COMFORT TEMPERATURE OF AIR-CONDITIONING LIVING ROOM WITH VARIOUS SET POINT OF TEMPERATURE UNDER HOT-HUMID CLIMATE

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DEDICATION

This thesis is dedicated to my husband, sons, parents, siblings, and in-laws for their support and encouragement for me to complete this study.

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ABSTRACT

The use of an air-conditioner (AC) becomes essential in residential buildings, particularly in a hot and humid climate, to provide a comfortable environment for human activities. There is a scarcity of significant research exploring thermal comfort for residential buildings with AC usage and indoor comfort temperature on various AC settings based on the sensitivity and assessment of thermal comfort requirements in the living room area. Moreover, the behavior of AC set point practice for non-commercial buildings, which is recommended to be not below than 24℃, is not stated in the guidelines and standards mentioned for government office buildings in Malaysia. Thus, this study aims to evaluate the personal characteristics and adaptive behavior, estimate the comfort temperature at various indoor temperatures and compare the established comfort temperature with related local and international standards. The field measurement and survey has been carried out in two living rooms located in Universiti Teknologi Malaysia, Kuala Lumpur and Universiti Malaysia Pahang, Pekan at four different AC set point temperatures (i.e., 16℃, 20℃, 24℃, and 28℃) for 63 university students with 252 samples collected. The mean indoor thermal parameters were measured within a 10 s time interval. The Chi-square results indicated that the difference in gender and body mass index had no significant effect on the thermal sensation of respondents, while the water intake and clothing insulation level affect personal thermal comfort. Besides, the results of Griffiths' method had disclosed that the mean comfort temperature based on operative temperature for respondents was found to be 24.3℃, which is within the range of indoor thermal comfort zone of 23℃ and 27℃, as recommended by local and international standards. It is essential to provide the owner with guidelines to set the AC temperature above the established comfort temperature to fit the buildings' functionality. It would be beneficial towards achieving better health, saving power, and reducing electricity consumption while maintaining the thermal comfort requirements, especially in Malaysia and other countries experiencing hot and humid climate.

ABSTRAK

Penggunaan penyaman udara (AC) menjadi satu keperluan dalam bangunan kediaman, terutamanya dalam iklim panas dan lembap, bagi menyediakan persekitaran yang selesa untuk aktiviti manusia. Terdapat kekurangan penyelidikan penting yang meneroka keselesaan terma untuk bangunan kediaman dengan penggunaan AC dan suhu keselesaan dalaman pada pelbagai tetapan AC berdasarkan sensitiviti dan penilaian keperluan keselesaan terma di kawasan ruang tamu. Selain itu, tingkah laku penyesuaian terhadap suhu tetapan AC bagi bangunan bukan komersial, yang disyorkan supaya tidak kurang daripada 24℃, tidak disarankan dalam garis panduan dan piawaian seperti yang dinyatakan untuk bangunan pejabat kerajaan di Malaysia. Oleh itu, kajian ini bertujuan untuk menilai ciri-ciri peribadi dan tingkah laku penyesuaian, anggaran suhu keselesaan pada pelbagai tetapan suhu penyejukan di ruang tamu dan membandingkan suhu keselesaan yang diperoleh dengan piawaian tempatan dan antarabangsa yang berkaitan. Kajian dan tinjauan lapangan telah dijalankan di dua ruang tamu yang terletak di Universiti Teknologi Malaysia, Kuala Lumpur dan Universiti Malaysia Pahang, Pekan pada empat suhu tetapan AC yang berbeza (iaitu, 16℃, 20℃, 24℃, dan 28℃) untuk 63 pelajar universiti dengan 252 sampel yang terkumpul. Purata setiap parameter terma dalaman seperti suhu udara, suhu glob, kelembapan relatif, dan kelajuan udara diukur. Keputusan Chi-square menunjukkan bahawa perbezaan jantina dan indeks jisim badan tidak mempunyai kesan yang signifikan terhadap sensasi terma responden, manakala pengambilan air dan tahap penebat pakaian mempengaruhi keselesaan terma peribadi. Selain itu, keputusan kaedah Griffiths telah mendedahkan bahawa purata suhu keselesaan berdasarkan suhu operasi bagi responden adalah pada 24.3℃, berada dalam julat zon keselesaan terma dalaman 23℃ dan 27℃, seperti yang disyorkan oleh piawaian tempatan dan antarabangsa. Adalah penting untuk menyediakan garis panduan kepada pemilik untuk menetapkan suhu AC melebihi suhu keselesaan yang diperoleh mengikut kesesuaian fungsi bangunan. Ia akan memberi manfaat ke arah mencapai kesihatan yang lebih baik, menjimatkan kuasa, dan mengurangkan penggunaan elektrik disamping mengekalkan keperluan keselesaan terma, terutamanya di Malaysia dan negara beriklim panas dan lembap yang lain.

