming of this approach is the lack of control over the environmental parameters.

This study was designed to combine the advantages of both methodologies, which are the controlled conditions of the laboratory studies and applicability and external validity of the field studies. To achieve this model office environment has been built in an environmental chamber. The experiments were carried out at the Workplaces Ergonomic Simulator Chamber (WES-103) in Universiti Malaysia Pahang (UMP). Figure 3.2 shows the model of office room in an environmental chamber. For this study the York Prestige Ceiling type of air conditioner was used to explore the environment climate in the chamber. This model is ideally suited for use in the hot climate in Pahang. The dimension of this air condition is 21.8 cm × 108 cm × 63 cm. The material of environmental chamber is Polyurethane insulated panels. Table 3.1 presented the details of specification of climate chamber. The environmental chamber and data acquisition tools are described in the following section.

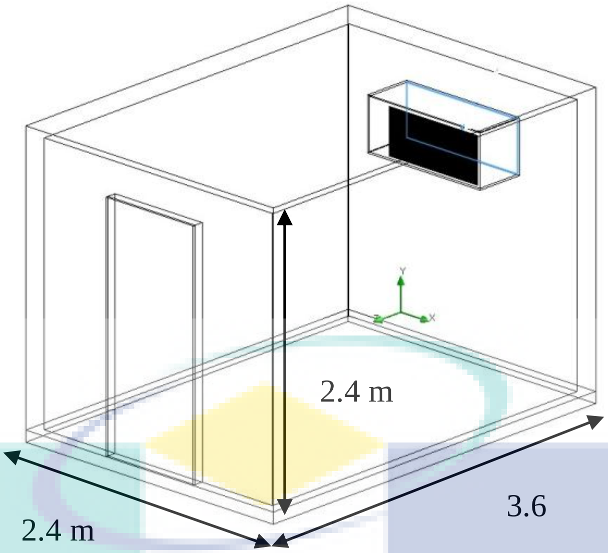


Figure 3.2 Environmental Chamber: Layout of the Environmental Chamber.

Table 3.1 Specification of Environmental Chamber

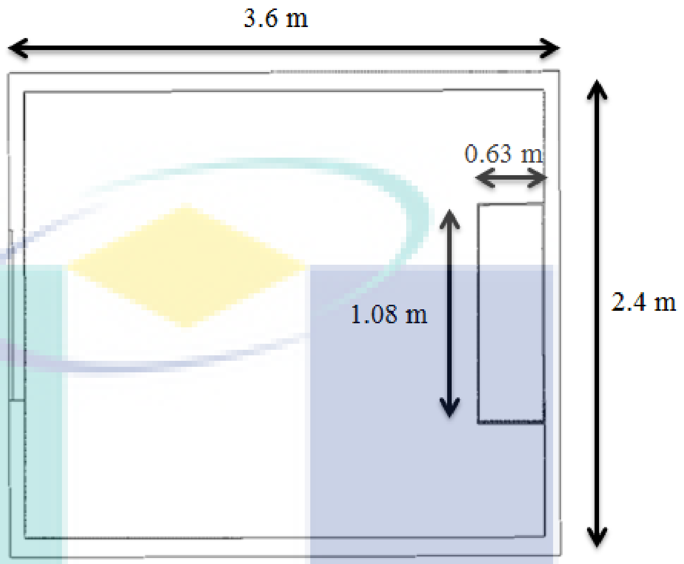
Property	Result
Density	40-45 kg/m^3
Thermal conductivity	0.017 W/mK
Compressive strength	180-250 kPa
Thermal coefficient	0.239-0.151 W/(mK)
Operating temperature	-68 ^{o}C to 121 ^{o}C

3.3.1 Environmental Chamber

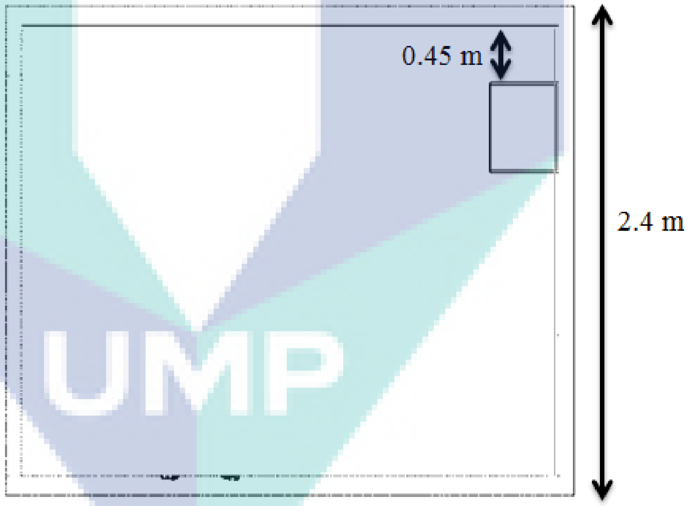
An environmental chamber study has advantages in its capability to fully control the test environment and to use certain simulated tasks flexibly.

The dimension (3.6 m × 2.4 m × 2.4 m) and layout of the environmental chamber is provided in Figure 3.2. This environmental chamber is in a closed condition and modified as an office workstation. In this environmental chamber, half of that is used as the test station which includes a computer for the subjects to work on and to use in responding to the thermal questionnaire, a chair and table. Besides that, this environmental chamber equipped with wall-hanging air conditioning facing the workstation. Figure 3.3 shows the environmental chamber in three views. There are top, side and front view. This three view of the environmental chamber used for simulation section.

(a) Top view



(b) Side View



(c) Front view

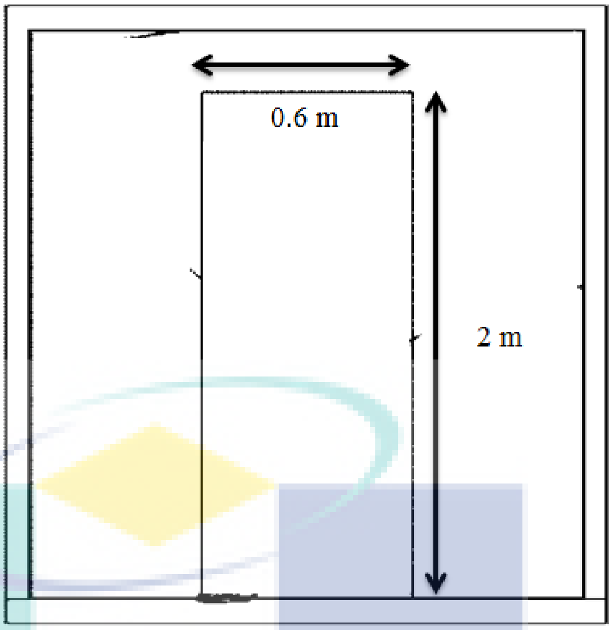


Figure 3.3 Environmental Chamber: (a) Top View, (b) Side View and (c) Front View.

A thermal comfort test with human subjects was designed to test the individual as well as the interaction effects of dynamic personal and environmental comfort variables. One of the objectives of the study is to investigate whether there are significant differences in heart rate and skin temperature between cool and warm thermal conditions. The research design and the methodology were adapted from the previous studies of Gagge et al. (1967), Strigo et al. (2000), Astrand et al. (2003), Zhang (2003), Van den Heuvel et al. (2004) and Kistemaker et al. (2006).

3.3.2 Data Acquisition Tools

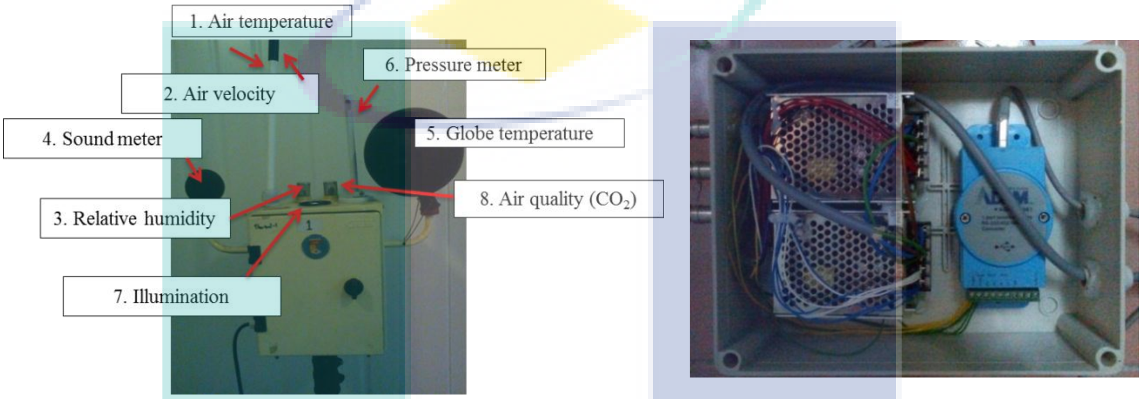
The physiology and environmental data collected through the sensors and data acquisition (DAQ) boards as presented in Table 3.2. In this study the physiological measurement was done using thermistors and sensors where data were displayed through computer display.

Table 3.2 Device for Physiological Measurement

No.	Tools		Purpose
1.		Thermistor	Skin temperature measurement
2.		Heart rate sensor	Heart rate measurement
3.		Computer: Data acquisition display	Heart rate data display
4.		Body weight monitor	Body weight
5.		Control panel	Temperature controls for climate chamber

Figure 3.4 shows the equipment for the measurement of all the various parameters defining the quality of an environment from the thermal, sound, illumination and chemical. The range includes a large variety of sensors and PC software for data acquisition and elaboration. Particularly for the calculation of the thermal comfort indices of the incoming data.

Environment measurement is a portable equipment illustrated in Figure 3.4 and it is aiming of measuring:



(a)

(b)

Figure 3.4 Equipment for Environment Measurement, (a) Sensor (b) Data Logger.

This equipment consists of a line of instruments, sensors, accessories and software programs for the acquisition, display, recording and processing of a large variety of technical parameters, managed in an integrated information environment.

All the sensors are shown in Appendix B and were installed on a tripod with the sensors placed at the level of the zone recommended by ASHRAE 55. The sensors were placed on the level at 1.1 m recommended by ASHRAE 62 (2004) considering the sedentary activity level (1.0, 1.2 and 1.6 Met) required in the experiments. ASHRAE 55 is for applicability of methods for determining acceptable thermal conditions in occupied spaces, while ASHARE 62 is ventilation for acceptable indoor air quality.

To display all the collected environment data from the chamber as present in Figure 3.5, data acquisition interface was developed using ADAM 4017 as can be seen from the Figure 3.6. Based on a sensing interval of 10 min, the interface continuously shows all eight collected data, including ambient temperature, air velocity, relative humidity, noise level, radiant temperature, pressure level, illumination and CO_2 level of the chamber.

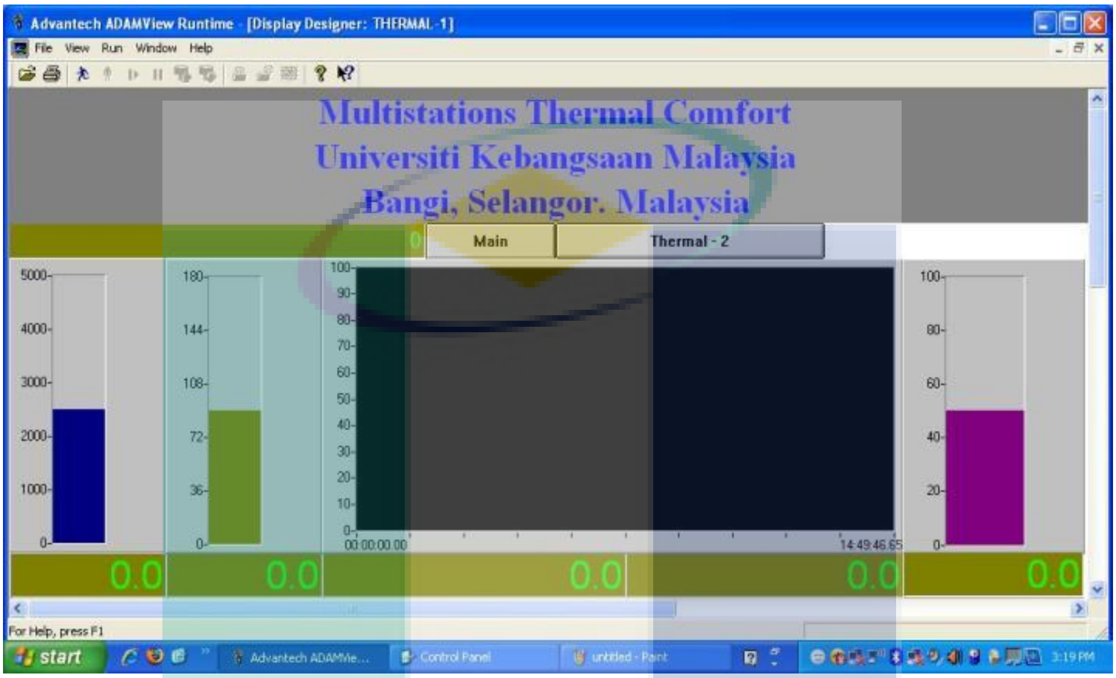


Figure 3.5 Data Collection Display from the Environment and Human Subjects.

Figure 3.6 PC Software – ADAM 4017.

Environment measurement adapts to diverse measurement and data acquisition needs. Many parameters related to the operational data acquisition system, system, are user programmable. The user can set up specific preferences such as automatic start/end date and time for the survey.

The ADAM-4017 is a 16-bit, 8-channel analog input module that provides programmable input ranges on all channels. This module is an extremely cost-effective solution for industrial measurement and monitoring applications. Its opto-isolated inputs provide 3000 VDC of isolation between the analog input and the module, protecting the module and peripherals from damage due to high input-line voltages. ADAM-4017 offers signal conditioning, A/D conversion, ranging and RS-485 digital communication functions. This module protects the equipment from ground loops and power surges by providing optoisolation of A/D input and transformer based isolation up to 3000 VDC. The ADAM-4017 uses a 16-bit microprocessor-controlled sigma-delta A/D converter to convert sensor voltage or current into digital data. The digital data is then translated into engineering units. When prompted by the host computer, the module sends the data to the host through a standard RS-485 interface. The detail specification of data logger was presented in Table 3.3.

Table 3.3 Specification of Data Logger for Environment Measurement

General	
Power consumption	1.2 W @ 24 V_{DC}
Watchdog timer	System (1.6 second) & Communication
Supported protocols	ASCII command and Modbus/RTU
Analog Input	
Channels	8 differential
Channel independent configuration	yes
Input impedance	Voltage: 20 MΩ Current: 120 Ω
Input type	mV, V, mA
Input range	±150 mV, ±500 mV, ±1 V, ±5 V, ±10 V, ±20 mA, 4 ~ 20 mA

3.4 Human Subject Experiments

Thermal comfort tests with human subjects were conducted to test the thermal comfort and thermal sensation of human for various thermal conditions. 15 volunteers (eight male and seven female) were recruited in this study. The details about subjects can see in Appendix C. The number of subjects in the study was agreed by Goldman (2005). The author has 50 years' experience in the field of human thermal comfort and state that the minimum subject for the study of human comfort is as many as six people. For further details about human subjects, the experiment can be referred to Table 2.7 in Chapter 2.

The impression of a human in a certain indoor environment is based on personal experience and the physiological and psychological state of this human, for example, the 'sensor'. The term comfort might be used to describe a feeling of contentment, a sense of cosines or a state of physical and mental well-being. Objective information is obtained when the indoor environment is measured by a technique that can register a specific quantity unbiased and with a given accuracy. The data then can be used to describe the indoor environment.

Each temperature can be set and adjusted by the switch box in the panel controller. Figure 3.7 showed the experiment spatial arrangement of the study. One unit air conditioning system was used to keep the interior of the office cooler. Environment equipment was mounted 1.1 m above the floor in the office (marked with 'x' in Figure 3.7). This diagram illustrated the environment of equipment was placed behind and left of the subject. The task for the subject was doing office work as shown in Figure 3.7, the subject sitting and facing the laptop while typing.

All 15 subjects were using in this study to measure skin temperature, heart rate and productivity while doing multitask in the chamber (represent an office room). There are three tasks the subjects must follow such as relaxing while sitting, typing or writing and printing paperwork as shown as in Table 3.4.

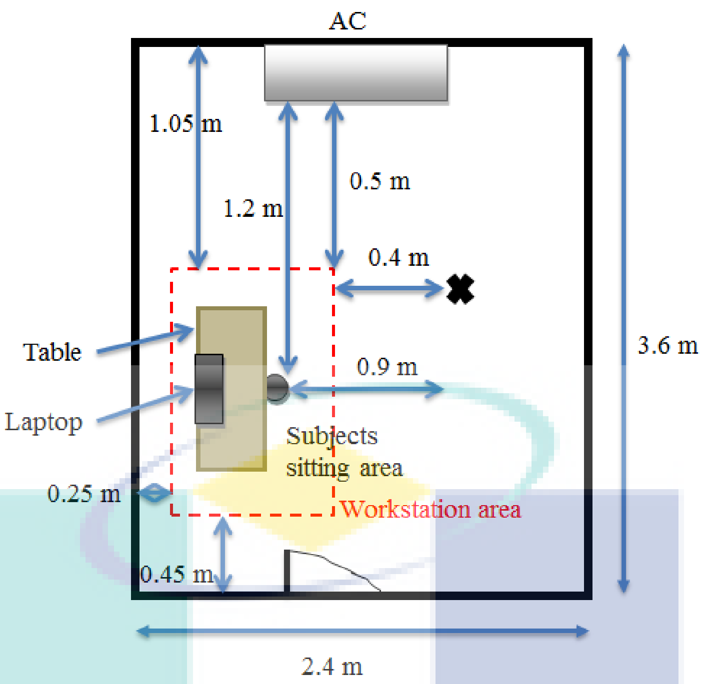


Figure 3.7 The Experiment Spatial Arrangement.

Table 3.4 Types of the Task with the Metabolic Rate

No	Types of the Task	Metabolic Rate (Met)
1	Thinking	1.0
2	Sitting while typing	1.2
3	Printing	1.6

The steps and duration of experiment were shown in Table 3.5. The subjects entered the chamber and spent 10 min in the chamber prior to the test acclimatize with the room temperature (Gagge et al., 1969; Strigo et al., 2000 and Tanabe et al., 2007). All the three tasks of activities during which the subjects were exposed to multiple thermal conditions. All tasks which are explained in Table 3.3 were repeated with five temperature setting of air conditioning (19, 21, 23, 26 and 29 ^{o}C). The actual test had three tasks and lasted for 3 hours 20 min with two breaks.

Thermal conditions of this range from sedentary activity and neutral room temperatures to high metabolic activity and high room temperatures which fall clearly outside the comfort zone based on ASHRAE Standard 55 (2004). One of the premises of this study is that thermal comfort is a psychological phenomenon and can be achieved even the physical conditions suggest otherwise.

Table 3.5 Steps and Duration of Experiment

Step	Activity	Duration (min)
1	Measured demographic of subjects	30
2	Standby in a waiting room	10
3	Start the measurement with Task 1 (19, 21, 23, 26 and 29 ^{o}C)	10 x 5 = 50
4	Break	5
5	Task 2 (19, 21, 23, 26 and 29 ^{o}C)	10 x 5 = 50
6	Break	5
7	Task 3 (19, 21, 23, 26 and 29 ^{o}C)	10 x 5 = 50
	Total	200

3.4.1 Physiological Information

Physiological and psychological stimuli invoke several physiological responses, including blood pressure, heart rate, electromyogram, skin conductance level, electroencephalogram, skin temperature, and body core temperature (Boregowda and Karwowski, 2005). Cacioppo et al. (1987) stated that heart rate was the most favored measure of physiological arousal. In this study, heart rate was used as the main indicator of the metabolic activity.

The summary statistic as illustrated in Table 3.6 to help make the important features of a data of subjects stands out. The two most commonly used summary statistics are the mean and the standard deviation. The mean gives an indication of the centre of the data of subjects and the standard deviation gives an indication of how spread out the data subject (Navidi, 2011).

3.4.2 Skin Temperature (T_{sk}) Measurement

Existing thermoregulation models have selected three to fifteen body segments for skin temperature measurement to estimate mean skin temperature (Yao et al., 2007). The most frequently used body locations for assessing skin temperature in the 16 existing thermoregulation models are the chest, thigh, anterior-calf, wrist, posterior

Table 3.6 Comparison Summary of Demographic Information by the Subjects with the Previous Study

Variables	**Choi and Loftness (2012)**	**Zhai et al. (2015)**		**Present study**	
Sex	**All**	**Male**	**Female**	**Male**	**Female**
Age (years)	27	26	23	25	24
Weight (kg)	67.4	177	169	72	59
Height (cm)	171	75.2	59.8	165	158
BMI	22.8	24	21	26.5	23.8
A_{DU} (m^2)				1.79	1.60

upper arm, forehead, abdomen, hand, foot and scapula. The body areas are ordered by the selection frequency in the existing models alongside the sum of the weight factors assigned in each model's formula.

These body locations for skin temperature sensors are important for both control effectiveness and for practical system application of wearable sensors. In this research, 11 body locations were selected from those most frequently used in the existing models to measure skin temperatures, which are the forehead, posterior upper arm, wrist, back of the hand, chest, belly, thigh, anterior calf, posterior calf, and instep of a foot. The sensing interval was 10 min for all the measurements. As the posterior-calf has a larger weight factor than the scapula, and is a more convenient sensor location, the researcher selected the posterior-calf as the 10 skin area for the experiment.

Thermocouple sensors used to measure skin temperature during the experimental chamber is running. Usually, the thermocouple sensors were held to the skin of different sites on the subjects (see Figure 3.8) with porous medical tape to measure the local skin temperatures.

3.4.3 Heart Rate (*HR*) Measurement

To investigate the relations between heart rate and thermal sensation, heart rate was also measured with a 10 min sensing interval, using a heart rate sensor worn on the chest. To measure heart rate electrode must be put at the right point which is less in the

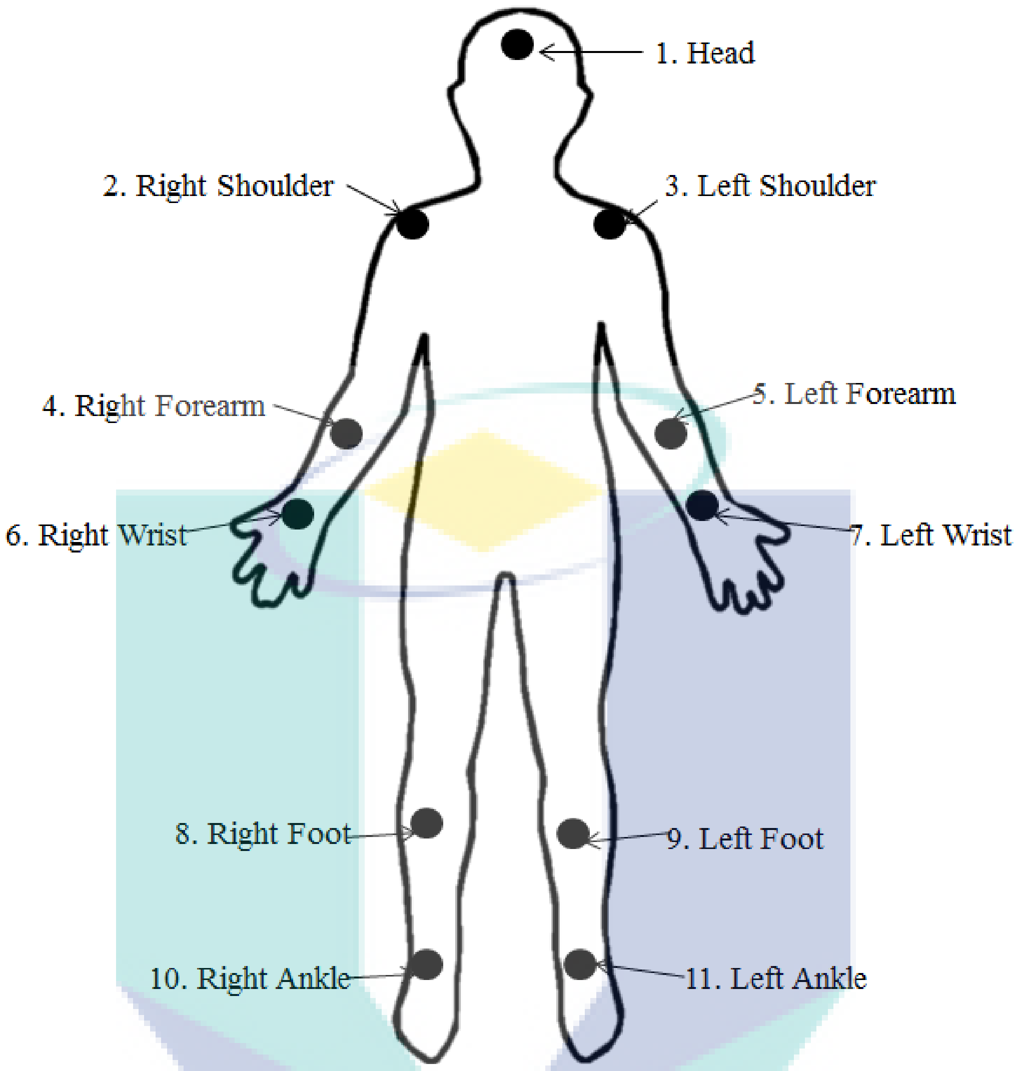
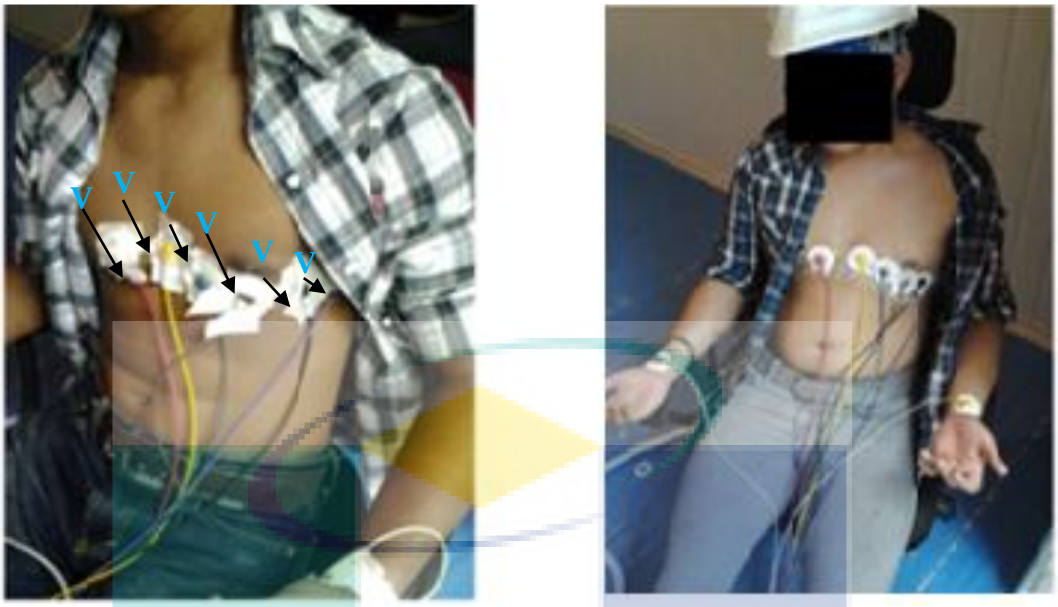


Figure 3.8 Measurement Points of Skin Temperature.

mediastinum behind the sternum between the lungs, just above the diaphragm. Six unipolar leads and also known as precordial leads, label as V1, V2, V3, V4, V5 and V6 as shown as in Figure 3.9.

3.5 Environmental Information

All the environmental parameters other than air temperature must be held constant. This included mean radiant temperature, CO_2 concentration, indoor pressure, relative humidity and air velocity. All the environmental parameter was control using the main switch box in the chamber. Table 3.7 presents the acceptable range for Malaysia's climate.



[redacted]

Figure 3.9 Measuring Point of Heart Rate on Subject.

Table 3.7 Acceptable Range for Specific Physical Parameters

Parameter	**Acceptable Range**
Air temperature, T_a	23-26 ^{o}C
Relative humidity, *RH*	40-70 %
Air velocity, *v*	0.15-0.50 m/s

Source: ICOP (2010)

3.5.1 Air Temperature

Symmetric thermal conditions are critical to thermal sensation as defined by ASHRAE 55 Standards, so the test chamber was controlled to ensure whether the difference between set point temperatures (19, 21, 23, 26 and 29 ^{o}C). In this study, there are five set points of temperatures was selected, which is 19, 21, 23, 26 and 29 ^{o}C. This is because in Malaysia, the temperature at 19-23 ^{o}C was cool and the temperature at 24-29 ^{o}C was hot. So, in the range of temperature, the author finding which temperature was comfort in Malaysia's building.

3.5.2 Mean Radiant Temperature, Relative Humidity and Air Velocity

To maintain a consistent thermal condition in each experiment and to estimate the mean radiant temperature, relative humidity and air velocity were also measured.

Maximum air velocities which occurred during air pulsing next to the subject's neck and the face are presented in Table 3.8 together with the mean air velocities. This air speed is consistent with the high temperature tests found in the literature (Zhou et al., 2006; Toftum, 2004; Tanabe and Kimura, 1994).

Table 3.8 Maximum and Mean Air Flow Conditions Patterns

	Head only	**Head/Hands/Feet**
Nozzle exit	2.13 m/s	1.09 m/s
Neck (5.08 cm away)	0.79 m/s	0.41 m/s
Face (5.08 cm away)	0.34 m/s	0.29 m/s
Mean air velocity	0.28 m/s	0.22 m/s
Max *Tu*	30 %	31 %

Turbulence intensity is closely related to the sensation of draught, which is the unwanted cooling of the body. Airflows with high turbulence intensities perceived as uncomfortable by people (Mayer, 1993; Fanger et al., 1988). Turbulence intensities which have occurred during the tests were calculated using Eq. (3.1) (Wessel et al., 2006; Mayer, 1987). Maximum turbulence intensities (Tu) were 38 % and 31 % of head only and head/hands/feet respectively.

$$Tu = \frac{\sigma_v}{\bar{v}} * 100 \qquad (3.1)$$

where,

σ_u = Standard deviation of the air velocity
$\bar{v}$ = Mean air velocity

Mayer (1987) published the allowable turbulence intensity limits as a function of mean air velocity to avoid draught discomfort (see Figure 3.10). Draught is less of a problem at higher temperatures and used the 23 °C curve which is conservative for 24 °C and 28.3 °C of room temperatures. The test conditions of this study which is 0.28 m/s and 38 % turbulence intensity were shown on Mayer's plot. The turbulence intensities within the comfort limits and should not cause draught discomfort according to Mayer's findings.

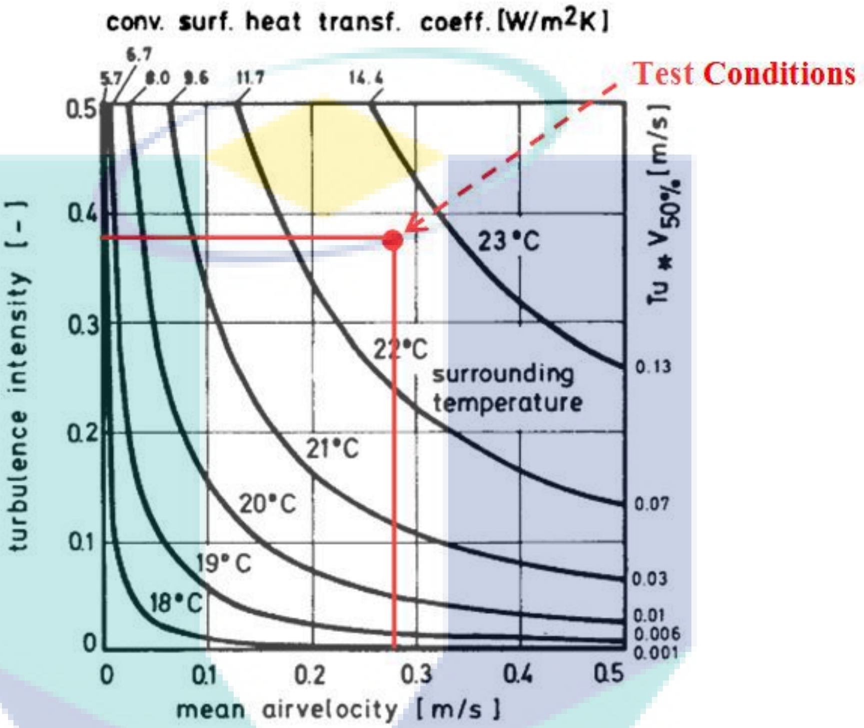


Figure 3.10 Limits of Draught Discomfort as a Function of Mean Air Velocity and Turbulence Intensity.

Source: Mayer (1987)

Fanger et al. (1988) investigated the effect of turbulence intensity on draught sensation and determined the dissatisfaction levels as shown in Figure 3.11. The test conditions of our study are also shown on Fanger's figure. This figure suggests that for 0.28 m/s airflow and medium turbulence intensity, 15 % of the people are dissatisfied due to draught. Fanger et al. formulated the draught dissatisfaction formula (DR) which is still in use by ASHRAE Standard 55 (2004) and ISO 7730 (2005).

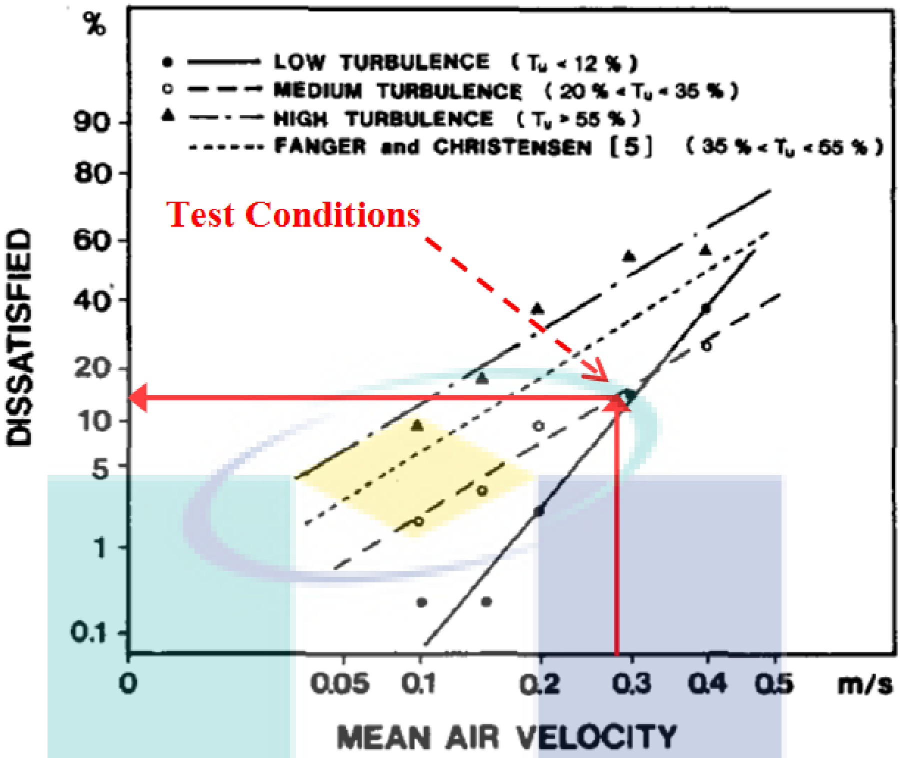


Figure 3.11 Percent of Dissatisfied Due to Draught as a Function of Mean Air Velocity for Three Turbulence Intensity Bins.

Source: Fanger et al. (1988)

3.6 Statistical Analysis

The main methodology of this study is based on investigating the relationships between the measured environmental data and user responses to the environmental conditions. A major focus point is the predictability of the subjective responses by physiological conditions and environmental factors.

The environmental, physiological and the subjective thermal data were analyzed using three-factor analysis of variance (ANOVA), multivariate regression analysis, independent sample's t-test for pairwise comparisons and correlation analysis. This research was a mixed design with temperature and gender as between-subject variables and metabolic rate. The main dependent variables were the thermal comfort, thermal sensation, thermal satisfaction, and temperature preferences. In all statistical analysis, the results were accepted significant at $\alpha = 0.05$ or $p < 0.05$.

Assuming that the null hypothesis of a statistical analysis is the equality of two values; the p-value is the probability of rejecting the equality when the two values are actually equal. Rejecting the null hypothesis in such a case is also called the type I error (Ott and Longnecker, 2001). α is then the maximum allowable probability that something is a result of a random variation in the data instead of the result of an investigated cause.

Shapiro-Wilk's for data counts less than 2000 and Kolmogorov-Smirnov for data counts more than 2000 was used to test the normality with a null hypothesis that the data is normally distributed (Kacmarczyk et al., 2004; Melikov and Knudsen, 2007; Zhang and Zhao, 2008). Each subject was exposed to all combinations of treatments in the same session. Therefore, three-factor repeated measure's analysis of variance (ANOVA) was used in which within-subject variables (repeated measures) were metabolic rate, airflow location and frequency (Kistemaker et al., 2006; Kacmarczyk et al., 2004; Hot et al., 1999; Melikov and Knudsen, 2007; Toftum and Nielsen, 1996; Zhang and Zhao, 2008). The null hypothesis was that the mean value of the dependent variable was the same across all the combinations of factor levels. ANOVA tables were presented as the analysis report. The sphericity of the data was checked with the null hypothesis that the relationships between different combinations of factors were the same. The likeliness of the relationship was based on equal variances of the differences between different combinations of the factors. The dependent variables in these analyses were the thermal responses of the test subjects. For some of the analysis, Turkey's Post Hoc model was used for pairwise comparisons (Yao et al., 2008).

Independent sample's t-test was used to compare the results from two different populations. The null hypothesis of this test was that the means of the two populations are the same. The independent sample's t-test was used to compare subjective responses or physiological data for known groups such as two different room temperature conditions, two genders and three levels of metabolic rate. The t-test was also used to follow up some of the ANOVA test for group differences to determine which group was different than the others.

The regression analysis, which is predicting a quantitative data using another quantitative data (Ott and Longnecker, 2001), was used to determine the causal relationships between various environmental, physiological, and subjective data. The unit of association in these analyses is the time. Models were developed in the form of:

$$y = \beta_0 + \beta_1 x + \varepsilon \tag{3.2}$$

where, y is the predicted variable, β_0 is the intercept, β_1 is the slope of the fitted line, and ε is the random error term. The regression analysis was used to predict thermal comfort from thermal sensation votes and thermal sensation from various skin temperature sites. A stepwise regression analysis was used to determine which skin temperature sites correlated best with the mean skin temperature (Olesen, 1984). In stepwise regression analysis, the combinations of independent variables that had the highest correlation with the dependent variable were determined.

3.7 Computational Analysis of Air-Conditioning Temperature on Comfort Parameters Effects

Computational Fluid Dynamics (CFD) is the general term to describe the numerical methods which solves partial differential equations for the conservation of mass, momentum, energy, species concentrations and the turbulence. The resulting simulation provides information on the spatial distribution of pressure, air velocity, temperature, particle concentration and turbulence (Chen, 2004; Zhai et al., 2007). CFD is used to simulate the thermal comfort conditions from component scale, such as heating and cooling equipment to atmospheric scales. A summary of the development of the CFD methodologies was presented by Nielsen et al. (2004).

In this study, the comfort parameter of the room is influenced by the air-conditioner temperature. Thus, CFD is performed to predict the results of comfort parameter's distribution of environment and thermal parameters of the human manikin at different from the air-conditioner output temperature. Table 3.8 listed the initial conditions that are included in the CFD environment for the flow analysis.

Table 3.9 Initial Conditions of Flow Simulation

Parameter	**Surface/Components**	**Value**
$T_{wall,1}$	Wall 1, Wall 2	24.5 °C
$T_{wall,2}$	Wall 3, Wall 4, Door	23.5 °C
$T_{wall,3}$	Ceiling, Floor	24.5 °C
T_{fan}	Inlet air-conditioning	19, 21, 23, 26, 29 °C
$T_{environment}$	Surrounding	27 °C
$P_{environment}$	Surrounding	101 325 Pa
$Q_{manikin}$	Manikin	144 W
RH	Surrounding	70 %
Gravity	X	0 m/s^2
	Y	-9.81 m/s^2
	Z	0 m/s^2
Fluid type	Air	Laminar and turbulent

After the setup, the components will be generated in the computational domain. It constructed the mesh at various refinements for the components and the model is ready for simulations. The same setup is used to compare the environment with and without the presence of the human manikin (see Figure 3.12). The results obtained are compared to the experimental values (see Appendix K).

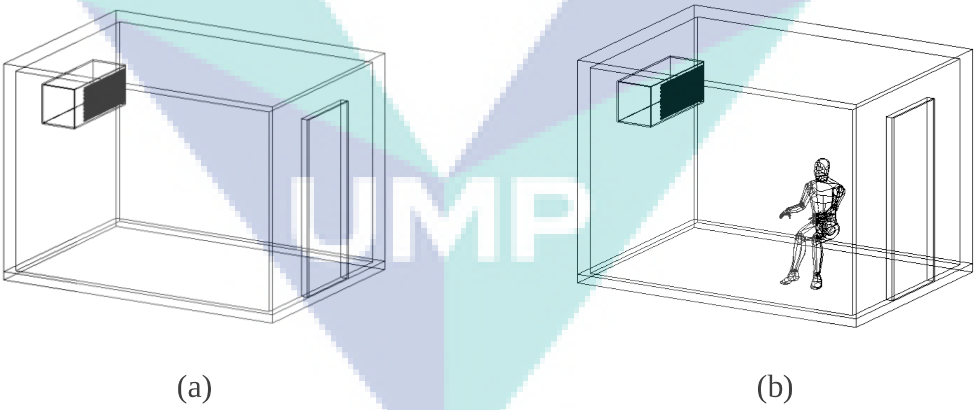

(a) (b)

Figure 3.12 Environmental Chambers (a) without and (b) with the Manikin.

3.8 Summary

The study was divided into three phases, which are literature review, experimental development and the data collection and analysis. Each phase is completed by a rigorous order and control. This study requires a total of 15 subjects who will complete the tasks given under the influence of certain environmental parameters in a controlled room. All the controls and environmental data collection will be supervised properly and regularly during the study. All the data collected in this study were analyzed using Minitab Software and Solidwork for simulation.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, the results of thermal comfort, thermal sensation, skin temperature and heart rate from the use of analysis of variance are presented. All the data were collected, recorded, analyzed and discussed. This process is carried out by several methods and preparatory measures as described in the Chapter 3. Following the description of the data collected for each data are presented with the result's ANOVA and the related discussion.

4.2 Results of the Study

From the study, the results of the data collected for each subject were analyzed. All the results for each parameter and subjects were compared to obtain accurate results. The indoor environment was evaluated to have the biggest influence on the focus or performance in relation to job dissatisfaction and job stress (Roelofsen, 2002). Lan et al., (2009) points out that office work performance contributes substantially to productivity gain in today's world and recent research has focused on the impact of indoor environment quality on office work. Air temperature was deemed to be one of the most important indoor environment factors that effected office occupant in the building. In this study, five room temperatures (19 ^{o}C, 21 ^{o}C, 23 ^{o}C, 26 ^{o}C and 29 ^{o}C) were investigated based on comfort from cold to hot. For the statistical analysis, the significance level was set to be 0.05 (p<0.05).

4.2.1 Thermal Comfort

The objective of this section is to characterize thermal comfort differences as well as room temperature preferences between males and females in metabolic rate conditions at five constant room temperatures of chamber setting, which is 19 ^{o}C, 21 ^{o}C, 23 ^{o}C, 26 ^{o}C and 29 ^{o}C. This section covers the environmental and personal factors of thermal comfort that were presented in the literature and extends the conditions to higher metabolic rates with room temperatures of chamber setting. There were three tasks of activity that being carried out by each subject, which were thinking (1.0 Met), sitting while typing (1.2 Met) and printing (1.6 Met). In this study, the author classified 1.0 Met, 1.2 Met and 1.6 Met as a low, medium and high activity scale respectively.

4.2.2 Thermal Sensation

Thermal comfort is essentially an emotional response contrary to the thermal sensation which is a rational response (Tanabe and Kimura, 1994). Thermal sensation which is the feeling of cold or warmth is based on the signals from the thermoreceptors. The thermoregulation center in the hypothalamus collects data from skin thermoreceptors as well as from the internal organs through the blood stream and generates a thermal sensation response which can vary between extremely cold to extremely hot. A thermal comfort feeling is generated after the evaluation of the thermal sensation through psychological processes.

4.2.3 Thermal Environment Responses for Metabolic Rate of Activity

An analysis of thermal comfort and thermal sensation based on the metabolic rate is illustrated in Figure 4.1. Medium metabolic rate responses were calculated from the average of the data during the exercise periods. Thermal sensation votes are less than ‘slightly warm’ (+1) in all metabolic rate. It was previously stated that a thermal sensation vote between +0.5 and -0.5 is accepted as comfortable. Thermal comfort voters supported this assumption. Thermal comfort of the subjects has been always above zero, which is the ‘comfortable’ zone. Thermal comfort and sensation votes during the medium metabolic rate were closer to the high metabolic rate responses than lower metabolic rate.

