THERMAL COMFORT AND INDOOR AIR CONDITIONS IN LABORATORIES AT UNIVERSITI SAINS MALAYSIA

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THERMAL COMFORT AND INDOOR AIR CONDITIONS IN LABORATORIES AT UNIVERSITI SAINS MALAYSIA

by

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DECLARATION

I declare that the contents presented in this thesis are my own original research work which was done in Universiti Sains Malaysia. Whenever contributions of others are involved, every efforts is made to indicate this clearly, with due reference to literature, and acknowledgement of collaborative research and discussion. This thesis has not been submitted for any other degree.

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In my capacity as a main supervisor of the candidate’s thesis, I certify that the above statements are true to the best of my knowledge.

Signature:

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Date: 15/9/2016

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LIST OF ABBREVIATION

ACH	Air Changes per Hour
ACMV	Air-Conditioning and Mechanical Ventilation Systems
ACS	Adaptive Comfort Standard
AHU	Air Handling Unit
APEX	Accelerated Programme for Excellence
ASHRAE	American Society of Heating, Air conditioning &
BRI	Building-Related Illness
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamic
CFM	Cubic Feet per Minute
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DI	Discomfort Index
DOSH	Department of Occupational Safety and Health
ET	Effective Temperature
HVAC	Heating, Ventilating, and Air-Conditioning
IAQ	Indoor Air Quality
ICT	Information and Communication Technology
IEQ	Indoor Environment Quality
ISO	International Standard Organization
LPG	Liquefied Petroleum Gas
MMS	Malaysian Meteorological Service
MRT	Mean Radiant Temperature
MTSV	Mean Thermal Sensation Votes
NIOSH	National Institute for Occupational Safety and Health
NPAAQS	National Primary Ambient Air Quality Standards

O & M	Operation and Maintenance
OA	Outdoor Air
PET	Physiological Equivalent Temperature
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PPM	Parts per million
RH	Relative Humidity
RPM	Respirable Particulate Matter
SBS	Sick Building Syndrome
SET	Standard Effective Temperature
SIAQG	Singapore Indoor Air Quality Guidelines
SPM	Suspended Particle Matter
SPM	Suspended Particle Matter
SPSS	Statistical Package for Social Science
TCM	Thermal Comfort Measurement
THI	Temperature Humidity Index
TSV	Thermal Sensation Votes
TVOC	Total Volatile Organic Compounds
U.S. EPA	United State Environmental Protection Agency
UFP	Ultrafine Particle Counter
USM	Universiti Sains Malaysia
UTCI	Universal Thermal Climate Index
VOCs	Volatile Organic Compounds
VVOC	Very Volatile Organic Compound
WBGT	Wet-Bulb Globe Temperature
WHO	World Health Organization

LIST OF SYMBOLS

%	Percent
G	Gram
hp	Horsepower
m	Metre
m^2	Square-metre
m^3	Cubic-metre
m/s	Metre per second
mg	Mili-gram
km	Kilo-metre
ppm	Parts per million
sec	Second
°C	Degree Celsius
°F	Degree Fahrenheit

LIST OF APPENDICES

KESELESAAN TERMA DAN KEADAAN UDARA DALAMAN DI DALAM MAKMAL-MAKMAL DI UNIVERSITI SAINS MALAYSIA

ABSTRAK

Makmal merupakan fasiliti yang amat penting di universiti bagi pelajar bidang sains. Pelajar-pelajar layak mendapatkan persekitaran dalaman yang sihat dan kondusif untuk aktiviti pembelajaran mereka. Oleh itu kajian ini dijalankan untuk menentukan tahap keselesaan terma dan kualiti udara dalaman bagi makmal pelajar ijazah pertama yang berhawa dingin di Universiti Sains Malaysia. Data yang dibentangkan dalam kajian ini adalah berdasarkan kepada pengukuran lapangan dan penilaian persepsi. Dalam Fasa 1, pengukuran lapangan merangkumi pengukuran suhu udara, halaju udara, kelembapan relatif, kepekatan CO_2 dan CO dalam lapan makmal. Keputusan menunjukkan bahawa Makmal Dispensing tidak mematuhi had kepekatan CO_2 dan CO yang ditetapkan oleh garis panduan ICOP JKKP (2010). Pengiraan keselesaan terma mengikut ASHRAE 55 (2010) menunjukkan bahawa makmal-makmal Dispensing dan Industrial 148 tidak mematuhi ASHRAE 55. Jawapan persepsi kepada suhu (keselesaan terma) menggunakan ASHRAE skala sensasi terma menunjukkan bahawa kebanyakan makmal-makmal tidak berada dalam keadaan terma yang boleh diterima. Dalam Fasa 2, kedua-dua ukuran lapangan dan persepsi telah dilakukan dalam Makmal Dispensing. Responden dari tiga kumpulan kelas praktikal, A, B dan C terlibat dalam penyiasatan ini. Ramalan pilihan min (PMV) dikira berdasarkan teori Fanger. Selain itu undi sensasi haba (TSV) dikira berdasarkan kajian tersebut. Dalam kajian ini, hubungan yang kuat di antara data lapangan dan persepsi telah diperolehi dengan $R^2= 0.99$. Titik neutral telah beralih kepada +0.2 daripada 0 berdasarkan ASHRAE skala sensasi terma. Adalah didapati bahawa suhu berkesan neutral berdasarkan TSV (pengukuran persepsi) adalah lebih kurang 0.80°C lebih tinggi daripada berdasarkan PMV (pengukuran lapangan). Adalah diperhatikan bahawa kelas praktikal yang melibatkan penggunaan penunu Bunsen meningkatkan kepekatan CO_2, CO dan formaldehid. Carta psikometrik menunjukkan bahawa keselesaan terma dalam Makmal Dispensing untuk kumpulan praktikal A, B dan C mematuhi ASHRAE 55. Secara keseluruhannya keselesaan terma dan kualiti udara dalaman adalah berada dalam

julat boleh diterima berdasarkan ASHRAE (2010) dan ICOP JKKP (2010), namun begitu ianya dipengaruhi oleh jenis ujikaji yang dijalankan di dalam makmal tersebut.

