THERMAL COMFORT STUDY IN MALAYSIAN UNIVERSITIES AIR-CONDITIONING OFFICE ROOMS WITH VARIOUS SET-POINT TEMPERATURES

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DEDICATION

For my better half and family whom I love dearly.

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ABSTRACT

Thermal perception in colder and warmer air-conditioner settings could help navigate cooling energy in hot and humid climates in fulfilling occupants' comfort needs. The desire to be outside one's current thermal environment could signal that the thermal comfort needs are not being met. The study of preferred temperature could reveal the link between thermal comfort and preference. Additionally, several contextual factors could affect thermal comfort. This study investigated comfort temperatures, occupants' preferred temperature and the effect of personal and building characteristics on thermal comfort. A semi-controlled field study was conducted in nineteen office spaces yielding 628 samples from 42 occupants. Four set-point temperature conditions: Original, Original ±2 °C, and MS Standard, were established to explore thermal comfort in biased and non-biased environments. The results showed that the majority of the occupants felt more comfortable when the indoor air temperature was increased. The overall comfort temperature estimated via Griffith's method was 24.6 °C, and the proportion of comfort votes depleted when the operative temperature reached 26 °C. The investigation of thermal preference revealed that occupants wanted to be in a colder environment despite already being in a comfortable state. The preferred temperature was approximately 23.9 °C using the probit method. Analysis via t-test and one-way analysis of variance showed that those with higher Body Mass Index (*BMI*) and above-average body surface area had significantly lower comfort temperature and preferred much more humid surroundings. Statistically, the characteristics of a building have the most impact in determining the comfort temperature. Larger offices with more than five-people occupancy had significantly lower comfort temperatures, and offices with no shading device, opened window blinds, and tiled flooring had higher comfort temperatures. The findings of this study would most benefit engineers, architects, and policymakers to chart sustainable building design that prioritises occupants' comfort.

ABSTRAK

Persepsi terhadap terma semasa suhu penghawa dingin di tetapan yang sejuk dan hangat boleh membantu pengurusan tenaga penyejukan yang digunakan dalam iklim panas dan lembap bagi memenuhi keperluan keselesaan penghuni. Keinginan seseorang untuk tidak berada dalam keadaan terma yang sedia ada menunjukkan keselesaan terma tidak terjangkau. Kajian berkenaan suhu pilihan boleh mendedahkan hubungan antara keselesaan terma dan terma pilihan. Tambahan pula, terdapat beberapa faktor yang bergantung kepada konteks dapat mempengaruhi keselesaan terma. Kajian lapangan separa terkawal telah dilakukan di sembilan belas ruang pejabat yang menghasilkan 628 sampel daripada 42 penghuni. Kajian ini menyiasat suhu keselesaan, suhu pilihan penghuni dan kesan ciri peribadi dan bangunan ke atas keselesaan terma. Empat keadaan suhu, *Original*, *Original ±2 °C* dan *MS Standard* telah diwujudkan untuk meneroka keselesaan terma dalam persekitaran yang berbeza. Keputusan menunjukkan bahawa penghuni umumnya berasa lebih selesa apabila suhu udara meningkat. Suhu keselesaan keseluruhan yang dianggarkan melalui kaedah Griffith ialah 24.6 °C, dan kadar undi selesa berkurangan apabila suhu operasi mencapai 26 °C. Siasatan terhadap pilihan terma mendedahkan bahawa penghuni mahu berada dalam persekitaran yang lebih sejuk walaupun sudah berada dalam keadaan selesa. Suhu pilihan adalah kira-kira 23.9 °C menggunakan kaedah probit. Analisis melalui ujian-t dan analisis varians sehala menunjukkan bahawa mereka yang mempunyai Indeks Jisim Tubuh (*BMI*) yang lebih tinggi dan kawasan permukaan badan melebihi purata mendapat suhu keselesaan yang jauh lebih rendah dan lebih suka persekitaran yang lebih lembap. Ciri-ciri bangunan memberi impak secara siknifikan terhadap suhu keselesaan. Pejabat yang besar dan menghuni lebih daripada lima orang mempunyai suhu keselesaan yang jauh lebih rendah manakala pejabat tanpa tirai atau tirai tingkap yang dibuka dan lantai berjubin mempunyai suhu keselesaan yang lebih tinggi. Penemuan kajian ini dapat memberi manfaat kepada jurutera, arkitek dan penggubal dasar untuk mencatat reka bentuk bangunan mampan yang mengutamakan keselesaan penghuni.