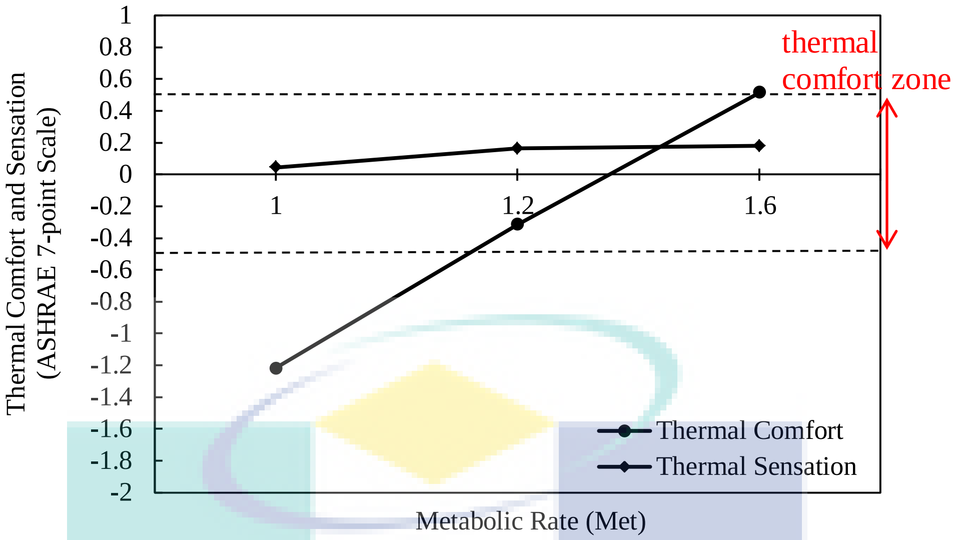


Figure 4.1 Thermal Comfort and Thermal Sensation based on Metabolic Rate.

4.3 Physiological Signals of Thermal Comfort

This section of the study had two objectives. The first objective focused on the relationship of three physiological signals (heart rate and skin temperature) to the thermal comfort responses of people. The second objective focused on psychological stress, which is common in work environments and its effect on thermal comfort.

4.3.1 Skin Temperature, T_{sk}

To calculate an average body skin temperature of the subjects, the 11 collected data from skin the head to ankle are simply averaged. The average skin temperature normally shows the highest level at 1.6 Met and the lowest at 1.0 Met as illustrated in Figure 4.2-4.6. Figure 4.2 shows the skin temperature with three activities at room temperature 19 ^{o}C. Since the temperature is significantly lower than the standby room, the skin temperature decreases as the subjects stay longer because they lose their body heat to the environment and the performed activity levels are not high enough to compensate for the body heat loss. The average skin temperature also varies depending on individual physiology in similar thermal conditions. The range of skin temperatures across the subjects is between 32.76 °C and 33.09 °C depending on individual physiological characteristics and activity levels.

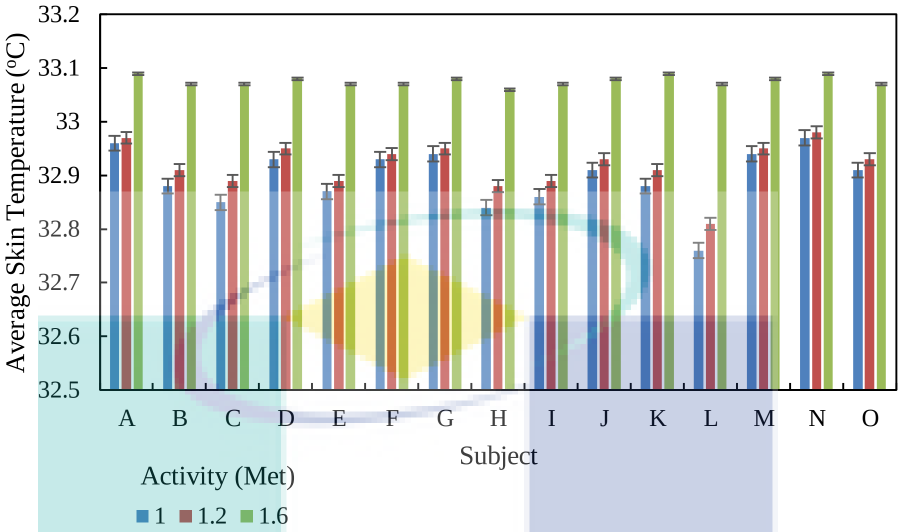


Figure 4.2 Skin Temperatures with Three Activities at Room Temperature 19 °C.

Figure 4.3 presented skin temperature with three activities at room temperature 21 °C. This graph shows the range of skin temperatures across the each of the subjects is between 33.02 °C and 33.46 °C. The difference of temperature between room temperature 19 °C and 21 °C are 0.37 °C. However, in Figure 4.4 illustrated skin temperature with three activities at room temperature 23 °C. The range of skin temperatures for each of the subjects is between 33. 25 °C and 33.86 °C. The lowest and highest for room temperature 19-23 °C for all subjects is subject L.

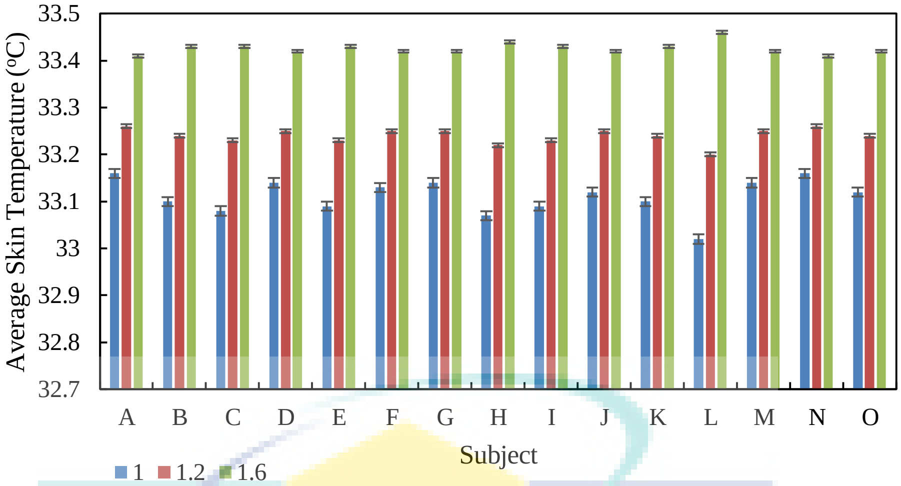


Figure 4.3 Skin Temperatures with Three Activities at Room Temperature 21 ^{o}C.

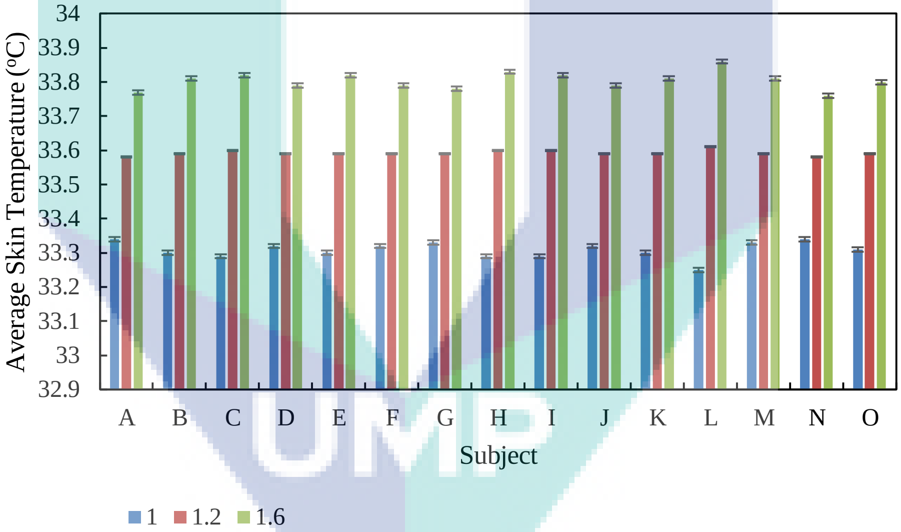


Figure 4.4 Skin Temperatures with Three Activities at Room Temperature 23 ^{o}C.

Figure 4.5 and 4.6 shows the skin temperature with three activities at room temperature 26 ^{o}C and 29 ^{o}C. These room temperatures are the category as a warm chamber. Typically, the average skin temperature increases slightly as the activity level increase. However, the pattern is consistent compared to the case of the room temperature at 19 ^{o}C and 21 ^{o}C. Much different between activity level 1.2 Met and 1.6 Met. The range of skin temperature across the subjects is between 34.22 °C and 34. 89

°C depending on individual physiological characteristics and activity levels. This result shows the Female (subject L) is very uncomfortable in room temperature 21 °C, 23 °C, 26 °C and 29 °C. At the activity level at 1.6 Met, subject L higher than others.

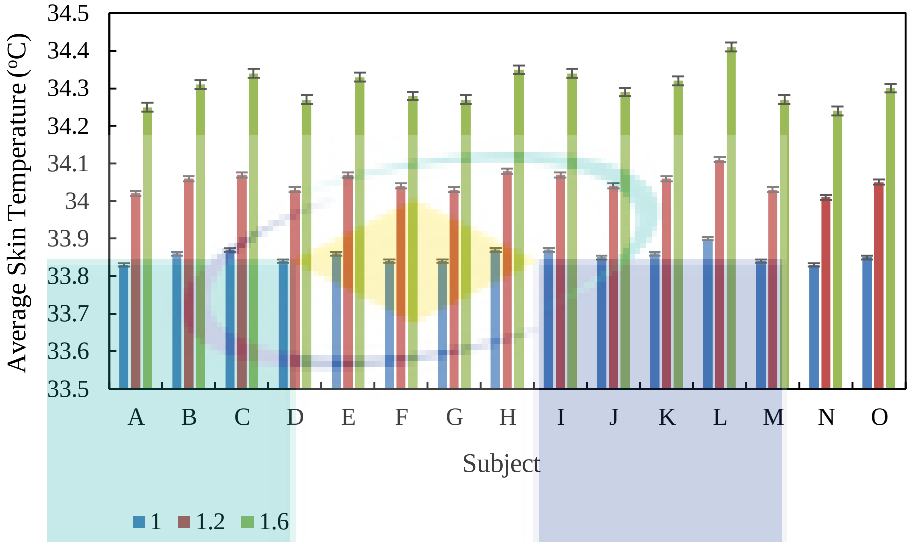


Figure 4.5 Skin Temperatures with Three Activities at Room Temperature 26 °C.

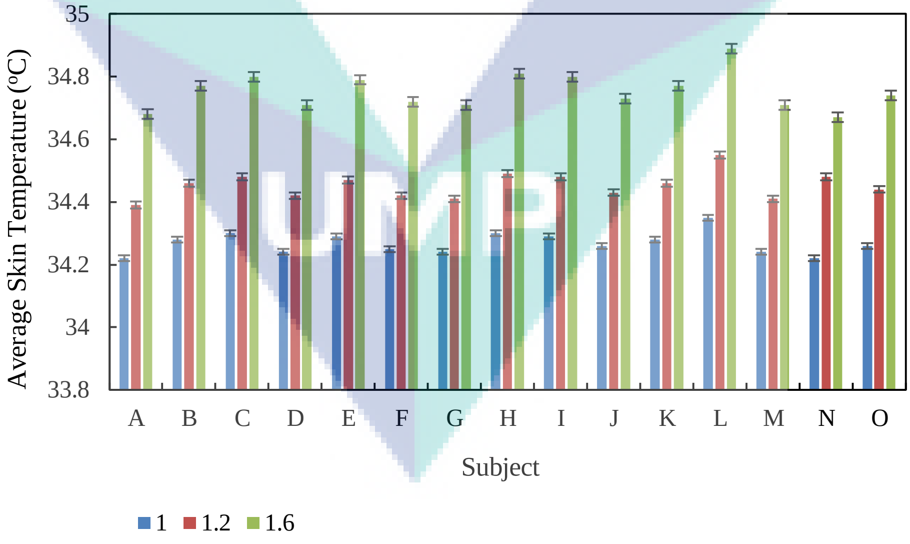


Figure 4.6 Skin Temperatures with Three Activities at Room Temperature 29 °C.

Figure 4.8 shows the effect of skin temperature on room temperature at different body segments. There are 11 body segments consists Head (1), Right Shoulder (2), Left

Shoulder (3), Right Forearm (4), Left Forearm (5), Right Wrist (6), Left Wrist (7), Right Foot (8), Left Foot (9), Right Ankle (10) and Left Ankle (11) as illustrated in Figure 4.7. Figure 4.8 presented the highest body segment effect is left shoulder. This is because the left shoulder position is opposite to the door of the environmental chamber. The entire body segment on the left position is higher than the right position. Since the right position faces the hanging wall of air conditioning unit. It also happens on the right forearm and right foot, both this body segments are placed on the table and on the floor. Furthermore, no barriers for temperature go through to these body segments.

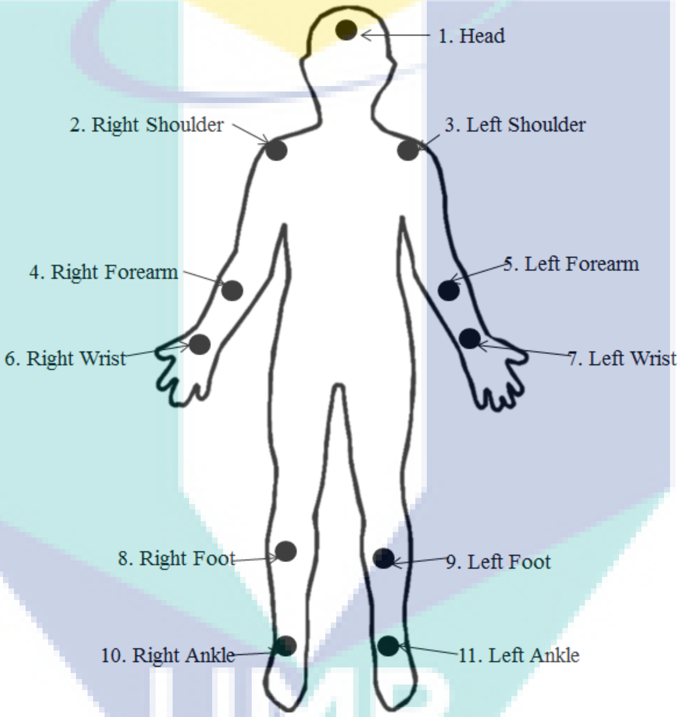


Figure 4.7 Body Segments.

The relationship between the thermal comfort and the thermal sensation was established in previous sections. This section presents the relationship between the mean skin temperature and the thermal sensation which will also allow the prediction of thermal comfort. Research showed that thermal sensation is a function of mean skin temperature. An analysis of the relationship between the mean skin temperature and the thermal sensation was conducted in order to determine the effect of metabolic rate on that relationship. The data were grouped based on the metabolic rate of the subjects.

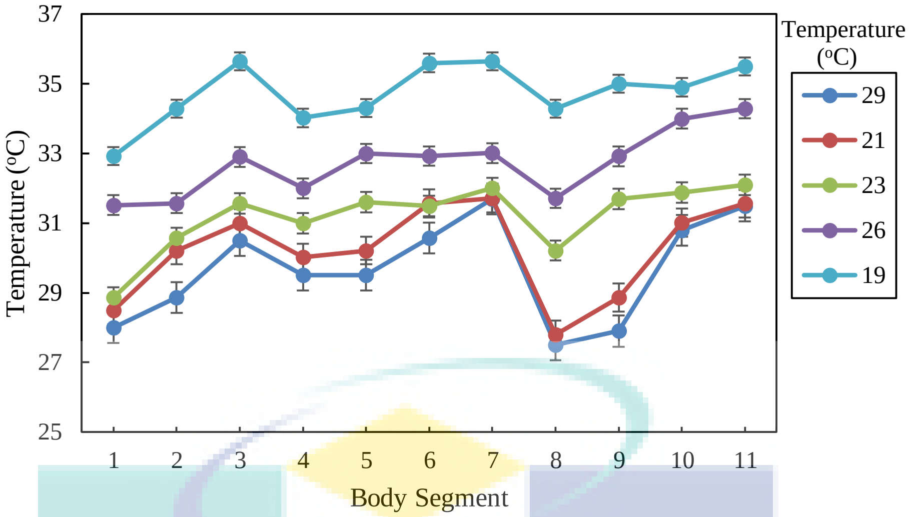


Figure 4.8 Effect of Skin Temperature on Room Temperature at Different Body Segments.

Appendix G shows that different levels of mean skin temperature and metabolic rate generated different thermal sensation values ($p < 0.001$). Figure 4.9 shows that thermal sensation increased with the mean skin temperature in all three metabolic rates. For a given mean skin temperature, higher metabolic rate yielded a higher thermal sensation except around 34.89 °C mean skin temperature (p-value < 0.001). The results of the regression analysis for thermal sensation (see Figure 4.9) show a strong linear dependency for skin temperature of human. The change in mean skin temperature yielded similar changes in thermal sensation for low and medium metabolic rate conditions. However, the change in thermal sensation during the high metabolic conditions was less than the other two conditions. It can be seen that a straight line fits the data well for 1.0, 1.2 and 1.6 Met (R^2=0.7541, R^2=0.8679 and R^2=0.8467) respectively.

Under all conditions of activities, overall thermal sensation and skin temperature are correlated with each other closely. Skin temperature of 34.89 ^{o}C corresponds to thermal sensation of 0.79, that is to say, the subjects felt uncomfortable when their whole body is 34.89 ^{o}C which are more rigid than the definition proposed by Gagge et al. (1967) and Fanger (1970).

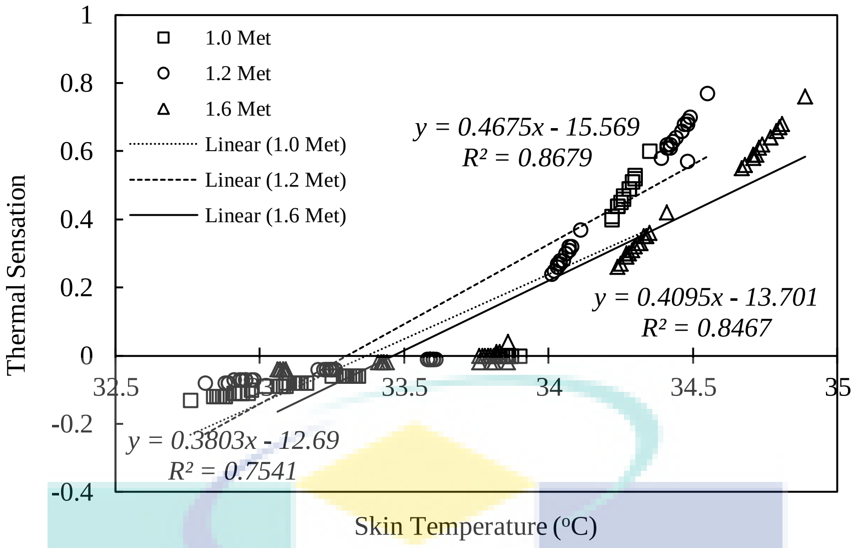


Figure 4.9 The Relationship Between Skin Temperature and Thermal Sensation under Three Metabolic Rate Conditions.

Skin is the interface between the body and the environment and is the most important sensory organ which houses cold and warm thermoreceptors. Thermoreceptor response is affected by both the condition of the body as well as the environment. Thermal sensation is the perception of the thermal conditions based on the integration of the skin and deep body thermoreceptors. This study showed a significant relationship between the mean skin temperature and the thermal sensation for different metabolic rate conditions. The relationship depends on both the absolute as well as the derivative of the skin temperature. These findings were also consistent with thermoreceptor responses, which have a static and a dynamic component based on the absolute temperature and the change in the temperature.

Since the thermal sensation is based on the skin temperature and thus the thermoreceptor response, it is possible to manipulate thermal sensation by changing the skin temperature conditions. Stimulating the cold receptors at varying levels is a strategy which can yield sensation of coolness while avoiding thermoreceptor adaptation. Thermoreceptor and thermal sensation adaptation occur when there is a constant stimulus to the skin (Ring et al., 1993; Greenspan et al., 2003). Preventing skin thermoreceptors to adapt improve the effectiveness of the external stimulus. Changing the skin temperature to desired conditions can be a viable strategy in thermal environmental design. The same principles can be incorporated into the physical design of the occupied space in the form of cool or warm surfaces.

4.3.2 Heat Balance and Heat Loss of the Human Body

An analysis was conducted to determine the heat balance of the body and its effect on thermal comfort. First, determined whether there is a heat storage within the body or not. Second, it determined the amount of heat that was transferred from the core to the skin and its effect on thermal comfort. In the last stage, conducted an analysis of local and general heat loss to the environment and their effect on general thermal sensation.

Body Core Temperature, T_{cr}

A number of steady states and transient human thermal models were presented in the Chapter 2. Those models are based on the heat balance of the human body with the environment. In this section, a heat balance analysis of the human body based on the specific test conditions was presented.

The amount of heat stored inside the body was calculated through the increase in body temperature. The tympanic temperature measurements showed that the core body temperature is relatively stable throughout the experiment (see Table 4.1) and the difference between the measurements was statistically insignificant. Therefore, there was no heat storage in the body between the body temperature measurements and all the generated heat was dissipated to the environment through conduction, convection, radiation and evaporation.

Table 4.1 Body Core Temperature

Mean Body Core Temperature (^{o}C)	Body Core Temperature, Std. Dev.
36.85	0.029

Evaporative Heat Loss

The evaporative heat losses for males and females are similar and calculated values were 5.01 W/m^2 respectively as illustrated in Table 4.2.

Table 4.2 Evaporative Heat Loss for Males and Females

Gender	**Average Met**	**Average Surface Area (m^2)**	**Duration of Test (hour)**	**Evaporative Heat Loss (W/m^2)**
Male	1.27	1.79	3.20	5.01
Female	1.27	1.60	3.20	5.01

Heat Transfer between the Core Body and the Skin Temperature

An analysis was conducted to determine the relationship between the heat conduction through the body and the thermal comfort. The difference between the core temperature and skin temperature (ΔT_{cr}-T_{sk}) was normalized for body mass index (*BMI*) to take into account the insulation properties of the body. A significant correlation was detected between the ΔT_{cr}-T_{sk} and the thermal comfort at $\alpha = 0.05$ (Pearson correlation: 0.58). Figure 4.10 showed the relationship between these two variables. The correlation was also significant without *BMI* normalization, however, with a low correlation coefficient (Pearson correlation: 0.21). This shows that thermal discomfort increases with the increased thermal strain on the body, which is the difference between the core body and the skin temperature. It can be seen that core body temperature a straight line fit data well (R^2=0.58).

Heat balance analyses were conducted including heat generation, heat storage and heat transfer between the body core and the skin surface and between the skin surface and the environment. The body could release the generated heat; therefore, heat storage was neglected. This finding can also be supported with the skin temperature. The skin temperature kept rising during the metabolic transients and didn’t reach a plateau. This means skin wettedness didn’t reach unity (maximum skin wettedness, $w = 1.0$) which would stabilize skin temperature at a steady temperature. Therefore, it was

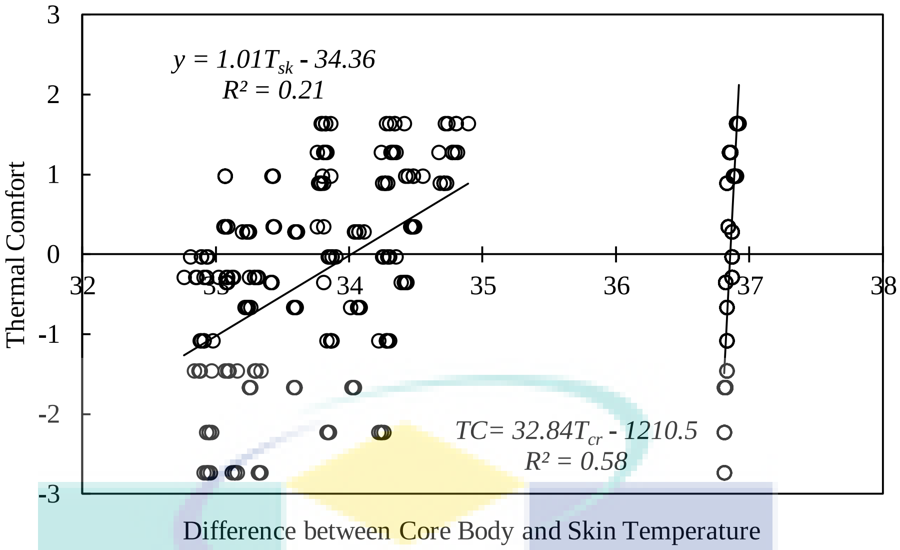


Figure 4.10 Correlations between Thermal Comfort and the Difference between Core Body and Skin Temperature.

concluded that the body could handle more heat generation before it started storing heat.

A second analysis of heat transfer between the core and the skin showed that thermal comfort was negatively correlated with the temperature difference between the core and the skin surface (ΔT_{cr}-T_{sk}). A new index was proposed, which is ΔT_{cr}-T_{sk} normalized based on *BMI*. *BMI* in this index represented the insulation properties of the mass and the heat transfer surface from the core to the skin. In the final analysis of the heat balance section, thermal sensation was correlated to the local heat loss from the head, hands and the feet. This analysis was based on the temperature difference between the local body section and the immediate local environment. All significant relationships were detected between the three body parts heat loss and the thermal sensation.

4.3.3 Heart Rate, *HR*

In this section, an analysis was conducted to determine the relationships between the *HR* and the subjective thermal responses. For the analysis, data from the first 3 hours of the test was used, during which subjects were sedentary. In the first 30 min, subjects were in a relaxed state with closed eyes and without any activity. No sedentary conditions were not included in this analysis since increased body activity triggers multiple physiological mechanisms, which may interfere with the relationships between the previously mentioned variables. Tests were conducted in 19 ^{o}C, 21 ^{o}C, 23 ^{o}C, 26 ^{o}C and 29 °C room temperatures. We conducted ANOVA calculations to determine whether increased skin wettedness due to the higher room temperature.

The traditional approach to determining metabolic conditions in thermal environmental design is to assign a metabolic rate based on the nature of the activity in the environment. This approach assumes stable conditions so long as the activity remains the same. ISO 8996 (2004) suggests a time averaged approach if the type of activity is variable in an environment. In order to validate this assumption, this study analyzed the heart rate and metabolic rate data. Results showed that even when there was minimal activity, the *HR* still fluctuated within ±7 bpm which were equal to the momentary metabolic rate fluctuations of ±0.17 Met. The average heart rate among all the subjects stayed relatively stable during the same period (±1 bpm). The ANOVA showed no significant difference of average heart rate on activity 1.2 Met (p = 0.223) (see Table 4.3). However, the ANOVA showed a significant of average heart rate of activity 1.0 and 1.6 Met (p = 0.002 and 0.022) respectively.

The effect of psychological stress on heart rate was presented in the previous studies (Andreassi, 2000; Spalding et al., 2004; Alderman et al., 2007). They find that the psychological stress increases heart rate, which increases energy expenditure.

Table 4.3 ANOVA Test with all the Activities

Activity (Met)	**Average**	**Std. Dev.**	***p*-value**
1.0	81.38	17.28	0.002*
1.2	85.64	17.98	0.223
1.6	93.38	16.41	0.022*

*Statistical significant

The results of heart rate responses from the subjects under five room temperatures are presented in Figure 4.11. The line of dark blue, red, green, purple and light blue referred to room temperature consists, 19 ^{o}C, 21 ^{o}C, 23 ^{o}C, 26 ^{o}C and 29 ^{o}C. There are 15 subjects involved in this study from A to O. Although the subject done the same task but the heart rate level is the show difference for each other.

The subjects repeated the task at difference room temperature. Based on the result, the subject's heart rate reading lower while relaxing at 1.0 Met. Besides that, the heart rate keeps increasing when subjects begin thinking and typing. Finally, subjects are doing printing task and movement around the workstation (1.6 Met); this task generates the higher heart rate reading as compared with those at the lower activity level.

Even though the statistical significance of ANOVA test not consistent for all activity levels, but it also can show the level of heart rate reading and comfortable for the subjects. Certainly, the 1.6 Met tasks generated the highest heart rates in each chamber room temperature, as compared with those at lower activity levels, which are 1.0 and 1.2 Met.

According to Zhu (2009), building occupant that stays in one room with constant temperature for an extended period of time may decrease their body's ability to regulate body temperature, moreover, spending an excessive amount of time in same or constant temperature is unhealthy and not comfort. From the result, the comfort zone for office room temperature is 23 ^{o}C and 50-60 % relative humidity. The result can be proving and supported by the result of heart rate reading using ECG and according to thermal sensation scale, the comfort zone of workplaces must be neutral or 0 of *PMV* readings.

Moreover, overcooling appears to be a common phenomenon in local offices. Based on findings about overcooling, the studies by Ailu and Victor. (2012) reported that one third of the respondents felt overcooling in office within 8 hours working hour time in Singapore. Another study in Hong Kong also reported that many offices (60 %) fell on the cooler side of the ASHRAE thermal comfort envelope. Overcooling might cause thermal discomfort and energy wastage in the building.

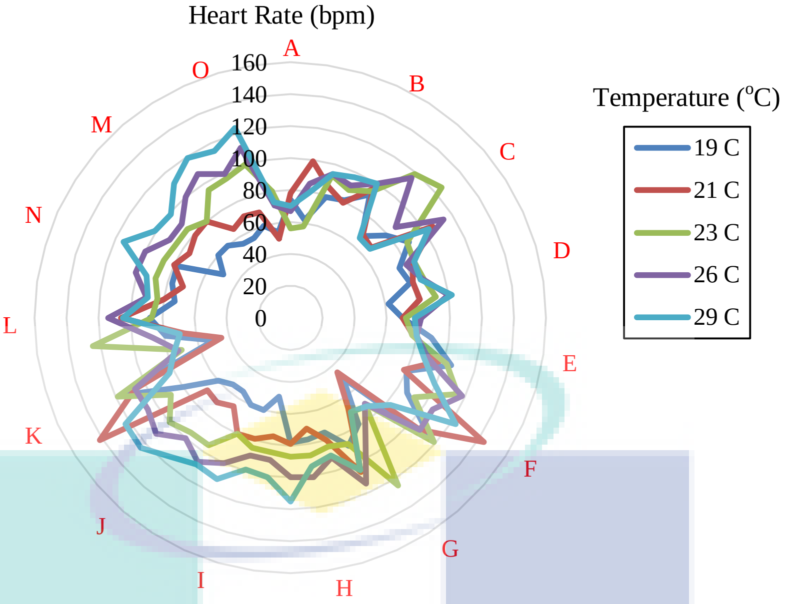


Figure 4.11 Comparisons between Heart Rate Responses from the Subjects and Different Room Temperature.

This study suggests that the subjects maintained their performance by exerting more effort when the workload demand increased in thermal discomfort environment. Haneda et al. (2009) found similar results when examining the effects of thermal discomfort on the performance of office work. Consciously, protecting the level of task performance by ‘trying hard’, can counteract an impaired operator state as well as enable dealing with increased task demands (Hockey, 1986). The performance of these tasks and activities would deteriorate when the amount of resources was insufficient to deal with both the task demands and thermal stress, such as that participants would be able to maintain their performance level until the resources were overloaded (Hocking et al., 2001). Moreover, participants would like to exert more effort to maintain performance if needed when they were supplied with an extra bonus for better performance. The investment of effort has the advantage that task performance remains at a certain target level, but there are costs for this achievement. Short-lasting effort investment is probably without health consequences and is one of the advantages of human flexibility to deal with in demands. However, prolonged, continuous effort compensation can be a threat to good health, as it has been suggested that repetitive activation of the cardiovascular defense response may lead to hypertension (Johnson and Anderson, 1990).

The cost of effort investment can be partly illustrated by participants' motivation to work: they had lower motivation to work when they had to exert more effort to perform a task. Motivation plays an important role in worker productivity. Heerwagen (1998) showed that the relationship between buildings and worker performance was related to both motivation and ability. An individual has to want to do the task and then has to be capable of doing it. In addition to effort investment, well-being is also related to motivation to work. Fang et al. (2004) also found the perception of air freshness and acceptability improved greatly as temperature decreased and the intensity of fatigue, headache and difficulty in thinking clearly decreased at lower levels of air temperature. Due to the above reasons, high air temperature significantly reduced participants' motivation to do their work. In fact, the confidence that the fight for a healthy work environment and healthy workers is a prerequisite for innovation and productivity in a knowledge-based economy, is gaining more and more ground in companies (Hermans and Peteghem, 2006).

4.4 Computational Analysis of Human Effect on Thermal Environment

The importance of air conditioning is to ensure the rationality of indoor air distribution because it is closely related to the effect of adjusting indoor temperature, air conditioning energy consumption, human body comfort and health status. The rationality of the air flow in a room with air conditioning not only has an influence on indoor air adjustment but also directly affects the air conditioning system. Furthermore, it determines the impact of indoor air quality on human health. Therefore, the reasonable indoor air distribution must meet the requirements of energy saving, comfortable and healthy.

Human thermal comfort in a conditioned room is investigated using the coupled model described in Chapter 2. Heat transfer inside the human body is calculated for a given level of activity (metabolic rate), using the two node human thermoregulation model. Prediction of metabolic heat dispersal to the surroundings is accomplished by a Computational Fluid Dynamics (CFD) code. Results for different cases with varying supply air velocity, temperature and radiant temperature as well as the human metabolic rate are obtained to predict thermal comfort conditions in the room, using several comfort indices.

4.4.1 Environment Effects of Occupation in Conditioned Room

Results are obtained in empty and occupied room cases to show the effect of human occupation in a ventilated room on parameters such as radiant temperature (T_r), air temperature (T_a), air velocity (v), PMV and PPD indices. All results are presented in front view, side view and top view. Results CFD for empty room illustrated in Appendix J. In this section, there are field cloud pictures at three selected views. In this study, there is five room temperature, which is 19 °C, 21 °C, 23 °C, 26 °C and 29 °C.

In all the test conditions, subject had control of their room temperature, so in order to better observe the environment factors effects of the chamber; three views consist front view, side view and top view are established.

Radiant Temperature

The radiant temperature indicates the radiant energy exchange for a room, defined as "the uniform surface temperature of an imaginary black enclosure in which the radiation from the occupant equals the radiant transfer in the actual non-uniform enclosure (Fanger, 1970). Figure 4.12 compares the results radiant temperature of non-occupied and occupied under different room temperature. The graph shows that there has been a steady increase under the five room temperature. There were different results between non-occupied and occupied, which is radiant temperature higher when the chamber in occupied. The higher different between non-occupied and occupied is room temperature at 19 °C which is 3.1 °C. At room temperature 26 °C, the difference is 0.8 °C and smaller than other room temperatures. The different room temperatures at 21 °C, 23 °C and 29 °C are 1.8 °C, 1.0 °C and 1.3 °C, respectively.

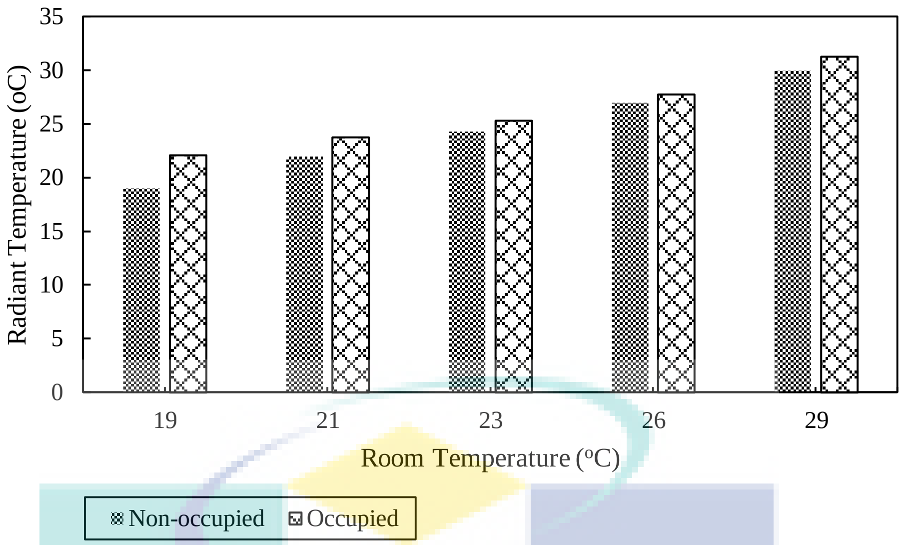
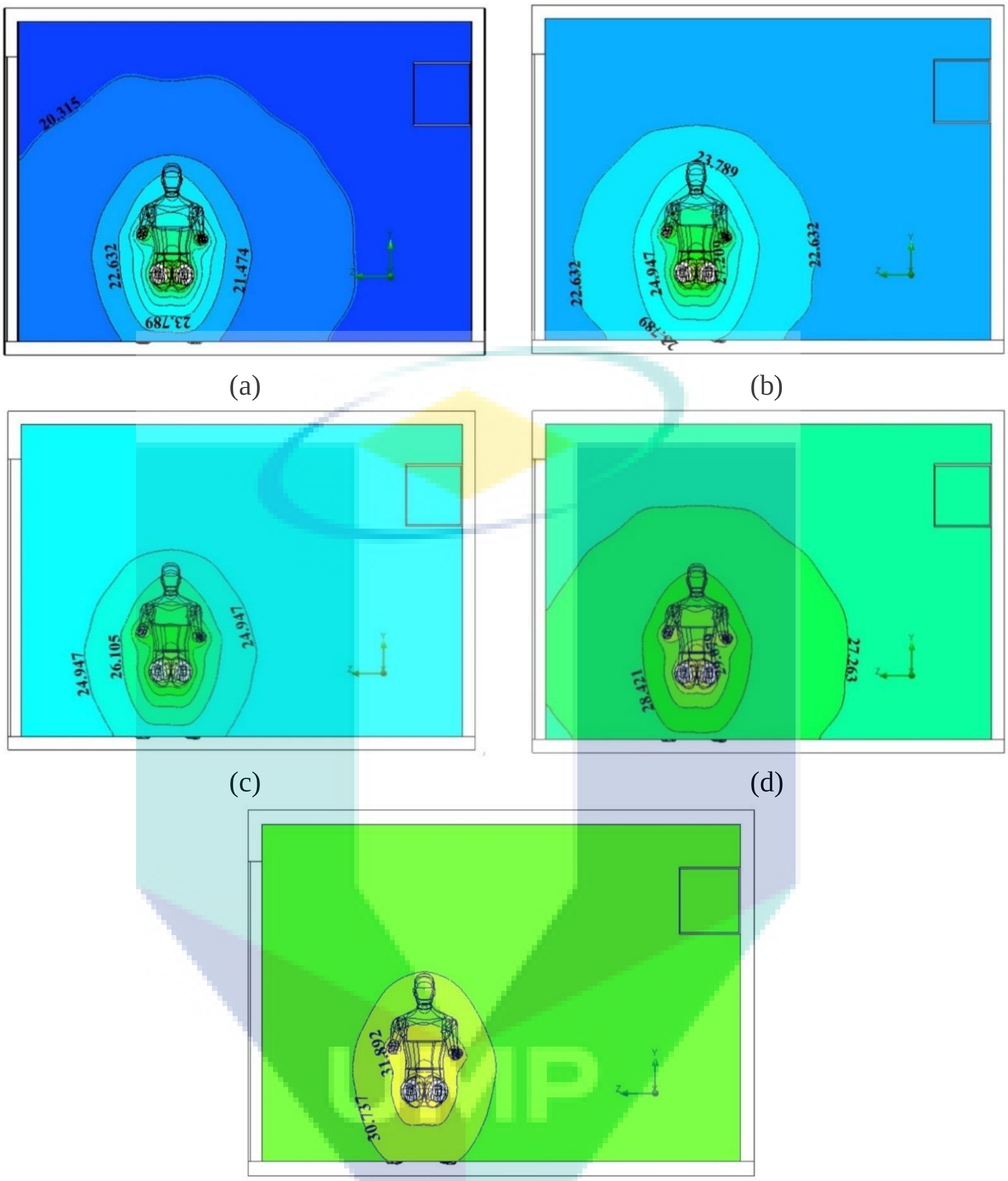


Figure 4.12 Change in Radiant Temperature of Non-Occupied and Occupied under Different Room Temperature.

Figure 4.13 (a) represent the radiant temperature contour at 19 °C room air temperature setting. In the Figure 4.13 of (b), (c), (d) and (e), it indicates the temperature setting of 21 °C, 23 °C, 26 °C and 29 °C respectively.

Figure 4.13 (e) illustrated the separation of the flow region areas around the human body and for the maximum radiant temperature is 31.9 °C at room temperature setting 29 °C. The maximum radiant temperature at room temperature 19 °C is 23.8 °C. A uniform radiant temperature distribution surrounds the human body and considerable decreases on the leeward side of the human body were confirmed. As expected, symmetric values of radiant temperature for both sides of the body were observed in the front direction (front view). Under the sideways direction, the left side indicates that radiant temperature higher than the right side. This evident can be seen in Figure 4.15, at room temperature setting 23 °C, the difference between the left and right side not exceed 1.0 °C.

Figure 4.16 presented the average radiant temperature distribution of the different room temperature. The results indicate that similar with three views, which front, side and top view. This critical overview shows once more that the radiant thermal field is an essential parameter of thermal comfort. Radiant effects commonly sensed by the occupants of offices occur. The presence of a strong thermal radiant field can also become a serious issue in the context of productivity. In many offices, due to limited space or other reasons, two or more people can occupy the same relatively small room. Imagine the situation where the one sitting near the wall or window with a strong radiant field is the one who prefers to be on the cooler side of thermal sensation and the one sitting near the inner wall prefers the warmer side of thermal sensation. In such a situation, conflicting thermal preferences due to the presence of radiant asymmetry can create the thermal comfort tension.

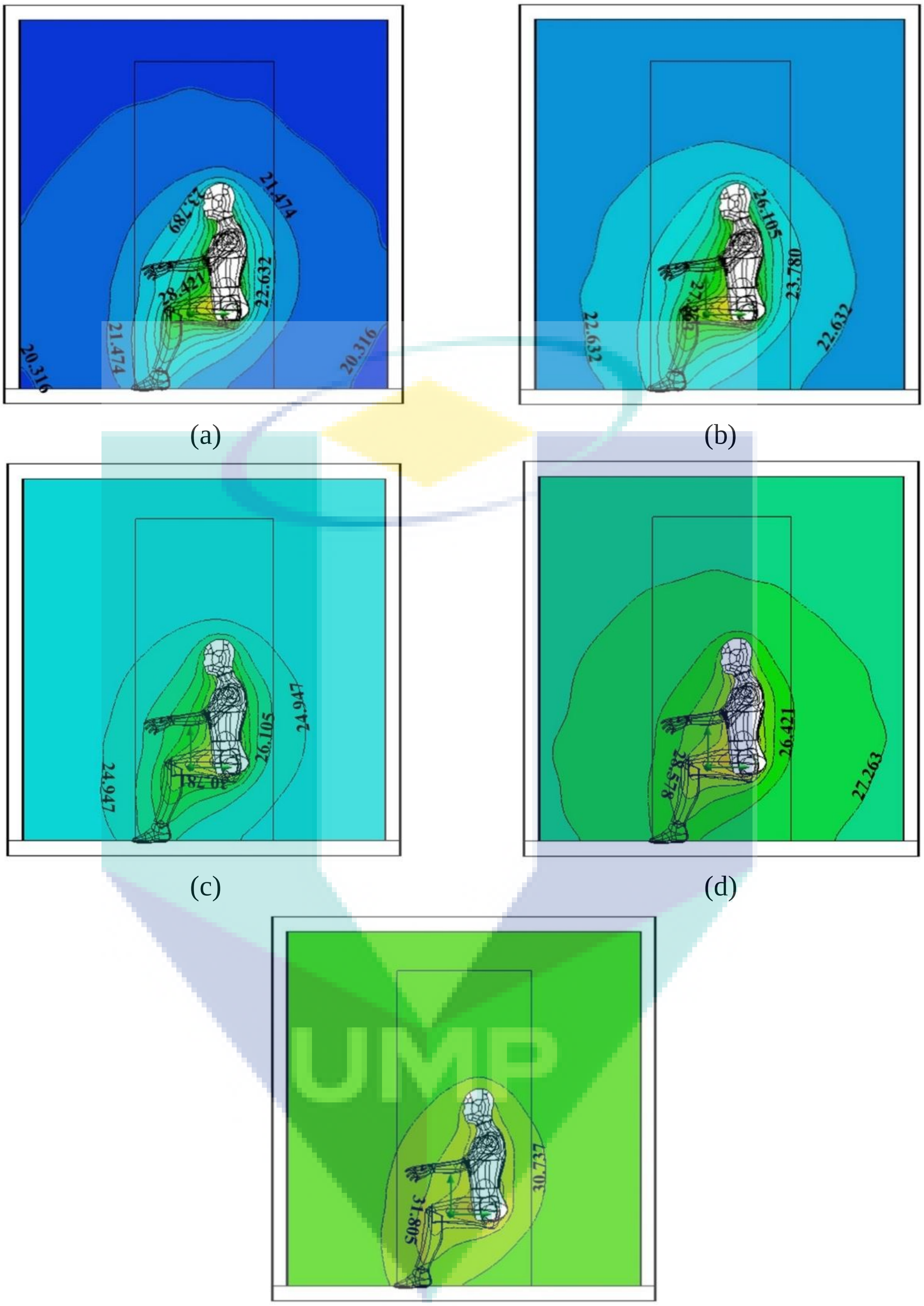


(a) (b)

(c) (d)

(e)

Figure 4.13 Effect of Radiant Temperature at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Front View.