THERMAL COMFORT AND INDOOR AIR CONDITIONS IN LABORATORIES AT UNIVERSITI SAINS MALAYSIA

ABSTRACT

In the university, laboratory is one of the most important facilities for science based students. The students are deserved to have a healthy indoor environment that is conducive for their learning activities. Therefore a study has been conducted to determine the level of thermal comfort and indoor air quality of air-conditioned undergraduate laboratories in Universiti Sains Malaysia (USM). Data presented in this study are based on field measurement and perception assessment. In Phase 1, field measurement consists of air temperature, air velocity, relative humidity, CO_2 and CO concentrations, were measured in eight laboratories. Results indicate that Dispensing Laboratory did not comply with the CO_2 and CO concentration limit set by ICOP DOSH (2010) guideline. Thermal comfort calculations according to ASHRAE 55 (2010) indicate that both Dispensing laboratory and Industrial 148 laboratories do not comply with ASHRAE 55. Perception responses to temperature (thermal comfort) using 7-point thermal sensation perception scale indicate that most of the laboratories are not in thermally acceptable condition. In Phase 2, both field and perception measurements were performed in Dispensing laboratory. Respondents from three practical class groups, A, B and C involved in the survey. Predicted mean vote (PMV) was calculated based on Fanger theory. In addition the thermal sensation vote (TSV) was calculated according to the survey. In this study, a strong relationship between field and perception data was obtained with $R^2 = 0.99$. The neutrality point has shifted to +0.2 instead of 0 on 7-point ASHRAE scale. It is found that the neutral effective temperature based on TSV (perception measurement) is approximately 0.8°C higher than that of based on PMV (field measurement). It is observed that practical class which involves the use of Bunsen burner increased the CO_2, CO and formaldehyde concentrations. Psychrometric charts indicates that thermal condition in Dispensing laboratory for practical groups A, B and C comply with ASHRAE 55. In conclusion, thermal comfort and indoor air condition in laboratories at USM is within acceptable level set by ASHRAE 55 (2010) and ICOP

DOSH (2010) respectively, however it is influenced by types of experiment conducted in the laboratories.

CHAPTER 1

INTRODUCTION

1.1 Overview

Indoor environment has considerably caught the attention of scientists and the general public in recent years as it is a fundamental environmental factor which capable of impacting health. Air quality of indoor environments is one of the main factors affecting health, well-being and productivity of people (Samuel and Abayneh, 2014). According to Dacarro et al. (2003), indoor air quality (IAQ) is one of the most significant factors affecting the health of people who inhale $10m^3$ of the air every day, and spend between 80-95% of their lives indoors.

IAQ can be defined as the air quality inside a building that will lead to the comfort and health of the occupants. Air pollutants produced by outdoor sources affect the environment and health of the occupants. According to Moonie et al. (2008) and Haverin-Shaughnessyet et al. (2012), air quality in classrooms and laboratories is of special concern for students in university, particularly those sensitive to poor air quality. Indoor air pollution in classrooms may increase the chance of short- and long-term health problems for students and staff. It might also reduce staffs' productivity and student's learning possibilities. In most of the laboratories and classrooms in universities in Malaysia, air conditioning during office hours is essential to provide thermal comfort in the building space (Ismail et al., 2009).

Air-conditioning and mechanical ventilation systems (ACMV) are installed in a large number of buildings in the tropical humid climate due to the elevated temperature and high relative air humidity. The air-conditioning and mechanical ventilation systems are used to maintain a thermally comfortable indoor environment by introducing and distribute fresh outside air in suitable quantities to maintain an adequate supply of fresh air. Adequate quantity of ventilation air is important to dilute and remove air contaminants present in the space. Inadequate ventilation was reported to be responsible for more than half of IAQ problems (Bas, 2004). According to Rackes and Waring (2014), ventilation plays a crucial role in promoting comfort and health to the building occupants. Good ventilation systems control temperature and humidity, provide thermal comfort, distribute adequate amounts of air, and remove pollutants.

Thermal comfort is one of the primary elements determining the quality of the indoor environment, and it is essential to the health of those who must routinely stay indoors over extended periods of time (Gail et al., 2015). Prolonged exposure to polluted indoor environments may cause various symptoms such as headaches, dizziness, nausea, fatigue, and dry skin. In 1982, a group of experts within the World Health Organization (WHO) described this multitude of symptoms and perceptions as sick building syndrome (SBS). A building can be diagnosed as sick if 20% or more of its occupants exhibit one or more of the above mentioned symptoms for two weeks and such symptoms disappear when leaving the building.

1.2 Background

Universiti Sains Malaysia (USM) was established as the second university in the country in 1969. USM is located approximately 9.7 km from Georgetown. USM has eight campuses, amongst are the main campus which is located in the island of Penang, the Engineering Campus in Nibong Tebal (approximately 50km from the main campus) and the Health Campus in Kubang Kerian, Kelantan (approximately 300km from the main campus). USM offers courses ranging from Natural Sciences, Applied Sciences, Engineering, Medical and Health Sciences, Pharmaceutical Sciences to Building Science and Technology, Social Sciences, Humanities, and Education.

In the year 2000, USM introduced its Kampus Sejahtera (Healthy Campus) program, which emerged from the realization that learning, quality of life, and health go hand in hand, and that the improvement thereof involves spiritual, social, physical, mental, intellectual, emotional, and environmental aspects (Lee et al., 2007). The indigenous word “Sejahtera” cuts across several dimensions of the spiritual, social, physical, mental, intellectual, emotional and environmental aspects. It acts as a societal glue that bonds things together in a harmonious and optimal balance with one another. The Healthy Campus concept emerged from the realisation that the main factors for enhancing learning are the quality of life and the health of students in a wider context.