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LIST OF ABBREVIATIONS

AC - Air-conditioners
ACMV - Air-Conditioning and Mechanical Ventilation
AH - Absolute Humidity
AMA - Air Movement Acceptance
AMV - Air Movement Vote
ANOVA - Analysis of Variance
APD - Actual Percentage of Dissatisfied
ASHRAE - The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BMI - Body Mass Index
CIBSE - Chartered Institute of Building Services Engineers
EN - European Standard
HP - Humidity Preference
HS - Humidity Sensation
IBM - International Business Machine
ISO - International Standard
KL - Kuala Lumpur
KLCC - Kuala Lumpur City Centre
MJIIT - Malaysia-Japan International Institute of Technology
MM - Mixed-mode
MS - Malaysian Standard
MV - Mechanically Ventilated
NV - Naturally Ventilated
OC - Overall Comfort
PMV - Predicted Mean Vote
PPD - Predicted Percetage of Dissatisfied
PWS - Personal Weather Station
RH - Relative Humidity
RTD - Resistance Temperature Detection
SA - Shah Alam

SHASE	-	Society of Heating, Air-conditioning, and Sanitary Engineering of Japan
SPSS	-	Statistical Package for Social Sciences
TA	-	Thermal Acceptability
TP	-	Thermal Preference
TSV	-	Thermal Sensation Vote
UiTM	-	Universiti Teknologi MARA
UK	-	United Kingdom
UTMKL	-	Universiti Teknologi Malaysia Kuala Lumpur

LIST OF SYMBOLS

ΔT - Temperature difference (°C)

a - Griffiths' constant

A_d - Dubois body surface area (m^2)

AH - Absolute humidity (g_v/kg_{da})

C - Convective heat transfer per unit area (W/m^2)

D - Diameter (m)

e - Euler's number

$\mathcal{E}$ - Emissivity

E - Evaporative heat loss per unit body surface area (W/m^2)

f_{cl} - Clothing area factor

h - Body height (m)

h_c - Convective heat transfer coefficient (W/m^2K)

I_{cl} - Clothing insulation (clo)

K - Conductive heat loss per unit area (W/m^2)

L - Energy loss to environment per unit area (W/m^2)

M - Metabolic rate (met)

N - Number of samples

p_a - Partial pressure of water vapour in air (kPa)

P - Total barometric pressure (mmHg)

p_v - Partial pressure of water vapour (mmHg)

Q_r - Total rate of heat loss through respiration (W/m^2)

Q_d - Dry heat exchange (W/m^2)

R_v - Gas constant of water vapour (461.5 J/kgK)

R_a - Gas constant of air (287.05 J/kgK)

RH - Relative humidity (%)

RHE - Radiative heat loss per unit area (W/m^2)

T_a - Indoor air temperature (°C)

T_c - Comfort temperature (°C)

T_{cg} - Comfort globe temperature (°C)

T_{ci} - Comfort air temperature (°C)

T_{cl} - Mean temperature of clothing surface (°C)

T_{cmrt} - Comfort mean radiant temperature (°C)

T_{cop} - Comfort operative temperature (°C)

T_g - Indoor globe temperature (°C)

T_{mrt} - Indoor mean radiant temperature (°C)

T_o - Outdoor air temperature (°C)

T_{od} - Daily mean outdoor air temperature (°C)

T_{pma} - Prevailing mean outdoor air temperature (°C)

T_{om} - Monthly mean outdoor air temperature (°C)

T_{op} - Indoor operative temperature (°C)

T_{rm} - Running mean outdoor air temperature (°C)

V_a - Air velocity (m/s)

W - Energy used for mechanical work (W/m^2)

w - Body weight (kg)

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CHAPTER 1

INTRODUCTION

1.1 Research Background

World demand for commercial air-conditioners (AC) in 2018 has a two per cent increase from the previous year, reaching 14.9 million units [1]. AC demand and energy use will likely rise further in tropical regions, considering it is the world's fastest-growing region [2]. As a result, more than half of buildings' energy consumption in the hot and humid tropical climate accounts for space cooling [3,4]. Due to modifying tropical lands, the rising surface temperature further boosts people's time indoors [5]. AC systems are typically equipped with temperature selections, allowing for customized indoor comfort and relief from frequent hot and humid outdoor conditions. A Philippines study found a 0.5% to 8.5% increase in electricity demand with every one-degree temperature rise, equivalent to 21 (±10.4) watts per person [6]. Many countries have suggested temperature guidelines for mechanically ventilated building systems to curb energy overuse. However, attempts to save energy often neglect human comfort [7].