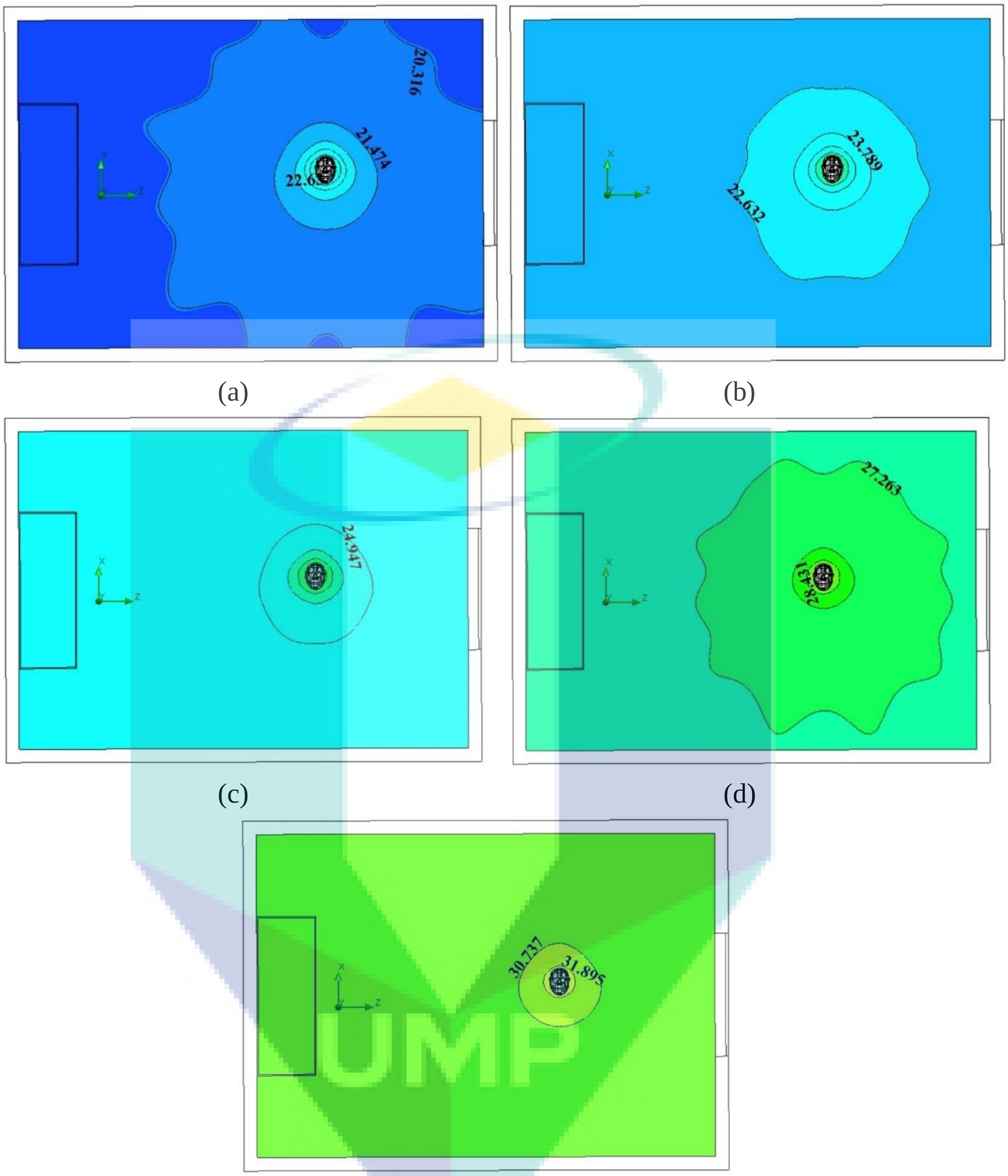


(a) (b)

(c) (d)

(e)

Figure 4.14 Effect of Radiant Temperature at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Side View.



(a) (b)

(c) (d)

(e)

Figure 4.15 Effect of Radiant Temperature at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Top View.

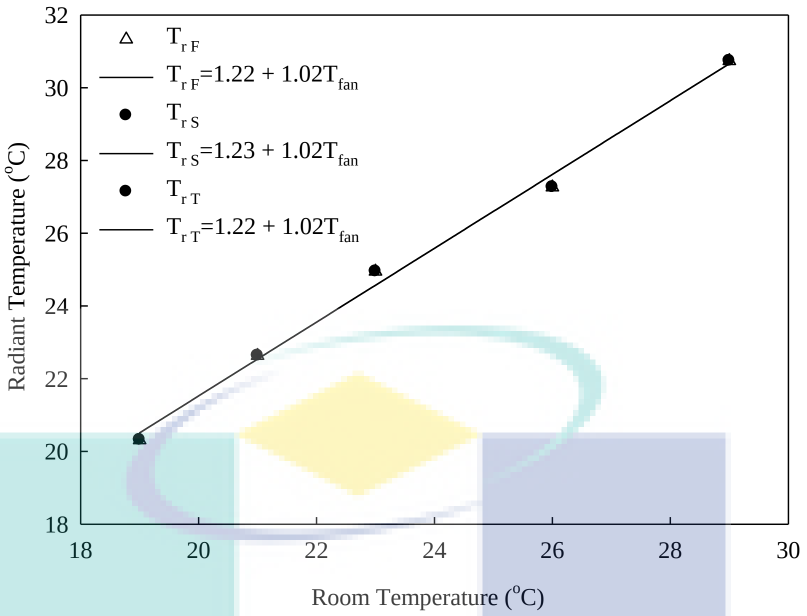


Figure 4.16 Effect of Radiant Temperature Distribution at the Different Room Temperature.

In general, the radiant temperature was related to the human body surface. In this study the radiant temperature comparatively higher in the occupied space compares to the non-occupied space.

Air Temperature

Figure 4.17 shows the results air temperature of non-occupied and occupied at different room temperatures. The room temperatures at 19 °C and 26 °C of non-occupied space are higher than the occupied. The differences are 0.8 °C and 0.3 °C respectively. The minimum air temperature difference is at room air temperature of 21 °C and 23 °C which is 0.1 °C. Meanwhile, the different temperature at room temperature 29 °C is 0.8 °C. The air temperatures different between non-occupied and occupied space is small. Figure 4.17 also indicates that the higher the supply air temperature, the faster air temperature rises.

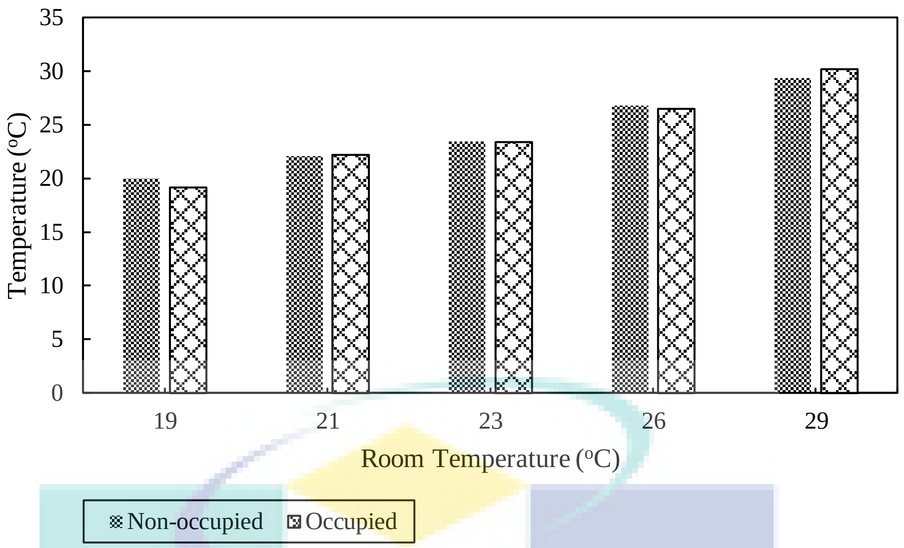
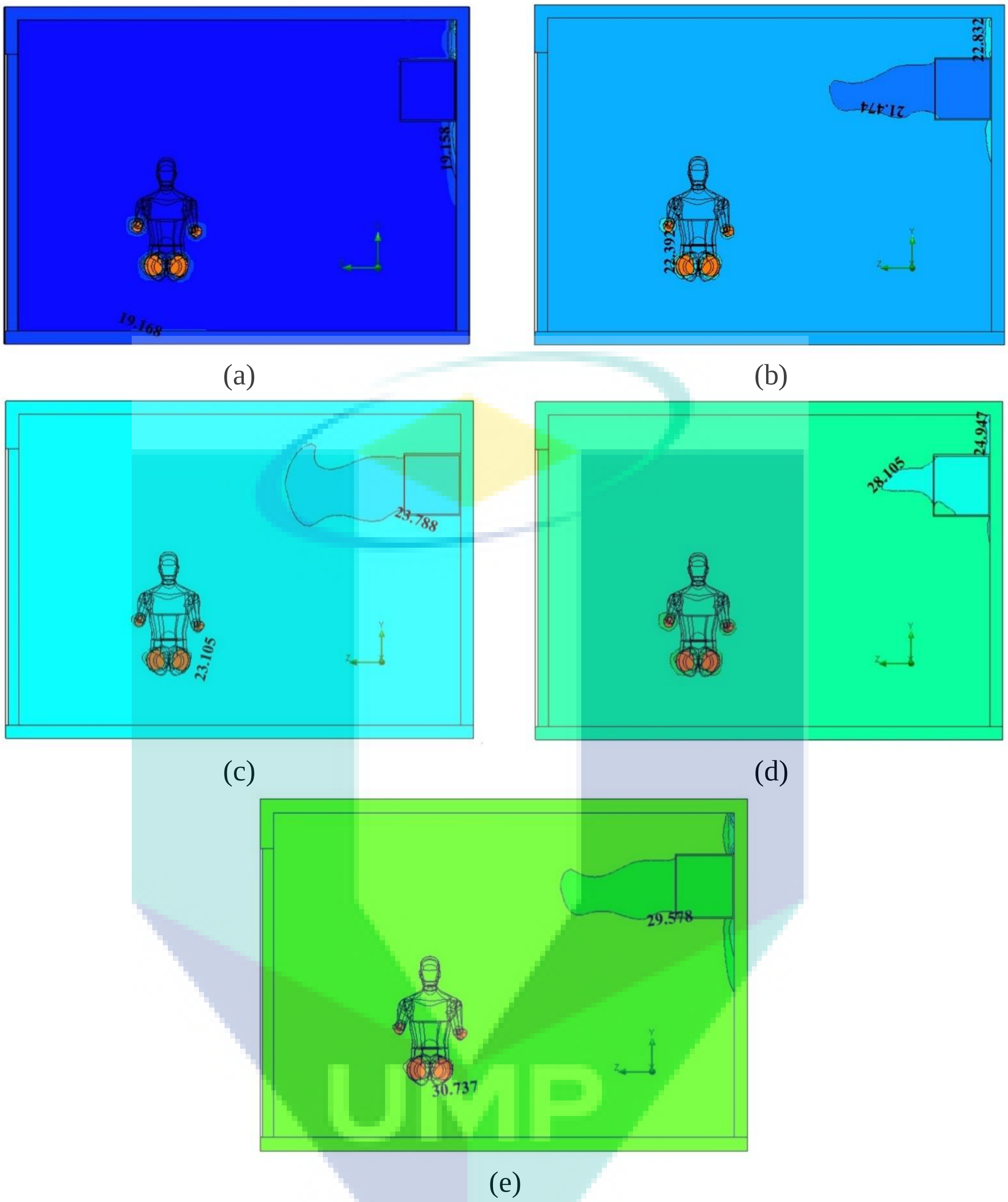


Figure 4.17 Change in Air Temperature of Non-Occupied and Occupied at Different Room Temperature.

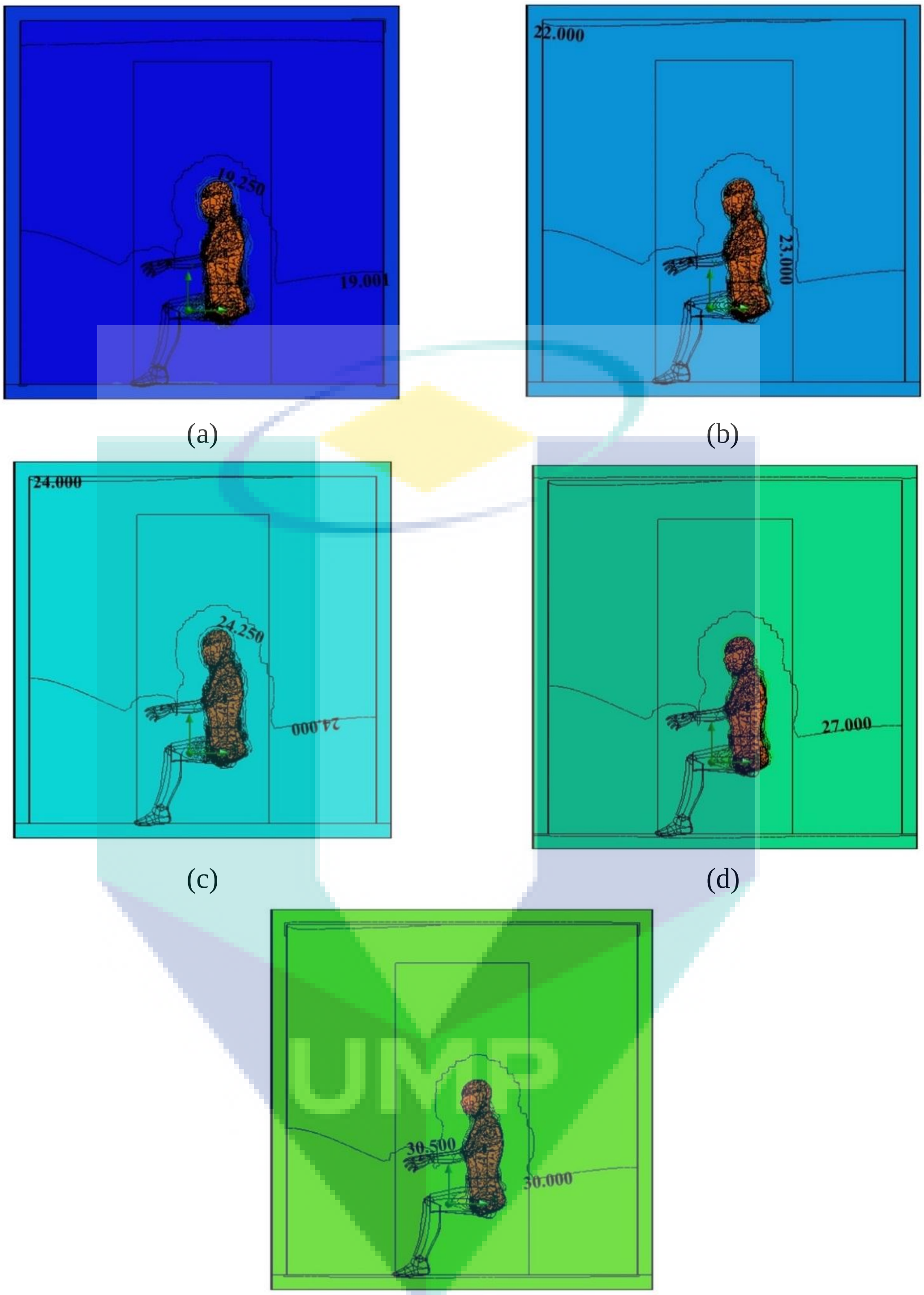
The temperature field of the whole chamber was obtained after CFD calculation. Compared with the point wise information about the actual subject's tests, the temperature fields of CFD results show more detailed information of heat transfer in the simulation.

The supply air temperature of the conditioned room is varied from of 19 °C to f 29 °C. Figure 4.18 shows the temperature distribution for front view. The left hand side region, or backside of the person (see Figure 4.19), was a zone with temperature as low as inlet air temperature, since the backside circulation caused by the mainstream was strong that make the air in that region well mixed with cooler air from the inlet, inducing heat transfer, mostly by convection. Air temperature in close space is uniform and not much different between around the human body and the surrounding. Figure 4.20 presents the air temperature distribution for a top view. There is not much air temperature difference. The effect of temperature on the air supply, the temperature is more noticeable for the subject that is the air temperature increase when approaching the subject.



(a) (b) (c) (d) (e)

Figure 4.18 Effect of Air Temperature at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Front View.

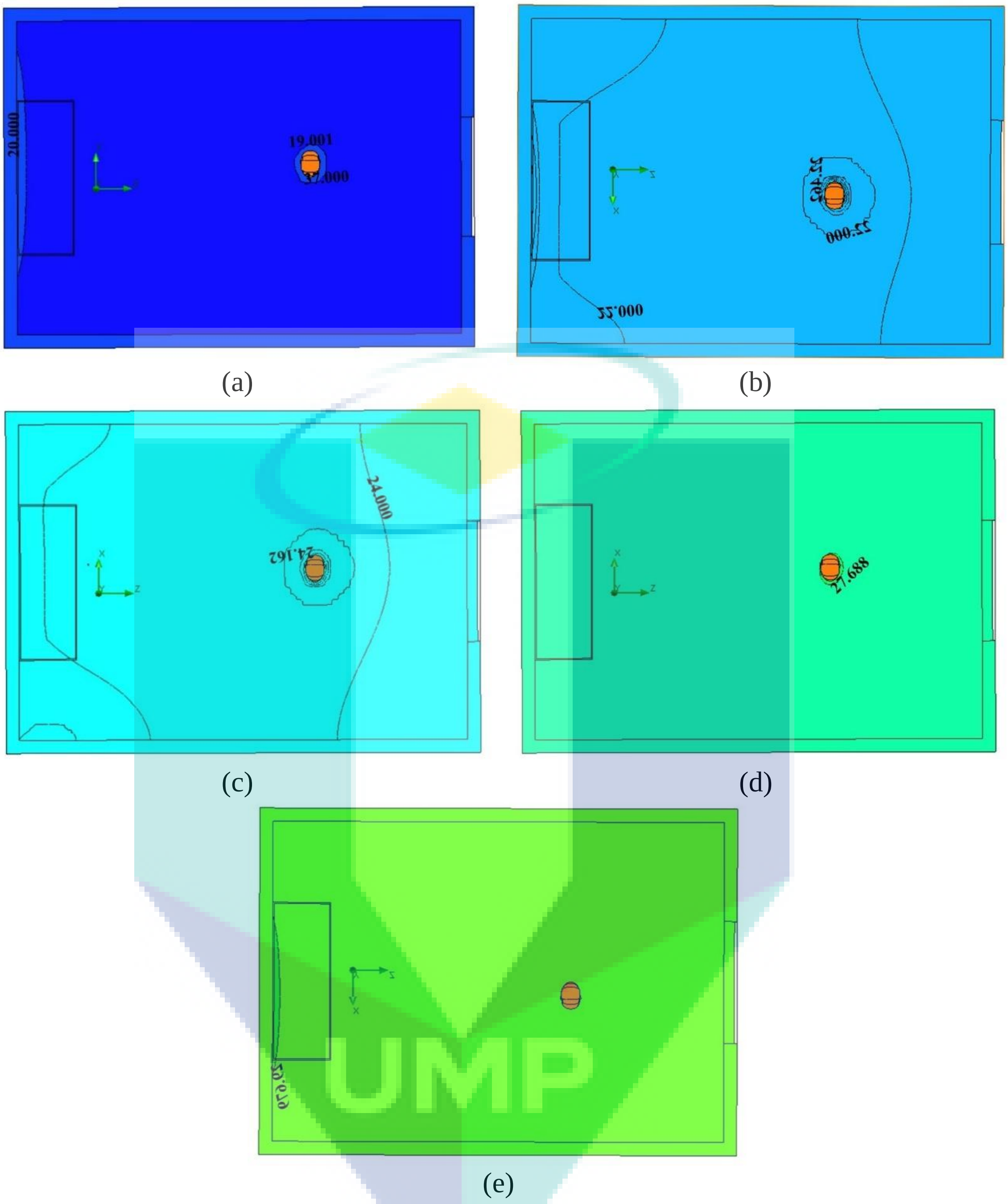


(a) (b)

(c) (d)

(e)

Figure 4.19 Effect of Air Temperature at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Side View.



(a) (b)

(c) (d)

(e)

Figure 4.20 Effect of Air Temperature at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Top View.

Figure 4.21 illustrated the average air temperature under different room temperature for front view, side view and top view. The results showed that the air temperature doesn’t differ much for three views.

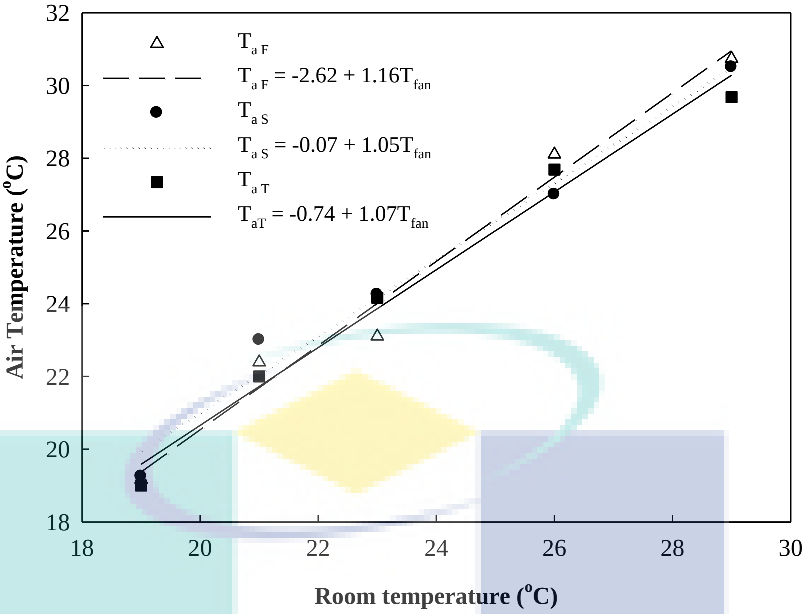


Figure 4.21 Effect of Air Temperature Distribution at the Different Room Temperature.

Air Velocity

The air velocity is one of the important parameters for the human thermal comfort; an increased air velocity will aid the evaporation of sweat thus leading to a cooling effect, particularly if loose clothing is worn (Catalina et al., 2009). However, if the air velocity is too high, it may cause discomfort and a sensation of draughtines. Figure 4.22 shows a comparison of air velocity at each supply air temperature between non-occupied and occupied space. It shows that supply air temperature at 21 oC, 23 ^{o}C and 26 ^{o}C for non-occupied is higher than the occupied space, which are 0.16 m/s, 0.22 m/s and 0.08 m/s respectively. Meanwhile, at supply air temperature of19 ^{o}C and 29 ^{o}C show that occupied space velocity is higher than non-occupied spaces which are, 0.12 m/s and 0.21 m/s respectively. The air velocity trend shows non-uniform, although the temperature supply is the increase. There is a clear trend that the higher the Met, the preferred air velocities is lower.

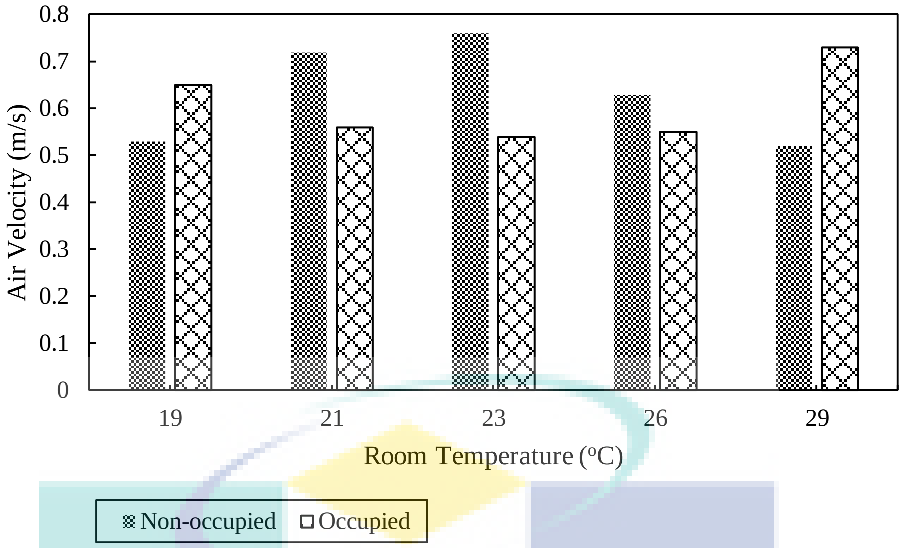
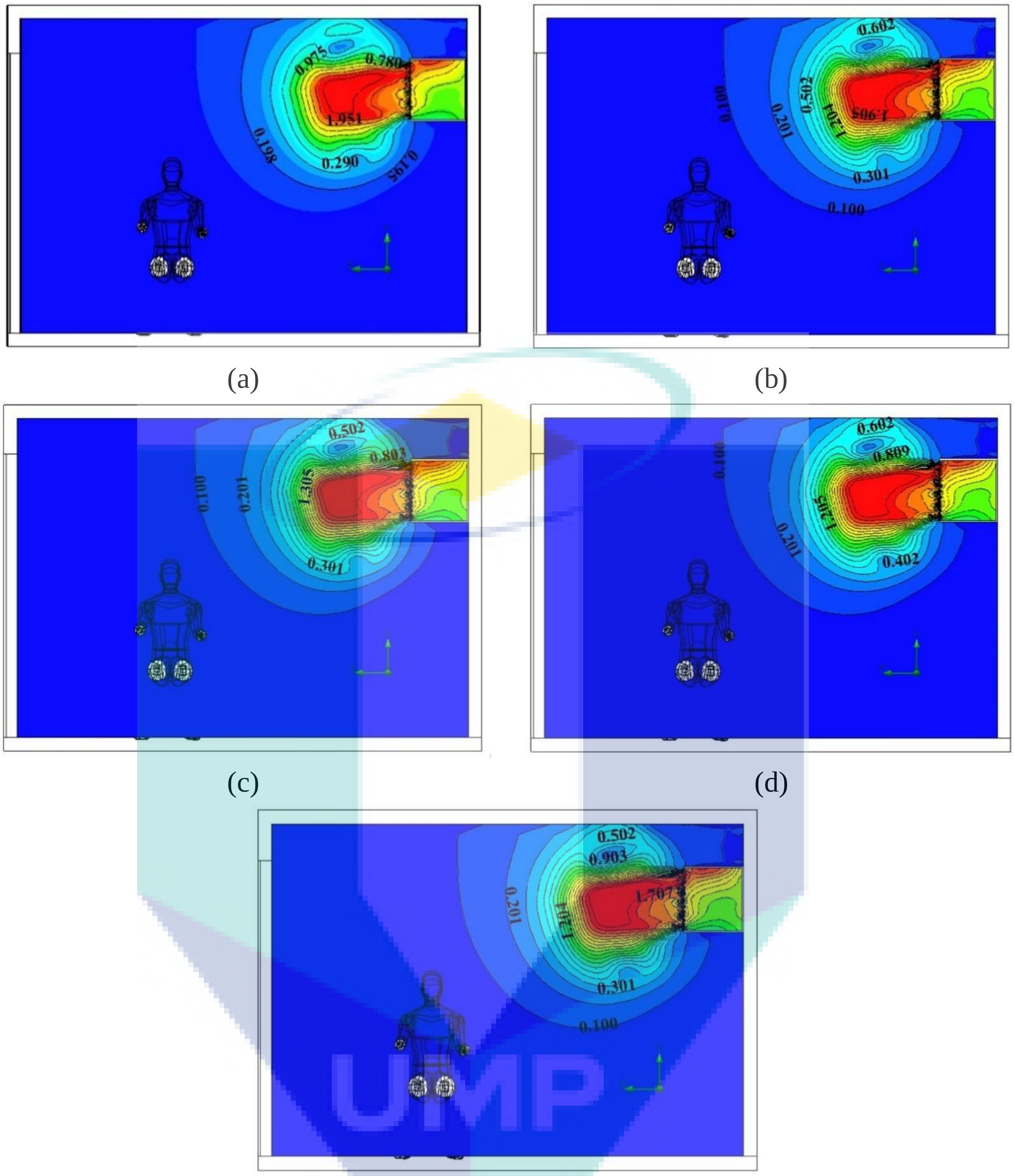


Figure 4.22 Change in Air Velocity of Non-Occupied and Occupied under Different Room Temperature.

Figure 4.23 shows the velocity distribution for five setting room temperature (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C for front view. The velocity vector field was plotted on color background showing speed distribution. The main flow slightly bent to the left then vertically swept along the local space near the person’s back, up to about 1.8 m height, spread and bent to the right toward the return outlet at reducing speed. The upward flow was dominated by forced convection from the imposed inlet velocity and also induced by natural convection due to the higher temperature surface along the person’s back, while the downward flow was under the effect of natural convection only because of its lower temperature. The upward and downward flow created a region of circulation near the backside of the person (left hand side on Figure 4.23). All the distribution of velocity was similar for all setting room temperature.

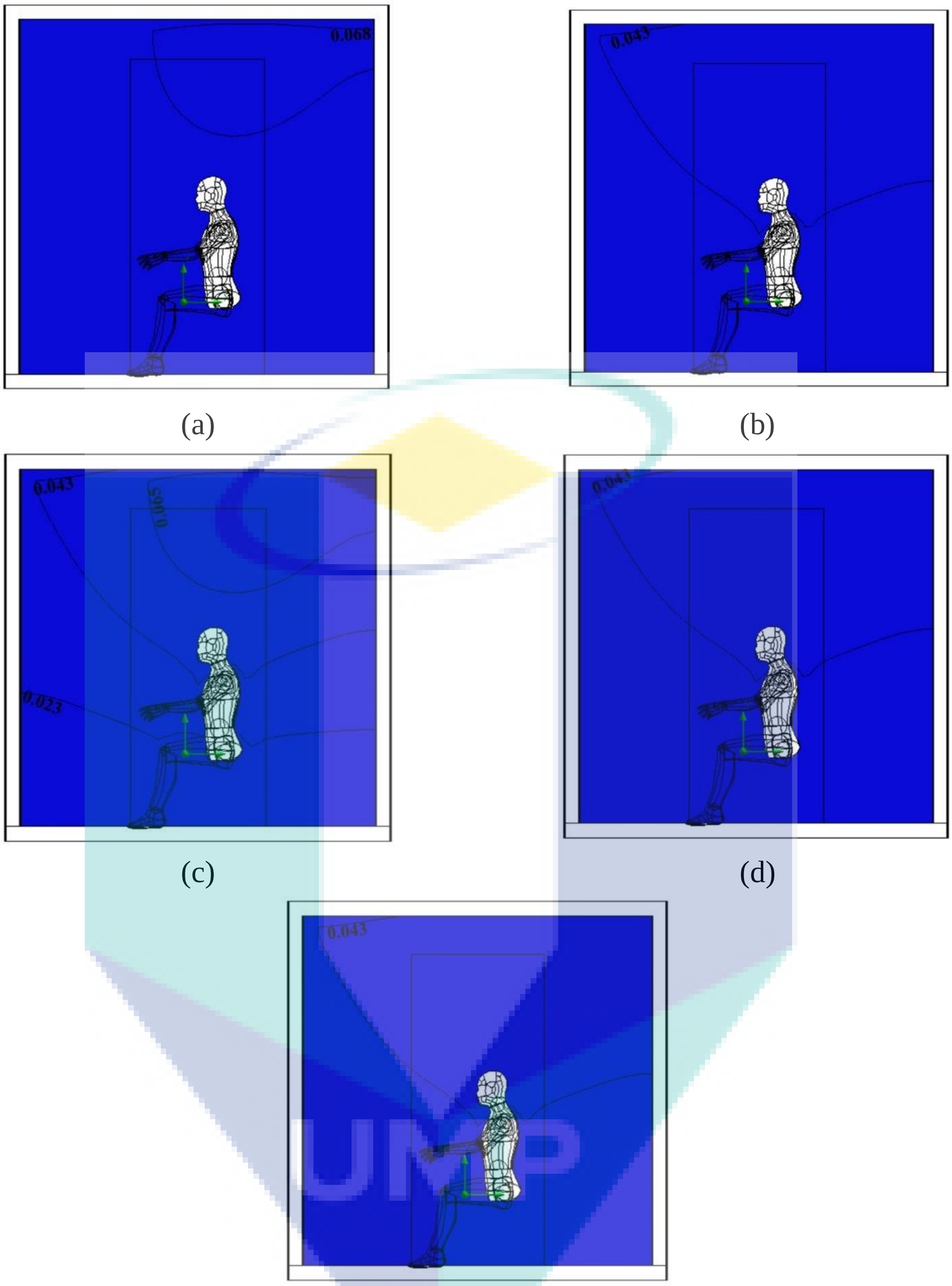


(a) (b)

(c) (d)

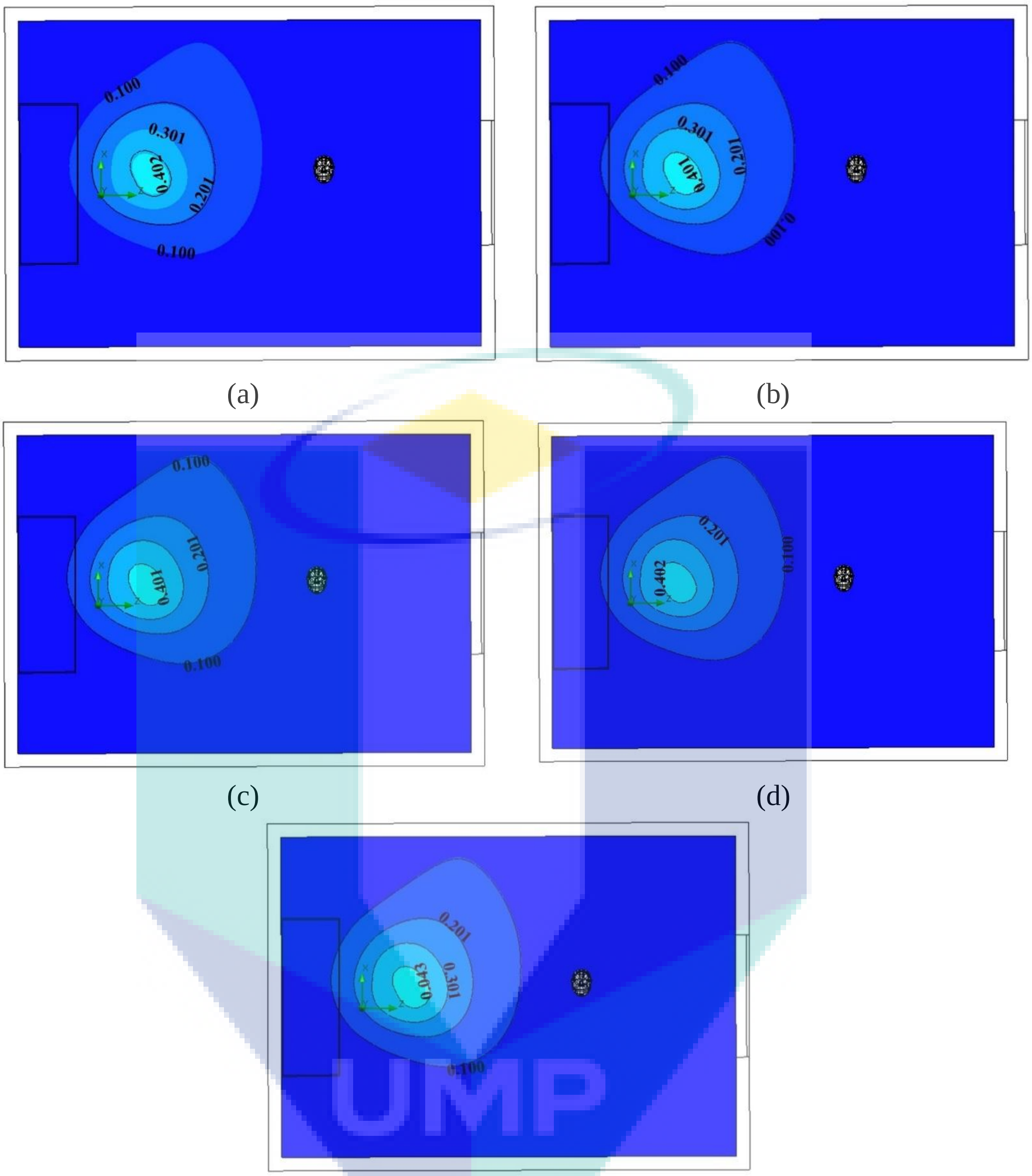
(e)

Figure 4.23 Effect of Air Velocity at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Front View.



(a) (b) (c) (d) (e)

Figure 4.24 Effect of Air Velocity at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Side View.



(a) (b)

(c) (d)

(e)

Figure 4.25 Effect of Air Velocity at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Top View.

Figure 4.26 illustrated that average air velocity under the different room temperature from front view, side view and top view. The results indicate that air velocity for top view is steady for all supply temperatures, it is 0.1 m/s. While, the results air velocity for front view is the steep decrease; it is from 0.15 m/s to 0.08 m/s. As can be seen from the Figure 4.26, the trend air velocity for side view is a gradual decrease; it is from 0.6 m/s to 0.03 m/s.

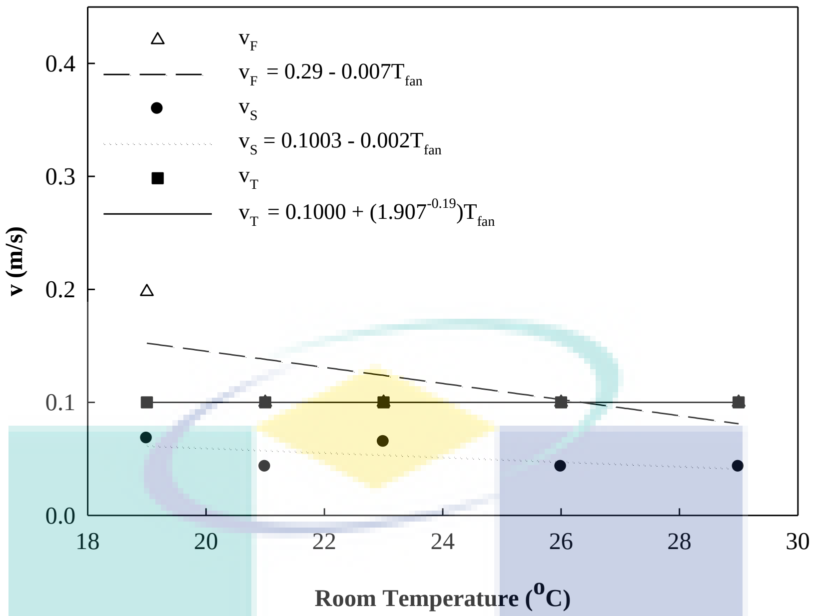


Figure 4.26 Effect of Air Velocity Distribution of the Different Room Temperature.

Predicted Mean Vote (PMV)

The *PMV* value has a range of 3.0 to be -3.0, corresponding to the hot to cold thermal conditions. Figure 4.27 shows that comparison *PMV* under different room temperature between non-occupied and occupied. The result *PMV* shows that non-occupied is higher than occupied. Supply temperature at 19 ^{o}C and 29 ^{o}C is almost warm. Meanwhile, supply temperature 21 ^{o}C and 26 ^{o}C are slightly warm. Supply temperature at the 23 ^{o}C indicates that the *PMV* is comfortable. From this, it is clearly identified that the temperature at 23 ^{o}C is comfort.

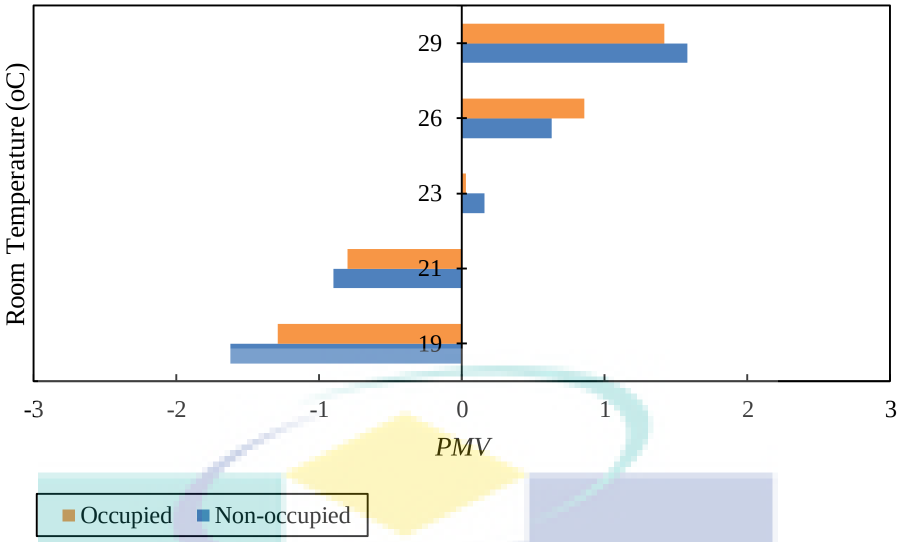
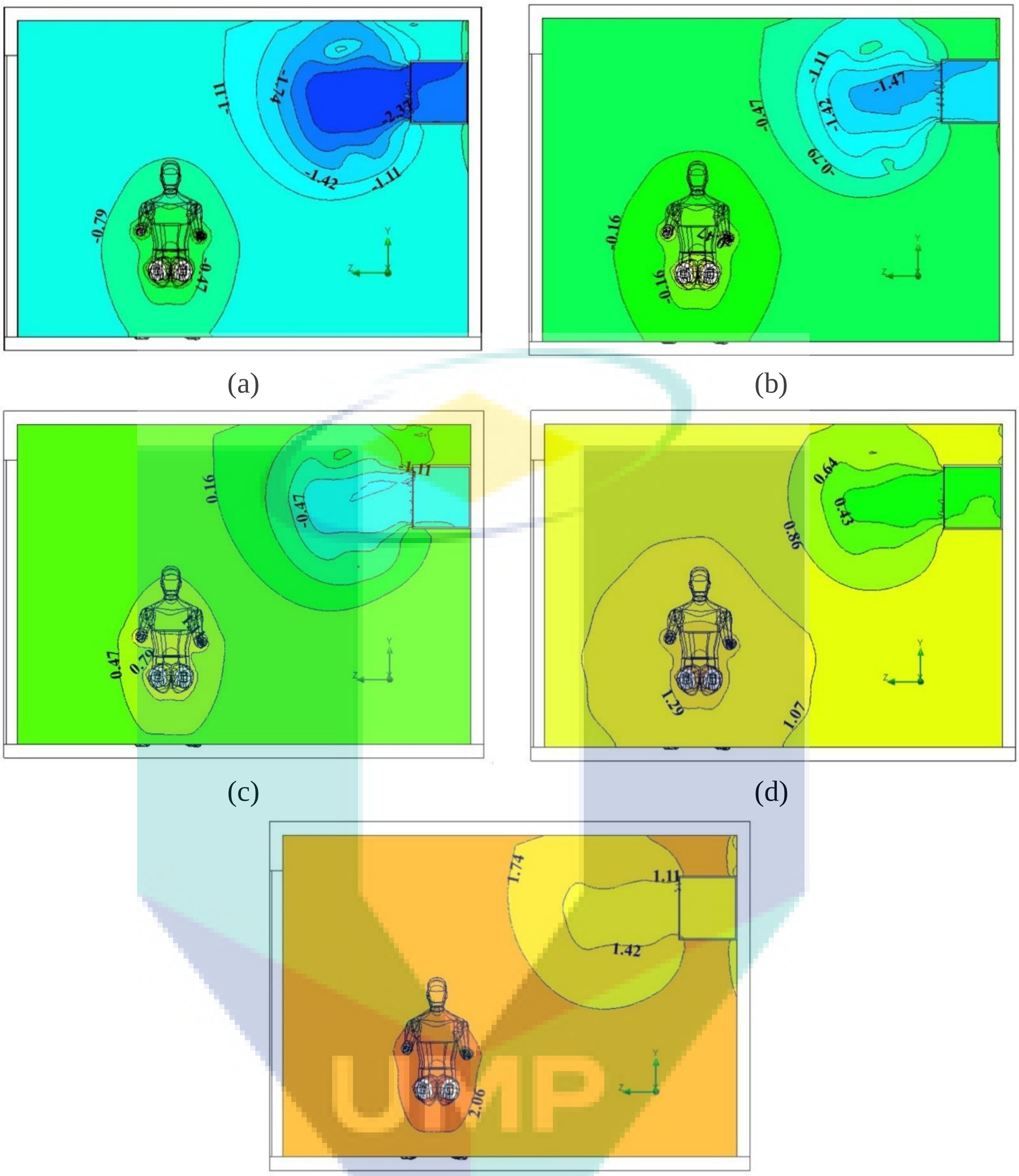


Figure 4.27 Change in *PMV* of Non-Occupied and Occupied under Different Room Temperature.

Figure 4.28, 4.29 and 4.30 show the *PMV* field cloud pictures in front, side and top view respectively. The three cross sections are representative. Firstly, by comparison the finding states that air room temperature thermostat setting effect in 23 °C is comfort than others. The value of *PMV* in room temperature thermostat setting 23 °C is 0.79 near the skin of an occupant. The *PMV* value near the human body is higher than surrounding. Since the radiant temperature is a result of the radiation exchanges between the surfaces and the human body, its value depends on the complex interaction of these factors.