According to Badarulzaman et al. (2006), the Healthy Campus convention aimed to create “a healthy campus environment” at USM in all aspects, including comfort, health, and friendliness, to promote the spirit of learning and working in the University. A year later, USM introduced its “University in a Garden” concept, which highlighted the close affinity between the University’s role as an institution of higher learning and its responsibility as part of the global ecological setting. In 2008, USM was selected to implement the Accelerated Programme for Excellence (APEX). A sustainable world, humanity and the future of the humankind are among the issues focused on by USM under this program. In 2013, USM came out with its USM Policy on Sustainability which one of the items stated in the policy involves complying with Indoor Air Quality (IAQ) standards.

There are few investigations on IAQ in school and university classrooms. Recently Ioan and Cristian (2015) reported on experimental and numerical research to assess indoor environment quality and schoolwork performance in university classrooms. They evaluated thermal comfort based on the predicted mean vote (PMV) and predicted percent dissatisfied (PPD) indices using subjective and experimental measurements in two air conditioned classrooms at a university. They found that the indoor environmental conditions were satisfactory, and all situations fit within the comfort limits. Ismail et al. (2010) studied on the environmental comfort in closed air conditioned information and communication technology (ICT) laboratory at Ungku Omar Polytechnic. The study revealed that the level of CO_2 in ICT laboratory exceeded the hazardous level thus can produce the negative impact to the productivity of the users. Valavanidis and Vatista (2006) investigated on the indoor air quality in the undergraduate and postgraduate laboratories in the Chemistry Department of the University of Athens. Their finding shows that levels of air pollutants (CO_2 and CO) were in acceptable range. As of this writing, studies that focused on the effect of IAQ and thermal comfort in university laboratories have been very limited.

1.3 Problem Statement

Universities are designed for higher learning where students spend most of their time in classroom, libraries, laboratories, hostels and other indoor environments. In most of the Sciences and Engineering courses, classes are conducted through classroom lectures, tutorials, practical trainings, fieldwork, seminars, and workshops. Lectures are the main approach of delivering the basic information to help the students to understand a particular subject area. In order to complement the theory that has been learnt through lectures, the students are required to undertake courses on laboratory works. Laboratory classes allow students to engage in practicum experiences and authentic discovery, apply theory to practice, and explore different methods of scientific inquiry while addressing current debates in the field and generating new knowledge.

The staff and students deserve a healthy indoor environment that is conducive for teaching and learning activities. Research on indoor thermal comfort in student accommodation quarters in USM has been carried out by Wafi and Ismail (2010). They have conducted a study on the relationship between the indoor thermal comfort and the external equatorial climate. They found that any method or technique to generate a more conducive living environment for students must take into account several constraints such design and planning authority, the use of the appropriate building material and the use of natural mechanisms of heat control and dissipation to induce thermal comfort as well as reduce the consumption of artificial energy resources. Inspired by lack of studies in the laboratories concerning the thermal comfort and effects of IAQ on student health, the present study was planned and carried out. This study will support the "Healthy Campus" program and "University in a Garden" concept of improving the quality of life and the health of students, as well as the University's policy on sustainability as mentioned beforehand. Actual thermal comfort and IAQ status especially in the laboratories is important to be determined since most of the science and engineering based students in the university spend their time. Good thermal comfort and IAQ in university provide a conducive environment for teaching and learning activities. Generally majority of IAQ problems are due to the inadequate ventilation provided to the occupants of the building.

Failure to prevent indoor air problems or failure to act promptly can have consequences such as impact on the learning environment, increase the chances for long- and short-term health problems for students and staffs and reduce thermal comfort and IAQ contributes to a favourable learning and working environment for students and staffs in institutional buildings to achieve the primary mission.

1.4 Research Question

The research questions that can be derived from the problem statement are:

1. What are the indoor thermal comfort level during the undergraduate laboratory classes
2. What are the occupant perceptions of their laboratory thermal environments
3. What are the conditions of air quality parameters that exist in the Dispensing laboratory with and without occupants
4. What is the influence of practical class group toward protocol of subjective perception on thermal environment, work environment, past and present health symptoms among students of Dispensing laboratory

1.5 Research Objectives

The research was aimed at finding the level of thermal comfort and indoor air conditions of an undergraduate laboratory classes in the Main Campus, Universiti Sains Malaysia. The selected laboratories were installed with the split type air-condition system. In order to achieve this aim, the objectives have been divided into Phase 1 and Phase 2. Following are the objectives;

Phase 1:

1. To determine the indoor thermal comfort level in 8 laboratories in 4 Science based Schools
2. To establish occupants' perceptions of thermal environment in 8 laboratories in 4 Science based Schools
3. To investigate the conditions of air quality parameters in 8 laboratories in 4 Science based Schools (i.e. air temperature, air velocity, relative humidity, carbon dioxide and carbon monoxide)

Phase 2:

4. To determine the indoor thermal comfort level in Dispensing laboratory with and without occupants

5. To establish students' perceptions of thermal environment in Dispensing laboratory
6. To investigate the conditions of air quality parameters in Dispensing laboratory (i.e. air temperature, air velocity, relative humidity, carbon dioxide, carbon monoxide and formaldehyde)
7. To establish students' perception of indoor air quality in Dispensing laboratory

1.6 Scope

Scope of the study covers the evaluation of thermal comfort and indoor conditions in selected laboratories in four sciences based School in the Main Campus. Field measurement and perception assessment were considered in the study. The field measurements by physical parameters were confined to air temperature, air mean radiant temperature, air relative humidity, air velocity, carbon dioxide, carbon monoxide, and formaldehyde. Thermal comfort was examined, with the exploration of various topics including factors which affect thermal comfort, the condition for thermal comfort, the predicted mean vote (PMV) index and the predicted percentage dissatisfied (PPD) index. For the perception measurement, questionnaire surveys are based on protocol of subjective perception on thermal environment and Industry Code of Practice for Indoor Air Quality Malaysia (2010).