The indoor environment is vital for office comfort and work performance [8,9]. Thermal comfort significantly affects indoor environment satisfaction more than visual, acoustic, and air quality [10]. A comfortable thermal environment in the workplace can have economic benefits as health and productivity are enhanced [11]. On the other hand, thermal discomfort leads to negative attitudes among office occupants and reduced enthusiasm for work activities [12]. One thermal condition may not satisfy all occupants in a shared space due to individual preferences. Based on Fanger's [13] studies, 5% of occupants would not be satisfied with the indoor environment although maximum comfort level is achieved. Thus, 80% of the majority votes is the threshold for an acceptable thermal environment, according to ASHRAE

Standard 55 by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers [14].

Thermal comfort was first estimated using the Predicted Mean Vote (*PMV*) indices and the Predicted Percentage of Dissatisfied (*PPD*). The *PMV* model utilizes the human body heat-balance concept [13]. This model was then argued to neglect thermal comfort's cultural and contextual influences as it is founded on a controlled experiment. Later, an adaptive thermal comfort model was introduced, suggesting that people adapt to the thermal environment via behavioural adjustments and acclimatization [15]. Most buildings in hot and humid climates use the Air-Conditioning and Mechanical Ventilation (ACMV) system to control the indoor thermal environment [16]. The *PMV* model predicts everyday comfort under a steady-state thermal environment and limited conditions such as ACMV buildings [17]. Meanwhile, the adaptive model factors in the outdoor parameters result in a broader comfort range and are commonly used to estimate thermal comfort in naturally ventilated spaces. Nonetheless, studies have implemented the adaptive model for ACMV buildings [16,18,19] to predict thermal comfort.

This research explores thermal comfort in hot and humid climates with various set-point indoor temperature conditions. Additionally, it investigates the subjective evaluation of thermal comfort parameters and occupants' thermal preferences. The findings of this study may shed light on how cooling energy is used in office buildings to provide thermal comfort and serve as a reference for building engineers, architects, and policymakers in considering occupants' indoor comfort.

1.2 Problem Statement

Located close to the equator, Malaysia has a hot and humid climate year-round. The high daytime temperature can induce heat stress, leading to decreased productivity and health problems. Thermal comfort in university buildings has been extensively studied and compared alongside government and privately owned offices, considering the similar building layouts and ventilation designs [16,20–23]. In the context of thermal comfort in ACMV office buildings in hotter climates, occupants may be inclined to use lower temperature settings. Still, underestimating cooling design value causes an over-cooling phenomenon in buildings resulting in an uncomfortably colder sensation. The uneven temperature distribution of localized AC in shared spaces may not satisfy the thermal comfort of occupants.

Additionally, the thermal discomfort experienced from a too cold or too warm environment can adversely affect office occupants' health and work productivity. Cooling energy use will be less efficient if it does not provide comfort, thus harming the environment and adding operation costs. Field studies on thermal comfort have looked into different building ventilation and adaptive relations, but there is a possibility of biased responses as occupants have complete authority over the temperature settings [16,18,24]. Consequently, the thermal awareness of temperature changes in field research is not sufficiently studied. Investigating thermal perception in existing buildings in colder and warmer conditions could be valuable in navigating cooling energy to address occupants' comfort, environmental care, and operating costs.

Besides the steady-state *PMV/PPD* thermal comfort model, international standards have considered the adaptive model to provide recommendations for the indoor environment. In Malaysia, buildings with mechanical cooling systems adopted the 2014 Malaysian Standard (MS) 1525 code of practice, referencing the ASHRAE Handbook [25]. However, there is no explicit remark that the guideline integrates local thermal comfort studies, which may lead to misrepresentation of indoor comfort, considering the cultural habit and adaption to climate conditions influences comfort expectations. The comfort perceptions obtained from this study may be beneficial for building managers and the relevant standards' regulatory boards.

Comfort temperature can be considered neutral temperature taken from ambient temperature and subjectively neutral thermal sensation. Neutral sensation alone may not accurately depict occupants' comfort as it neglects occupants' preference to be in a non-neutral environment. A person's inclination to be outside the existing thermal environment might indicate thermal comfort is not satiated. Several discrepancies have been found between preferred and comfort temperatures [26,27], but the studies on the relationship between thermal comfort and preference in hot and humid climates were limited [28,29]. Thus, investigating preferred temperature in this study could reveal the association between thermal preference and comfort in hot and humid climates.