Figure 4.31 illustrated that the average *PMV* results under the different room temperature from front view, side view and top view. All the result's trend shows that steep rise corresponding the supply temperature. The supply temperature at the 23 °C showed that close to 0 and definitely comfortable. At 29 °C, the results of *PMV* showed that warm that is 2 and at 19 °C, the results of *PMV* showed that slightly warm which is close to 1.

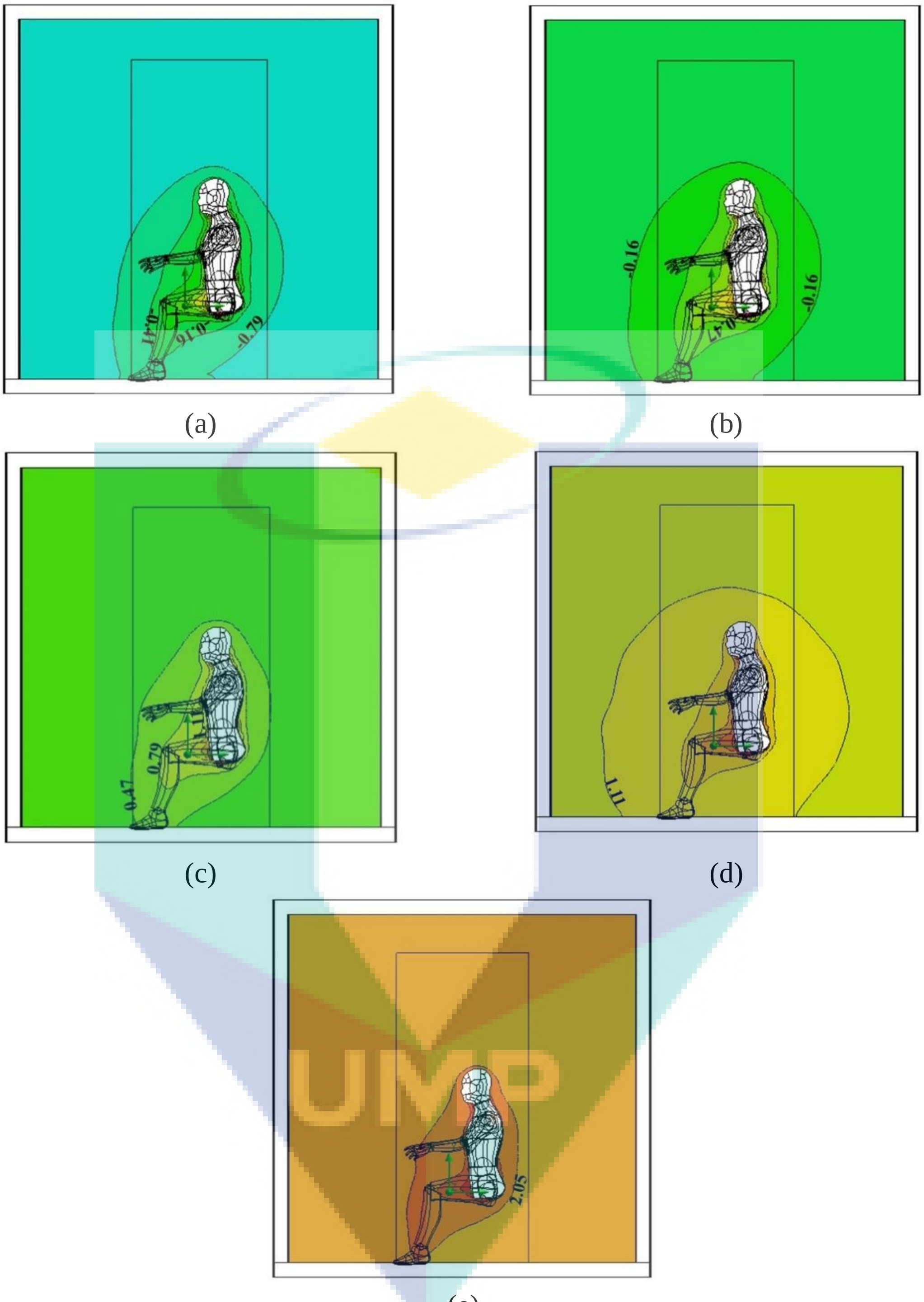


(a) (b)

(c) (d)

(e)

Figure 4.28 Effect of *PMV* at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Front View.

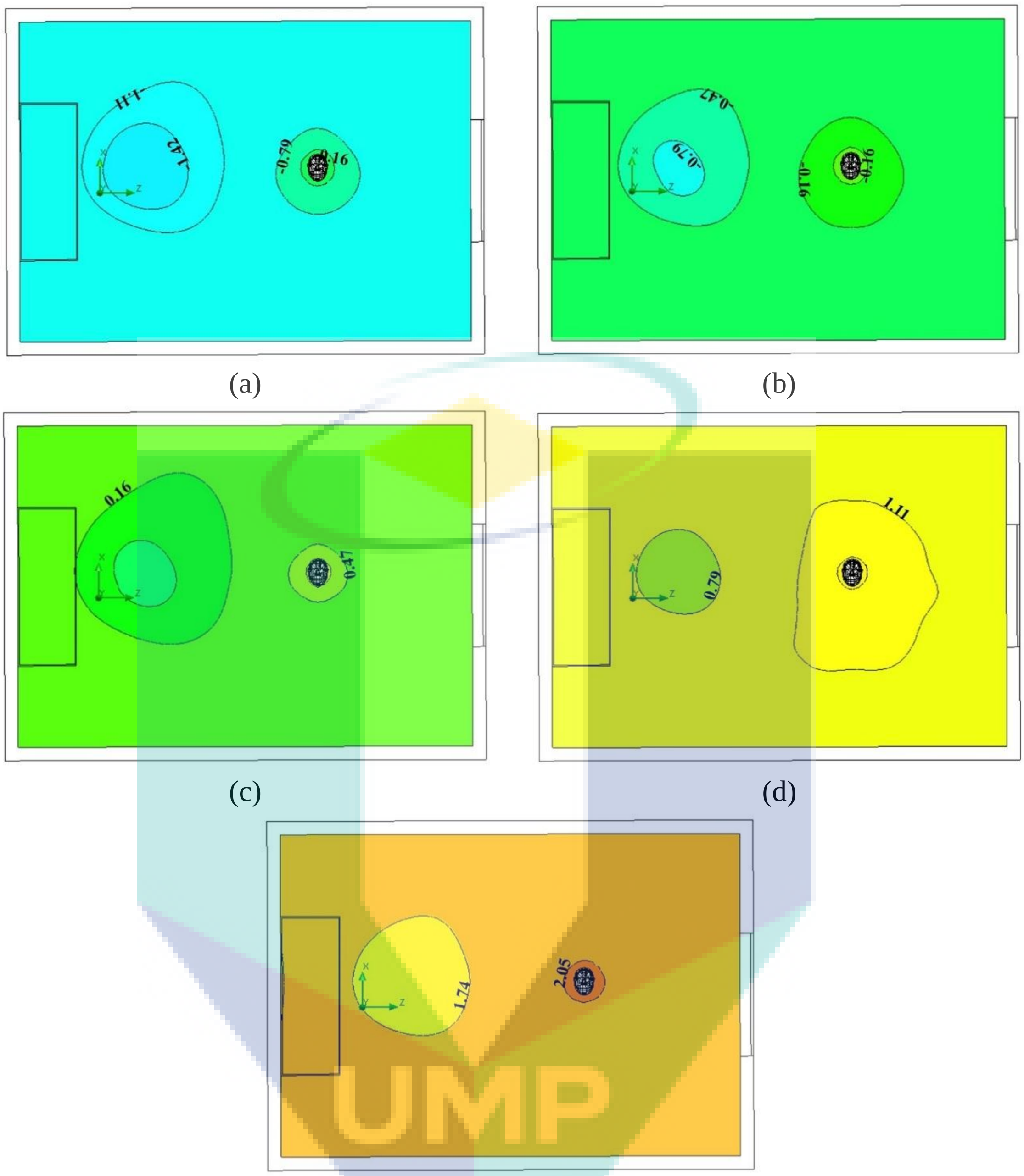


(a) (b)

(c) (d)

(e)

Figure 4.29 Effect of *PMV* at Different Room Temperature*;* (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Side View.



(a) (b)

(c) (d)

(e)

Figure 4.30 Effect of *PMV* at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Top View.

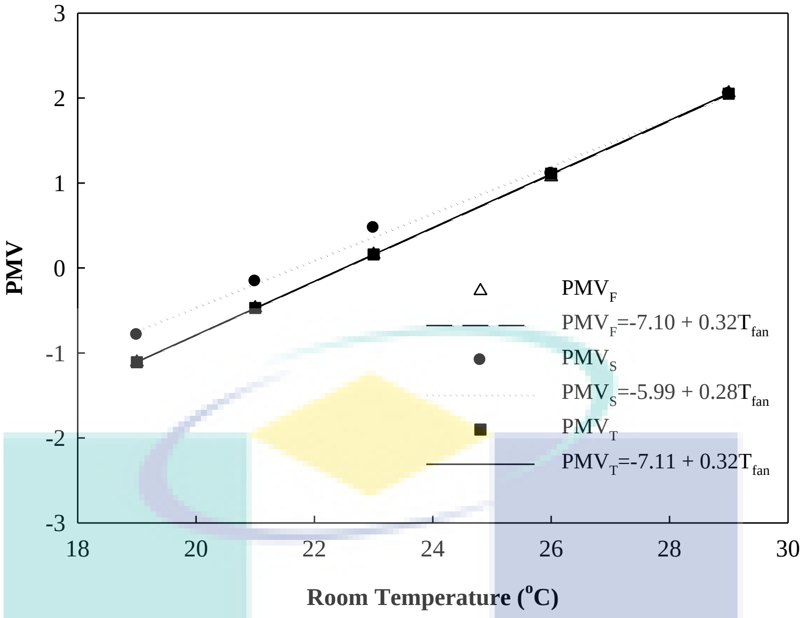


Figure 4.31 Effect of *PMV* Distribution of the Different Room Temperature.

Predicted Percentage Dissatisfied* (*PPD)

PPD is the reflection from *PMV*. *PPD* is aimed to predict how many people feel uncomfortable due to a particular thermal condition in a room. Figure 4.32 shows that comparison *PPD* under different room temperature between non-occupied and occupied. Supply temperature at 19 ^{o}C and 21 ^{o}C shows that *PPD* non-occupied is higher than occupied and the other is occupied higher than non-occupied. The supply temperature at the 23 ^{o}C shows that *PPD* is lower than 20 %, this result shows that 80 % are satisfied with the environment. At the 29 ^{o}C of supply temperature, 40 % satisfied with that environment, which mean 60 % dissatisfied with that environment.

Figure 4.33, 4.34 and 4.35 presents the effect of *PPD* under the different room temperature from front view, side view and top view. As can be seen from the distribution, temperature supplies at 21 ^{o}C and 23 ^{o}C are lower than 16 % when close to the subject. The highest percentage of dissatisfaction of comfort is temperature supply at 29 ^{o}C which is 78 %. Temperature supplies at 19 and 26 ^{o}C are higher than 20 % of percentage of dissatisfaction.

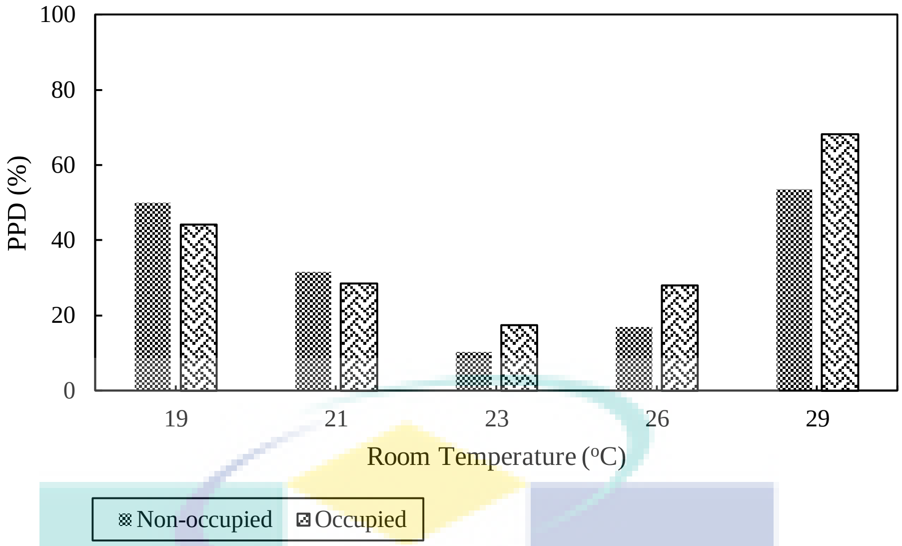
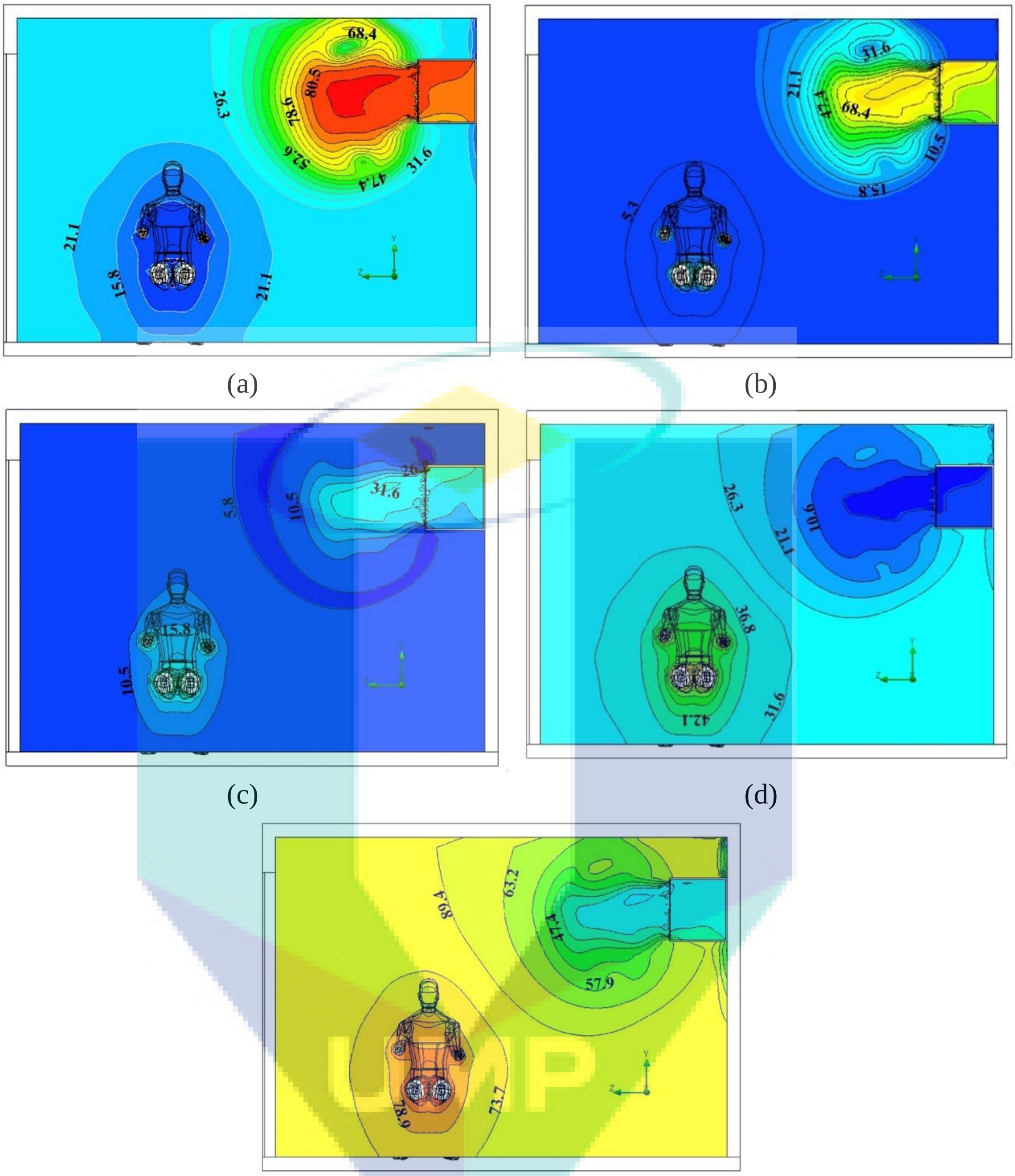


Figure 4.32 Change in *PPD* of Non-Occupied and Occupied under Different Room Temperature.

Figure 4.36 summarizes the average of the distribution of the effect *PPD* under different supply room temperatures from front view, side view and top view. All this three view trend is steady rise, according to the increasing of supply temperature. The highest percentage of average dissatisfaction of comfort is supply temperature at 29 °C which is 89 %. Meanwhile, the lower percentages of average dissatisfaction of comfort are supply temperature 21 °C and 23 °C which are 5 % and 6 %, respectively.

Under the condition of different supply of temperature, the indoor predicted of dissatisfaction of comfort is lower than 10 %, which mean meeting human thermal comfort requirements.

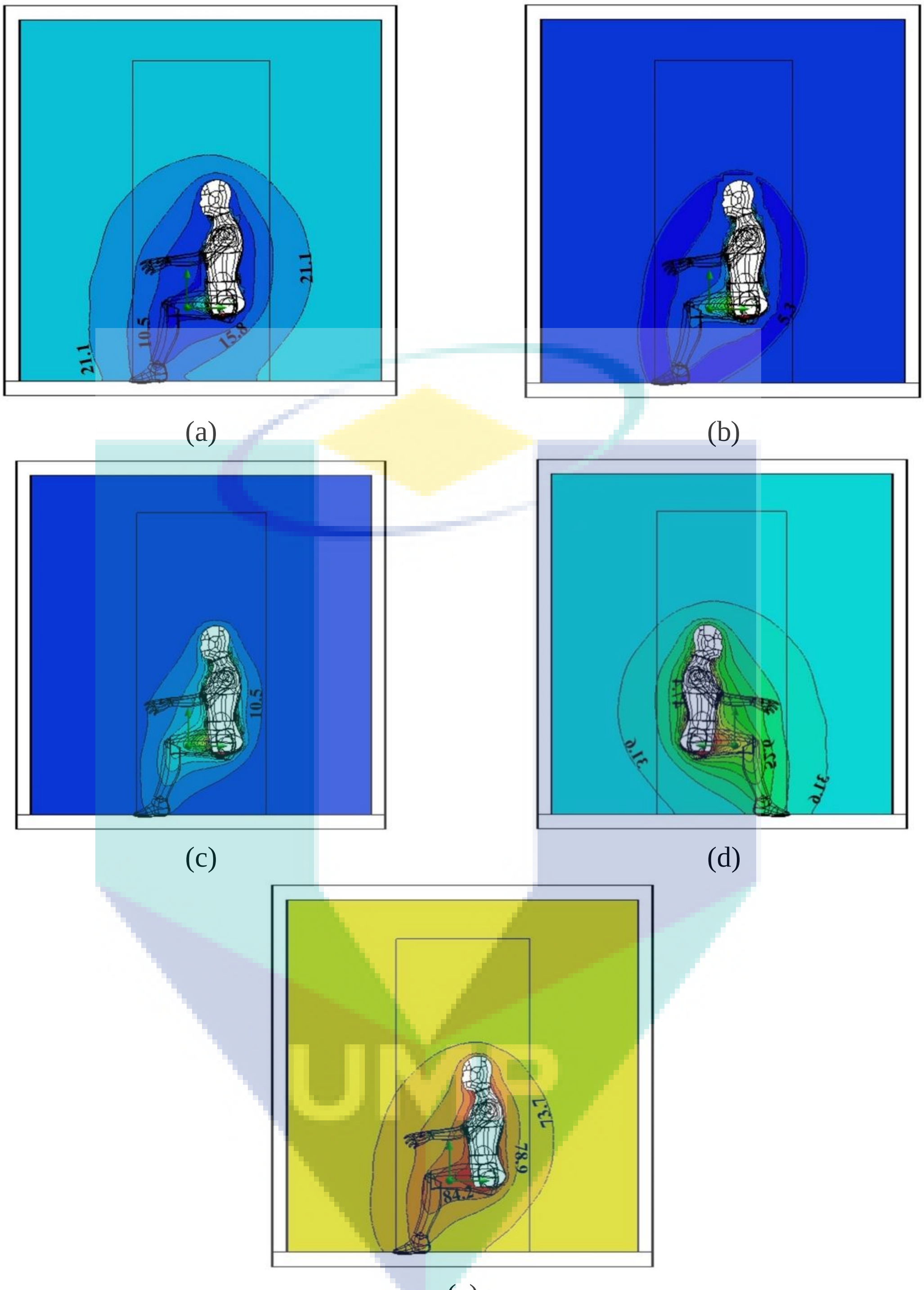


(a) (b)

(c) (d)

(e)

Figure 4.33 Effect of *PPD* at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Front View.

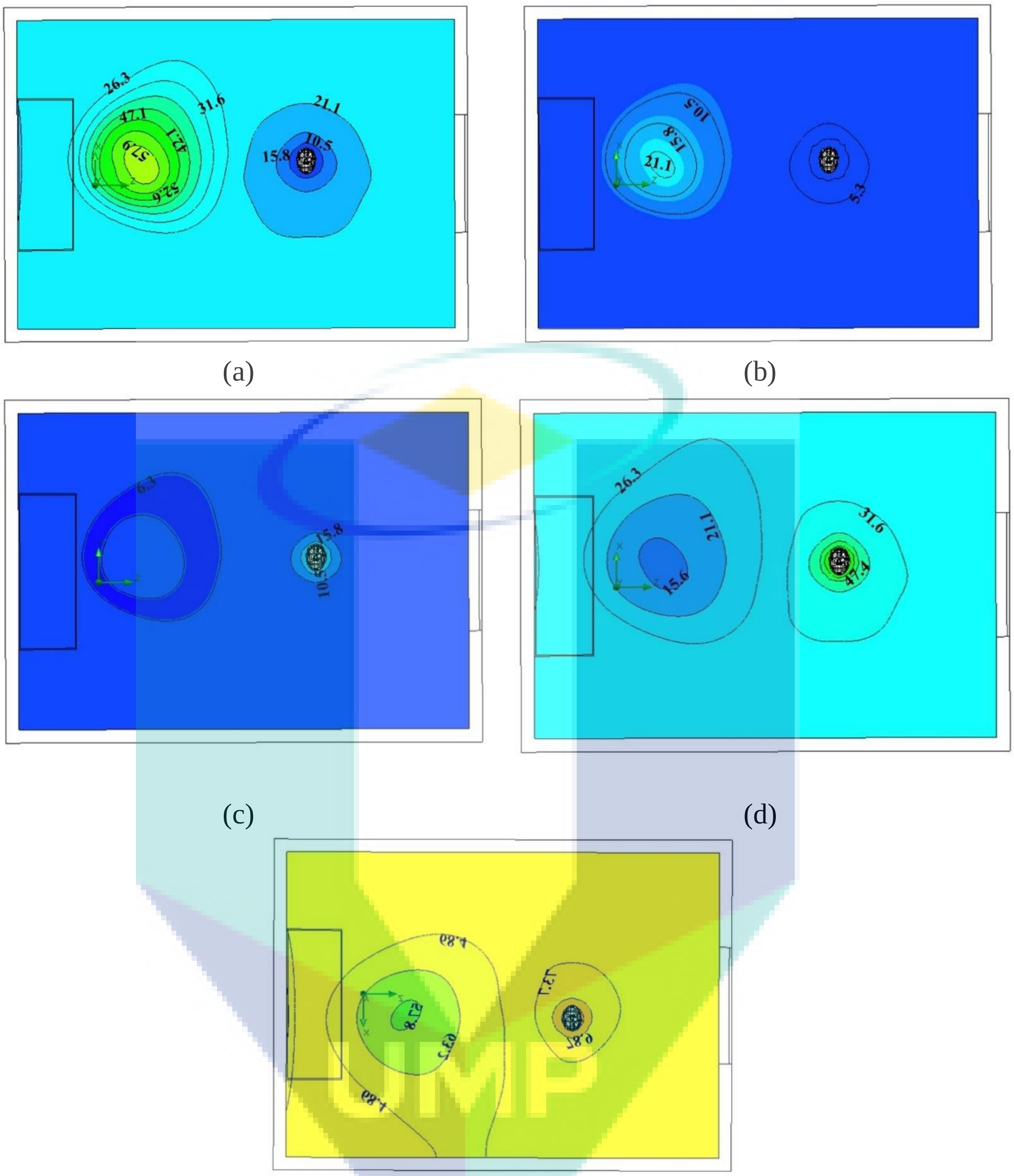


(a) (b)

(c) (d)

(e)

Figure 4.34 Effect of *PPD* at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Side View.



(a) (b)

(c) (d)

(e)

Figure 4.35 Effect of *PPD* at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Top View.

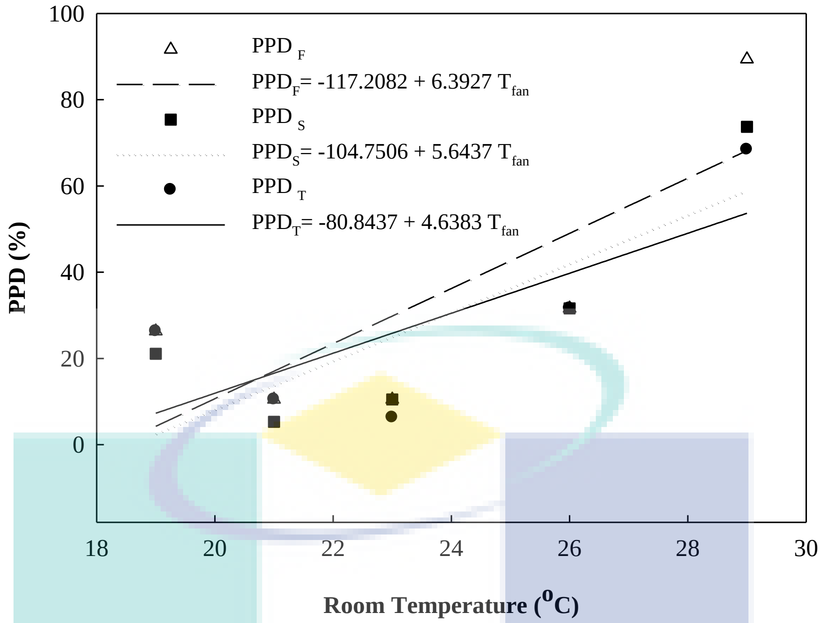


Figure 4.36 Effect of *PPD* Distribution of the Different Room Temperature.

4.4.2 Effects of Room Temperature on Skin Temperature

Figure 4.37, 4.38, 4.39, and 4.40 showed the manikin temperature ($T_{manikin}$) field cloud pictures in three selected cross section, which is front, side and top view. The simulation results (a) represented for room temperature of thermostat set at 19 ^{o}C, (b) represented for room temperature of thermostat set at 21 ^{o}C, (c) represented for room temperature of thermostat set at 23 ^{o}C, (d) represented for room temperature of thermostat setting at 26 ^{o}C and (e) represented room temperature of thermostat setting at 29 ^{o}C.

The skin temperature variation for different body segments such as the head (1), right shoulder (2), left shoulder (3), right forearm (4), left forearm (5), right wrist (6), left wrist (7), right foot (8), left foot (9), right ankle (10) and left ankle (11) versus time for different room temperature scenarios are displayed in Figure 4.37-4.40. At the beginning of the cooling process, the skin temperature for different body segments decreases for the short period (less than 3 min) because of the big difference between the skin temperature and the vehicular compartment. Then the skin temperature increases sharply till the 18 min mark, because the compartment temperature increases sharply due to the air conditioning process, then the skin temperature increases slowly with time until it reaches the steady-state value as depicted in Figure 4.40 (e). The amount of the temperature difference between starting and ending of the cooling process depended on the human segment and room temperature.

Figure 4.41 indicates the comparison of skin temperatures for different human body segments. It is clear that there is the same trend in these human body segments. The different skin temperatures also obtain from the left and right side. The left side is higher than the right side because the air conditioning unit is located these. High temperature would enhance the human physiological activities. When the body temperature reaches a certain high value, the human physiological function will be disordered, and this may lead to human skin injury or heat stress.

Table 4.4 presents the regression correlation the overall/body segment of skin temperature. The slopes exceed 1.00 for the body segment 8 and 9 (right and left foot), indicates that these body segments will experience more than one unit of thermal sensation variation when the skin temperature in these parts changed by 1 ^{o}C.

Table 4.4 Regressions of Overall/Body Segment Skin Temperature

Overall/Body Segment	**A**	**B**
1	0.53	17.55
2	0.49	19.42
3	0.50	20.53
4	0.45	20.79
5	0.49	20.07
6	0.47	21.36
7	0.38	23.77
8	0.70	13.74
9	0.72	14.24
10	0.45	21.82
11	0.44	22.63

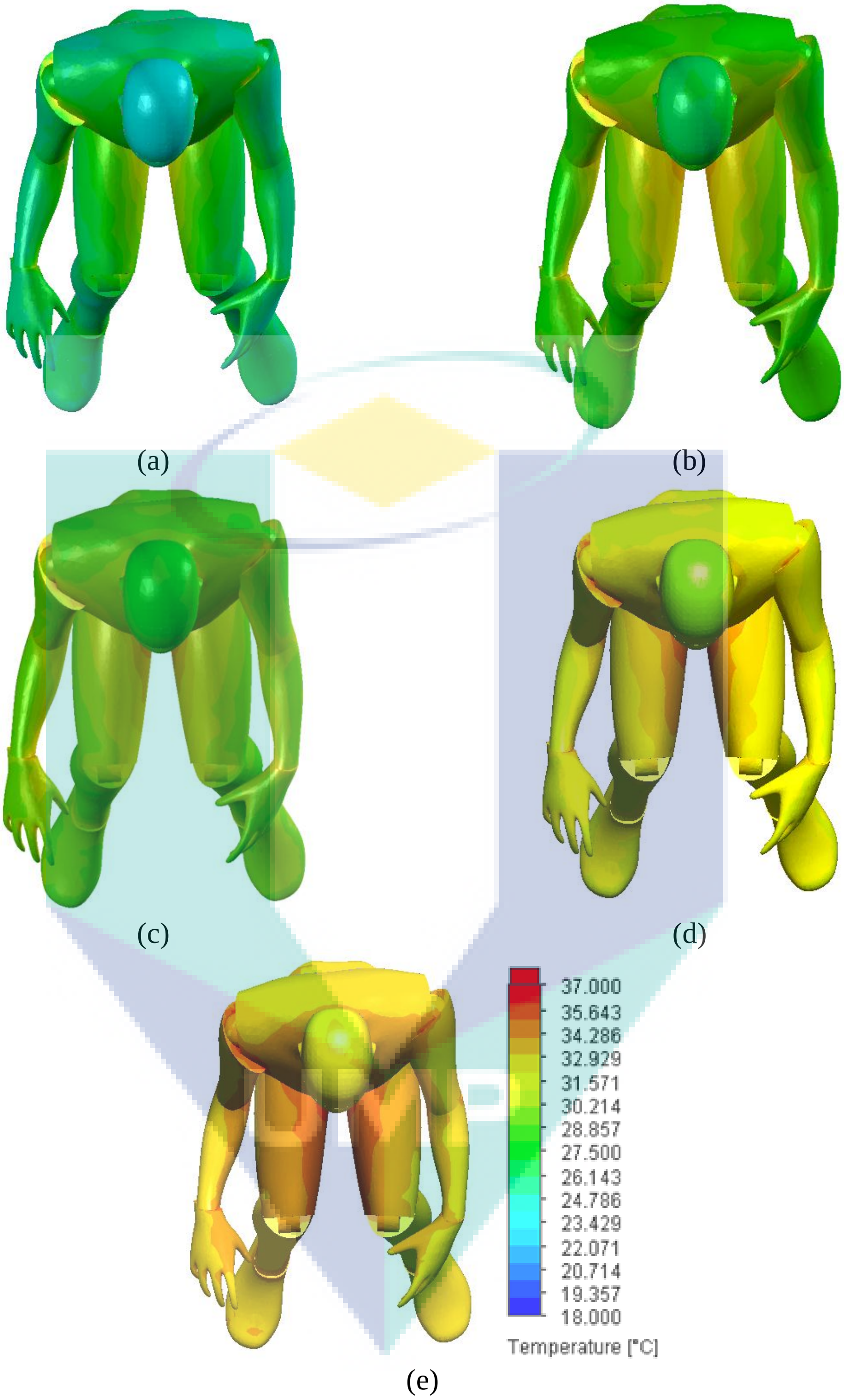


Figure 4.37 Effect of $T_{manikin}$ at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Top View.

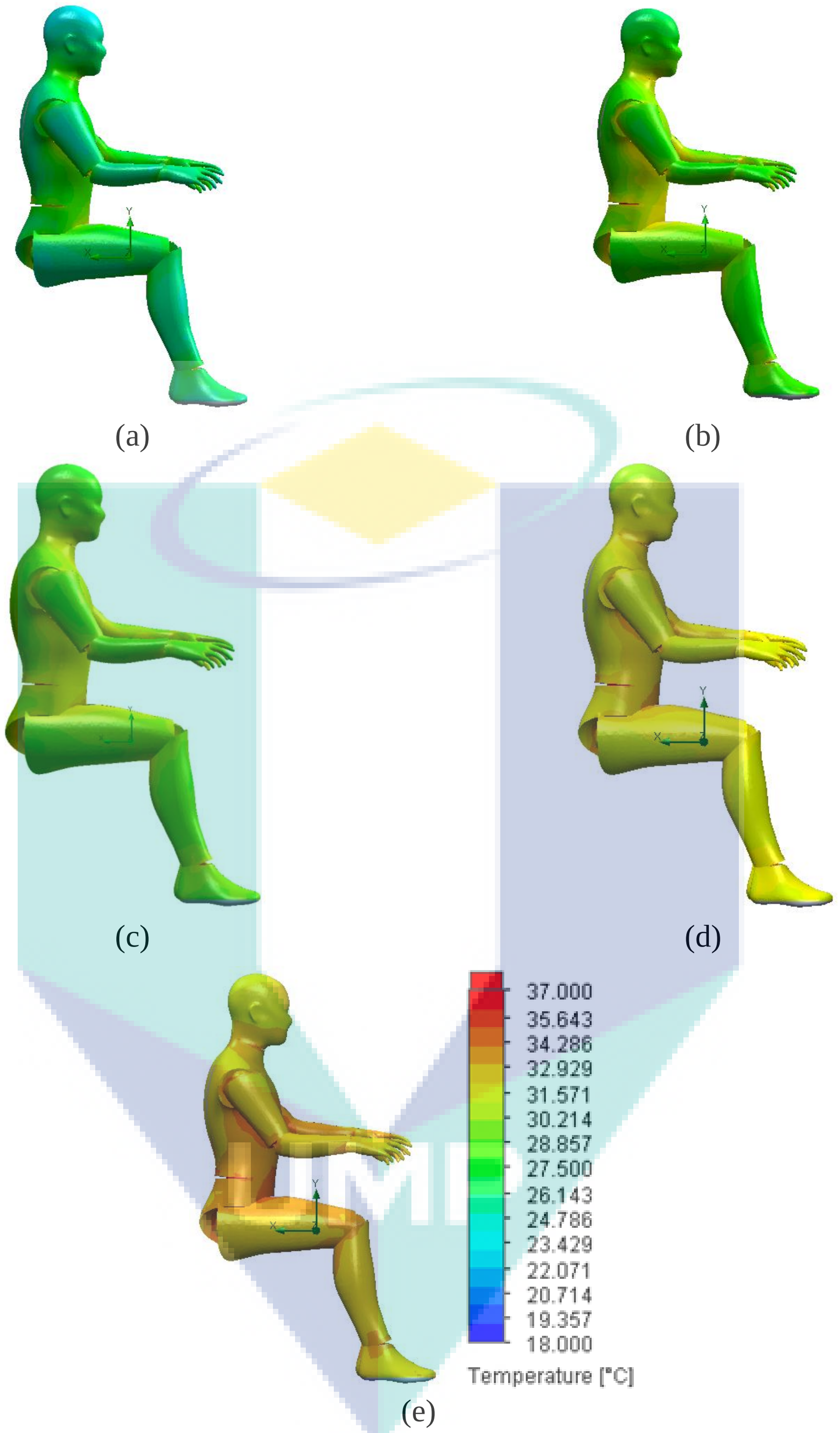


Figure 4.38 Effect of $T_{manikin}$ at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Side View.

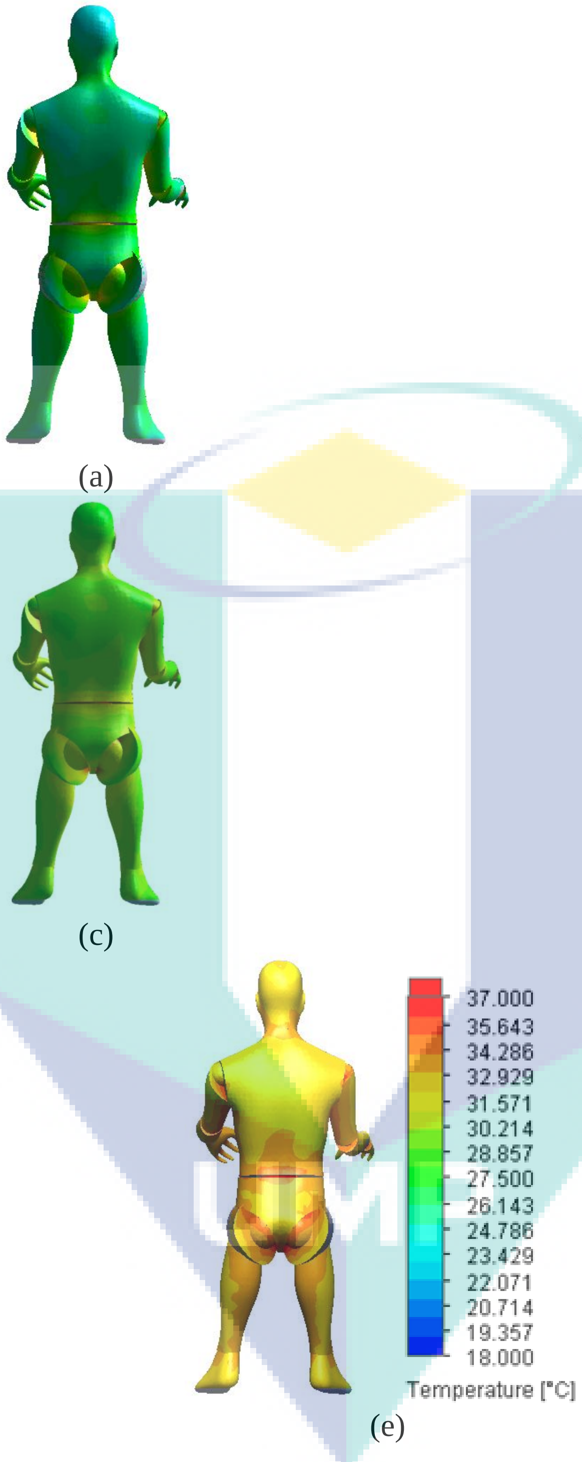
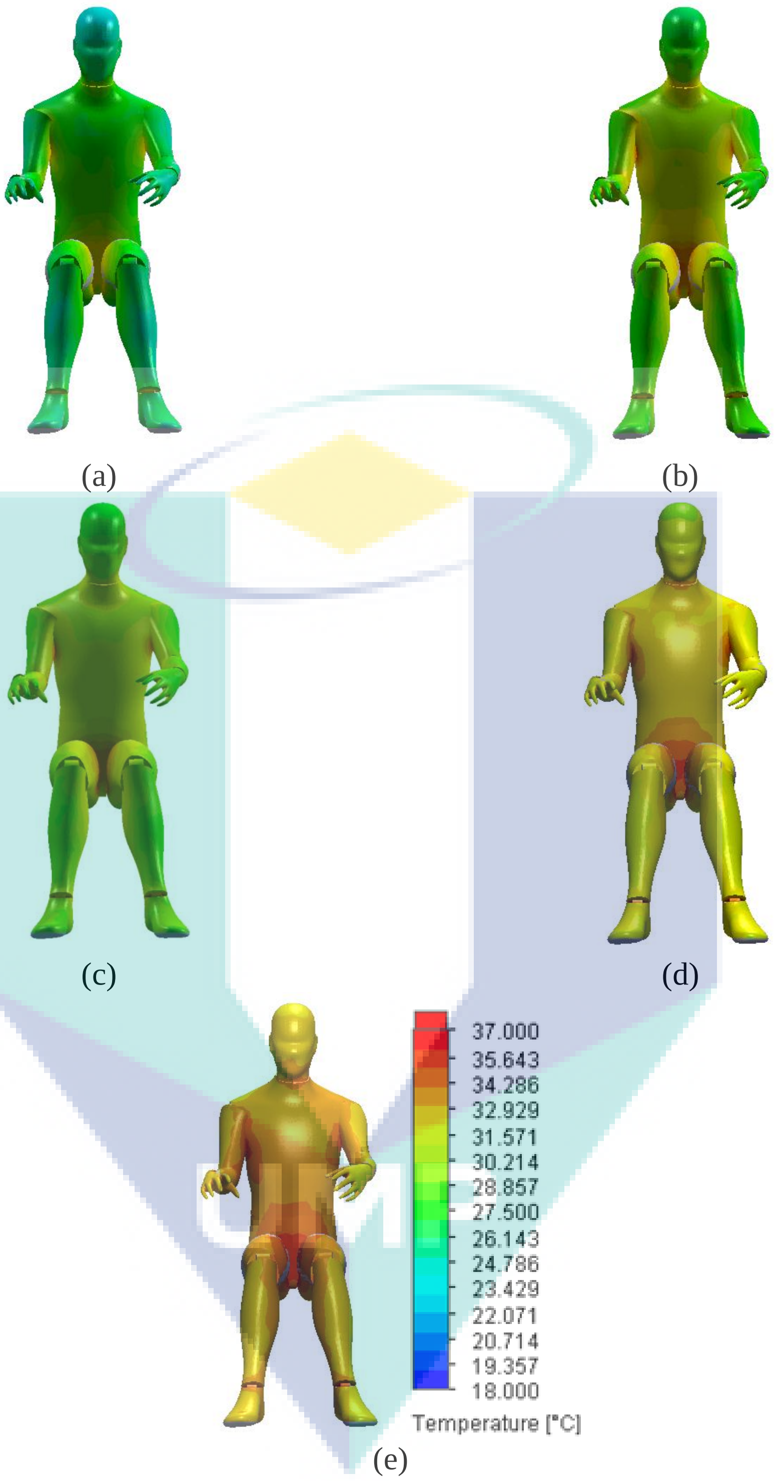


Figure 4.39 Effect of $T_{manikin}$ at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Rear View.



(a) (b) (c) (d) (e)

Figure 4.40 Effect of $T_{manikin}$ at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Front View.

The body segment with smaller than 1.00, their thermal sensations are less sensitive to the corresponding skin temperature. With this, results indicate that the greater slope, the greater influence made on the thermal sensation by the skin temperature.

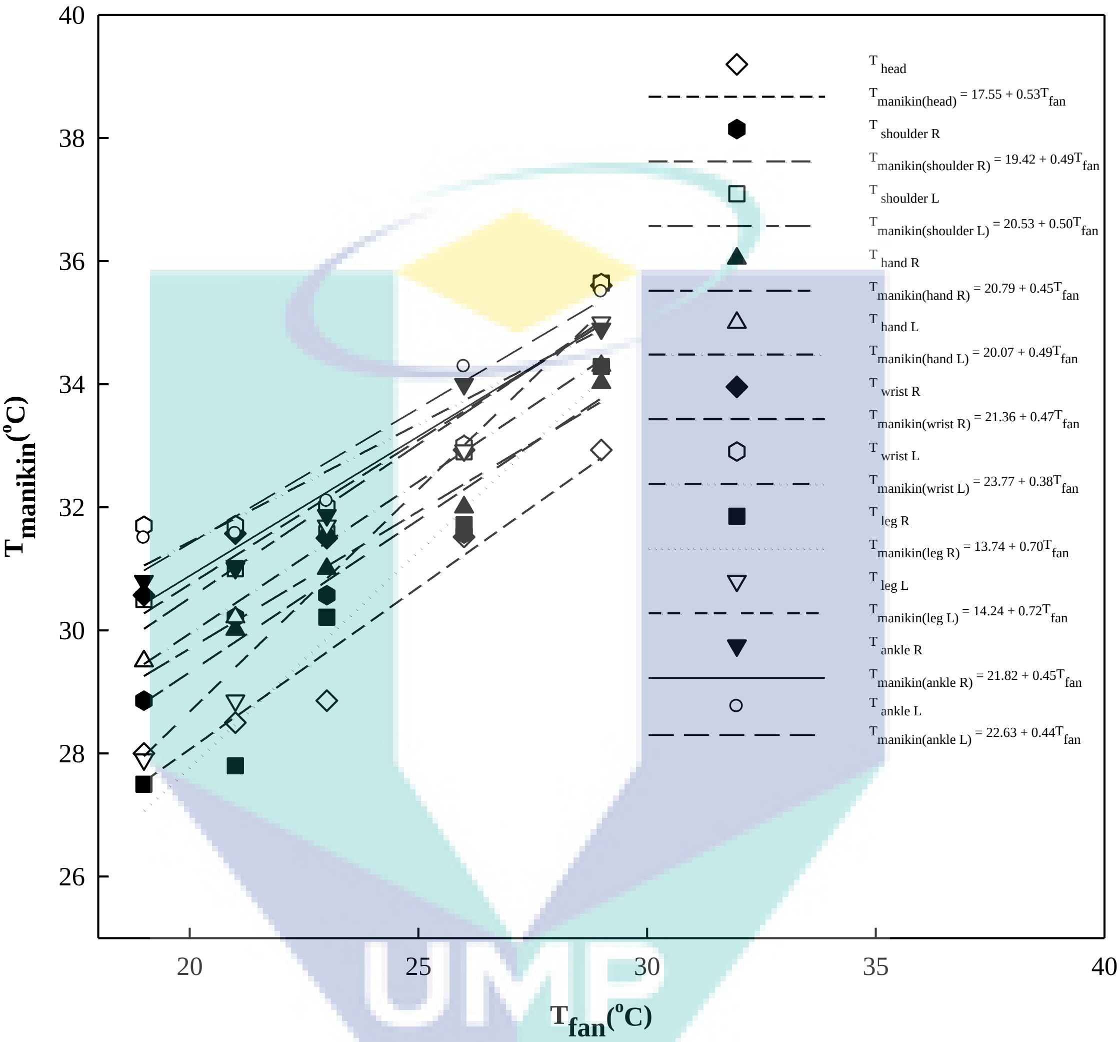


Figure 4.41 Effect of Skin Temperature Distribution of the Different Room Temperature.