1.7 Significance

Nowadays, there is an urgent necessity to study the thermal comfort and indoor air quality in the laboratory in order to provide a comfortable conducive environment for teaching and learning activities. Realizing most of the laboratories in USM are installed with the air-conditioning system, it is necessary to investigate the thermal comfort and existence of health symptoms in the laboratories. Research on indoor air quality in USM laboratories is in accordance to USM policy which is sustainability. The output of this research will contribute to the health of the staff and students for short and long time durations. Data form this research will lead to the establishment of foundation data for the laboratories thermal comfort and health symptoms study in Universiti Sains Malaysia. The findings may help the USM's management to ensure that the health of their workers and students are not affected by the indoor air problems and experienced any health symptoms repeatedly in the future through the improvement of air quality levels.

1.8 Research Limitation

There are two limitations in the study. Firstly, the study covers only two occasions field measurement and perception assessment were done simultaneously due to limited co-operation of the respondent and the supervisor. This is due to their tight activities in the laboratory. Secondly, the clo unit value was set at 1.2 clo based on the insulation of clothing in clo units as reported by Andris and Steven (1997).

1.9 Research Framework

Research framework of the present study is divided into Phase 1 and Phase 2. The flowchart of the research framework is shown in Figure 1.1 and Figure 1.2, respectively. According to the literature review, thermal comfort and indoor air quality are important in promoting the quality of life. People spent more time indoors than outdoors. Good thermal comfort and indoor air quality are generally associated with workplace productivity, enhances occupant comfort and health. In Phase 1, field measurement through measurement of air parameters such as air temperature, air relative humidity, air velocity, carbon dioxide and carbon monoxide are considered. Perception measurement based on Protocol of subjective perception on thermal environment is carried out. The assessment framework is based on two levels: physical and psychological. Objective aspects (i.e., physical characteristic) is measured to provide ‘‘climatic knowledge,’’ and subjective aspects (i.e., psychological characteristic) required comprehensive field interviews and observations to provide ‘‘human factors’’.

Based on the data analysis from Phase 1, Dispensing Laboratory does not meet the with the comfort criteria, thus detail investigation using field and perception measurement are carried out based on the flowchart of the research framework shown in Figure 1.2. Correlation between filed and perception measurements for Phase 2 is conducted.