Other than the environment and personal elements of thermal comfort, several contextual factors may affect comfort level. The physical differences of the human body influence thermal regulation; hence the connection with thermal comfort could be significant. Additionally, the direct surroundings in buildings can change how occupants perceive their thermal environment [30]. The anthropometrics and demographics have shown significant effects on thermal comfort [31,32]; however, there are limited studies relating building designs to thermal perceptions. Therefore, this study hopes to present the impact of individual and buildings characteristics on thermal comfort for sustainable building design.

1.3 Research Questions and Objectives

Based on the problem mentioned earlier, this study aims to answer the following questions

1) What are the comfort temperatures for occupants in Malaysian university office rooms when subjected to different indoor temperature conditions, and how does the compatibility of related local and international thermal environment standards compare with occupants' thermal comfort?

2) Do occupants prefer to be in a different thermal environment in Malaysian university office buildings?

3) Do personal and building characteristics in Malaysian university office buildings impact thermal comfort?

Therefore, the objectives of this study are as follows

1) To estimate occupants' comfort temperatures in Malaysian university office rooms when subjected to multiple set-point temperatures during daytime working hours and compare them with local and international standards.

2) To identify the preferred temperature and its relationship with comfort temperature.

3) To evaluate the relationship between personal and building characteristics with thermal comfort.

1.4 Research Scopes and Limitations

This study encapsulates the understanding and evaluation of thermal comfort in the context of the four environment parameters: air temperature, mean radiant temperature, relative humidity, and air velocity. Furthermore, the two personal variables of metabolic rate and clothing insulation are examined via questionnaires and assumptions from ASHRAE Standard 55 [14]. This study investigated office buildings at two universities in Kuala Lumpur and Shah Alam. Selected office rooms must have air conditioners with interchangeable temperature settings. The postgraduate rooms investigated had working stations similar to office rooms but with an added connecting laboratory. Additionally, the occupancy duration between students and staff was slightly different. Specifications of air conditioning unit, room illuminance, and energy usage are not within the scope of this study.

1.5 Research Significance

With the growing number of publications revolving around simulation-based thermal comfort research [33–36], field study contributes to validating the simulation study method before its implementation for a more practical and reliable result [37]. The validation also applies to climate chamber studies where subjects are placed in a controlled room adjusted according to the experiment's needs. This semi-controlled research combines fieldwork and controlled environment study to investigate occupants' thermal comfort by adjusting the indoor air temperature via AC settings in investigated offices. Therefore, the outcome of this study could directly benefit occupants' comfort and cooling energy usage of the investigated buildings.

1.6 Thesis Structure

This thesis is structured in six chapters, where the summarised details are as follows.

Chapter 1 explores the introduction covering the research background and problems within thermal comfort studies, forming research questions and objectives. Scopes, limitations, and significance are also introduced in this chapter, followed by the thesis structure and the chapter summary.

Chapter 2 explains the literature review of this research encompassing thermal comfort, including the effecting factors, *PMV/PPD*, and the adaptive model. The Malaysian standard for non-residential buildings was also presented alongside relevant international standards. This chapter reviews past studies on indoor thermal comfort in hot and humid climates and shows the research gaps.

Chapter 3 provides the research methodology starting with the geographical and climatology of the studied location, followed by details of investigated buildings and offices. Next, the field study process was explained, including the preliminary measurement, equipment setup, case studies and procedure for the different indoor temperature conditions, questionnaire survey, and instrument verification. Subsequently, the estimation of thermal comfort parameters was explicated. Finally, this chapter presented the analytical approaches used in this study.

Chapter 4 discusses the results obtained from the field measurement. Respondents' demographics and anthropometrics were initially presented. Thermal environment data comprised of outdoor and indoor variables categorized into different case studies came next. Then, the questionnaire survey results consist of subjective evaluations, adaptive actions, activity level, and clothing insulations are presented.

Chapter 5 presents the field data analysis and discusses the results. First is analysing comfort temperature using the regression, probit, and Griffiths' methods. The comfort temperatures were then compared with local and international standards. Secondly, preferred temperatures were calculated, and the relationship with comfort temperature was explained. Lastly, the effects of personal and building characteristics on thermal comfort were analysed using a t-test and Analysis of Variance (ANOVA).

Chapter 6 summarizes the findings from this research. Concluding remarks include comfort temperatures, local and international standards compatibility, preferred temperature implications, and the effects of personal and building characteristics. This section closes with research limitations and recommendations for future works.

1.7 Chapter Summary

This chapter offered some general background of thermal comfort study and then dived into the problem statements that specify tropical thermal comfort, followed by research questions and objectives. Next, research scopes, limitations, and significance were presented, and the thesis structure was written in the form of brief descriptions of each chapter. The next chapter reviews thermal comfort theory and recent related research.

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