Figure 4.42 presented the average skin temperatures simulated coincide well with the experimental results in terms of both the trend and the values. The average skin temperature difference between the simulation and human test data does not exceed 3.0 ^{o}C, which shows the simulation gives accurate predictions of the average skin temperature for the conditions ranging from cool to hot temperature. The deviations of the average skin temperature in the simulation at hot condition are higher than those of the neutral and cool condition.

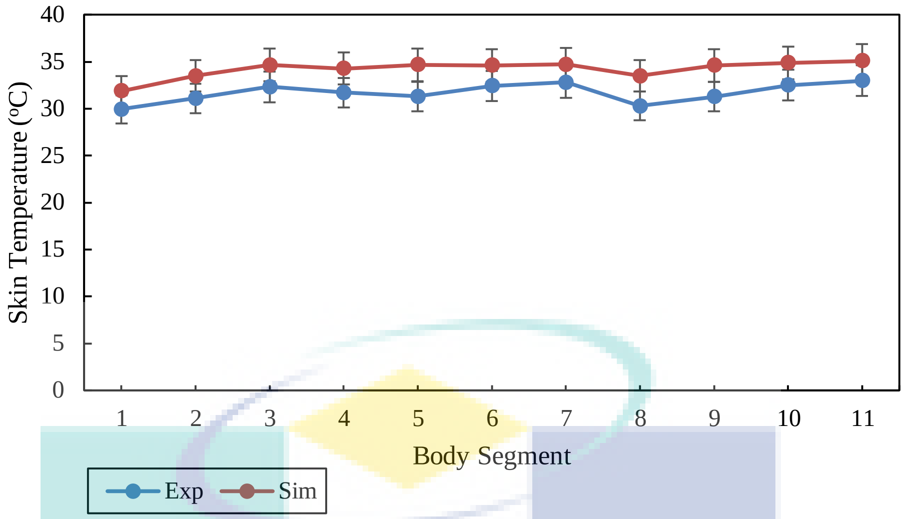


Figure 4.42 Body Segments of Average Skin Temperature in Experiment and Simulation.

4.5 Overall Thermal Comfort and Thermal Sensation

The current approach to thermal environment design deems the metabolic rate steady for a given task of the activity. The metabolic rate for office environments is considered around 1.0, 1.2 and 1.6 Met and evaluation of the thermal sensation is based on this value. However, as presented in Chapter 2, metabolic rate in sedentary environments is variable such that office workers are away from their workstations 30 % of the time (Bauman et al., 1994) or metabolic rate changes with the psychological stress. This section focused on the thermal comfort responses of people under dynamic conditions in which metabolic rate changes with respect to time in a typical office environment.

4.5.1 Correlation between Gender and Thermal Comfort

Thermal comfort votes showed significant differences (p<0.001) between the males and the females. Note that the p-value needs to be less than 0.05 to be accepted as significant. On average, thermal comfort males and females are similar votes each other. On the 7-point scale, thermal comfort votes for males and females were -1.22, -0.31 and 0.52 for metabolic rate 1.0, 1.2 and 1.6 Met (see Table 4.43). Figure 4.43 shows that metabolic rate has the same effect on both genders. Therefore, gender and metabolic rate have an interaction effect on thermal comfort (*p*=0.04) (see Appendix E). It can be seen from the Figure 4.43 that the comfort zone between 0.5 and -0.5. From the data Figure 4.43, occupant in activity 1.2 and 1.6 Met are in the comfort zone. Activity level 1.0 Met is outside in comfort zone, which is slightly cool.

Table 4.5 Thermal Comfort Votes under Three Tasks of Activity for Both of Gender

Gender	Metabolic Rate (Met)	Thermal Comfort
Male	Low (1.0)	-1.22
	Medium (1.2)	-0.31
	High (1.6)	0.52
Female	Low	-1.22
	Medium	-0.31
	High	0.52

4.5.2 Effects of Gender, Room Temperature and Metabolic Rate on Thermal Comfort

The second between subjects variable is the room temperature which has a significant effect on thermal comfort of both genders ($p<0.001$). The interaction of metabolic rate and room temperature is also significant at $\alpha = 0.05$ ($p = 0.029$) both males and females. All thermal comfort responses both genders were similar for 19 °C, 21 °C, 23 °C, 26 °C and 29 °C room temperatures (see Table 4.6). At room temperature 19 °C, the low activity, thermal comfort response was -2.73 (almost cold). At room temperature 29 °C, the high activity for thermal comfort response was 1.64 (slightly warm).

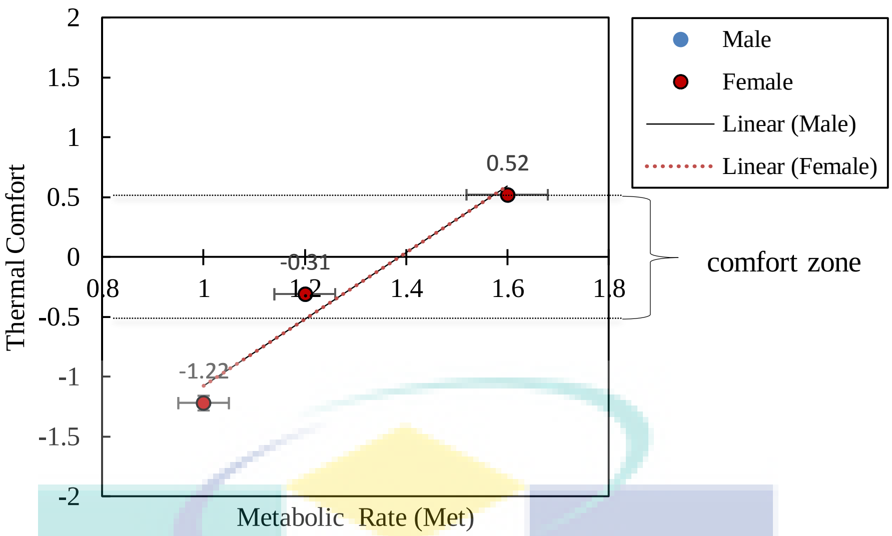


Figure 4.43 Effect of Metabolic Rate of Gender on Thermal Comfort.

The high metabolic rate condition yielded the largest thermal comfort difference between the five room temperatures for both genders. Transient conditions of metabolic rate created a negative perception of thermal environment at 29 °C room temperature (see Table 4.6). It can be seen from the Table 4.6 that the comfort zone between is 0.5 and -0.5. Room temperature 26 ^{o}C which is activity level 1.0 and 1.2 Met are in the comfort zone. Data from Table 4.6 also indicate that, room temperature 19 ^{o}C, 21 ^{o}C and 23 ^{o}C also in the zone comfort but only activity level 1.6 Met. The red box color shows that comfort zone.

During a low metabolic rate, room temperature had a minor effect on thermal comfort. There are two possible explanations, which are, the first; the high metabolic rate creates anticipation for low comfort and this anticipation is more pronounced than the thermal effect of high temperature. The second; high metabolic rate saturates the thermal comfort feeling and increased temperatures make a difference in the saturated thermal comfort feeling.

Table 4.6 Thermal Comfort Votes under Room Temperature and Metabolic Rate

Room Temperature (^{o}C)	Metabolic Rate (Met)	Thermal Comfort (Male)	Thermal Comfort (Female)
19	1.0	-2.73	-2.73
	1.2	-1.46	-1.46
	1.6	-0.29	-0.29
21	1.0	-2.23	-2.23
	1.2	-1.08	-1.08
	1.6	-0.03	-0.03
23	1.0	-1.67	-1.67
	1.2	-0.46	-0.46
	1.6	0.28	0.28
26	1.0	-0.35	-0.35
	1.2	0.35	0.35
	1.6	0.98	0.98
29	1.0	0.89	0.89
	1.2	1.28	1.28
	1.6	1.64	1.64

4.5.3 Correlation between Gender and Thermal Sensation

Thermal sensation votes showed significant differences between males and females ($p<0.001$). The interaction effects on thermal sensation between gender and metabolic rate were female, p = 0.034 and male, p = 0.032 (see Appendix F). Thermal sensation for females 0.05, 0.17, and 0.19 warmer than the males in high, medium and low metabolic rate conditions respectively (see Table 4.7). Figure 4.44 shows the relationship between thermal sensation and metabolic rate for males and females. This finding shows that females are generally more likely to express dissatisfaction with their environment than male. Females consistently felt less comfortable and felt warmer than males.

Previous research has found females to be significantly more sensitive (sensation) than males to heat using the method of limits (Kenshalo, 1986; Lautenbacher and Strain, 1991; Golja et al. 2003) and this study adds to the literature to confirm gender differences to heat using magnitude estimation. It has been suggested that body measures may correlate with the density of receptive units in the skin and thereby the number of stimulated afferent nerve fibres (Lautenbacher and Strain, 1991).

Females had a significantly lower body surface area compared to males (1.3±0.1 m^2 vs 1.6±0.2 m^2, *p*<0.05, respectively) speculatively given a higher sensor density.

Table 4.7 Thermal Sensation under Different Metabolic Rate Conditions

Gender	Metabolic rate (Met)	Thermal sensation
Male	Low (1.0)	0.04
	Medium (1.2)	0.16
	High (1.6)	0.17
Female	Low	0.05
	Medium	0.17
	High	0.19

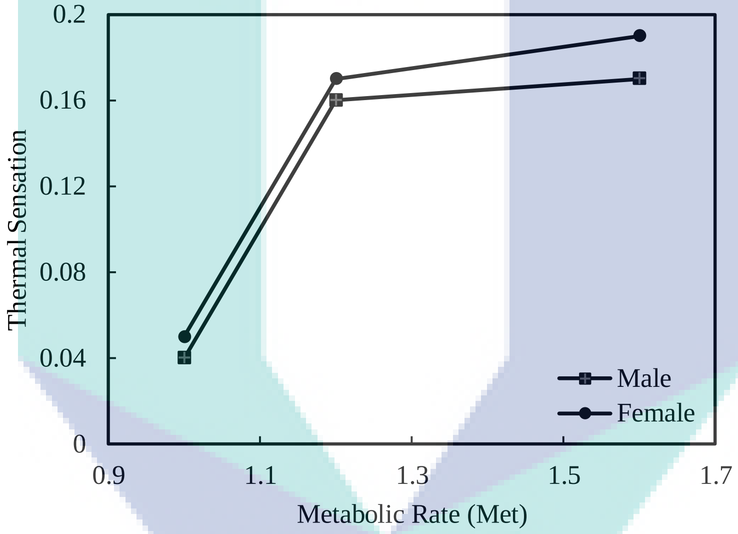


Figure 4.44 Effect of Metabolic Rate on Thermal Sensation at Different Gender

4.5.4 Effects of Gender, Room Temperature and Metabolic Rate on Thermal Sensation

Female and male thermal sensations are illustrated in Table 4.8, respectively. In *p*-value column, (M) refers to male and (F) refer to female. A significant overall effect of gender was observed (p<0.05) for sensations as female provided a warmer sensation than males. Thermal sensation is linearly correlated with metabolic rate under all five room temperature.

The relationship between metabolic rate and the subjective responses was shown that there has been slightly increased for room temperature 19 °C, 21 °C and 23 °C both gender. On the other hand, for room temperature 26 and 29 °C the data illustrated sharp rise from 1.0 to 1.2 Met and a marked drop to 1.6 Met. On the other hand, room temperature setting for 19 °C, 21 °C and 23 °C is below ‘0’ which is below ‘neutral’. ‘Neutral’ mean thermally neutral about temperature. This is cannot be explained by the heat balance of the body but may be explained by psychological factors. The most likely causes of subjects’ expectations of the thermal environment were shifted during the transient conditions. However, thermal conditions did not meet subjects’ expectations of improving thermal conditions, which created a negative feeling towards the thermal environment for short periods of time. The negative feeling disappears once the thermal conditions were steady, and subjects’ expectations were consistent with the thermal environment.

Table 4.8 Thermal Sensation under Different Five Room Temperature and Metabolic Rate Conditions

Room Temperature (^oC)	***p*-value**	**Metabolic Rate (Met)**	**Thermal Sensation (Male)**	**Thermal Sensation (Female)**
19	0.0017 (M) 0.0016 (F)	1.0	-0.11	-0.12
		1.2	-0.07	-0.07
		1.6	-0.04	-0.04
21	0.0018 (M) 0.0018 (F)	1.0	-0.08	-0.08
		1.2	-0.04	-0.04
		1.6	-0.02	-0.02
23	0.0019 (M) 0.0019 (F)	1.0	-0.06	-0.06
		1.2	-0.01	-0.01
		1.6	0	0.009
26	0.0059 (M) 0.0071 (F)	1.0	0	0
		1.2	0.27	0.31
		1.6	0.30	0.34
29	0.019 (M) 0.024 (F)	1.0	0.45	0.50
		1.2	0.63	0.67
		1.6	0.60	0.66

The gender differences observed between males and females cannot be due to differences in the thermal state of the body. Paulson et al. (1998) also noted gender differences to 5 seconds of noxious (50 °C) and innocuous (40 °C) thermal sensation. They claimed that these differences were indicative of different neural mechanisms that mediate thermal sensitivity between genders. Upon noxious heat stimulation (50 °C) females had a greater perception of pain than males which was also detected in a greater activation in the contralateral thalamus and interior insula (Paulson et al. 1998).

Reasons as why females are more sensitive to noxious and innocuous stimuli as indicated by perceptual responses and neural mechanisms still remains unclear but we hypothesis that it is associated with behavioural thermoregulation. According to Inoue et al. (2005) females produce less sweat than males and rely upon convective heat loss more than evaporative heat loss. Therefore, it would be beneficial for females being more sensitive to a heat than males in order to encourage behavioural responses to maintain thermal balance. With this in mind, these findings offer considerable evidence to support more gender specific testing in the areas of thermal sensitivity and behavioural thermoregulation.

4.6 Predicted Mean Vote (*PMV*) and Predicted Percentage Dissatisfied (*PPD*)

Thermal comfort standards specify comfort for the majority of the occupants in a given space. ASHRAE Standard 55 (2004) defines majority as 80 % of the occupants. It assumes that 10 % will experience discomfort due to general thermal sensation and another 10 % due to local thermal sensation. Thermal sensation data of our study also showed high correlation with the thermal comfort of the subjects (Pearson correlation 0.70). A mathematical relationship was constructed between thermal comfort and thermal sensation Eq. (4.1) (see Figure 4.45).

$$TC = 4.02TS - 0.86 \tag{4.1}$$

Human responses to the steady conditions were analyzed and the results are shown in Figure 4.45. Each point in this figure represents the mean vote of all subjects' responses for each condition. It can be seen that a straight line fits the data well ($R^2 = 0.70$).

Figure 4.45 shows the steady conditions; overall thermal sensation and comfort are correlated with each other closely. Thermal sensation mean vote of 0.77 corresponds to thermal comfort mean vote of 1.28, that is to said, the subjects first felt uncomfortable when their whole-body thermal sensation is 0.77, which is more rigid than the definition proposed by Gagge et al. (1967) and Fanger (1970).

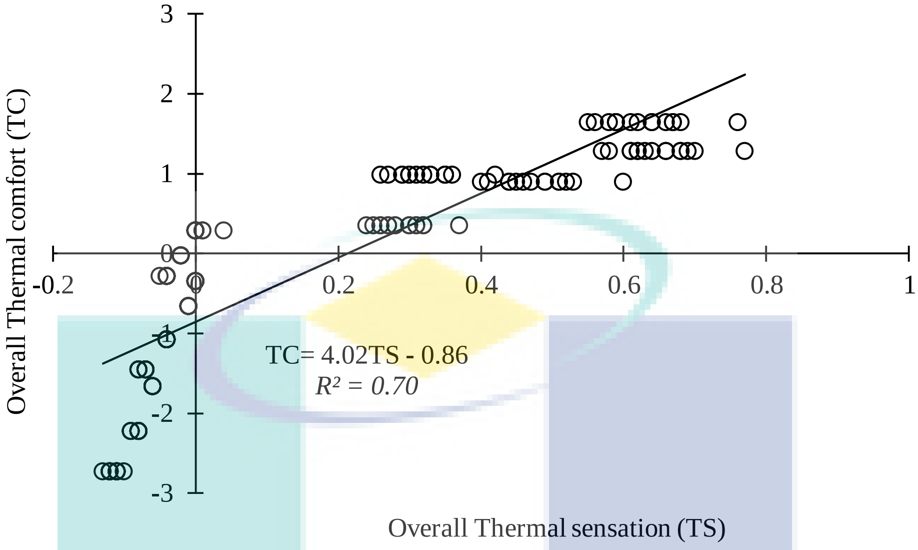


Figure 4.45 Correlations Between Thermal Sensation (TS) and Thermal Comfort (TC).

Similar studies were found in the literature (Zhang and Zhao, 2008b; Zhang et al., 2008a). Minor differences in correlation coefficients and mathematically fits between the previous studies and our study exist, which may be due to the complex nature of thermal environments and subjective responses. However, all the studies, including our show that the maximum thermal comfort corresponds with neutral (0) thermal sensation and thermal comfort decreases as the subjects feel warmer. The data of this study were also compared to the predicted percentage dissatisfied (*PPD*) formula of Fanger, which is also based on the human subject tests. The similar graph of 'percentage dissatisfied' versus thermal sensation to validate the data. The percentage of 'unacceptable thermal environment' votes were calculated for different levels of thermal sensation. The data matches well with the *PPD* calculation (Figure 4.46).

The *PMV-PPD* index has been widely in use since its introduction in the early 1970s. It was developed by Fanger (1970) as a steady-state heat balance calculation method which was fitted to the extensive subjective thermal comfort test data. *PMV* is a steady-state method and does not reflect the transient conditions since its data is based on test subjects' responses after more than one hour exposure to the steady thermal environments. In addition, the final *PMV* formula is lacking a time component which can enable transient calculations.

Subjects felt warm and slightly uncomfortable in the uniform conditions and face thermal sensation was equal to overall thermal sensation. When face cooling was supplied, face thermal sensation dropped immediately from warm to slightly cool, and overall thermal sensation dropped as well from warm to slightly warm and overall thermal comfort changed from slightly uncomfortable to slightly comfortable. After the first moment of face cooling, subjects' thermal responses changed gradually and slightly and reached almost constant at the end of the exposure.

The philosophy behind the *PMV* model is based on a deterministic approach of finding the optimal comfort conditions for the maximum possible number of people. This 'one-size-fits most' approach provides a description of thermal comfort by combining all the basic comfort variables in one simple to understand and easy to use an index. The real life application of the *PMV* index has been in the form of determining one average value for each comfort variable and calculating an average *PMV* value which reflects average thermal conditions. This value represents the average thermal sensation of the majority of the occupants.

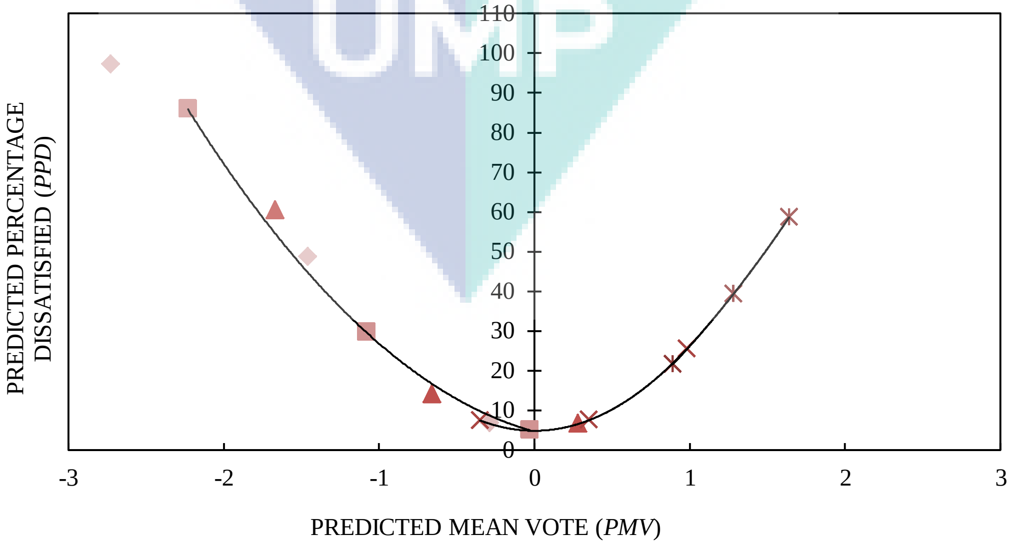


Figure 4.46 Effect of *PPD* and *PMV* to Room Temperature from Fanger's Eq. (2.14).

4.7 Summary

This chapter analyzed the effect of thermal comfort and sensation towards physiology factors. Table 4.9 presented to summarize the effect of occupied in conditioned room. While, Table 4.10 presented to summarize of effect of skin temperature in different room temperature.

The overall thermal sensation on the body will be influenced mainly by those body segments that have greatest thermal sensation under different condition's environment. The overall thermal comfort will follow the warmest environment (26 °C and 29 °C) and the coldest in a cool environment (19 °C and 23 °C) according to the *PMV* value in Table 4.9. Furthermore, the overall thermal comfort will closely follow the parts of the body that feel the most uncomfortable in a cool or warm environment.

Table 4.9 Summarize of Effect Occupied in Conditioned Room

	Room Temperature (°C)				
Parameter Response	**19**	**21**	**23**	**26**	**29**
Radiant Temperature (°C)	20.32	22.63	25.95	27.26	30.34
Air Temperature (°C)	19.14	22.46	23.84	27.60	30.31
Air velocity (m/s)	0.12	0.08	0.09	0.08	0.08
PMV	-0.1	-0.37	0.26	1.1	2.05
PPD (%)	25.6	8.8	9.1	31.6	77.1

According to the regression, body segment with smaller than 1.00, their thermal sensations are less sensitive to the corresponding skin temperature. With this, results indicate that the right and left foot (body segment 8 and 9) is sensitive about sensation. The heart rate shown that the experiments were performed to investigate how the environmental of temperature influences the subject and what the relationship exists between metabolic rates.

According to the results, activities sitting and printing were significant difference between heart rate and metabolic rate. Lastly, a variation of the *PMV* and *PPD* indices with the different activity task is investigated and under different room temperature conditions, approximately 23 °C air temperature is found as a suitable temperature for the thermal comfort.

Table 4.10 Summarize of Effect Skin Temperature in Different Room Temperature

Body Segment	**Room Temperature (°C)**				
	19	**21**	**23**	**26**	**29**
1	28.00	28.50	28.86	31.51	32.93
2	28.86	30.21	30.57	31.57	34.29
3	30.50	31.00	31.57	32.90	35.64
4	29.50	30.01	31.00	32.00	34.02
5	29.50	30.21	31.60	33.00	34.30
6	30.57	31.57	31.50	32.93	35.60
7	31.70	31.71	32.01	33.01	35.64
8	27.50	27.80	30.21	31.72	34.27
9	27.90	28.86	31.70	32.92	35.00
10	30.80	31.01	31.87	34.00	34.90
11	31.50	31.57	32.10	34.29	35.50

CHAPTER 5

CONCLUSIONS

5.1 Introduction

This study was conducted to analyze the effect and responsiveness of physiological factors to thermal comfort in air-conditioned environment. The results of this research are based on the objectives on described in Chapter 1. In this chapter also presented recommendation for future works as well as this research contribution in the studied field.

5.2 Conclusion

The results of this study indicate:

i. The study found that room temperature ranges between 21 ^{o}C - 29 ^{o}C and different metabolic rate give a difference heart rate level that indicates the level of comfort by subjects. Analysis of skin temperature showed that levels of temperatures vary, depending on the body segment considered and the subject. This finding is meaningful in that it showed the possibility of identifying the most responsive data location and to use the skin temperature data collected from that point to estimate a subject's thermal sensation. It showed the application potential of this finding for building that using mechanical systems (air conditioning) as an input to generate an optimal set- point temperature so that a subject's thermal sensation could be maintained at the neutral level while preventing over cooling or over heating conditions.

ii. Heart rate has the potential to be used as an index to illustrate the human thermal sensation. An analysis of the absolute level of heart rate data clearly showed a proportional relation to metabolic rate based on the activity level. Data on all the subjects shows significantly higher heart rates in the warm temperature and in the cool temperature at an activity level of 1.6 Met.
iii. The optimal thermal condition based on human physiology factors is 23 ^{o}C. At this temperature, the skin temperature and heart rate level shows by subject are at the medium level, so that subjects are comfortable to do their office task and may lead to increasing performance and productivity.

5.3 Recommendations for Future Study

There are several recommendations for future study presented as follows:

i. A limitation of the study is that only young and healthy students were recruited, thereby not a representative subpopulation of office workers. In the future study, another subpopulation of participants may be selected. This concerns the age, health and occupation of participants.
ii. According the physiological factor, there are many factors can affect the heart rate level of subjects not only *BMI* and movement, thus for future experimental study, they can consider the age of subjects because most of the office workers are people in the age of 30-58 years old.
iii. Longer exposure session, for example, exposure of at least 8 hours should be investigated. This is because to make the time like the actual office workers.
iv. Another important issue on the relationship between thermal environment and office worker is that thermal sensation relates not only to air temperature but also to humidity, air velocity, clothing and activity level. Many new technologies have been advanced for energy saving without causing thermal discomfort, for instance, by personalized ventilation or by modifying dress code/clothing. Therefore, other factors related to thermal sensation should be

taken into account in the future study, could be providing a guide for office environment design.

v. It is known that providing the subjects with environmental controls to adjust the variables (environmental parameters) can have a significant positive effect on the comfort of the subjects. Therefore, a future study is noted, which is based on the same environmental and personal variables with an added subject control over the thermal environment in the chamber.

vi. The suggestion of air temperature is acceptable based on the industry code of practice on indoor air quality 2010. From the finding shows slightly the difference between ASHRAE Standard 55-2007 that put an acceptable range between 24-26 ^{o}C. The accuracy and more relevant to follow is ISOP 2010 because Malaysia is located in the tropical region with a hot and humid climate. Therefore, future study should be conducted a range of temperature between 24-26 ^{o}C to get reliable and accurate results and data, especially for measurement of human performances.

5.4 Contribution

This study contributes to the body knowledge of thermal comfort towards human in the building. The contributions of this study are presented as follows:

i. This study is the comprehensive thermal comfort study in building and Malaysia's climate. The results of this study provide a better understanding of the general thermal environment and occupants’ thermal comfort perceptions of human in the building. This study also has a significant impact on understanding of thermal adaptation thermal comfort in the building.

ii. The proposed thermal comfort prediction model in this study can be used by designers and planners to evaluate human thermal comfort in the building in Malaysia.

iii. This study provides a link between the theoretical knowledge on human thermal perception and the practical task for every activity daily. The results contribute to the workstation design or planning practice to provide an appropriate thermal comfort condition in the building.

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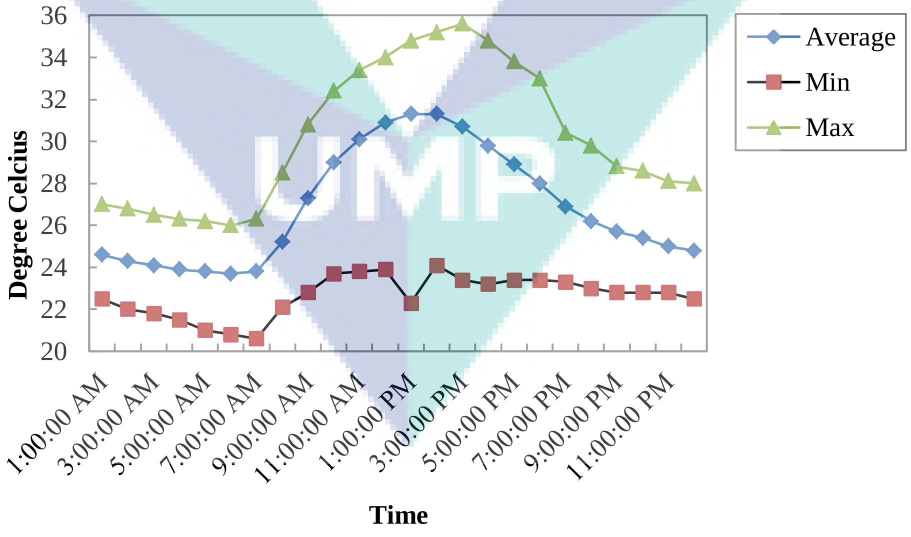
APPENDIX A

MALAYSIA WEATHER DATA

a. Dry Bulb Temperature

The daily average, maximum and minimum dry bulb temperature is provided by the chart in this section. The standard deviation is more than 2.0 °C from 2 pm to 6 pm indicating that the afternoon hours have a higher change of temperature from day to day; while in the hours of midnight to 7 am, the standard deviation of the dry bulb temperature is less than 1.0 °C, indicating a fairly consistent and predictable dry bulb temperature from midnight to early morning hours.

The average dry bulb temperature of the whole year (including day and night) is 26.9 °C. The average peak dry bulb temperature is just below 32.0 °C at the hour of 1 pm to 2 pm, while the maximum dry bulb temperature of the TRY is 35.6 °C at 3 pm. The average low dry bulb temperature is 23.7 °C at 6 am in the morning; while the lowest dry bulb temperature of the TRY is 20.6 °C at 7 am in the morning.

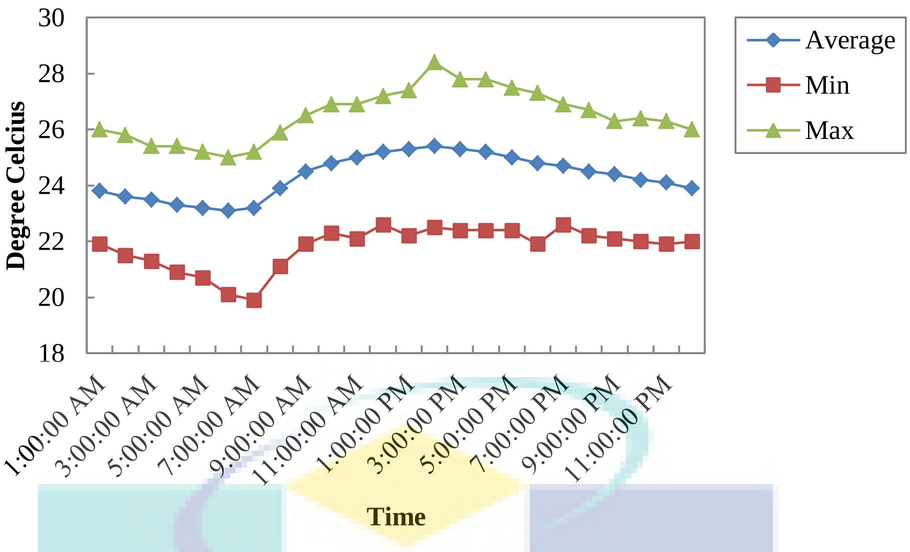


Hours	Average	Min	Max	Std. Dev.
1:00:00 AM	24.6	22.5	27.0	0.9
2:00:00 AM	24.3	22.0	26.8	0.9
3:00:00 AM	24.1	21.8	26.5	0.9
4:00:00 AM	23.9	21.5	26.3	0.9
5:00:00 AM	23.8	21.0	26.2	0.9
6:00:00 AM	23.7	20.8	26.0	0.9
7:00:00 AM	23.8	20.6	26.3	0.9
8:00:00 AM	25.2	22.1	28.5	1.1
9:00:00 AM	27.3	22.8	30.8	1.4
10:00:00 AM	29.0	23.7	32.4	1.5
11:00:00 AM	30.1	23.8	33.4	1.5
12:00:00 PM	30.9	23.9	34.0	1.7
1:00:00 PM	31.3	22.3	34.8	1.9
2:00:00 PM	31.3	24.1	35.2	2.1
3:00:00 PM	30.7	23.4	35.6	2.5
4:00:00 PM	29.8	23.2	34.8	2.6
5:00:00 PM	28.9	23.4	33.8	2.4
6:00:00 PM	28.0	23.4	33.0	2.1
7:00:00 PM	26.9	23.3	30.4	1.7
8:00:00 PM	26.2	23.0	29.8	1.4
9:00:00 PM	25.7	22.8	28.8	1.2
10:00:00 PM	25.4	22.8	28.6	1.1
11:00:00 PM	25.0	22.8	28.1	1.0
12:00:00 AM	24.8	22.5	28.0	0.9

b. Wet Bulb Temperature

The wet bulb temperature is fairly consistent between day and night and throughout the year. The average peak of the wet bulb temperature is 25.4 °C at 2 pm, while the maximum wet bulb temperature in the TRY is 28.4 °C at 2 pm.

The average low of wet bulb temperature is 23.1 °C at 6 am, and the bottom wet bulb temperature in the TRY is 19.9 °C at 7 am in the morning.

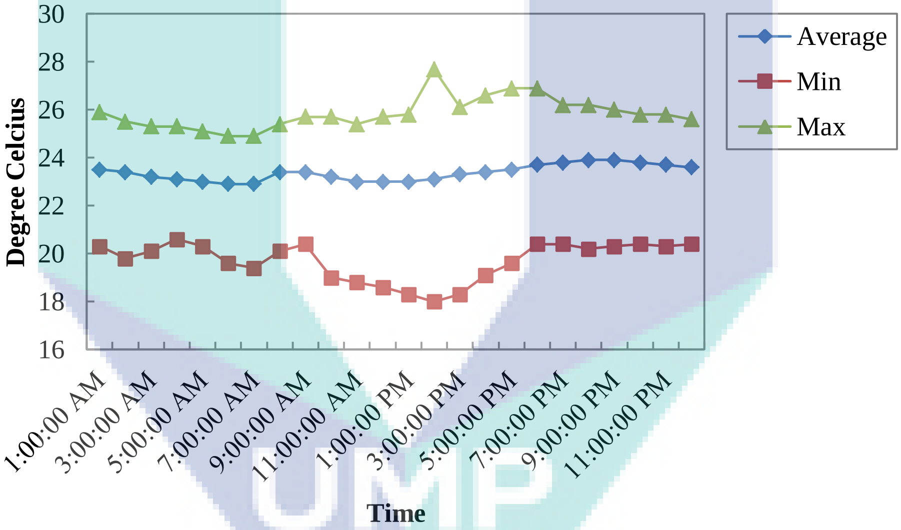


Hours	**Average**	**Min**	**Max**	**Std. Dev.**
1:00:00 AM	23.8	21.9	26.0	0.7
2:00:00 AM	23.6	21.5	25.8	0.7
3:00:00 AM	23.5	21.3	25.4	0.8
4:00:00 AM	23.3	20.9	25.4	0.8
5:00:00 AM	23.2	20.7	25.2	0.8
6:00:00 AM	23.1	20.1	25.0	0.8
7:00:00 AM	23.2	19.9	25.2	0.8
8:00:00 AM	23.9	21.1	25.9	0.8
9:00:00 AM	24.5	21.9	26.5	0.8
10:00:00 AM	24.8	22.3	26.9	0.9
11:00:00 AM	25.0	22.1	26.9	0.9
12:00:00 PM	25.2	22.6	27.2	0.8
1:00:00 PM	25.3	22.2	27.4	0.9
2:00:00 PM	25.4	22.5	28.4	1.0
3:00:00 PM	25.3	22.4	27.8	1.0
4:00:00 PM	25.2	22.4	27.8	1.0
5:00:00 PM	25.0	22.4	27.5	0.9
6:00:00 PM	24.8	21.9	27.3	0.9
7:00:00 PM	24.7	22.6	26.9	0.8
8:00:00 PM	24.5	22.2	26.7	0.8
9:00:00 PM	24.4	22.1	26.3	0.8
10:00:00 PM	24.2	22.0	26.4	0.8
11:00:00 PM	24.1	21.9	26.3	0.7
12:00:00 AM	23.9	22.0	26.0	0.8

c. Dew Point Temperature

The dew point temperature is directly linked to the moisture content in the air. However, the dew point temperature has the advantage of providing us information on the condensation risk due to exposure to outdoor air. Any surface temperature that is below the dew point temperature will have condensation on it. The average dew point temperature in the TRY is 23.4 °C and is fairly consistent day or night and throughout the year. The peak standard deviation of the dew point temperature is 1.5 °C at 2 pm in the afternoon.

More than 70 % of the hours, the dew point temperature is below 24.0 °C and more than 95 % of the hours the dew point temperature is below 25.0 °C.



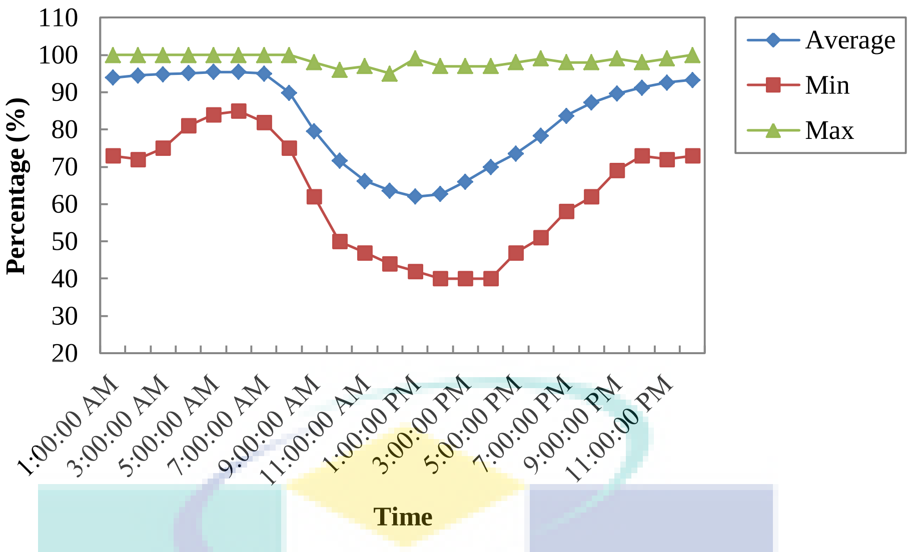
Hours	Average	Min	Max	Std. Dev.
1:00:00 AM	23.5	20.3	25.9	0.8
2:00:00 AM	23.4	19.8	25.5	0.8
3:00:00 AM	23.2	20.1	25.3	0.8
4:00:00 AM	23.1	20.6	25.3	0.8
5:00:00 AM	23.0	20.3	25.1	0.8
6:00:00 AM	22.9	19.6	24.9	0.8
7:00:00 AM	22.9	19.4	24.9	0.8
8:00:00 AM	23.4	20.1	25.4	0.8
9:00:00 AM	23.4	20.4	25.7	1.0
10:00:00 AM	23.2	19.0	25.7	1.1
11:00:00 AM	23.0	18.8	25.4	1.2

12:00:00 PM	23.0	18.6	25.7	1.2
1:00:00 PM	23.0	18.3	25.8	1.3
2:00:00 PM	23.1	18.0	27.7	1.5
3:00:00 PM	23.3	18.3	26.1	1.4
4:00:00 PM	23.4	19.1	26.6	1.4
5:00:00 PM	23.5	19.6	26.9	1.2
6:00:00 PM	23.7	20.4	26.9	1.0
7:00:00 PM	23.8	20.4	26.2	0.9
8:00:00 PM	23.9	20.2	26.2	0.9
9:00:00 PM	23.9	20.3	26.0	0.8
10:00:00 PM	23.8	20.4	25.8	0.8
11:00:00 PM	23.7	20.3	25.8	0.8
12:00:00 AM	23.6	20.4	25.6	0.8

d. Relative Humidity

Relative humidity is a measure of the amount of water (moisture) in air as compared to the maximum amount of water the air can absorb, expressed in percentage. It is not a direct indicator of how much water is in the air, as provided by the humidity ratio (moisture content) or dew point temperature. The dry bulb temperature determines the maximum moisture the air can absorb; therefore, relative humidity is directly linked to both the humidity ratio (moisture content) as well as dry bulb temperature, expressed in percentage of moisture in the air.

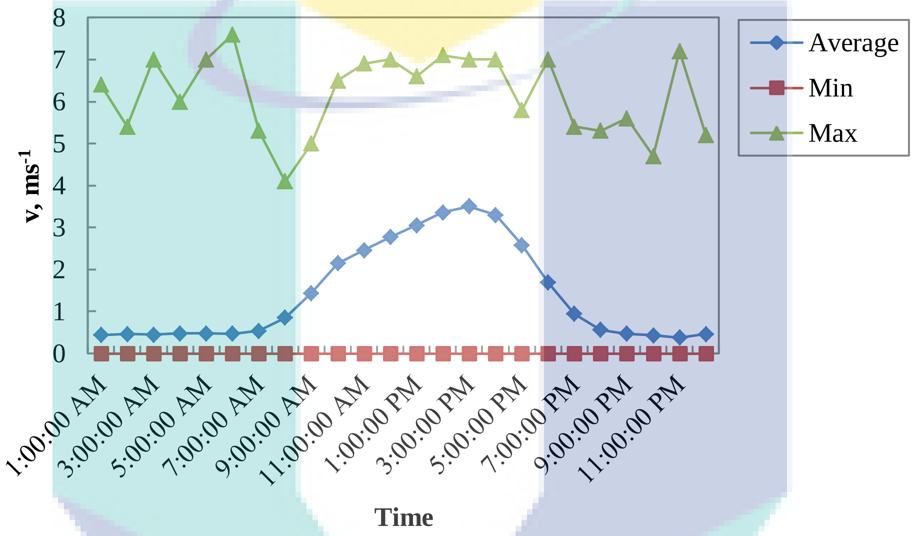
Due to the reason that moisture content in the air is fairly constant day or night, the changes of relative humidity is strongly related to the dry bulb temperature of the air. During night time and early morning hours when the dry bulb temperature is low; the relative humidity is very high (between 90 to 100 % relative humidity). However during daytime hours when the dry bulb temperature is high; the relative humidity has an average low of 62 %.



Hours	Average	Min	Max	Std. Dev.
1:00:00 AM	93.9	73	100	3.7
2:00:00 AM	94.5	72	100	3.5
3:00:00 AM	94.8	75	100	3.2
4:00:00 AM	95.1	81	100	3.1
5:00:00 AM	95.4	84	100	2.8
6:00:00 AM	95.4	85	100	2.8
7:00:00 AM	95.0	82	100	2.9
8:00:00 AM	89.9	75	100	4.2
9:00:00 AM	79.6	62	98	7.0
10:00:00 AM	71.6	50	96	7.8
11:00:00 AM	66.2	47	97	7.9
12:00:00 PM	63.6	44	95	8.3
1:00:00 PM	62.0	42	99	8.9
2:00:00 PM	62.7	40	97	10.7
3:00:00 PM	66.0	40	97	12.0
4:00:00 PM	70.0	40	97	13.0
5:00:00 PM	73.6	47	98	12.3
6:00:00 PM	78.3	51	99	10.7
7:00:00 PM	83.7	58	98	8.6
8:00:00 PM	87.2	62	98	6.8
9:00:00 PM	89.6	69	99	5.5
10:00:00 PM	91.2	73	98	4.8
11:00:00 PM	92.6	72	99	4.2
12:00:00 AM	93.3	73	100	4.0

e. Wind Speed

The average wind speed in the TRY showed that wind speed is low (less than 0.5 ms^{-1}) from the hours of 8 pm to 8 am. The wind speed starts to increase at 8 am and has an average peak of 3.5 ms^{-1} at 3 pm in the afternoon. The hourly maximum wind speed showed that it is possible to have high wind speed any time of the day, with the lowest chance of high wind speed is 8 am in the morning. The data also showed that it is also possible to zero wind speed at any time of the day.