Phase 1

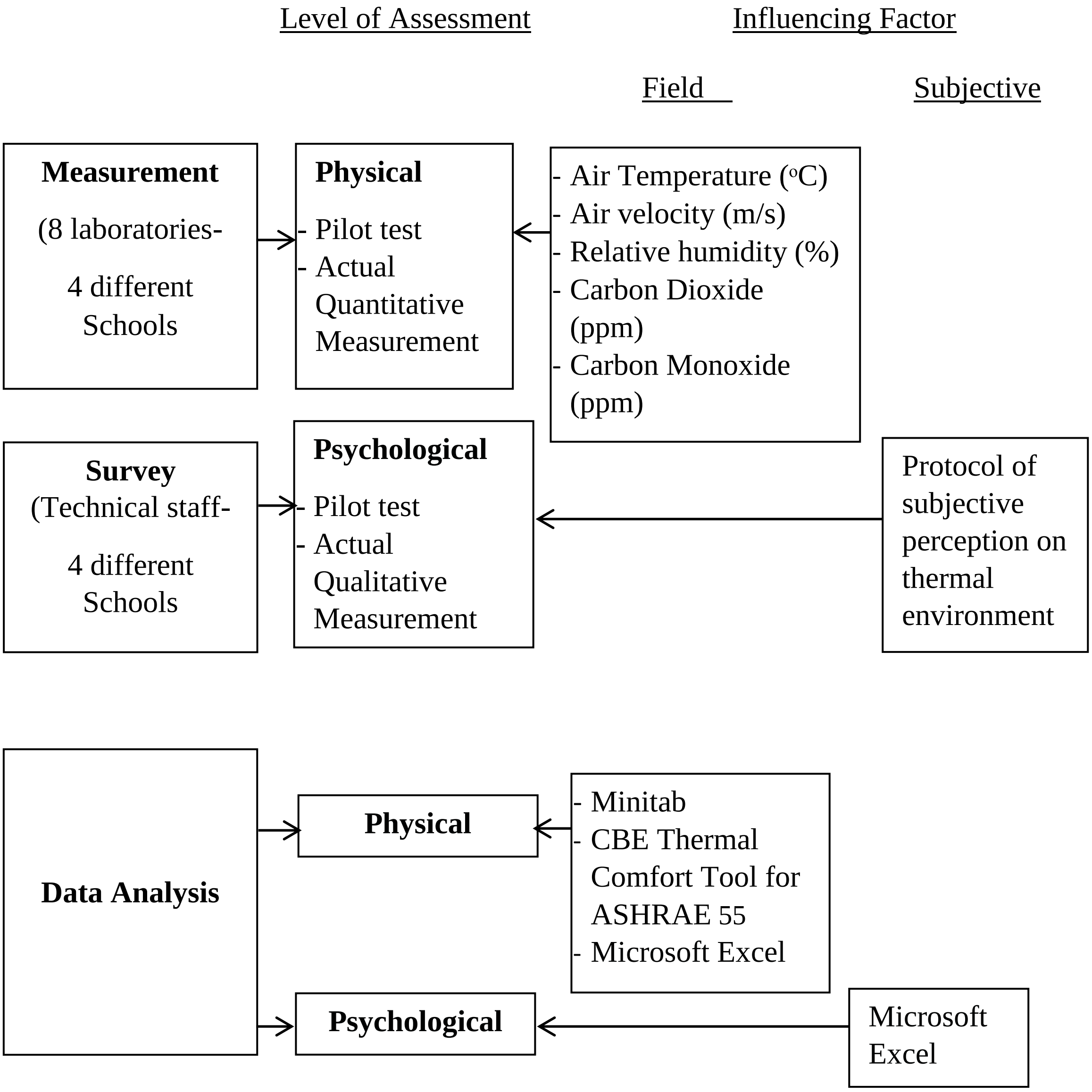

Figure 1.1: Flowchart of research framework for Phase 1

Phase 2

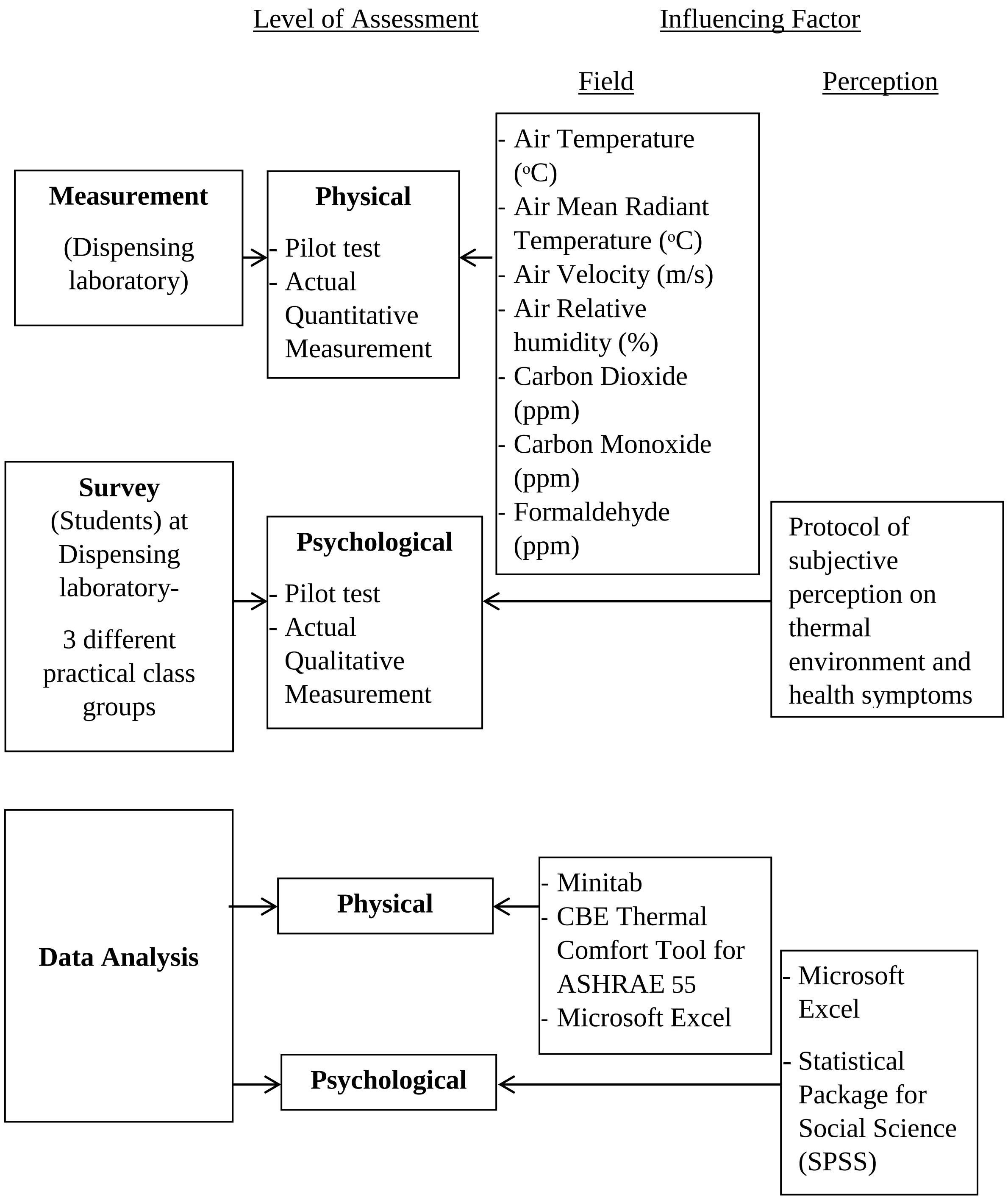

Figure 1.2: Flowchart of research framework for Phase 2

1.10 Thesis Organisation

Chapter 1 covers the general introduction, background of the study, problem statement, research questions, research objectives, scope and limitation of the research, and thesis organization.

Chapter 2 presents the comprehensive literature review, fundamental concepts of building thermal comfort, relationship between thermal satisfaction and the occupants, interaction of the human body with its surroundings, human factors, environmental factors affecting thermal comfort, thermal comfort models, thermal comfort zone, and review of previous thermal comfort studies, indoor air quality and sick building syndrome. Previous works on indoor air quality and thermal comfort in Malaysia are reported and summarized in this chapter.

Chapter 3 outlines the research methodology used in the present research work. Methods of field study using filed measurement and perception assessment are discussed in this chapter.

Chapter 4 presents the data analysis and discussion on the research findings by elaborating the results obtained.

Finally, Chapter 5 summarized the conclusion of the project. Recommendations for future works are also included in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

ASHRAE (2010) defines thermal comfort as a condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation. This condition can also be assessed by means of objective investigations looking at the human body as a thermodynamic system exchanging heat with the surrounding physical environment (Fanger & Toftum, 2002; Nicol & Humphreys, 1973). In physiological terms, thermal comfort is what we experience when the body functions well, with a core temperature of around 37°C and skin temperature of 32-33°C.