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LIST OF ABBREVIATIONS

AC	-	Air Conditioning
U_1	-	Living room 1
U_2	-	Living room 2
ASHRAE	-	American Society of Heating, Refrigerating and Air Conditioning Engineers
MS	-	Malaysia Standard
DOSH	-	Department of Occupational Safety and Health
CIBSE	-	Chartered Institution of Building Services Engineers
ISO	-	International Standards Organization
BMI	-	Body Mass Index
ANSI	-	American National Standards Institute
MJIIT	-	Malaysia Japan International Institute of Technology
IBM	-	International Business Machines
SPSS	-	Statistical Package for Social Sciences

LIST OF PARAMETERS

T_s	-	Set Point Temperature
T_a	-	Air Temperature
T_g	-	Globe Temperature
RH	-	Relative Humidity
V_a	-	Air Speed
p	-	Significance Level of Regression Coefficient
PMV	-	Predicted Mean Value
TSV	-	Thermal Sensation Value
met	-	Metabolic Rate
clo	-	Clothing Insulation
TP	-	Thermal Preference
N	-	Number of Sample
T_c	-	Comfort Temperature
T_n	-	Neutral Temperature
HF	-	Humidity Feeling
AMV	-	Air Movement Vote
HP	-	Humidity Preference
OC	-	Overall Comfort
T_{mrt}	-	Mean Radiant Temperature
T_{op}	-	Operative Temperature
AH	-	Absolute Humidity
T_{rm}	-	Running Mean Daily Outdoor Air Temperature
PPD	-	Percentage of Dissatisfied
APD	-	Actual Percentage of Dissatisfied
T_o	-	Outdoor Temperature
T_{om}	-	Mean Outdoor Temperature
S.D.	-	Standard Deviation
S.E.	-	Standard Error
R^2	-	Coefficient of Determination
α	-	Griffiths' Constant

T_{ca}	-	Comfort Air Temperature
T_{cgg}	-	Comfort Globe Temperature
T_{cop}	-	Comfort Operative Temperature
T_{cmrt}	-	Comfort Mean Radiant Temperature

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Malaysia situated near the equatorial region in Southeast Asia, is characterised by hot and humid weather. Therefore, residential buildings often face the challenge of maintaining comfortable thermal conditions in the building space. The indoor thermal environment is part of the indoor environmental quality component that closes influenced by climatic conditions (Jamaludin *et al.*, 2015). This is because building spaces located in this climate are regularly uncomfortable due to high temperatures, high relative humidity, and low air movement. (Amasuomo *et al.*, 2016), which leads to a state of thermal discomfort in the interior space. As a result of the tropics gradually becoming a rapidly developing city, the energy demand for indoor thermal comfort is increasing dramatically due to the population growth (Yang *et al.*, 2014; Waite *et al.*, 2017).