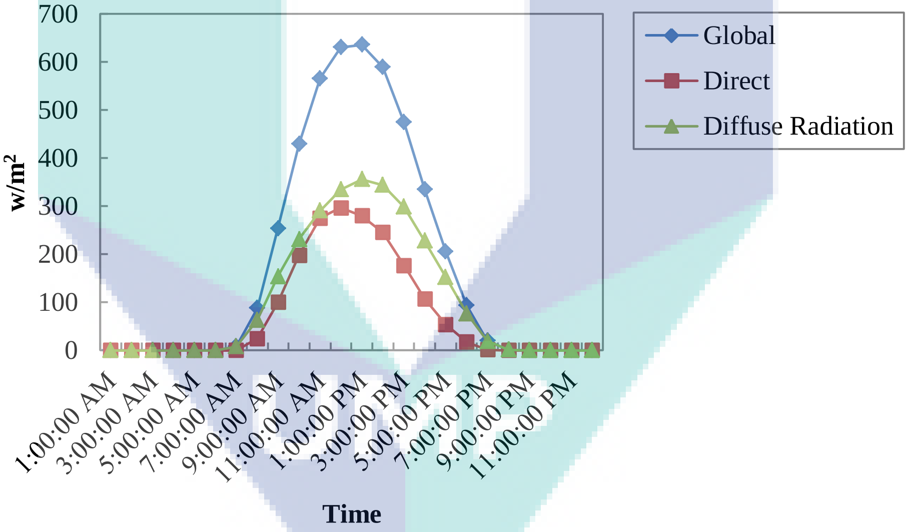


Hours	Average	Min	Max	Std. Dev.
1:00:00 AM	0.44	0.0	6.4	0.9
2:00:00 AM	0.46	0.0	5.4	0.9
3:00:00 AM	0.45	0.0	7.0	0.9
4:00:00 AM	0.48	0.0	6.0	1.0
5:00:00 AM	0.48	0.0	7.0	1.0
6:00:00 AM	0.47	0.0	7.6	0.9
7:00:00 AM	0.54	0.0	5.3	0.9
8:00:00 AM	0.85	0.0	4.1	1.0
9:00:00 AM	1.44	0.0	5.0	1.2
10:00:00 AM	2.15	0.0	6.5	1.4
11:00:00 AM	2.46	0.0	6.9	1.4
12:00:00 PM	2.77	0.0	7.0	1.4
1:00:00 PM	3.05	0.0	6.6	1.4
2:00:00 PM	3.36	0.0	7.1	1.5
3:00:00 PM	3.50	0.0	7.0	1.5
4:00:00 PM	3.30	0.0	7.0	1.5

5:00:00 PM	2.58	0.0	5.8	1.5
6:00:00 PM	1.69	0.0	7.0	1.3
7:00:00 PM	0.94	0.0	5.4	1.0
8:00:00 PM	0.56	0.0	5.3	0.8
9:00:00 PM	0.47	0.0	5.6	0.8
10:00:00 PM	0.43	0.0	4.7	0.8
11:00:00 PM	0.38	0.0	7.2	0.8
12:00:00 AM	0.46	0.0	5.2	0.9

f. Comparison of Global, Direct and Diffuse Solar Radiation

Placing the average global, direct and diffuse solar radiation in the same chart provides a distinct understanding that the average direct solar radiation is more intense in the morning while the average diffuse radiation is more intense in the afternoon hours.



Hours	Global	Direct	Diffuse Radiation
1:00:00 AM	0.0	0.0	0.0
2:00:00 AM	0.0	0.0	0.0
3:00:00 AM	0.0	0.0	0.0
4:00:00 AM	0.0	0.0	0.0
5:00:00 AM	0.0	0.0	0.0
6:00:00 AM	0.0	0.0	0.0
7:00:00 AM	7.7	0.0	7.7
8:00:00 AM	87.5	24.7	62.8
9:00:00 AM	253.6	99.8	153.8

10:00:00 AM	429.0	197.6	231.4
11:00:00 AM	565.7	275.2	290.4
12:00:00 PM	631.0	296.7	334.4
1:00:00 PM	635.9	279.7	356.2
2:00:00 PM	589.2	245.1	344.1
3:00:00 PM	474.6	176.2	298.4
4:00:00 PM	335.2	107.0	228.1
5:00:00 PM	205.7	53.4	152.3
6:00:00 PM	93.2	17.2	76.1
7:00:00 PM	20.0	1.2	18.8
8:00:00 PM	0.7	0.0	0.7
9:00:00 PM	0.0	0.0	0.0
10:00:00 PM	0.0	0.0	0.0
11:00:00 PM	0.0	0.0	0.0
12:00:00 AM	0.0	0.0	0.0

APPENDIX B

LIST OF SENSORS DEVICE FOR ENVIRONMENT MEASUREMENT

No	Device		Specification
1		Ambient temperature	Range: -20 to 100 ^{o}C Accuracy: ±0.5 ^{o}C
2		Air velocity	Range: 0 to 20 m/s Accuracy: ±5%
3		Humidity	Range: 0 to 100% Accuracy: ±3.5%
4		Noise meter	Range: 30 to 130 dB Accuracy: ±1.5 dB @ 94 dB for a 1 kHz sine wave
5		Globe temperature	Range: -20 to 100 ^{o}C Accuracy: ±0.5 ^{o}C
6		Pressure meter	Range: 800 to 1200 hPa Accuracy: ±2%
7		Lux meter	Range: 0 to 30 m/s Accuracy: ±3%
8		CO_2 sensor	Range: 0 to 1000 ppm Accuracy: ±40 ppm

APPENDIX C

DEMOGRAPHIC SUBJECTS

Respondents	**Sex**	**Age (years)**	**Weight (kg)**	**Height (cm)**	**A_{DU} (m^2)**	**BMI**
A	Male	22	80	165	1.87	29.4
B	Female	22	64	163	1.69	24.1
C	Female	26	55	154	1.52	23.2
D	Female	22	70	159	1.72	27.7
E	Male	25	64	170	1.74	22.1
F	Male	22	71	161	1.75	27.4
G	Male	27	79	172	1.92	26.7
H	Female	24	60	169	1.69	21.0
I	Male	24	63	170	1.73	21.8
J	Female	26	64	153	1.61	27.3
K	Female	23	60	155	1.59	25.0
L	Female	24	43	152	1.36	18.6
N	Male	26	82	165	1.89	30.1
M	Male	25	72	160	1.75	28.1
O	Male	25	65	157	1.66	26.4
Mean		**24**	**66**	**161**	**1.70**	**25.3**
Std. Dev.		**1.698739**	**10.148**	**6.69399**	**0.14425**	**3.34681**

APPENDIX D

ENVIRONMENTAL CHAMBER

Physical model to be calculated is environmental chamber with wall hanging air conditioning. The model parameters are as follows:

1. Chamber dimensions: x × y × z = 3.6 m × 2.4 m × 2.4 m
2. Reference coordinate system: Starting point coordinates (0, 0, 0) and ending point coordinates (3.6, 2.4, 2.4), corresponding to be lower left and top right corner points respectively in Figure D.
3. Wall hanging air conditioning air supply; Dimensions: 1.2 m × 0.1 m

In this study, zero equation turbulence model with free convection and mixed convection flow is adopted, which has a good performance to simulate the chamber with wall hanging air conditioning. To simplify the problem, assumptions made in physical model are as follows:

1. Floor surface temperature is well distributed
2. Indoor air is incompressible and conforms (Boussinesq, 1872) to hypotheses, namely changes of fluid density have an influence on buoyancy lift only
3. Indoor air flow is steady turbulent flow
4. Considering the room simulated is with good air tightness, so air leakage effect is out of consideration (Zhou and Haghighat, 2009)

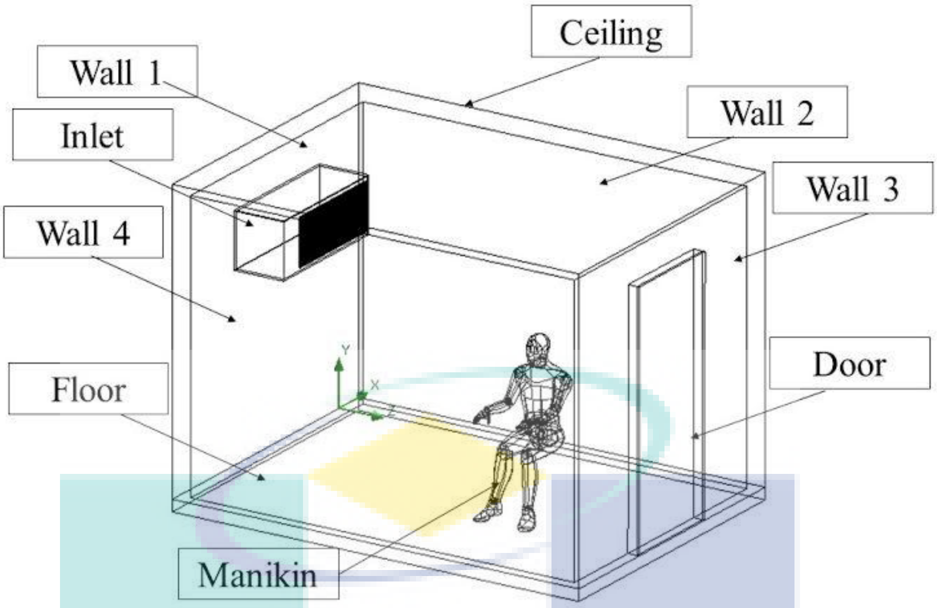


Figure D A Simplified Environmental Chamber.

APPENDIX E

ANOVA TABLE FOR GENDER AND METABOLIC ACTIVITY LEVEL HAS INTERACTION EFFECT ON THERMAL COMFORT

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	3	3.8	1.266667	0.093333
Column 2	3	-1.01	-0.33667	0.757433

ANOVA

Source of Variation	*SS*	*Degrees of Freedom*	*Mean Square*	*F Score*	*Significant*	*F crit*
Between Groups	3.856017	1	3.856017	9.064804	0.03952	7.708647
Within Groups	1.701533	4	0.425383			
Total	5.55755	5				

APPENDIX F

ANOVA TABLE FOR THERMAL SENSATIONWITH BOTH MALES AND FEMALES

Table F1 ANOVA Table for Thermal Sensation with Males

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	3	3.8	1.266667	0.093333
Column 2	3	0.37	0.123333	0.005233

ANOVA

Source of Variation	*SS*	*Degrees of Freedom*	*Mean Square*	*F Score*	*Significant*	*F crit*
Between Groups	1.960817	1	1.960817	39.78661	0.00323	7.708647
Within Groups	0.197133	4	0.049283			
Total	2.15795	5				

Table F2 ANOVA Table for Thermal Sensation with Females

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	3	3.8	1.266667	0.093333
Column 2	3	0.41	0.136667	0.005733

ANOVA

Source of Variation	*SS*	*Degrees of Freedom*	*Mean Square*	*F Score*	*Significant*	*F crit*
Between Groups	1.91535	1	1.91535	38.6679	0.003404	7.708647
Within Groups	0.198133	4	0.049533			
Total	2.113483	5				

APPENDIX G

ANOVA TABLE FOR THERMAL SENSATION AND SKIN TEMPERATURE WITH METABOLIC RATE

Dependent Variable: Thermal Sensation

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	225	7577.73	33.6788	0.331971
Column 2	225	28.9	0.128444	0.068614

ANOVA

Source of Variation	*SS*	*Degrees of Freedom*	*Mean Square*	*F Score*	*Significant*	*F crit*
Between Groups	126633	1	126633	632239.5	0.000	3.862
Within Groups	89.731	448	0.2003			
Total	126722.7	449				

R^2 = 0.904

APPENDIX H

DESCRIPTIVE ANALYSIS FOR BODY CORE TEMPERATURE

Descriptive Analysis, T_{cr}	
Mean	36.84515556
Standard Error	0.001945791
Median	36.83
Mode	36.83
Standard Deviation	0.029186864
Sample Variance	0.000851873
Kurtosis	-0.59038152
Skewness	0.677514552
Range	0.11
Minimum	36.81
Maximum	36.92
Sum	8290.16
Count	225

APPENDIX I

PSYCHOMETRIC CHART

In this section illustrated two chart which is psychometric chart and temperature-humidity chart. In both cases, the air temperature and relative humidity are represented by the red dot. The blue area represents the comfort zone on the chart for the respective conditions, where the *PMV* is between -0.5 and 0.5. Every chart has three blue area which different activity level (1.0, 1.2 and 1.6 Met). Blue are number one represented for 1.0 Met, number two represented for 1.2 Met and number three represented 1.6 Met.

ROOM TEMPERATURE AT 19 ^{o}C WITH DIFFERENT MET (1.0, 1.2 AND 1.6 MET)

#1: Maximum air speed has been limited due to no occupant control			
#2: Maximum air speed has been limited due to no occupant control			
	#1	#2	#3
Compliance	*x*	*x*	√
PMV	-2.23	-1.39	-0.42
PPD	86 %	45 %	9 %
Sensation	Cool	Slightly cool	Neutral
SET	19.1 ^{o}C	20.5 ^{o}C	23.3 ^{o}C

T_{db}	29.1 ^{o}C
Rh	100 %
W_a	26.3 gw/kg
T_{wb}	29.3 ^{o}C
T_{dp}	29.4 ^{o}C
h	67.2 kJ/kg

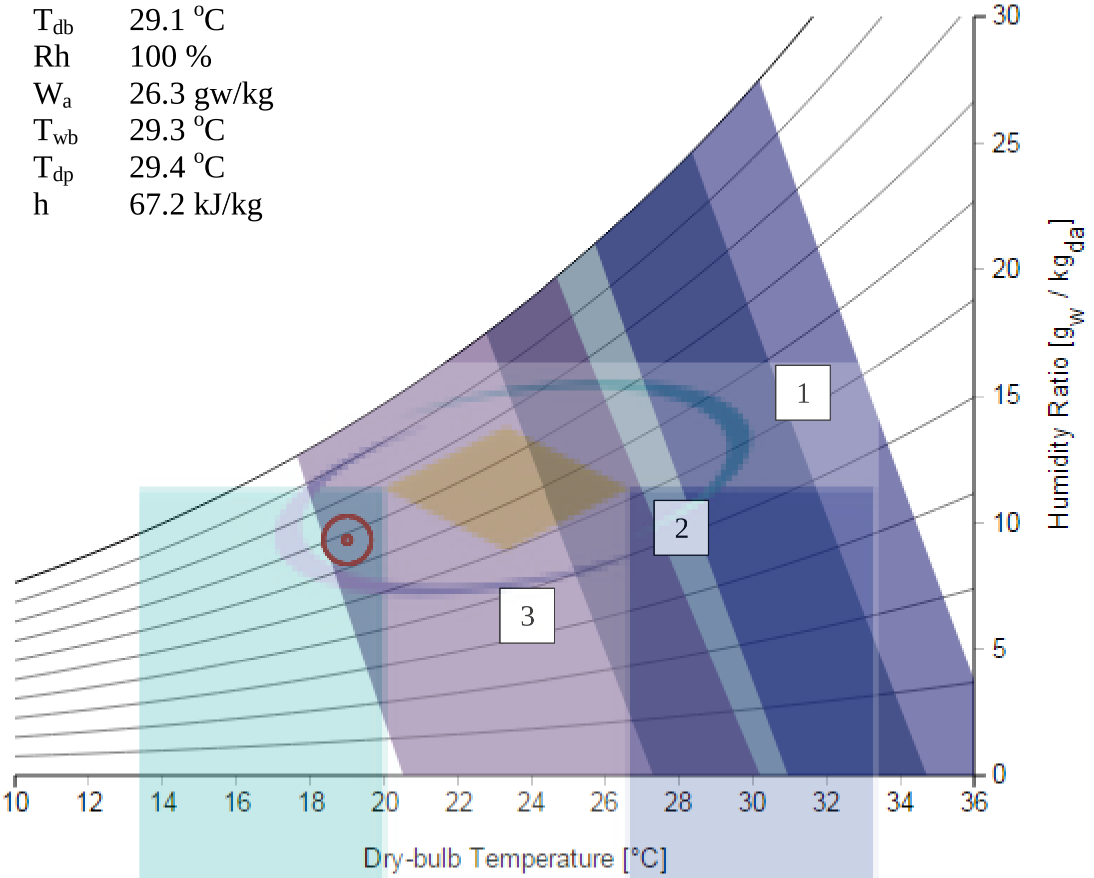


Figure I1 Psychometric Chart for Room Temperature at 19 ^{o}C.

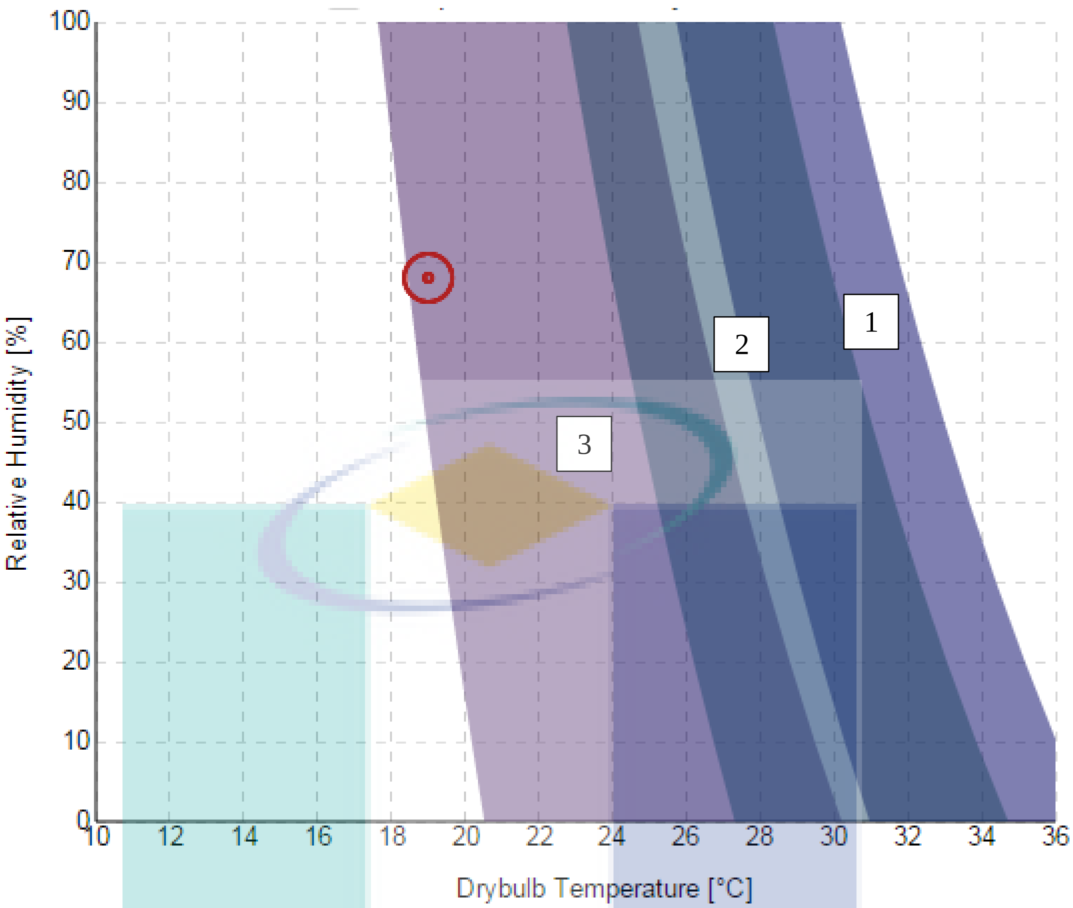
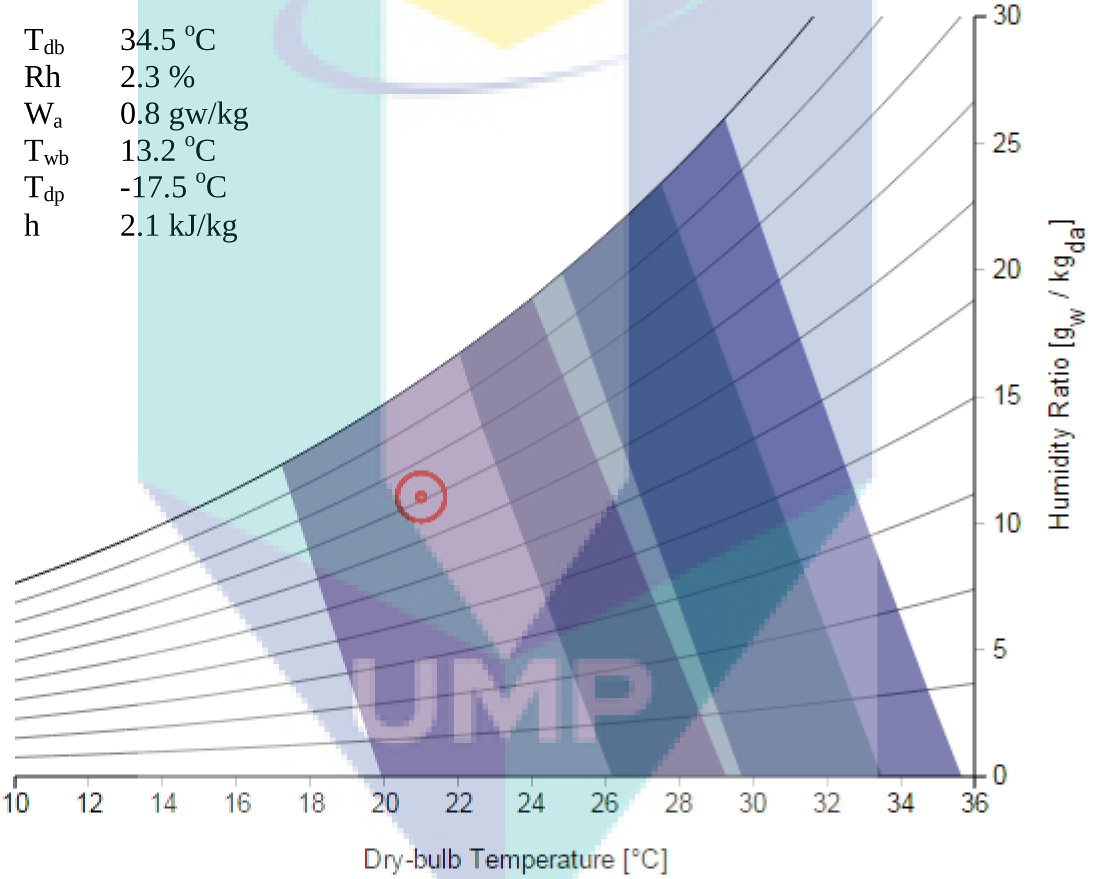


Figure I2 Temperature-Humidity Chart for Room Temperature at 19 °C.

ROOM TEMPERATURE AT 21 °C WITH DIFFERENT MET (1.0, 1.2 AND 1.6 MET)

#1: Maximum air speed has been limited due to no occupant control			
#2: Maximum air speed has been limited due to no occupant control			
	#1	#2	#3
Compliance	*x*	*x*	√
PMV	-1.59	-0.87	-0.05
PPD	56 %	21 %	5 %
Sensation	Cool	Slightly cool	Neutral
SET	20.8 °C	22.1 °C	25.0 °C



T_{db}	34.5 °C
Rh	2.3 %
W_a	0.8 gw/kg
T_{wb}	13.2 °C
T_{dp}	-17.5 °C
h	2.1 kJ/kg

Figure I3 Psychometric Chart for Room Temperature at 21 °C.

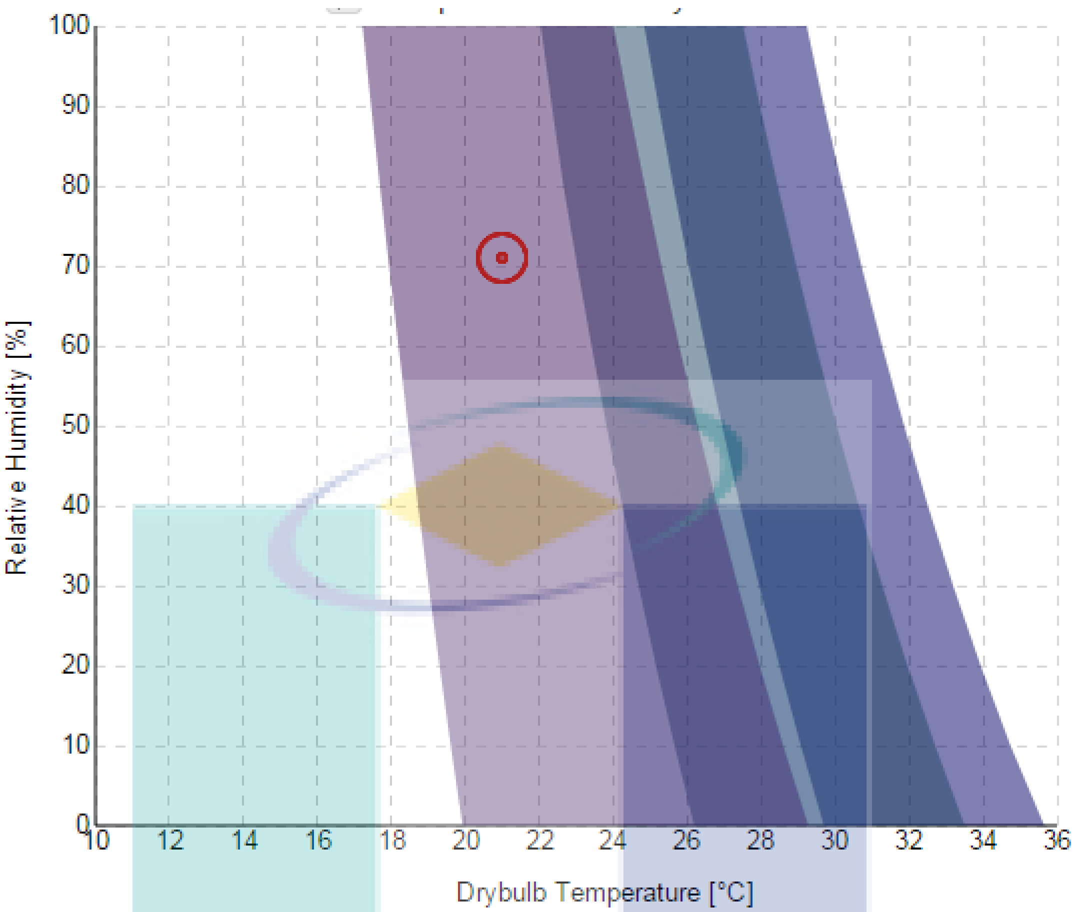


Figure I4 Temperature-Humidity Chart for Room Temperature at 21 ^{o}C.

ROOM TEMPERATURE AT 23 ^{o}C WITH DIFFERENT MET (1.0, 1.2 AND 1.6 MET)

#1: Maximum air speed has been limited due to no occupant control			
#2: Maximum air speed has been limited due to no occupant control			
	#1	#2	#3
Compliance	*x*	*x*	√
PMV with elevated air	-1.08	-0.48	0.17
PPD with elevated air	29 %	10 %	6 %
Sensation	Slightly cool	Neutral	Neutral
SET	22.1 ^{o}C	23.3 ^{o}C	25.9 ^{o}C
Drybulb temperature at still air	22.3 ^{o}C	22.2 ^{o}C	21.9 ^{o}C
Cooling effect	0.7 ^{o}C	0.8 ^{o}C	1.1 ^{o}C
Air speed range	0.0-0.0 m/s	0.0-0.2 m/s	0.0-0.3 m/s

T_{db}	35.6 ^{o}C
Rh	65.6 %
W_a	24.4 gw/kg
T_{wb}	29.7 ^{o}C
T_{dp}	28.1 ^{o}C
h	62.7 kJ/kg

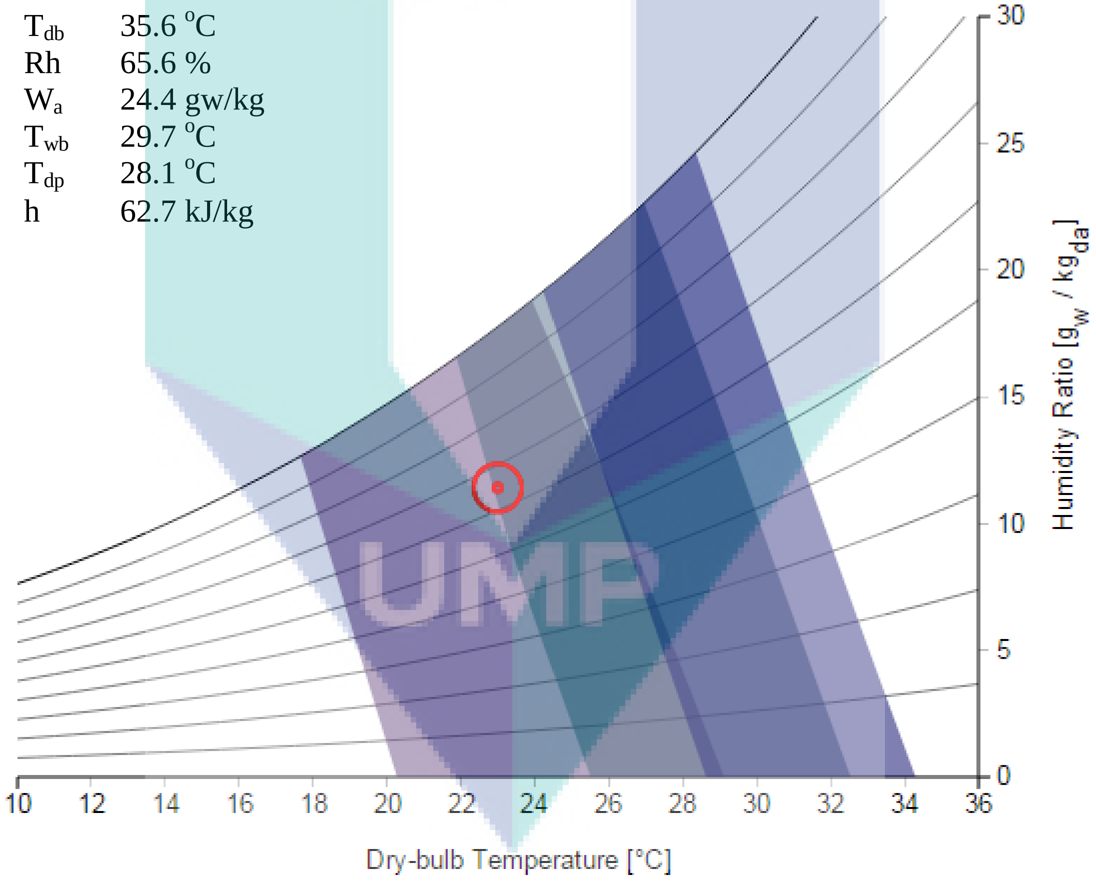


Figure I5 Psychometric Chart for Room Temperature at 23 ^{o}C.

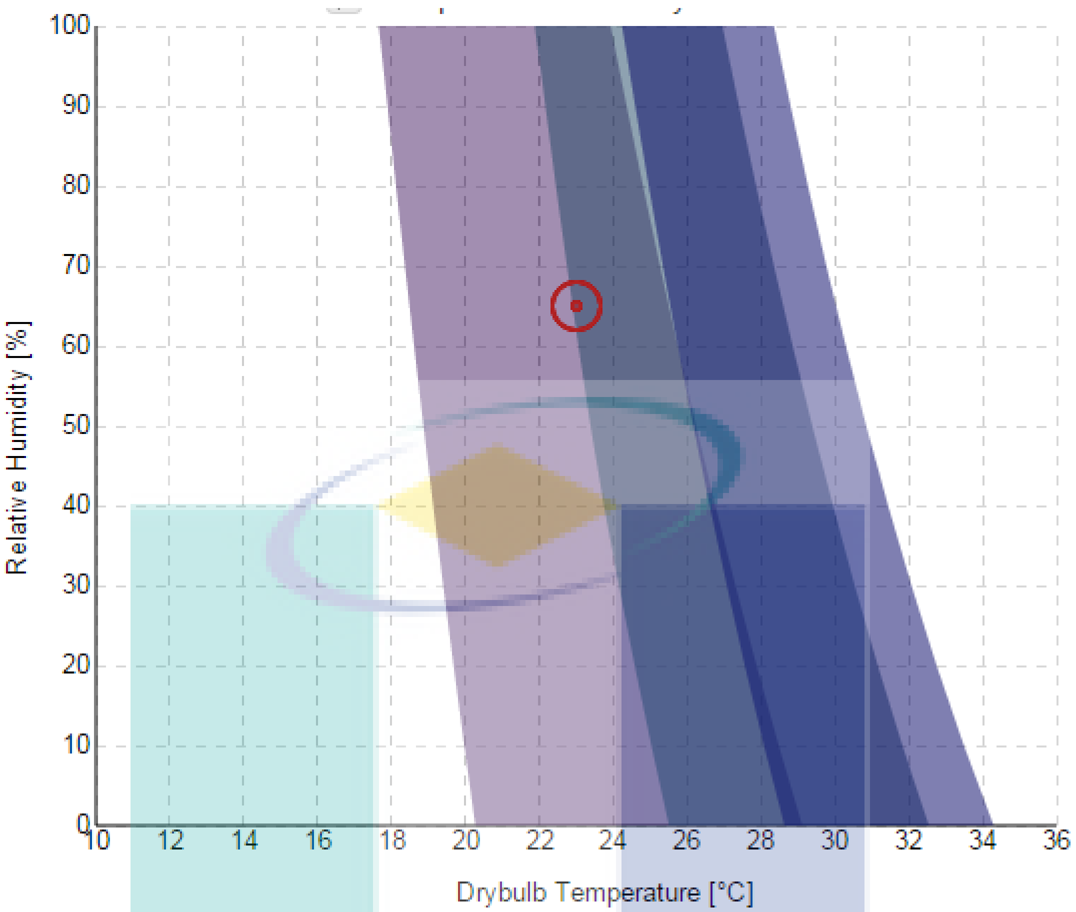
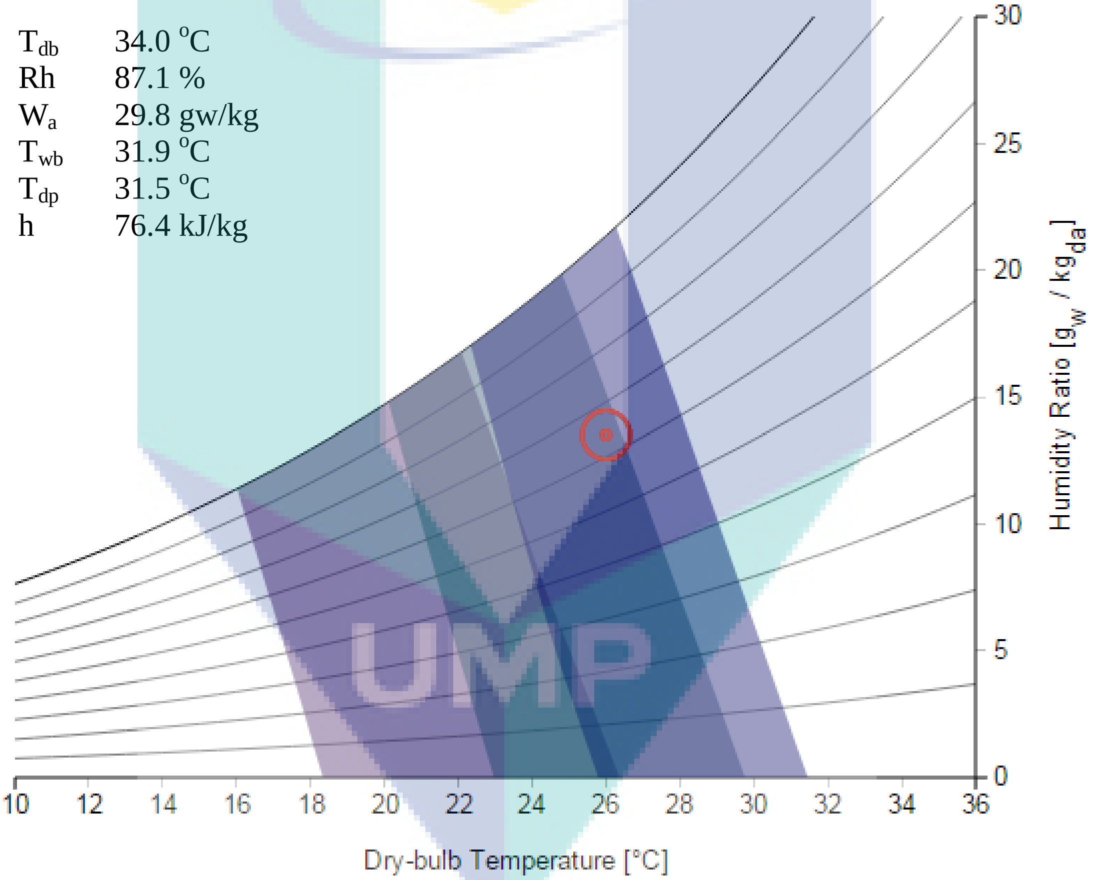


Figure I6 Temperature-Humidity Chart for Room Temperature at 23 ^{o}C.

ROOM TEMPERATURE AT 26 °C WITH DIFFERENT MET (1.0, 1.2 AND 1.6 MET)

	#1	#2	#3
Compliance	√	√	*x*
PMV with elevated air	0.12	0.44	0.86
PPD with elevated air	5 %	9 %	21 %
Sensation	Neutral	Neutral	Slightly warm
SET	25.5 °C	26.7 °C	29.2 °C
Drybulb temperature at still air	25.4 °C	25.1 °C	24.8 °C
Cooling effect	0.6 °C	0.9 °C	1.2 °C
Air speed range	0.0-0.5 m/s	0.2-0.8 m/s	0.4-0.8 m/s



T_{db}	34.0 °C
Rh	87.1 %
W_a	29.8 gw/kg
T_{wb}	31.9 °C
T_{dp}	31.5 °C
h	76.4 kJ/kg

Figure I7 Psychometric Chart for Room Temperature at 26 °C.

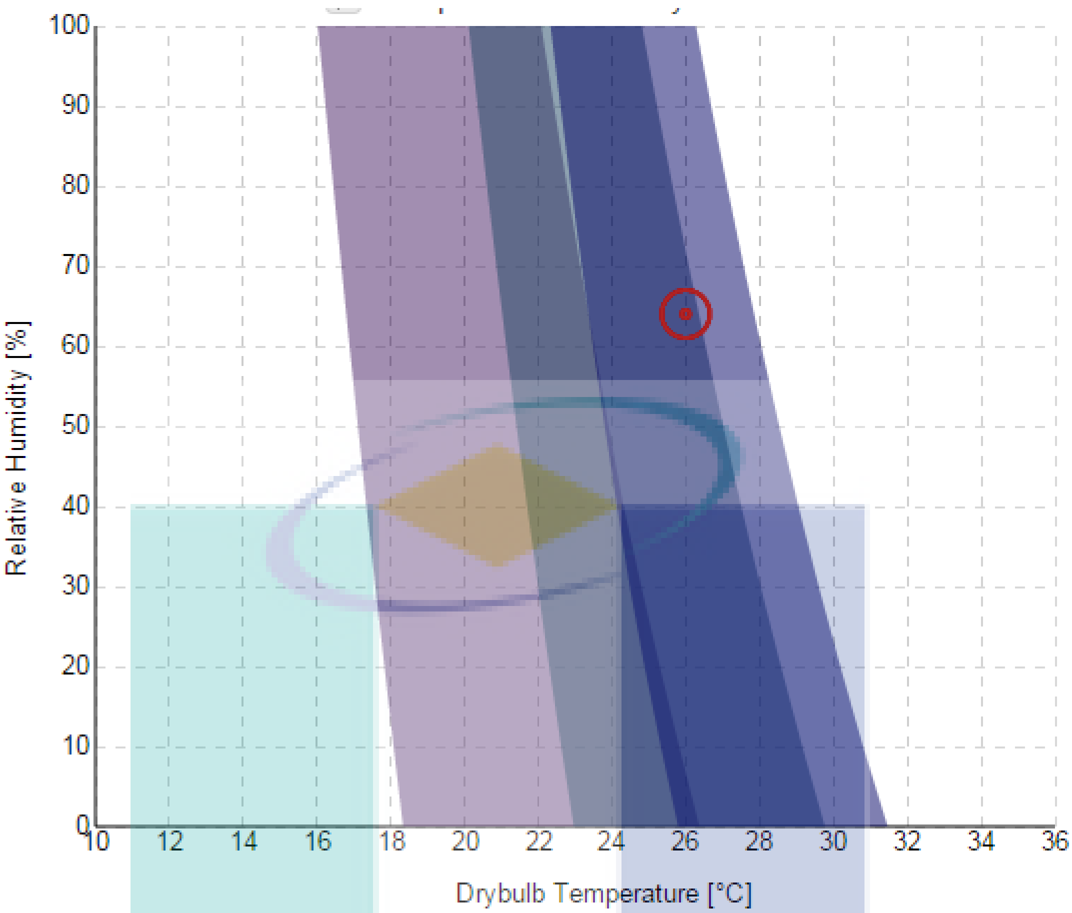
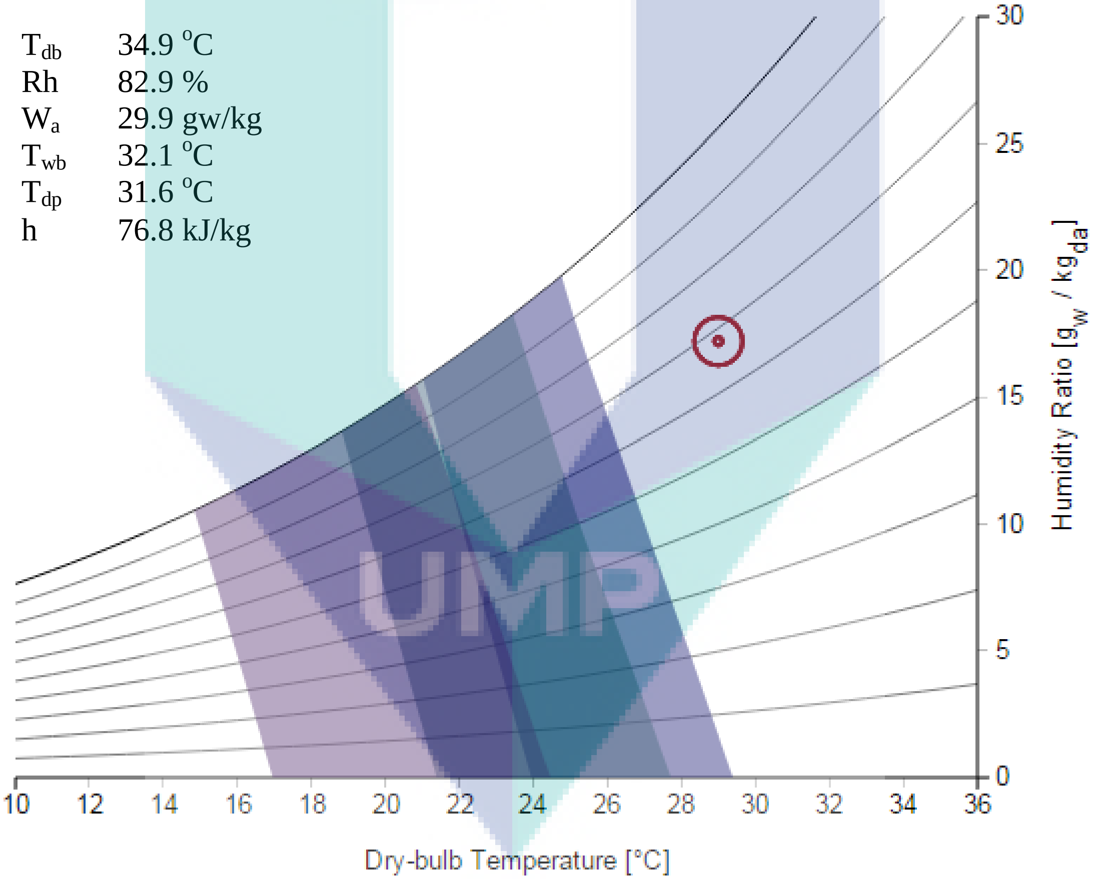


Figure I8 Temperature-Humidity Chart for Room Temperature at 26 °C.

ROOM TEMPERATURE AT 29 ^{o}C WITH DIFFERENT MET (1.0, 1.2 AND 1.6 MET)

#3: Maximum air speed has been limited due to no occupant control			
	#1	#2	#3
Compliance	*x*	*x*	*x*
PMV with elevated air	1.15	1.30	1.52
PPD with elevated air	33 %	40 %	52 %
Sensation	Slightly warm	Slightly warm	Warm
SET	28.8 ^{o}C	30.1 ^{o}C	32.5 ^{o}C
Drybulb temperature at still air	28.3 ^{o}C	28.1 ^{o}C	27.9 ^{o}C
Cooling effect	0.7 ^{o}C	0.9 ^{o}C	1.1 ^{o}C
Air speed range	0.6-0.8 m/s	0.8-0.8 m/s	0.0-0.0 m/s



T_{db}	34.9 ^{o}C
Rh	82.9 %
W_a	29.9 gw/kg
T_{wb}	32.1 ^{o}C
T_{dp}	31.6 ^{o}C
h	76.8 kJ/kg

Figure I9 Psychometric Chart for Room Temperature at 29 ^{o}C.