Thermal comfort and well-being of the occupants are critical in assessing the quality of a building design. In fact, indoor thermal condition has serious implications on the health of the occupants (Nazanin, 2011). Recent years have seen issues related to thermal comfort gaining more momentum in tropical countries. It was reported that people in developed countries spend more than 90% of their time indoors (Tunga & Erik, 2009). Besides the thermal conditions of an environment, comfort and health also depend on the composition of the air itself. For example, people feel uncomfortable when the air is odorous or stale. Poor air quality and thermal conditions can lead to occupants’ dissatisfaction and discomfort, a reduction in their performance, and a greater incidence of absenteeism. Poor conditions can also affect occupants' health, creating physical symptoms such as headaches, nose, throat, eye and skin irritation, nausea and drowsiness.

World Bank (2014) reported that 85% of the population will be located in developing countries in 2030. Hence, it is predicted that the increased amount of time people spend inside buildings will be significant. This growth is leading to an increase in the urban density of buildings, especially in the city center, thereby influencing the characteristics of indoor environments that increasingly rely on artificial systems to operate satisfactorily. In developed countries, the building sector (residential, commercial and public) uses between 20% and 40% of final energy consumption through air-conditioning systems and artificial lighting (Pérez-Lombard et al., 2008). The high energy consumption of air-conditioning is largely due to the need of thermal comfort inside the building.

Indoor air quality and thermal comfort are two important aspects of indoor environmental quality that receive considerable attention by many disciplines such as engineering, architecture, physiology, medicine, geography and climatology. International and regional standards prescribe conditions intended to foster environments that are acceptable to occupants. Report by deDear (1998) and Fisk (2000) indicated that although there is considerable field data on air quality and thermal comfort, there is far less data that assesses occupant satisfaction across a large number of buildings using a systematic method, and using occupant opinions as a measure of building performance is still far from standard practice.

2.2 Thermal Comfort Parameters

Thermal comfort is difficult to measure because it is highly subjective. It has been known for a long time that the thermal comfort of a human being is not exclusively a function of air temperature, but also of five other less obvious parameters; mean radiant temperature, relative air velocity, relative humidity, activity level and clothing thermal resistance. However, the combined quantitative influence of all the parameters was not known until the ‘Comfort Equation’ established by Fanger was introduced in 1973 (Fanger, 1973). When any combination of these parameters satisfies this equation, the thermal comfort of a majority of individuals can be stated as neutral.

2.2.1 Factors Influencing Thermal Comfort

In recent years, the field of research in thermal comfort has attracted the attention of many researchers around the world, perhaps partially due to the increased public discussion about climate change (Ricardo et al., 2015). Overall thermal comfort and the assessment of indoor environmental quality do not depend solely on physical parameters. The human body's physiological and psychological responses to the environment are dynamic and integrate various physical phenomena that interact with the space (light, noise, vibration, temperature, humidity, etc.) (Parsons, 2000).

Madhavi et al. (2012) identified that thermal comfort as a six-dimensional topological solid, having at least six parameters that give dimensions to any unique thermal condition. Two of these, activity and clothing are specific to an individual while air temperature, humidity, air velocity and radiation are the properties of the environment. Under isothermal and steady state conditions, the heat balance of the body can be defined by these vital six variables. In addition, there are several other minor parameters like health and light which also influence thermal comfort. Cain (2002) reported that three main groups of factors that affect comfort; environmental conditions, characteristics of the individual, clothing and activity of the individual. The simplified diagram is shown in Figure 2.1.

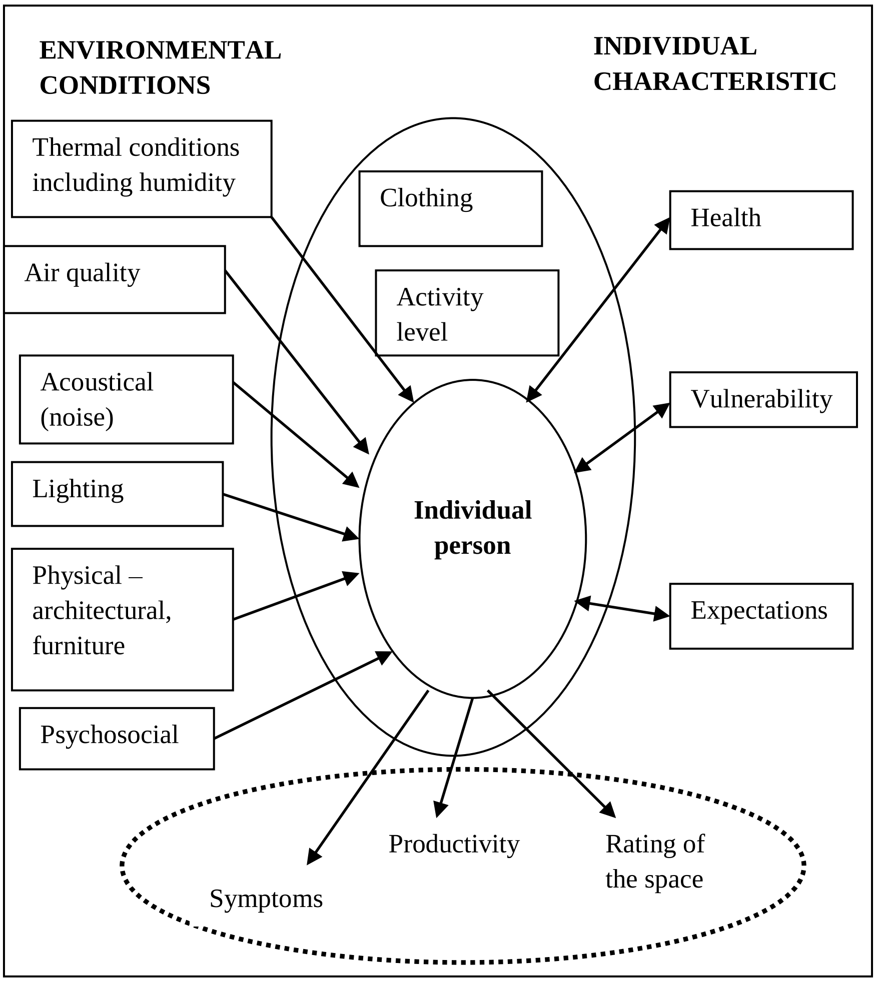

Figure 2.1: Personal Environment Model (Cain, 2002)

2.2.1(a) Environmental Factors

The most important environmental factors contributing to thermal comfort are air temperature, radiant temperature (i.e. the temperature of the walls, floor, windows etc.), humidity and air velocity.