When the indoor thermal environment does not meet expectations, occupants will influence the thermal comfort environment by installing electric mechanical cooling units. Paradoxically, the demand for space cooling is highly desirable, and the dependency on the air-conditioning (AC) system is unavoidable, designed to maintain indoor thermal comfort. Besides, occupant behavior such as adjusting clothing, opening windows, and other options can significantly affect the AC operations and contribute to increased energy consumption (Xia *et al.*, 2019). Hence, occupants' behavior is substantially related to AC usage in the living room or bedroom that will significantly contribute to overall energy consumption for residential buildings (Brounen *et al.*, 2012; Parker *et al.*, 2012). In short, AC produces comfortable indoor conditions where humans feel very comfortable. It helps people work efficiently while improving the quality of one's work so that people can work vigorously. Occupant responses may differ because individuals' physiological and psychological receptions may vary even while they are experiencing the same internal thermal environment

(Wang *et al.*, 2020). It is crucial to conclude that respondents in the same thermal environment and have similar age, gender, and metabolic rates may have different thermal acceptances and preferences (Shahzad and Rijal, 2019; Wang *et al.*, 2020).

The adaptations in any thermal condition primarily depend on physiology, psychology, environment, and behavior in a building (Hélder Silva Almeida, 2010; Bhatt, 2017) which prudent this state of responses under unfavorable conditions. For instance, the human body's metabolic rate, the thermal resistance of clothing insulation, air temperature, relative humidity, air speed, and surfaces' temperature. Human interaction greatly influences adaptation to the environment and behavior within a building. This also affects thermal satisfaction and households' energy consumption (Brager *et al.*, 2004; Humphreys *et al.*, 2007a). The neutral thermal sensation in a condition of feeling neither cold nor hot is widely used by applying the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 55 seven-point thermal sensation scale to assess thermal comfort (Shahzad *et al.*, 2018).

1.2 Problem Statement

The living room is a common area where people prefer to spend a lot of the time unwinding in front of the television, entertaining family and friends should always feel comfortable regardless of the outdoor environment. Personal characteristics are commonly associated with a significant effect and the individual's ability to respond or adapt to the thermal environment. Based on gender, body mass index, the behavioral adaptation of water intake, and clothing insulation are necessary to evaluate their influence on occupants of residential buildings in hot and humid climates for better comfort. Gender differences affect heat balance, thermoregulation, and thermal perception. Based on previous studies, the neutral temperature between the two genders with most cases showing that females preferred to be warmer (Karyono, 2000; Rajasekar and Ramachandraiah, 2010; Indraganti and Rao, 2010; Chow *et al.*, 2010; Fong *et al.*, 2010) and highly sensitive to the temperature variations (Hwang *et al.*, 2006; Chow *et al.*, 2010; Wang and Hong, 2020). In addition, for body mass index,

females have several morphological differences, including the surface area to volume ratio of body segments, an average of body size, and muscle mass (Young and Lee, 1997; Tikuisis *et al.*, 2001). Besides, the differences in clothing level between the genders often have different *clo* values based on the individual variations (Mishra and Ramgopal, 2013). When the stress factor is due to heat, exercise, and dehydration, a person will drink in a hot and cold environment. The water intake of respondents increases at an ambient temperature of about 27℃, the temperature at which sweating begins (Greenleaf, 1993).

Understanding the lowest setting temperature used to accelerate cooling for indoor spaces should be avoided. The setting temperature is for reference on the controller, and the actual indoor temperature is hovering between the AC air temperature and the ambient temperature. A study by Uno *et al.* (2003) disclosed that the low room temperature resulted from applying a typical set point temperature between 18℃ and 26℃, respectively. Besides, Kubota *et al.* (2011) had obtained that almost 30% of the households with AC would use the set point temperature of below than 23℃, while less than 15% were using the set point temperature of 24℃ and above. Based on a survey by Aqilah et al. (2019), 92% of the occupants would prefer to use the set point temperature below the recommended range of Malaysia Standard, i.e., 24 to 26℃.In addition, all government offices in Malaysia are urged to apply the set point of AC temperature no lower than 24℃ as stated in Malaysia Standard (2014), promoting energy-efficient practices.