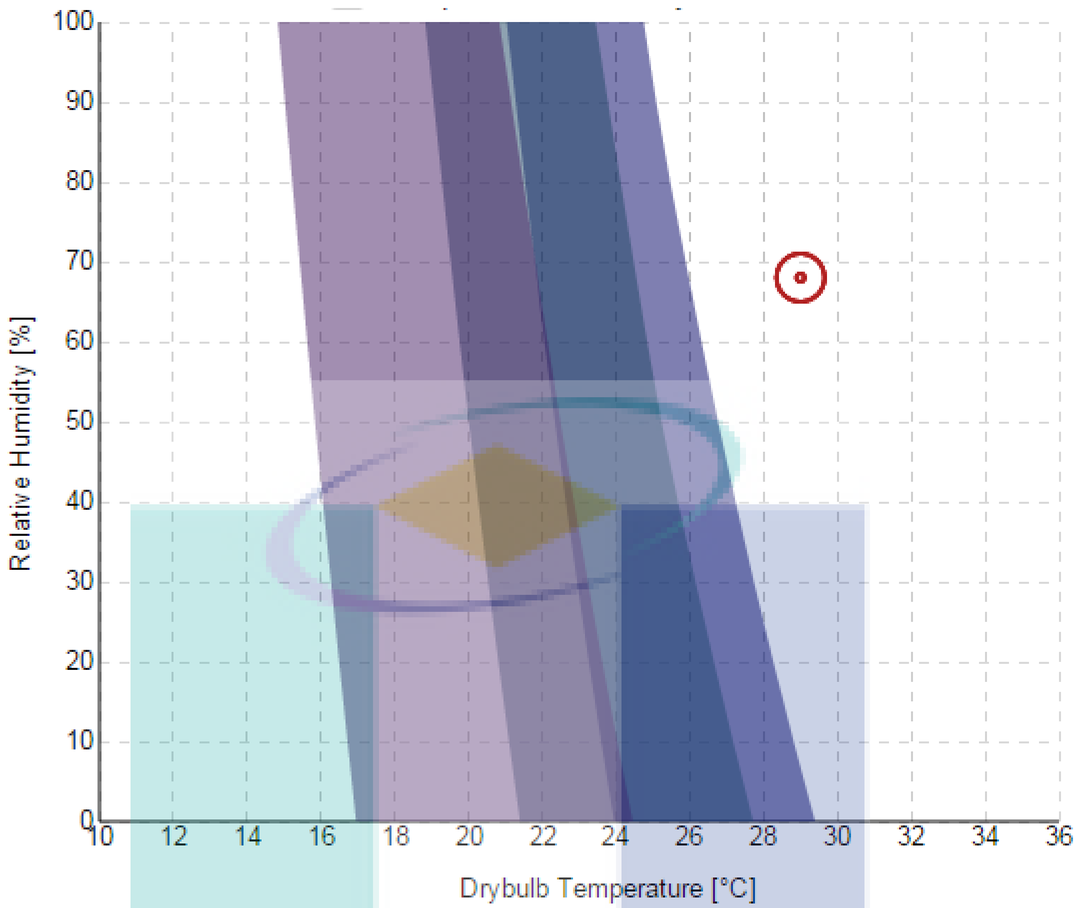
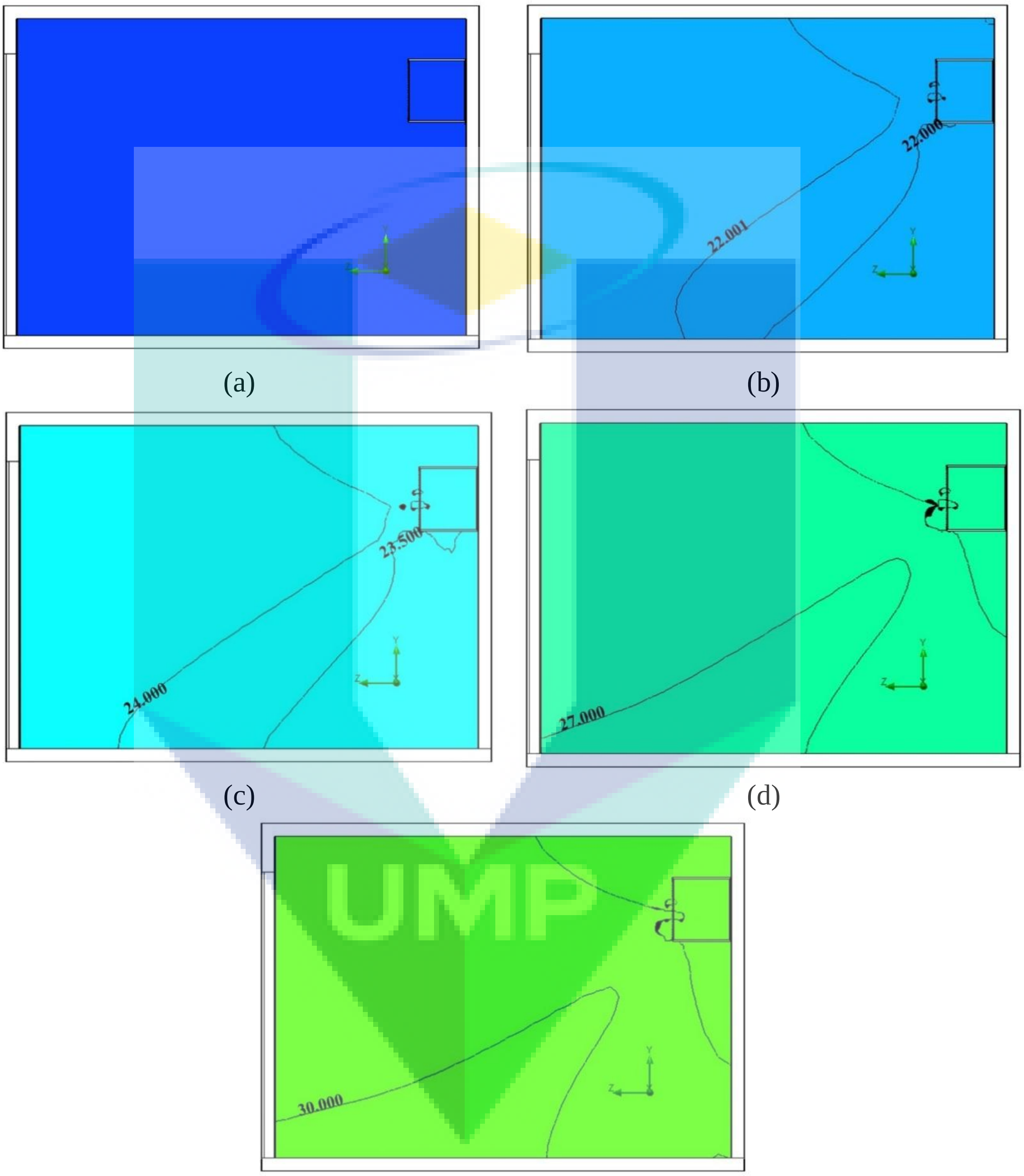


Figure I10 Temperature-Humidity Chart for Room Temperature at 29 ^{o}C.

APPENDIX J

NON-OCCUPIED CHAMBER FLOW SIMULATION



(a) (b) (c) (d) (e)

Figure J1 Effect of Radiant Temperature at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Front View.

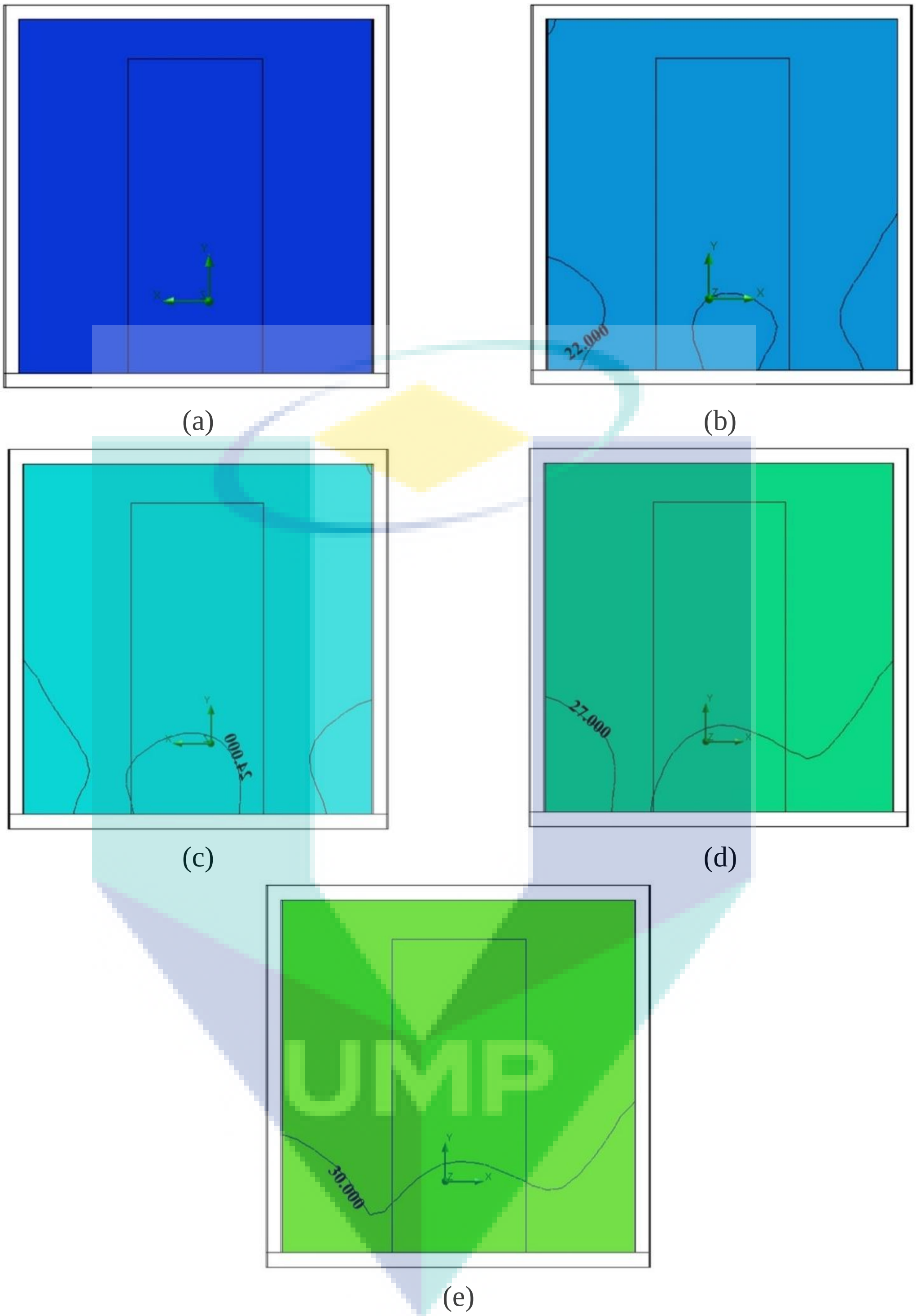
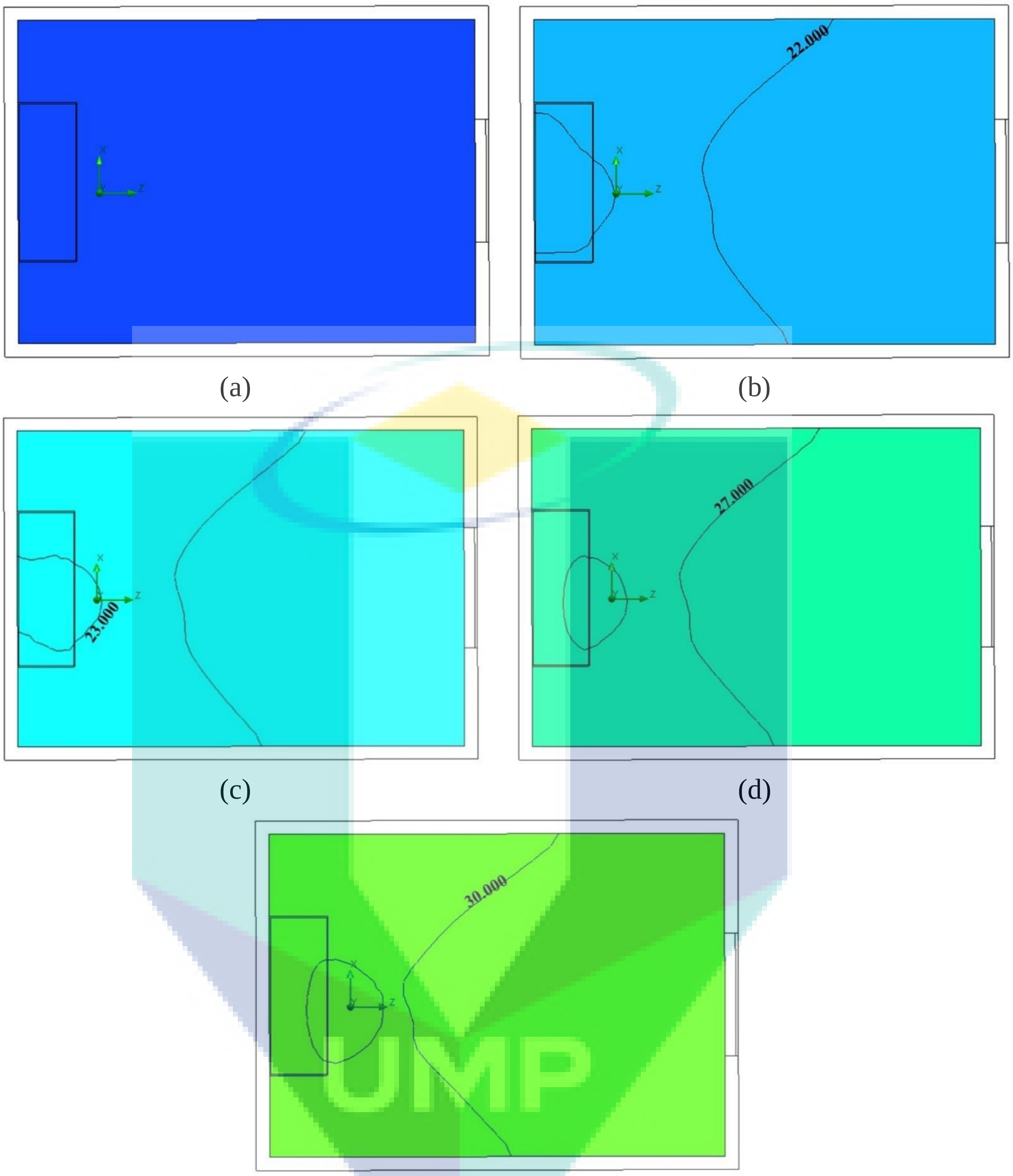


Figure J2 Effect of Radiant Temperature at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Side View.

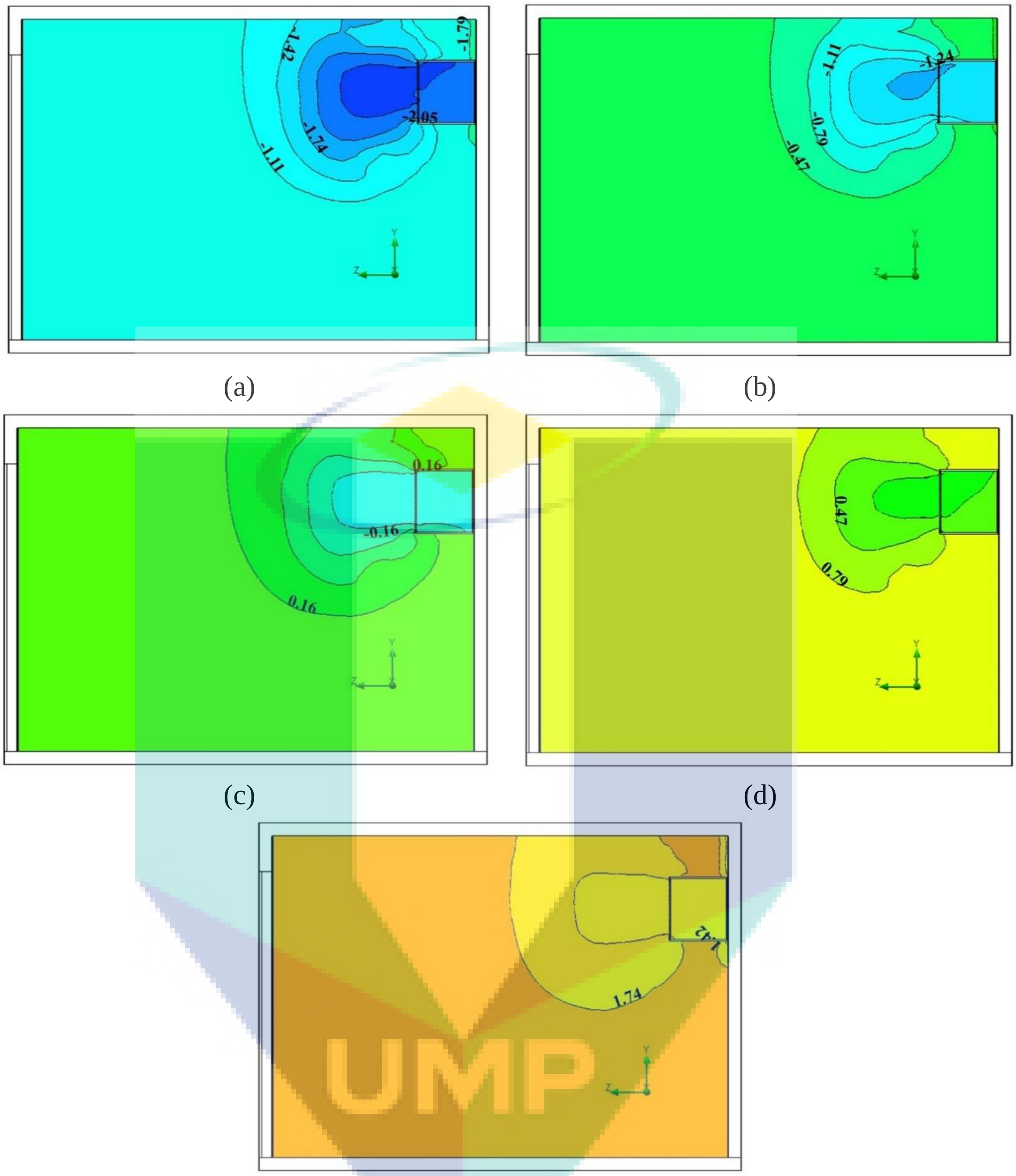


(a) (b)

(c) (d)

(e)

Figure J3 Effect of Radiant Temperature at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Top View.

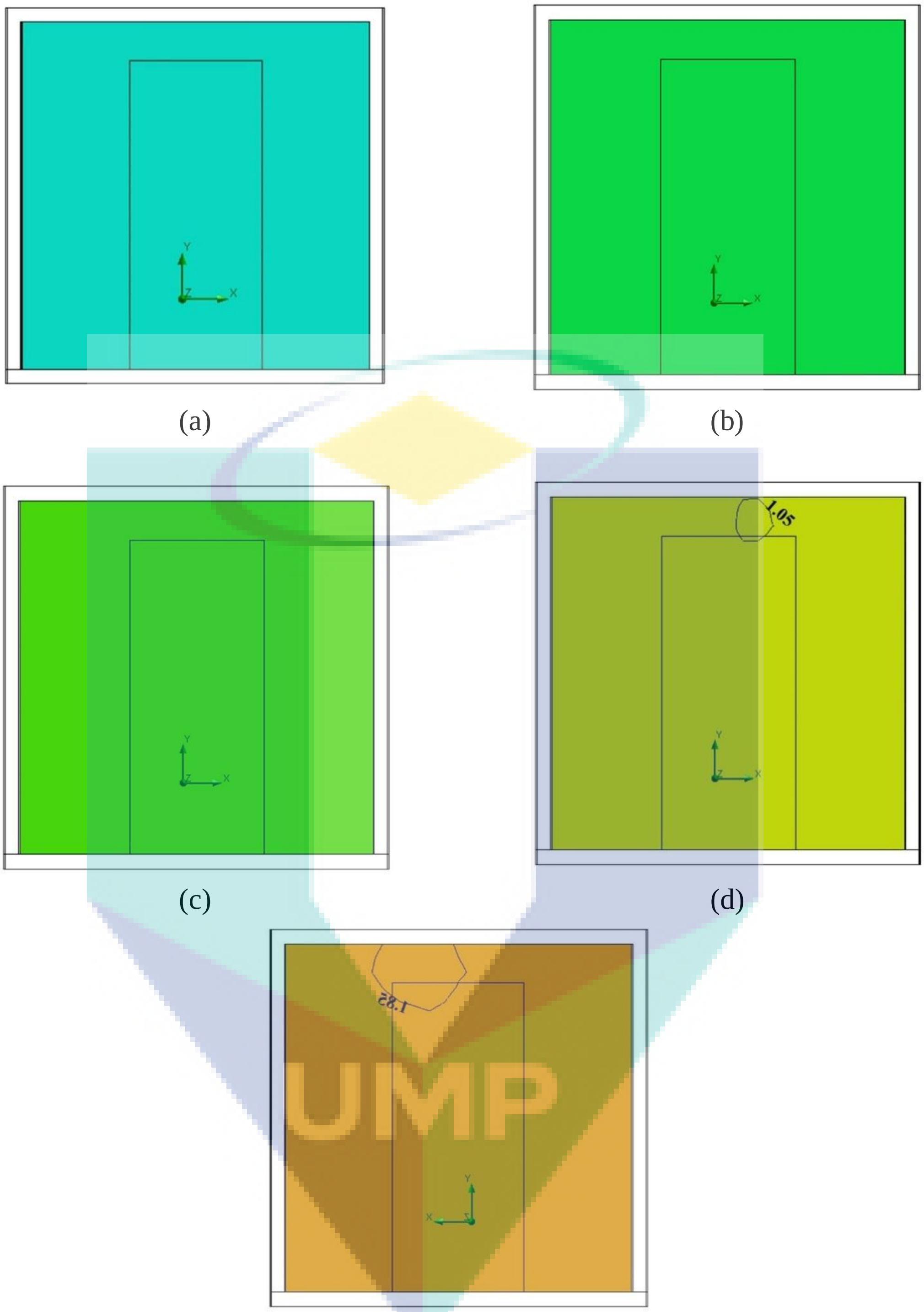


(a) (b)

(c) (d)

(e)

Figure J4 Effect of *PMV* at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Front View.

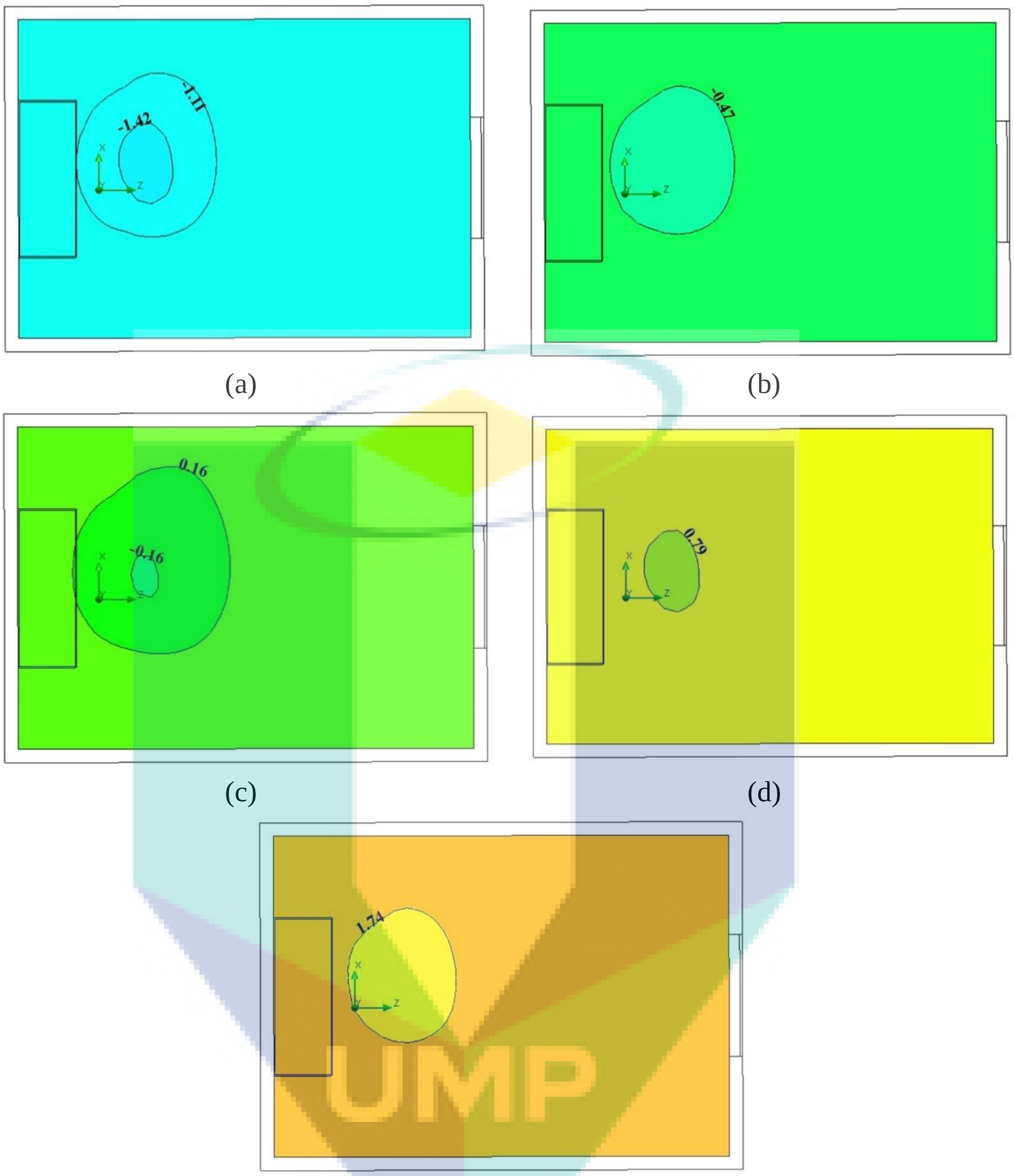


(a) (b)

(c) (d)

(e)

Figure J5 Effect of *PMV* at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Side View.

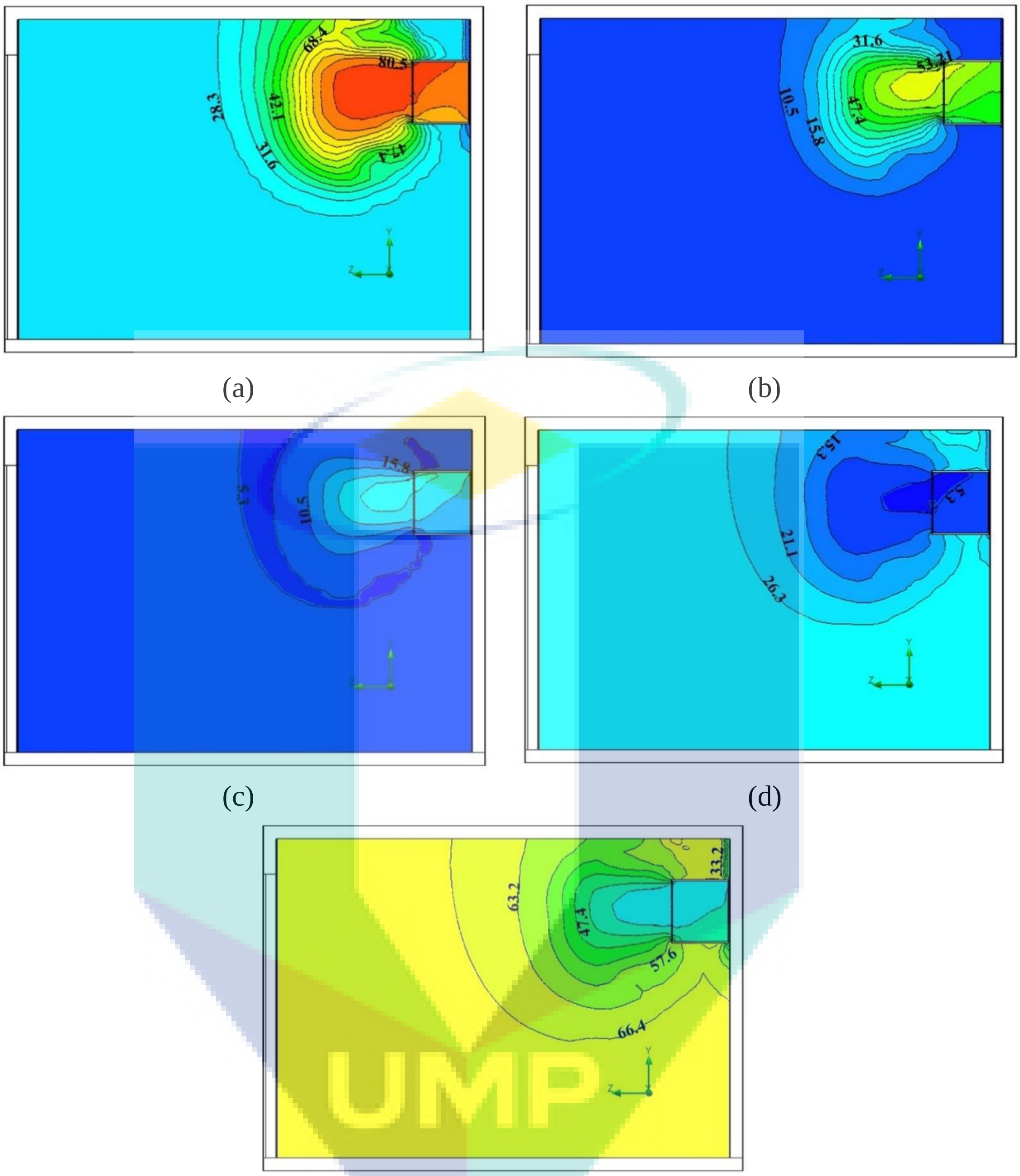


(a) (b)

(c) (d)

(e)

Figure J6 Effect of *PMV* at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Top View.

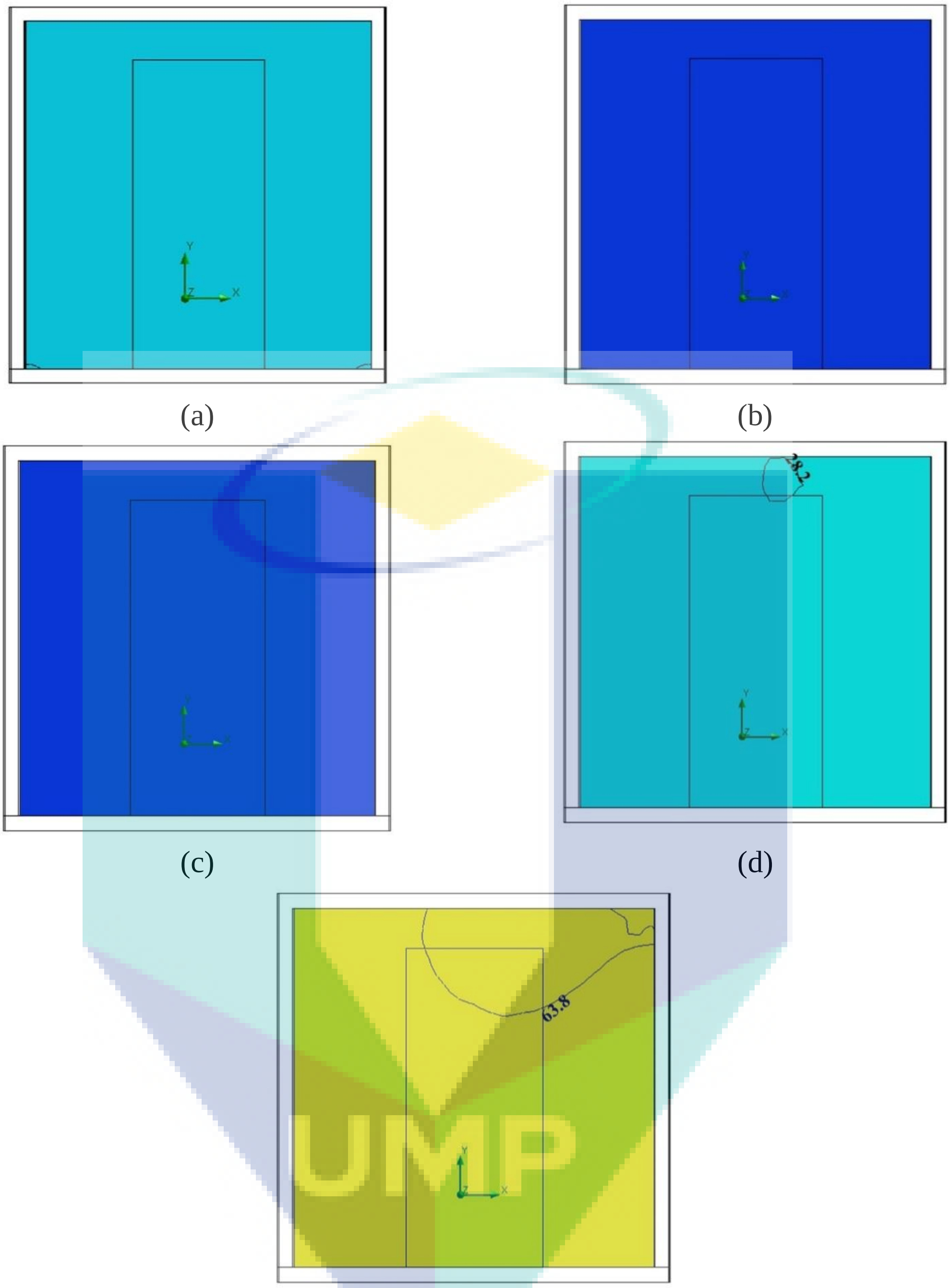


(a) (b)

(c) (d)

(e)

Figure J7 Effect of *PPD* at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Front View.

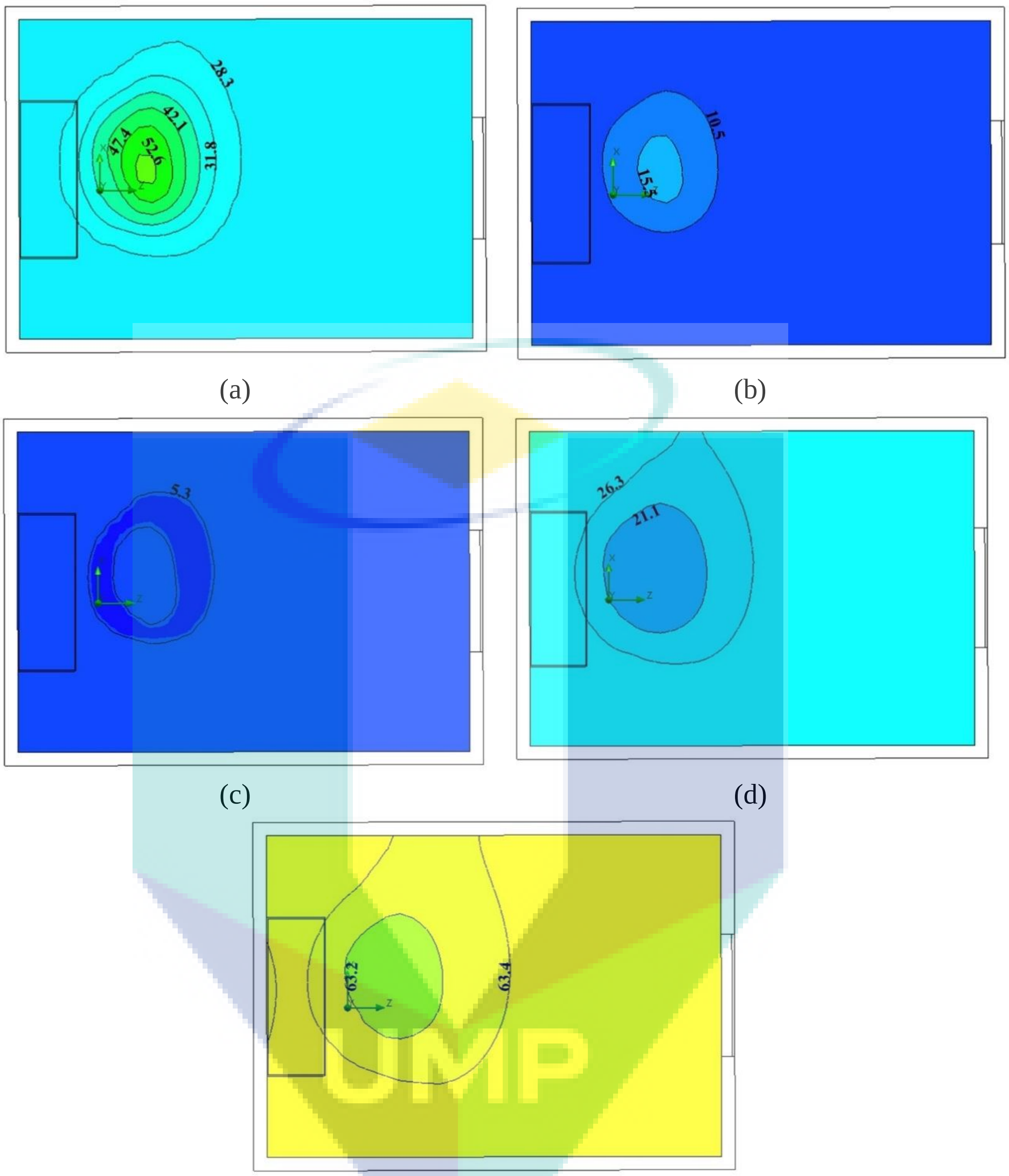


(a) (b)

(c) (d)

(e)

Figure J8 Effect of *PPD* at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Side View.

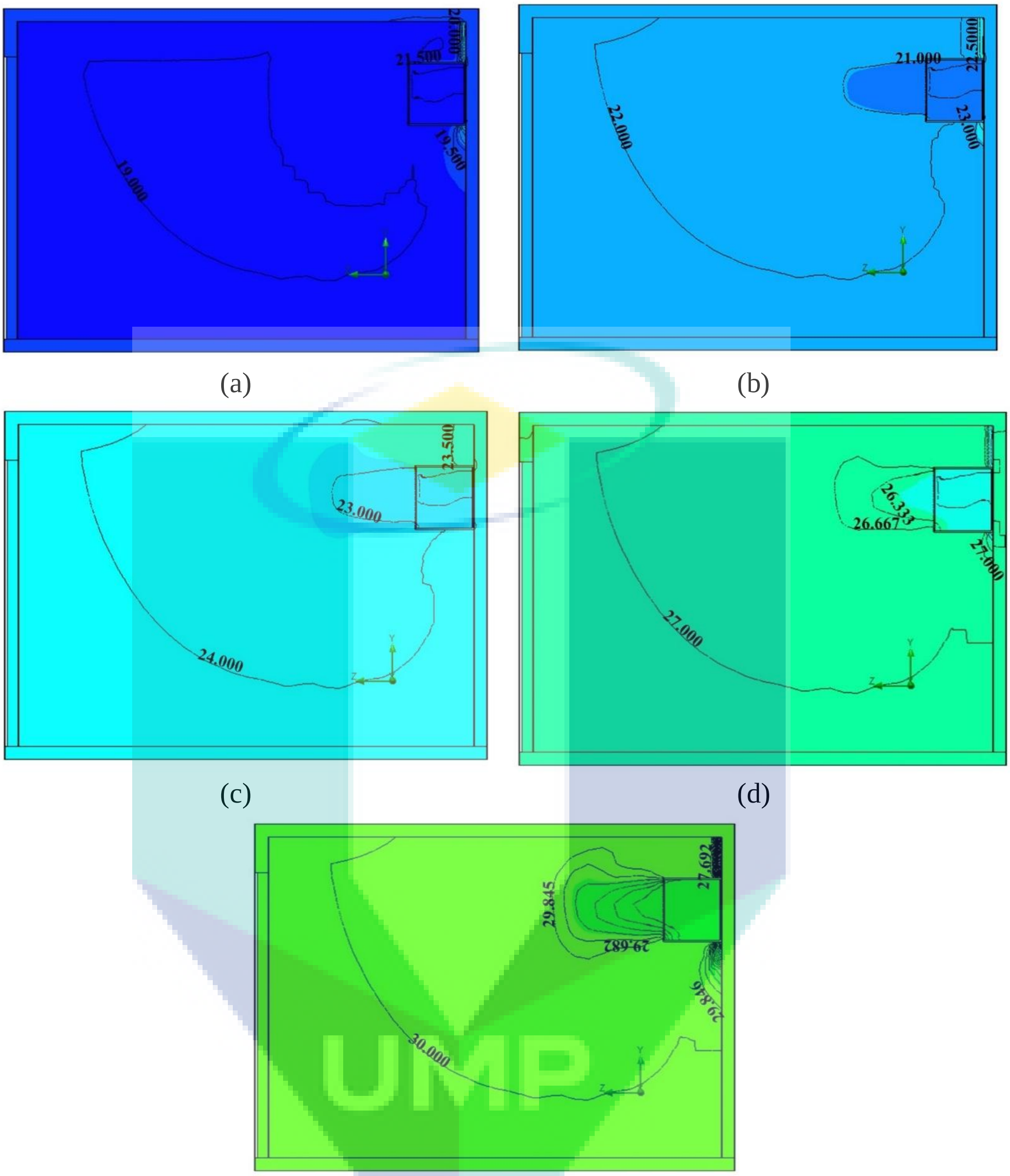


(a) (b)

(c) (d)

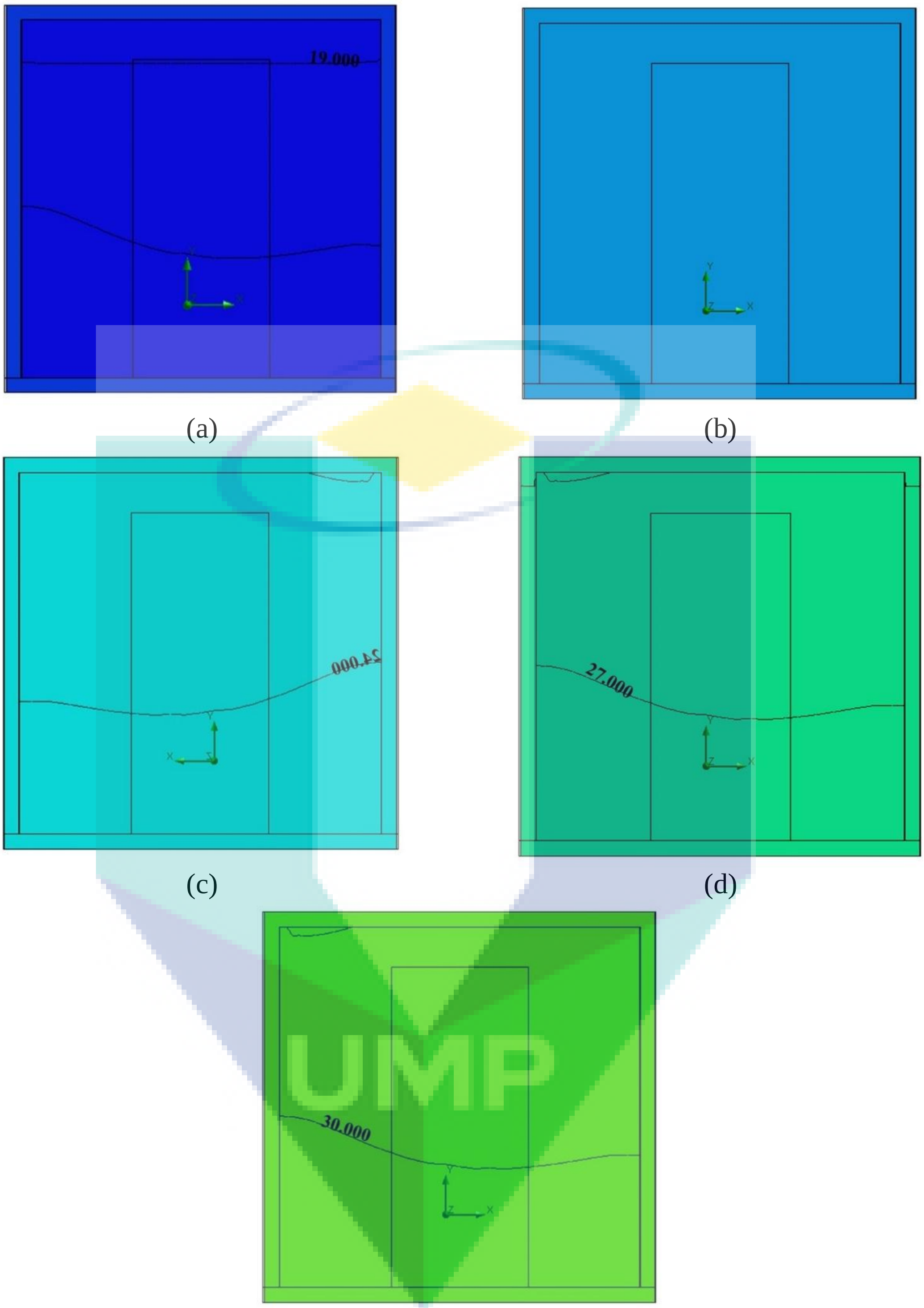
(e)

Figure J9 Effect of *PPD* at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Top View.



(a) (b) (c) (d) (e)

Figure J10 Effect of Air Temperature at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Front View.