2.2.1(a)(i) Air Temperature

The air temperature is the average temperature of the air surrounding the occupant, with respect to location and time. According to ASHRAE 55 standard (2010), the spatial average takes into account the ankle, waist and head levels, which vary for seated or standing occupants. Air temperature is measured with a dry-bulb thermometer and for this reason it is also known as dry-bulb temperature. This is the temperature of the air surrounding the body. It is usually given in degrees Celsius (°C).

2.2.1(a)(ii) Mean Radiant Temperature

Thermal radiation is the heat that radiates from a warm object. Radiant heat may be present if there are heat sources in an environment. Examples of radiant heat sources include: the sun, fire, electric fires, ovens, walls, floors, windows, etc. The radiant temperature is related to the amount of radiant heat transferred from a surface, and it depends on the material’s ability to absorb or emit heat, or its emissivity.

2.2.1(a)(iii) Relative Humidity

Relative humidity (RH) is the ratio of the amount of water vapor in the air to the amount of water vapor that the air could hold at the specific temperature and pressure. While the human body has sensors within the skin that are fairly efficient at feeling heat and cold, RH is detected indirectly. Sweating is an effective heat loss mechanism that relies on evaporation from the skin. However at high RH, the air has closed to the maximum water vapor that it can hold, therefore evaporation and heat loss decreased. On the other hand, very dry environments (RH < 20-30%) are also uncomfortable because of their effect on the mucous membranes. The recommended level of indoor humidity is in the range of 30-60% in air conditioned buildings but new standards such as the adaptive model allow lower and higher humidities, depending on the other factors involved in thermal comfort (Balaras, 2006; Wolkoff & Kjaergaard, 2007).

A way to measure the amount of relative humidity in the air is to use a system of dry-bulb and wet-bulb thermometers. The former measures the temperature with no regard to moisture, such as in weather reports. The latter has a small wet cloth wrapped around the bulb at its base, so the measurement takes into account water evaporation in the air. The wet-bulb reading will thus always be at least slightly lower than the dry bulb one. The difference between these two temperatures can be used to calculate the relative humidity where the larger the temperature difference between the two thermometers, the lower the level of relative humidity (Montanini, 2007; Toida et al., 2006).

The effects of low relative humidity and high air velocity were tested on humans after bathing. Researchers found that low relative humidity engendered thermal discomfort as well as the sensation of dryness and itching. It is recommended to keep relative humidity levels higher in a bathroom than other rooms in the house for optimal conditions (Hashiguchi & Tochihara, 2009).

In workplaces which are not air conditioned, or where the weather conditions outdoors may influence the indoor thermal environment, relative humidity may be higher than 70%. Humidity in indoor environments can vary greatly, and may be dependent on whether there are drying processes (paper mills, laundry etc.) where steam is given off. In hot environments, humidity is important because less sweat evaporates when humidity is high (80%+). The evaporation of sweat is the main method of heat reduction.

2.2.1(a)(iv) Air Velocity

Air velocity (V) is defined as the rate of air movement at a point, without regard to direction. According to ASHRAE Standard 55 (2010), it is the average speed of the air to which the body is exposed, with respect to distance and time.

Air velocity is an important factor in thermal comfort for example:

- still or stagnant air in indoor environments that are artificially heated may cause people to feel stuffy. It may also lead to a build-up in odour
- moving air in warm or humid conditions can increase heat loss through convection without any change in air temperature
- physical activity also increases air movement, so air velocity may be corrected to account for a person's level of physical activity
- small air movements in cool or cold environments may be perceived as a draught as people are particularly sensitive to these movements

2.2.1(b) Individual Factors

Clothes and activity are two individual factors that have significant correlation with thermal comfort.

2.2.1(b)(i) Clothes

The amount of thermal insulation worn by a person has a substantial impact on thermal comfort, because it influences the heat loss and consequently the thermal balance. Layers of insulating clothing prevent heat loss and can either help keep a person warm or lead to overheating. Generally, the thicker the garment is, the greater insulating ability it has. Depending on the type of material the clothing is made out of, air movement and relative humidity can decrease the insulating ability of the material (Havenith, (1999); McCullough et al. (2009).

In field survey, clothing insulation is always the most troublesome because of the great variety of subject's clothes. According to Nguyen et al. (2012), clothing insulation can only be estimated precisely by using thermal manikin. However, even in an experiment in controlled climate chamber where clothing insulation was calculated using a sophisticated thermal manikin, the obtained insulation values varied between manikin. The clothing can be predicted, however according to Ter Mors et al. (2011), practical methods to do this are not accurate and affect the uncertainty in the final thermal sensation prediction to a large extent. Improving the methods to determine clothing insulation can improve accuracy and quality of predicted mean vote (PMV) based prediction. Havenith et al. (2002) in their study concluded that moisture and air speed can cause a reduction of clothing vapour resistance, this subsequently affect the estimation of PMV. In ASHRAE database, all clothing insulation estimations in the field surveys were converted using ASHRAE 55-1992 clo estimation method.