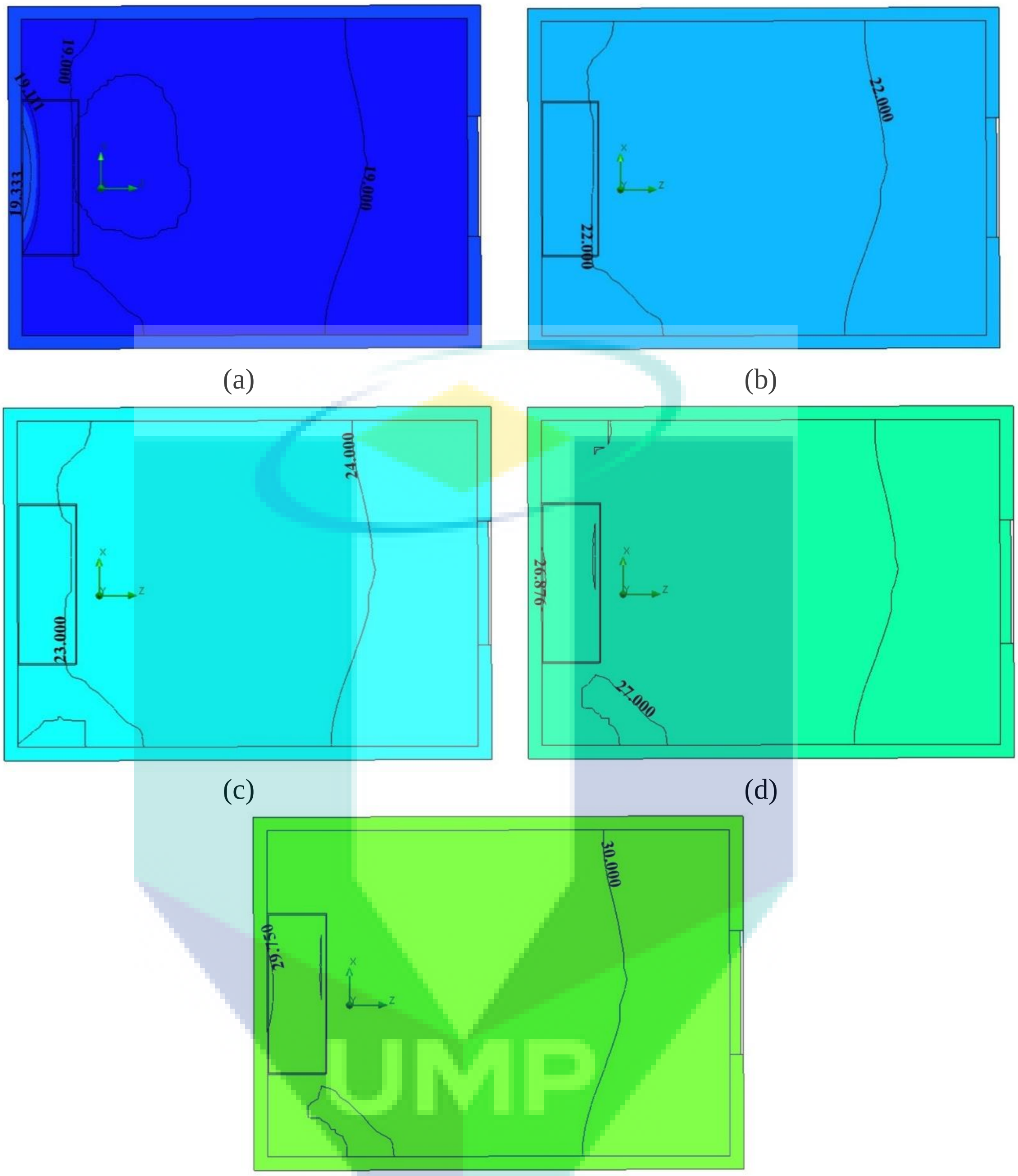


(a) (b)

(c) (d)

(e)

Figure J11 Effect of Air Temperature at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Side View.

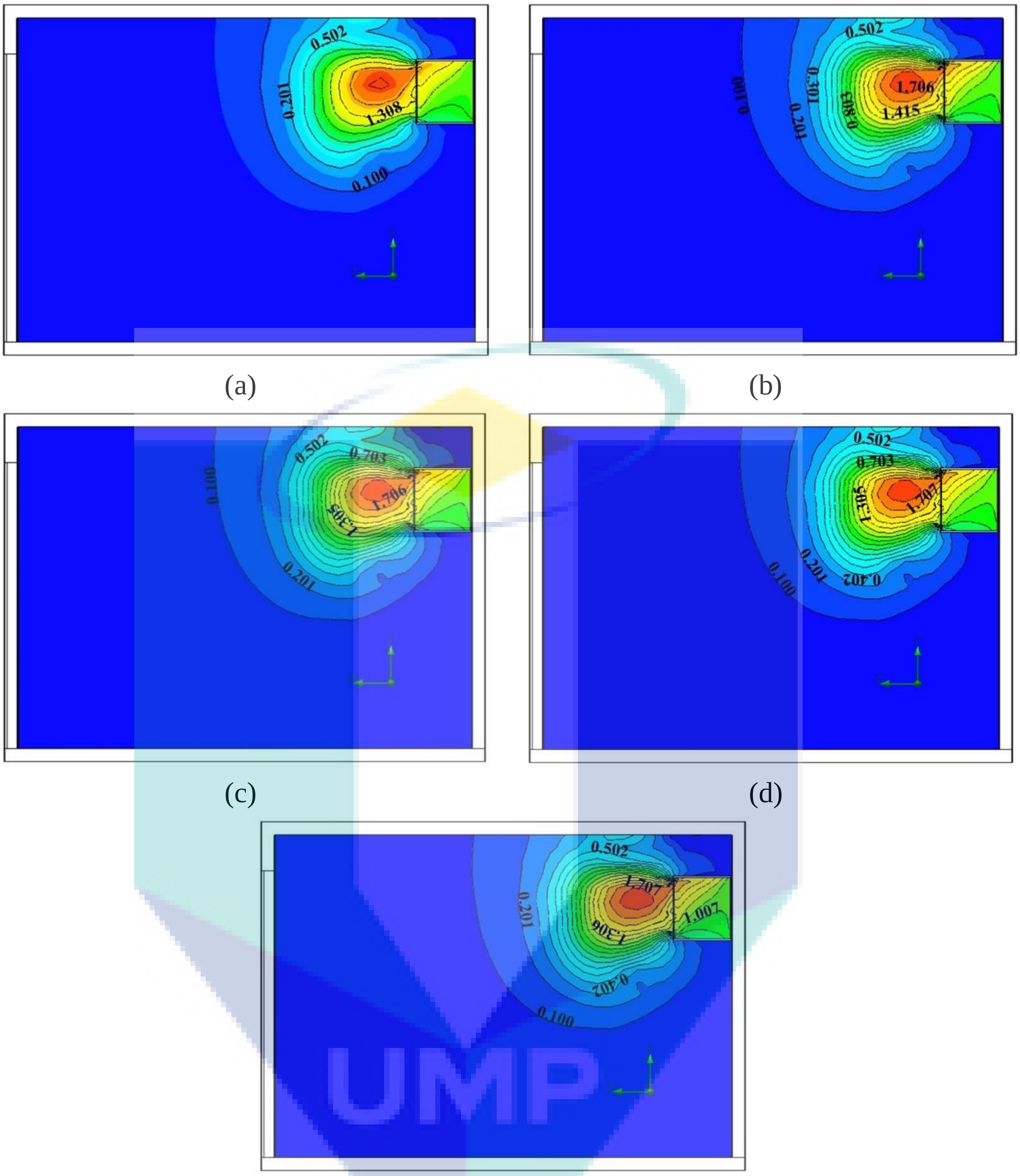


(a) (b)

(c) (d)

(e)

Figure J12 Effect of Air Temperature at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Top View.



(a) (b)

(c) (d)

(e)

Figure J13 Effect of Air Velocity at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Front View.

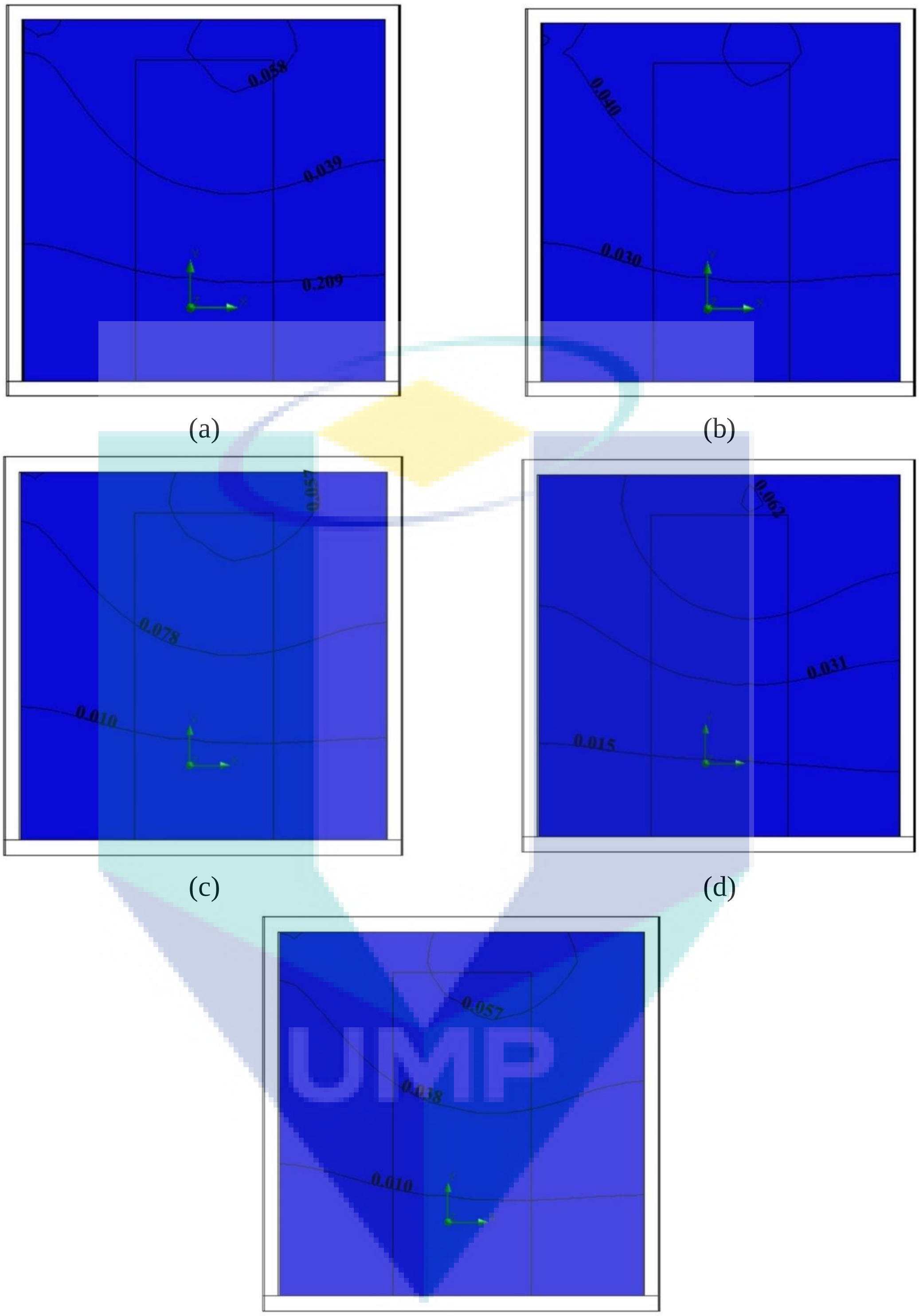
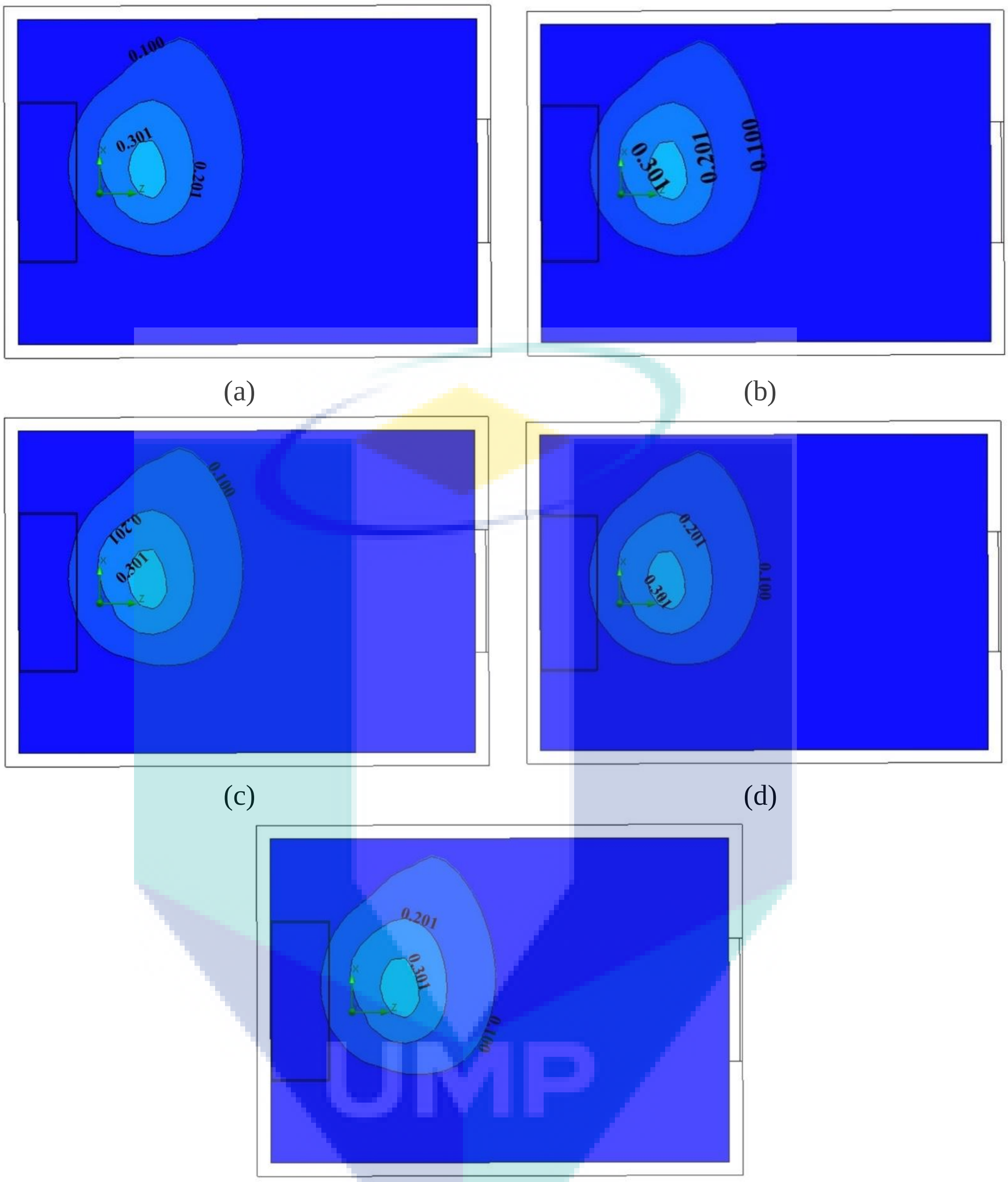


Figure J14 Effect of Air Velocity at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Side View.



(a) (b)

(c) (d)

(e)

Figure J15 Effect of Air Velocity at Different Room Temperature; (a) 19 °C (b) 21 °C (c) 23 °C (d) 26 °C and (e) 29 °C from Top View.

APPENDIX K

DATA COLLECTION

Temperature setting, 19 °C

		New Effective Temperature, ET*	SET	DISC	TSENS	PMV	PPD	HEAT STRESS INDEX, HSI	Skin Temperature, Tsk	Core Temperature, Tcr	Heart Rate, HR
A	1	20.31	18.66	0	-0.11	-2.73	97.11	-14.97	32.96	36.81	73
	1.2	20.22	19.43	-0.07	-0.07	-1.46	48.73	-3.8	32.97	36.83	74
	1.6	20.16	20.87	-0.04	-0.04	-0.29	6.78	12.12	33.09	36.87	62
B	1	20.31	18.67	0	-0.12	-2.73	97.11	-14.65	32.88	36.81	79
	1.2	20.21	19.43	-0.07	-0.07	-1.46	48.73	-3.52	32.91	36.83	81
	1.6	20.16	20.87	-0.04	-0.04	-0.29	6.78	12.21	33.07	36.87	92
C	1	20.31	18.67	0	-0.12	-2.73	97.11	-14.53	32.85	36.81	68
	1.2	20.12	19.43	-0.08	-0.08	-1.46	48.73	-3.4	32.89	36.83	79
	1.6	20.16	20.87	-0.04	-0.04	-0.29	6.78	12.24	33.07	36.87	88
D	1	20.31	18.66	0	-0.11	-2.73	97.11	-14.84	32.93	36.81	75
	1.2	20.22	19.43	-0.07	-0.07	-1.46	48.73	-3.68	32.95	36.83	78
	1.6	20.16	20.87	-0.04	-0.04	-0.29	6.78	12.16	33.08	36.87	62
E	1	20.31	18.67	0	-0.12	-2.73	97.11	-14.57	32.87	36.81	70
	1.2	20.21	19.43	-0.08	-0.08	-1.46	48.73	-3.44	32.89	36.83	89
	1.6	20.16	20.87	-0.04	-0.04	-0.29	6.78	12.23	33.07	36.87	105
F	1	20.31	18.66	0	-0.11	-2.73	97.11	-14.83	32.93	36.81	80
	1.2	20.22	19.43	-0.07	-0.07	-1.46	48.73	-3.68	32.94	36.83	87

	1.6	20.16	20.87	-0.04	-0.04	-0.29	6.78	12.23	33.07	36.87	117
G	1	20.31	18.66	0	-0.11	-2.73	97.11	-14.87	32.94	36.81	50
	1.2	20.22	19.43	-0.07	-0.07	-1.46	48.73	-3.71	32.95	36.83	79
	1.6	20.16	20.87	-0.04	-0.04	-0.29	6.78	12.15	33.08	36.87	88
H	1	20.3	18.67	0	-0.12	-2.73	97.11	-14.47	32.84	36.81	75
	1.2	20.21	19.43	-0.08	-0.08	-1.46	48.73	-3.36	32.88	36.83	77
	1.6	20.16	20.87	-0.04	-0.04	-0.29	6.78	12.15	33.06	36.87	78
I	1	20.31	18.67	0	-0.12	-2.73	97.11	-14.54	32.86	36.81	50
	1.2	20.21	19.43	-0.08	-0.08	-1.46	48.73	-3.42	32.89	36.83	60
	1.6	20.16	20.87	-0.04	-0.04	-0.29	6.78	12.24	33.07	36.87	60
J	1	20.31	18.66	0	-0.11	-2.73	97.11	-14.78	32.91	36.81	55
	1.2	20.22	19.43	-0.07	-0.07	-1.46	48.73	-3.63	32.93	36.83	55
	1.6	20.16	20.87	-0.04	-0.04	-0.29	6.78	12.18	33.08	36.87	60

Air Temperature	Mean Radiant Temperature	Air Velocity, m/s	RH %	Metabolic Rate, met	Clothing insulation, clo
21	23	0.4	68	1	0.5
20.3	22.7	0.3	67	1.2	0.5
19.6	22.4	0.2	66	1.6	0.5
19.6	22.1	0.1	66	1	0.5
19.8	25.9	0.1	66	1.2	0.5
20.1	21.8	0	66	1.6	0.5
20.5	21.6	0	66	1	0.5
20.7	21.6	0.2	69	1.2	0.5
20.2	21.5	0.3	71	1.6	0.5
19.8	21.5	0.3	68	1	0.5
19.5	21.4	0.1	68	1.2	0.5
19.6	21.3	0	68	1.6	0.5

19.8	21.1	0	68	1	0.5
20.1	21	0	68	1.2	0.5
20.4	21	0	68	1.6	0.5
20.7	21	0	68	1	0.5
20.8	21	0.3	72	1.2	0.5
20.9	21.1	0	68	1.6	0.5

Temperature setting, 21 °C

		New Effective Temperature, ET*	SET	DISC	TSENS	PMV	PPD	HEAT STRESS INDEX, HSI	Skin Temperature, Tsk	Core Temperature, Tcr	Heart Rate, HR
	1	22.02	20.36	0	-0.08	-2.23	85.81	-7.69	33.16	36.81	74
A	1.2	21.99	21.29	-0.04	-0.04	-1.08	29.59	4.38	33.26	36.83	78
	1.6	22.13	22.69	-0.02	-0.02	-0.03	5.01	21.15	33.41	36.87	99
	1	22.02	20.36	0	-0.08	-2.23	85.81	-7.42	33.1	36.81	85
B	1.2	21.99	21.29	-0.04	-0.04	-1.08	29.59	4.52	33.24	36.83	79
	1.6	22.14	22.7	-0.02	-0.02	-0.03	5.01	21.04	33.43	36.87	96
	1	22.02	20.36	0	-0.09	-2.23	85.81	-7.31	33.08	36.81	69
C	1.2	21.99	21.29	-0.04	-0.04	-1.08	29.59	4.58	33.23	36.83	67
	1.6	22.14	22.7	-0.02	-0.02	-0.03	5.01	20.99	33.43	36.87	106
	1	22.02	20.36	0	-0.08	-2.23	85.81	-7.59	33.14	36.81	84
D	1.2	21.99	21.29	-0.04	-0.04	-1.08	29.59	4.44	33.25	36.83	80
	1.6	22.13	22.7	-0.02	-0.02	-0.03	5.01	21.11	33.42	36.87	82
	1	22.02	20.36	0	-0.08	-2.23	85.81	-7.35	33.09	36.81	70
E	1.2	21.99	21.29	-0.04	-0.04	-1.08	29.59	4.56	33.23	36.83	78
	1.6	22.14	22.7	-0.02	-0.02	-0.03	5.01	21.01	33.43	36.87	97
	1	22.02	20.36	0	-0.08	-2.23	85.81	-7.58	33.13	36.81	78
F	1.2	21.99	21.29	-0.04	-0.04	-1.08	29.59	4.44	33.25	36.83	107
	1.6	22.13	22.7	-0.02	-0.02	-0.03	5.01	21.11	33.42	36.87	144
	1	22.02	20.36	0	-0.08	-2.23	85.81	-7.61	33.14	36.81	45
G	1.2	21.99	21.29	-0.04	-0.04	-1.08	29.59	4.42	33.25	36.83	67
	1.6	22.13	22.7	-0.02	-0.02	-0.03	5.01	21.12	33.42	36.87	106
	1	22.02	20.36	0	-0.09	-2.23	85.81	-7.27	33.07	36.81	80
H	1.2	21.99	21.29	-0.04	-0.04	-1.08	29.59	4.6	33.22	36.83	70

	1.6	22.14	22.71	-0.02	-0.02	-0.03	5.01	20.97	33.44	36.87	79
I	1	22.02	20.36	0	-0.09	-2.23	85.81	-7.33	33.09	36.81	75
	1.2	21.99	21.29	-0.04	-0.04	-1.08	29.59	4.57	33.23	36.83	79
	1.6	22.14	22.7	-0.02	-0.02	-0.03	5.01	21	33.43	36.87	80
J	1	22.02	20.36	0	-0.08	-2.23	85.81	-7.53	33.12	36.81	66
	1.2	21.99	21.29	-0.04	-0.04	-1.08	29.59	4.47	33.25	36.83	70
	1.6	22.13	22.7	-0.02	-0.02	-0.03	5.01	21.09	33.42	36.87	69

Air Temperature	**Mean Radiant Temperature**	**Air Velocity, m/s**	**RH %**	**Metabolic Rate, met**	**Clothing insulation, clo**
20.1	20.8	0	69	1	0.5
20.4	20.8	0	70	1.2	0.5
20.8	20.9	0	70	1.6	0.5
21.1	20.9	0	71	1	0.5
21.4	21	0	71	1.2	0.5
21.7	21.2	0	72	1.6	0.5
21.9	21.3	0	72	1	0.5
22.2	21.4	0	72	1.2	0.5
22.3	21.6	0	72	1.6	0.5
22.4	21.7	0	73	1	0.5
22.6	21.8	0	73	1.2	0.5
22.8	22	0	74	1.6	0.5
22.9	22.1	0	75	1	0.5
23.1	22.2	0	75	1.2	0.5
23.2	22.3	0	74	1.6	0.5
23.3	22.5	0	74	1	0.5
23.4	22.6	0	73	1.2	0.5
23.3	22.2	0	75	1.6	0.5

Temperature setting, 23 ^{o}C

		New Effective Temperature , ET*	SET	DISC	TSENS	PMV	PPD	HEAT STRESS INDEX, HSI	Skin Temperature , Tsk	Core Temperature , Tcr	Heart Rate, HR
	1	23.84	21.82	0	-0.06	-1.67	60.37	0.23	33.34	36.81	56
A	1.2	23.9	23.27	-0.01	-0.01	-0.66	14.08	13.88	33.58	36.83	56
	1.6	24.04	24.48	0	0	0.28	6.62	29.84	33.77	36.87	58
	1	23.84	21.82	0	-0.06	-1.67	60.37	0.42	33.3	36.82	88
B	1.2	23.91	23.27	-0.01	-0.01	-0.66	14.08	13.82	33.59	36.83	93
	1.6	24.04	24.49	0	0	0.28	6.62	29.51	33.81	36.87	94
	1	23.84	21.82	0	-0.06	-1.67	60.37	0.49	33.29	36.82	87
C	1.2	23.91	23.27	-0.01	-0.01	-0.66	14.08	13.79	33.6	36.83	119
	1.6	24.04	24.49	0.01	0.01	0.28	6.62	29.4	33.82	36.87	125
	1	23.84	21.82	0	-0.06	-1.67	60.37	0.31	33.32	36.82	85
D	1.2	23.91	23.27	-0.01	-0.01	-0.66	14.08	13.85	33.59	36.83	87
	1.6	24.04	24.48	0	0	0.28	6.62	29.7	33.79	36.87	92
	1	23.84	21.82	0	-0.06	-1.67	60.37	0.46	33.3	36.82	72
E	1.2	23.91	23.27	-0.01	-0.01	-0.66	14.08	13.8	33.59	36.83	77
	1.6	24.04	24.49	0	0	0.28	6.62	29.44	33.82	36.87	102
	1	23.84	21.82	0	-0.06	-1.67	60.37	0.31	33.32	36.82	92
F	1.2	23.91	23.27	-0.01	-0.01	-0.66	14.08	13.85	33.59	36.83	115
	1.6	24.04	24.48	0	0	0.28	6.62	29.7	33.79	36.87	119
	1	23.84	21.82	0	-0.06	-1.67	60.37	0.29	33.33	36.81	71
G	1.2	23.91	23.27	-0.01	-0.01	-0.66	14.08	13.86	33.59	36.83	87
	1.6	24.04	24.48	0	0	0.28	6.62	29.73	33.78	36.87	125
	1	23.84	21.82	0	-0.06	-1.67	60.37	0.52	33.29	36.82	84

H	1.2	23.91	23.27	-0.01	-0.01	-0.66	14.08	13.78	33.6	36.83	87
	1.6	24.05	24.49	0.01	0.01	0.28	6.62	29.36	33.83	36.87	87
	1	23.84	21.82	0	-0.06	-1.67	60.37	0.48	33.29	36.82	80
I	1.2	23.91	23.27	-0.01	-0.01	-0.66	14.08	13.79	33.6	36.83	85
	1.6	24.04	24.49	0	0	0.28	6.62	29.42	33.82	36.87	85
	1	23.84	21.82	0	-0.06	-1.67	60.37	0.34	33.32	36.82	95
J	1.2	23.91	23.27	-0.01	-0.01	-0.66	14.08	13.84	33.59	36.83	95
	1.6	24.04	24.49	0	0	0.28	6.62	29.64	33.79	36.87	100

Air Temperature	Mean Radiant Temperature	Air Velocity, m/s	RH %	Metabolic Rate, met	Clothing insulation, clo
24.3	27.1	0.1	62	1	0.5
24.3	26.7	0.1	62	1.2	0.5
24.5	26.4	0.1	61	1.6	0.5
24.8	26.2	0.1	61	1	0.5
24.9	26.1	0.1	61	1.2	0.5
25.1	26	0.1	62	1.6	0.5
25.4	26	0.1	62	1	0.5
25.6	26	0.1	62	1.2	0.5
25.7	26	0.1	62	1.6	0.5
25.8	26.1	0.1	62	1	0.5
25.2	26.1	0.4	65	1.2	0.5
24.2	26	0.4	63	1.6	0.5
24.1	25.8	0.1	63	1	0.5
24.1	25.6	0	63	1.2	0.5
24.3	25.4	0	63	1.6	0.5
24.4	25.4	0	63	1	0.5
24.6	25.3	0	64	1.2	0.5

24.8	25.3	0	64	1.6	0.5

Temperature setting, 26 ^{o}C

		New Effective Temperature, ET*	SET	DISC	TSENS	PMV	PPD	HEAT STRESS INDEX, HSI	Skin Temperature, Tsk	Core Temperature, Tcr	Heart Rate, HR
	1	27.01	25.5	0	0	-0.35	7.49	17.69	33.83	36.82	67
A	1.2	27.21	26.67	0.36	0.25	0.35	7.51	32.11	34.02	36.84	79
	1.6	27.31	27.57	0.4	0.27	0.98	25.47	46.99	34.25	36.88	85
	1	27.01	25.5	0	0	-0.35	7.49	17.49	33.86	36.82	91
B	1.2	27.23	26.68	0.43	0.3	0.35	7.51	31.75	34.06	36.84	94
	1.6	27.33	27.58	0.49	0.33	0.98	25.47	46.31	34.31	36.89	100
	1	27.02	25.5	0	0	-0.35	7.49	17.41	33.87	36.82	87
C	1.2	27.23	26.68	0.45	0.32	0.35	7.51	31.62	34.07	36.84	114
	1.6	27.34	27.58	0.53	0.35	0.98	25.47	46.06	34.34	36.89	116
	1	27.01	25.5	0	0	-0.35	7.49	17.61	33.84	36.82	80
D	1.2	27.22	26.67	0.39	0.27	0.35	7.51	31.96	34.03	36.84	86
	1.6	27.32	27.57	0.44	0.3	0.98	25.47	46.71	34.27	36.89	100
	1	27.02	25.5	0	0	-0.35	7.49	17.43	33.86	36.82	82
E	1.2	27.23	26.68	0.44	0.31	0.35	7.51	31.66	34.07	36.84	80
	1.6	27.34	27.58	0.51	0.35	0.98	25.47	46.15	34.33	36.89	90
	1	27.01	25.5	0	0	-0.35	7.49	17.6	33.84	36.82	118
F	1.2	27.22	26.67	0.39	0.27	0.35	7.51	31.95	34.04	36.84	106
	1.6	27.32	27.57	0.44	0.3	0.98	25.47	46.69	34.28	36.89	107
	1	27.01	25.5	0	0	-0.35	7.49	17.63	33.84	36.82	71
G	1.2	27.21	26.67	0.38	0.26	0.35	7.51	31.99	34.03	36.84	87
	1.6	27.32	27.57	0.43	0.29	0.98	25.47	46.77	34.27	36.89	114
	1	27.02	25.5	0	0	-0.35	7.49	17.37	33.87	36.82	91
H	1.2	27.24	26.68	0.46	0.32	0.35	7.51	31.56	34.08	36.84	101

	1.6	27.34	27.59	0.54	0.36	0.98	25.47	46.96	34.35	36.89	100
I	1	27.02	25.5	0	0	-0.35	7.49	17.42	33.87	36.82	90
	1.2	27.23	26.68	0.45	0.31	0.35	7.51	31.63	34.07	36.84	90
	1.6	27.34	27.58	0.52	0.35	0.98	25.47	46.1	34.34	36.89	100
J	1	27.01	25.5	0	0	-0.35	7.49	17.57	33.85	36.82	107
	1.2	27.22	26.67	0.4	0.28	0.35	7.51	31.89	34.04	36.84	100
	1.6	27.32	27.57	0.45	0.31	0.98	25.47	46.58	34.29	36.89	111

Air Temperature	**Mean Radiant Temperature**	**Air Velocity, m/s**	**RH %**	**Metabolic Rate, met**	**Clothing insulation, clo**
27.5	29.5	0	65	1	0.5
27.5	29.2	0	64	1.2	0.5
27.6	29	0	64	1.6	0.5
27.8	28.8	0	64	1	0.5
27.9	28.7	0	64	1.2	0.5
28.1	28.7	0	64	1.6	0.5
28.2	28.7	0	64	1	0.5
28.4	28.7	0	64	1.2	0.5
28.5	28.7	0	64	1.6	0.5
28.5	28.7	0	64	1	0.5
28.6	28.7	0	64	1.2	0.5
28.7	28.8	0	64	1.6	0.5
28.9	28.8	0	65	1	0.5
28.4	28.8	0.2	65	1.2	0.5
27.4	28.7	0.1	66	1.6	0.5
27.2	28.5	0	64	1	0.5
27.2	28.3	0	64	1.2	0.5
27.2	28.2	0	64	1.6	0.5

Temperature setting, 29 ^{o}C

		New Effective Temperature, ET*	SET	DISC	TSENS	PMV	PPD	HEAT STRESS INDEX, HSI	Skin Temperature, Tsk	Core Temperature, Tcr	Heart Rate, HR
A	1	30.05	28.84	0.55	0.41	0.89	21.61	38.63	34.22	36.83	70
	1.2	30.39	29.96	1	0.58	1.28	39.27	55.43	34.39	36.85	70
	1.6	30.67	30.73	1.06	0.56	1.64	58.66	70.6	34.68	36.9	79
B	1	30.1	28.85	0.66	0.49	0.89	21.61	38	34.28	36.83	94
	1.2	30.44	29.99	1.13	0.66	1.28	39.27	55.54	34.46	36.85	97
	1.6	30.71	30.77	1.21	0.64	1.64	58.66	69.3	34.77	36.91	100
C	1	30.12	28.85	0.7	0.52	0.89	21.61	37.77	34.3	36.83	66
	1.2	30.46	30	1.17	0.69	1.28	39.27	54.22	34.48	36.86	66
	1.6	30.73	30.79	1.27	0.67	1.64	58.66	68.83	34.8	36.91	103
D	1	30.07	28.84	0.6	0.44	0.89	21.61	38.37	34.24	36.83	85
	1.2	30.41	29.97	1.05	0.61	1.28	39.27	55.07	34.42	36.85	85
	1.6	30.69	30.75	1.12	0.59	1.64	58.66	70.06	34.71	36.91	102
E	1	30.11	28.85	0.69	0.51	0.89	21.61	37.85	34.29	36.83	78
	1.2	30.45	30	1.15	0.68	1.28	39.27	54.33	34.47	36.85	80
	1.6	30.72	30.78	1.25	0.66	1.64	58.66	69	34.79	36.91	87
F	1	30.07	28.84	0.6	0.45	0.89	21.61	38.35	34.25	36.83	83
	1.2	30.42	29.97	1.06	0.62	1.28	39.27	55.05	34.42	36.85	99
	1.6	30.69	30.75	1.12	0.59	1.64	58.66	70.02	34.72	36.91	123
G	1	30.07	28.84	0.59	0.44	0.89	21.61	38.43	34.24	36.83	73
	1.2	30.41	29.97	1.04	0.61	1.28	39.27	55.15	34.41	36.85	70
	1.6	30.68	30.75	1.11	0.58	1.64	58.66	70.17	34.71	36.9	105
H	1	30.13	28.85	0.72	0.53	0.89	21.61	37.67	34.3	36.83	90
	1.2	30.47	30.01	1.19	0.7	1.28	39.27	54.08	34.49	36.86	94

	1.6	30.73	30.79	1.29	0.68	1.64	58.66	68.64	34.81	36.91	115
I	1	30.12	28.85	0.7	0.51	0.89	21.61	37.8	34.29	36.83	99
	1.2	30.46	30	1.16	0.68	1.28	39.27	54.26	34.48	36.86	101
	1.6	30.72	30.78	1.26	0.67	1.64	58.66	68.9	34.8	36.91	111
J	1	30.08	28.84	0.62	0.46	0.89	21.61	38.25	34.26	36.83	109
	1.2	30.42	29.98	1.08	0.63	1.28	39.27	54.9	34.43	36.85	115
	1.6	30.69	30.76	1.15	0.61	1.64	58.66	69.81	34.73	36.91	124

Air Temperature	**Mean Radiant Temperature**	**Air Velocity, m/s**	**RH %**	**Metabolic Rate, met**	**Clothing insulation, clo**
29.8	29.6	0	68	1	0.5
29.8	29.7	0	68	1.2	0.5
29.8	29.7	0	68	1.6	0.5
29.8	29.7	0	68	1	0.5
29.9	29.7	0	68	1.2	0.5
29.9	29.7	0	68	1.6	0.5
30	29.7	0	68	1	0.5
30	29.8	0	68	1.2	0.5
30	29.8	0	68	1.6	0.5
30.1	29.8	0	68	1	0.5
30.1	29.9	0	68	1.2	0.5
30.2	29.9	0	68	1.6	0.5
30.1	29.9	0	69	1	0.5
30.2	29.9	0	69	1.2	0.5
30.2	29.9	0	69	1.6	0.5
30.2	30	0	69	1	0.5
30.2	30	0.1	69	1.2	0.5
30.2	30	0	69	1.6	0.5

APPENDIX L

LIST OF PUBLICATIONS

Book

1. Ahmad Rasdan Ismail, Norfadzilah Jusoh (Editor). (2011). *Pengenalan keselesaan terma: Kearah persekitaraan kerja yang ergonomik.* Universiti Malaysia Pahang (UMP): Kuantan. ISBN: 978-967-0120-18-8.

Journal

1. Bakar, R.A., Jusoh, N., Ismail, A.R. and Ali, T.Z.S. (2016). Effect on human metabolic rate of skin temperature in an office occupant. *MOTEC WOC*. Accepted. ISSN: 2261236X.

2. Tanti Ali, Norfadzilah Jusoh, Rosli Abu Bakar, Teoh Suh Jie and Kumaran Kadirgama. (2015). Thermal effect of thermal energy storage (TES) tank for solar energy application during charging cycle based on the grid sensitivity analysis. *Energy Procedia. 79*, 245-251. DOI: 10.1016/j.egypro.2015.11.472.

3. Ahmad Rasdan Ismail, Norfadzilah Jusoh, Rosli Abu Bakar, Nor Kamilah Makhtar, Suriatini Ismail. (2015). An analysis in the implication of the thermal energy distribution towards human comfort in an office space. *International Journal of Creative Future and Heritage (TENIAT). 3*(1), 15-30. ISSN 2289-4527.

4. Norfadzilah Jusoh, Rosli Abu Bakar, Ahmad Rasdan Ismail and Tanti Zanariah Shamshir Ali. (2015). Computational analysis of thermal building in a non-uniform thermal environment. *Energy Procedia. 68,* 438-445. DOI: 10.1016/j.egypro.2015.03.275.

5. Norfadzilah Jusoh, Rosli Abu Bakar, Ahmad Rasdan Ismail, Tanti Zanariah Shamshir Ali and Farrah Wahida Mustafar. (2015). The impact of thermal history on buildings occupants' thermal assessments in air-conditioned office buildings. *Journal of Advanced & Applied Sciences (JAAS). 3*(5), 169-168.

6. Ahmad Rasdan Ismail, Rosli Abu Bakar and Norfadzilah Jusoh. (2013). Experimental study of thermal effect on skin temperature: Discussion of methodology. *Advanced Engineering Forum. 10,* 71-76. DOI: 10.4028/www.scientific.net/AEF.10.71.

7. Rosli Abu Bakar, Ahmad Rasdan Ismail, Norfadzilah Jusoh and Abdul Mutalib Leman. (2012). Indoor thermal comfort studies: A case study at Higher Institution in East Cost of Malaysia. *The Journal of Occupational Safety and Health. 9*(3), 65-72. ISSN 1675-5456.

8. Ahmad Rasdan Ismail, Norfadzilah Jusoh, Mohd Nizam Ab. Rahman, Rozli Zulkifli and Kumaran Kardigama. (2011). Thermal comfort assessment at parcel and logistic industry: A field study in Malaysia. *The Journal of the Institution of Engineers Malaysia (IEM). 72*(3), 36-40. ISSN 0126-513X.

9. Ismail, A.R., Jusoh, N., Makhtar, N.K., Zainuddin, K.A., Ariffin, M.N. and Aris, M.J.N. (2011). Assessment of environmental factors ergonomics and thermal comfort: A study at discrete manual automotive assembly line. Malaysian Journal of Ergonomics. 1, 42-54. ISSN 2232-1101.

International Conference

10. Bakar, R.A., Jusoh, N., Ismail, A.R. and Ali, T.Z.S. (2016). Study of effect of human metabolic rate in skin temperature in office environment. *Proceeding of the 2nd International Conference on Automotive Innovation and Green Energy Vehicle.* Malaysia Automotive Institute (MAI) Cyberjaya, Selangor, Malaysia: 2-3 August.

11. Rosli Abu Bakar, Norfadzilah Jusoh, Ahmad Rasdan Ismail, Tanti Zanariah Shamshir Ali, and Musthafah Mohd Tahir. (2016). Experimental study on skin temperature of people in office activities at different air temperatures. *Proceeding of the Engineering Technology International Conference (ETIC).* Ho Chi Minh City, Vietnam: 4-5 August.

12. Rosli Abu Bakar, Gan Leong Ming, Chang Sik Lee, Zarina Amat Jafar and Norfadzilah Jusoh. (2015). Generation of alternative hydrogen fuel using renewable and non-renewable energy sources. *Proceedings of the 3rd International Conference on Sustainable Energy Engineering and Application (ICSEEA 2015)*. Bandung, Indonesia: 5-7 October.

13. Tanti Ali, Norfadzilah Jusoh, Rosli Abu Bakar, Teoh Suh Jie and Kumaran Kadirgama. (2015). Thermal effect of thermal energy storage (TES) tank for solar energy application during charging cycle based on the grid sensitivity analysis. *Proceeding of the 3rd International Conference on Alternative Energy in Developing Countries and Emerging Economies (AEDCEE 2015)*. Sheraton Grande Sukhumvit Hotel, Bangkok, Thailand: 27-30 May.

14. Ahmad Rasdan Ismail, Norfadzilah Jusoh, Rosli Abu Bakar, Nor Kamilah Makhtar and Suriatini Ismail. (2015). Implication of thermal energy distribution towards human comfort in an office space: A field analysis. *Proceeding of the 3rd International Conference on Energy Systems and Technologies (ICEST 2015)*. Cairo, Egypt: 16-19 February.

15. Norfadzilah Jusoh, Rosli Abu Bakar, Ahmad Rasdan Ismail and Tanti Zanariah Shamshir Ali. (2014). Computational analysis of thermal building in a non-uniform thermal environment. *Proceeding of the 2nd International Conference on Sustainable Energy Engineering and Application (ICSEEA 2014)*. Grand Hotel Preanger, Bandung, Indonesia: 14-15 October. ISBN: 978-602-17952-1-7.

16. Nor Kamilah Makhtar, Ahmad Rasdan Ismail, Rosnah Mohd Yusoff, Norfadzilah Jusoh. (2013). Assessment of thermal comfort in technical school under tropical climate: A survey finding. *Proceeding of the International Conference on Engineering Education (ICEE 2013)*. Madinah, Kingdom of Saudi Arabia: 25-27 December.

17. Ahmad Rasdan Ismail, Rosli Abu Bakar and Norfadzilah Jusoh. (2013). Experimental study of thermal effect on skin temperature: Discussion of methodology. *Proceeding of the 2nd International Conference on Ergonomics (ICE 2013)*. Berjaya Times Square Hotel, Kuala Lumpur, Malaysia: 2-4 September 2013.

18. Jusoh, N., Ismail, A.R., and Bakar, R.A. (2013). A study of indoor human thermal comfort under air conditioning system at low energy building. *Proceeding of the 2nd International Conference on Alternative Energy in Developing Countries and Emerging Economies (AEDCEE 2013)*. Pullman Bangkok King Power Hotel Bangkok, Thailand: 30-31 May, pp. 434-438.

19. Norfadzilah Jusoh, Rosli Abu Bakar and Ahmad Rasdan Ismail. (2012). Indoor thermal comfort studies under the control air conditioner: Field work in Universiti Malaysia Pahang climate. *Proceeding of the International Conference Postgraduate Education (ICPE-5)*. Universiti Teknologi Malaysia (UTM), Skudai, Malaysia: 17-19 December.

20. Ismail, A.R., Makhtar, N.K., Jusoh, N., Kardigama, K., Adib, M.A.H.M., Salaam, H.A., Anuar, Z., and Azmi, N.S.N. (2011). Thermal comfort assessment at technical school: Field measurement and survey approach. *Proceeding of the International Conference Mechanical Engineering Research (ICMER 2011)*. M.S Garden Hotel, Kuantan, Malaysia: 5-7 December.

National Conference

21. Norfadzilah Jusoh, Rosli Abu Bakar, Ahmad Rasdan Ismail, Tanti Zanariah Shamshir Ali and Farrah Wahida Mustafar. (2015). The impact of thermal history on building occupants’ thermal assessment in air conditioned office buildings. *Proceeding of the 2nd National Conference for Postgraduate Research (NCON-PGR 2015)*. Universiti Malaysia Pahang, Gambang, Kuantan: 24-25 January.

22. Norfadzilah Jusoh, Rosli Abu Bakar and Ahmad Rasdan Ismail. (2012). Methodology for the Design of Environmental Control for Occupant Comfort. *Proceeding of the National Conference Postgraduate Research (NCON-PGR 2012)*. Universiti Malaysia Pahang, Kuantan: 7-9 September.

23. Rosli Abu Bakar, Ahmad Rasdan Ismail, Norfadzilah Jusoh, Abdul Mutalib Leman. (2012). Indoor thermal comfort studies: A case study at Higher Institution in East Cost of Malaysia. *Scientific Conference on Occupational Safety and Health (SCI-COSH 2012).* National Institute of Occupational Safety and Health, Bangi, Selangor: 12-13 Dec 2012.