Andris and Steven (1997) reported that 1 clo is the insulating value of a normal business suit, with cotton underwear. Shorts with short-sleeved shirts would be about 0.25 clo, heavy winter suit with overcoat around 2 clo and the heaviest arctic clothing 4.5 clo. Students mostly attired in western style outfits: combination of shirt/t-shirt, trousers/jeans. Five common ensembles were identified (shown in Table 2.1) and their clo values were assigned to subjects depending on what fit best. The clo values given in Table 2.1 taken into account insulations of undergarments and foot wear.

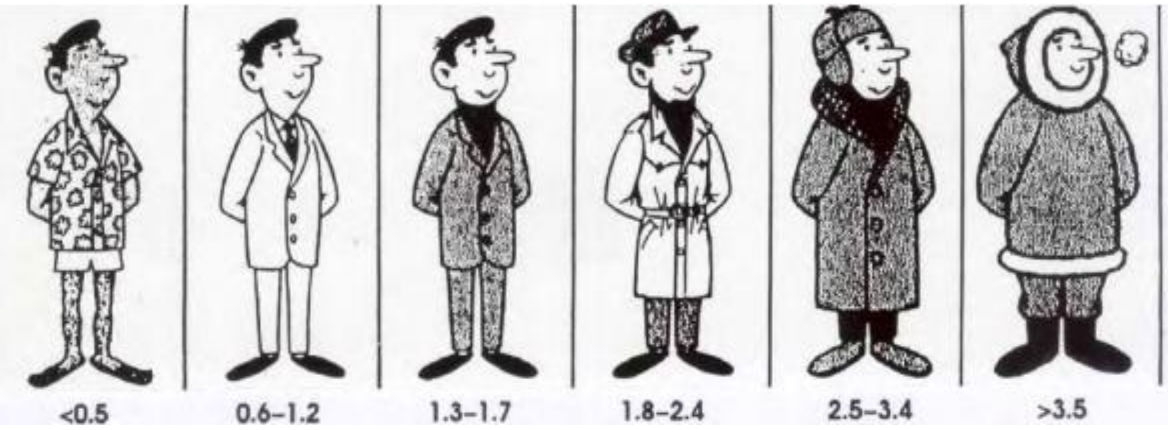

Figure 2.2: Insulation of clothing in clo units (Andris and Steven, 1997)

Table 2.1 Clothing ensemblers (Mishra & Ramgopal, 2014)

Ensemble	Clo value
T-shirt, thick trousers	0.39
Half-shirt, thin trousers	0.50
Half-shirt, thick trousers	0.59
Full-shirt, thin trousers	0.56
Full-shirt, thin trousers	0.65

2.2.1(b)(ii) Activity

Activity level is measured in terms of metabolic rate, or ‘met’. The most accurate method for determining met is through laboratory studies, where heat or oxygen production are measured for participants conducting specific activities (Havenith et al, 1999; Olesen & Parsons, 2002). People have different metabolic rates that can fluctuate due to activity level and environmental conditions (Toftum, 2005). The ASHRAE 55-2010 Standard defines metabolic rate as the level of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface. Metabolic rate is expressed in met units, which are defined as 1 met = 58.2 W/m^2, which is equal to the energy produced per unit surface area of an average person seated at rest. The surface area of an average person is 1.8 m^2 (ASHRAE, 2010).

Alternatively, the participant’s heart rate can be measured and compared to previously developed tables of heart rate for specific activities. All of these methods, however, are time-consuming and invasive, and are generally not practical for use by thermal comfort researchers. Instead, these researchers rely on estimates, based on tables of met rates for specific activities and occupations, developed from laboratory studies. In most studies, an average met rate is assumed for the group (usually 1.2 met for sedentary office work). Previous study asked occupants to record their activities over the last hour, and this information is used to develop a more accurate average for the group, or individualised met estimates for each participant (Cena, 1994). Examples of metabolic rates for common activities are given in Table 2.2. ASHRAE Standard 55 (2010) provides a table of met rates for a variety of activities. For intermittent activity, the Standard states that is permissible to use a time-weighted average metabolic rate if individuals are performing activities that vary over a period of one hour or less. For longer periods, different metabolic rates must be considered.

According to ASHRAE Handbook of Fundamentals (2005), estimating metabolic rates is complex, and for levels above 2 or 3 met – especially if there are various ways of performing such activities – the accuracy is low. Therefore, the Standard is not applicable for activities with an average level higher than 2 met. Met values can also be determined more accurately than the tabulated ones, using an empirical equation that takes into account the rate of respiratory oxygen consumption and carbon dioxide production. Another physiological yet less accurate method is related to the heart rate, since there is a relationship between the latter and oxygen production.

Food and drink habits may have an influence on metabolic rates, which indirectly influences thermal preferences. These effects may change depending on food and drink intake (Szokolay, 2010). Body shape is another factor that affects thermal comfort. Heat dissipation depends on body surface area. A tall and skinny person has a larger surface-to-volume ratio, can dissipate heat more easily, and can tolerate higher temperatures more than a person with a rounded body shape.

Table 2.2: Metabolic rates for typical task (ASHRAE, 2010)

Activity	met	W/m^2	W(av)
Sleeping	0.7	40	70
Reclining, lying in bed	0.8	46	80
Seated, at rest	1.0	58	100
Standing, sedentary work	1.2	70	120
Very light work (shopping, cooking, light industry)	1.6	93	160
Medium light work (house, machine tool)	2.0	116	200
Steady medium work (jackhammer, social dancing)	3.0	175	300
Heavy work (sawing, planing by hand, tennis)	6.0	350	600
Very heavy work (squash, furnace work)	7.0	410	700

2.2.2 Thermal Comfort Model

Thermal comfort assessment is a prime measure in indoor environment design to evaluate occupant satisfaction. Thermal comfort models for predicting occupant satisfaction and for designing an acceptable thermal environment can be found in literature. There are two distinct approaches related to indoor thermal comfort. The first approach is the classic steady-state model developed by Fanger (1970) for air-conditioned spaces, which is based on a heat balance model of the