In the forecast, AC usage is growing in demand, and it will drive the global electricity demand up to 30% by 2050 (Energy Agency, 2020). However, public awareness regarding the environmental impacts of AC usage remains low. The guidelines of the AC usage are designed as a recommendation of the appropriate range of the set temperature based on the building's functionality, which should help to increase understanding of the negative impacts of AC. However, there is inadequate information and guidelines for AC temperature setting ranges for residential buildings. It is questionable if the established comfort temperature can be compared to the local and international indoor thermal environmental standards correlated with their appropriate applicability for residential sectors.

Due to insufficient quantitative evidence, the sensitivity and thermal comfort requirements are different for occupants, especially in a living room area with AC usage for cooling purposes and the average comfort temperature, need to be identified exceptionally. The AC usage addressing thermostat setting and a comprehensive study to grasp the occupants' behavior towards AC usage related to personal characteristics to achieve indoor thermal comfort in residential buildings, particularly in Malaysia and other hot and humid countries, has not been sufficiently studied.

1.3 Research Questions

Based on problems identified towards AC usage in various set point temperatures, the research questions of this study are as follows:

a) How do behavioral adaptations of gender, individual body mass index (*BMI*), water intake and clothing insulation affect the thermal comfort scale (i.e., thermal sensation, thermal preference, overall comfort, and others)?

b) What is the comfort temperature of respondents at various indoor temperature in living room?

c) How can the comfort temperature for a living room be correlated with relevant indoor local and international thermal environment standards (i.e., MS1525:2007, DOSH:2010, ASHRAE Standard 55, and CIBSE Guide A)?

1.4 Research Objectives

Based on problems in section 1.2 and research questions in section 1.3, the objectives of this research towards AC usage in various set point temperatures are:

a) To evaluate the personal characteristics (gender, body mass index) and the adaptive behavior (water intake and clothing insulation) on thermal comfort.

b) To estimate comfort temperature at various indoor temperature in a living room space based on field survey data.

c) To compare the established comfort temperature with related local (MS1525:2007, DOSH:2010) and international (ASHRAE Standard 55, CIBSE Guide A) indoor thermal environmental standards.

1.5 Research scope

This study was conducted in a living room in two universities in Kuala Lumpur and Pahang, Malaysia, namely Universiti Teknologi Malaysia and Universiti Malaysia Pahang. There is a limitation on the weather change throughout the day; sunny and rainy. During the survey period, the outdoor air temperature range was recorded between 24.3℃ and 33.2℃. The living rooms were equipped with AC of split unit type: ceiling cassette and wall-mounted. However, the horsepower of the AC is neglected since the room is well equipped. Each room's windows, blinds, and doors remained closed throughout the measurement period. The living room is an environment model operating as the actual living room, including the furniture layout and atmosphere; it is the residential buildings' common area where people tend to spend time together with family and friends.

Another limitation in this study was to find respondents. The measurements might take some time for respondents to come repeatedly to complete the total of four cases of set point temperature, i.e., 16℃, 20℃, 24℃, and 28℃. To avoid any inconvenience in completing the measurement and survey session, the targeted respondents were voluntary university students, with 43 respondents from U_1 and 20 respondents from U_2. In addition, the focus on the young adult among the university students might be advantageous as they have a high preference for a lower temperature compared to the elderly (Hoof and Hensen, 2006; Schellen *et al.*, 2010). Student samples are prevalent in psychological studies as these groups were established to provide a moderately good estimate as representative samples (Fischer and Schwartz, 2011). However, only the respondents with a good health condition (i.e., not having

flu, cold or fever, and taking any medication) could participate in this experiment. Throughout the measurement period, respondents were free to wear casual clothes. Only certain low physical activities in a sedentary manner (i.e., using a smartphone, reading, watching a movie or drama, having a slow volume chat, and sitting quietly) were only allowed. Besides, respondents must remain seated at their respective seating locations until each session is completed.

The measurements were conducted between 0800 and 1700 hours from September 2019 until February 2020. The six factors which affect thermal comfort of respondent comprise of air temperature (T_a), globe temperature (T_g), relative humidity (RH), air speed (V_a), clothing insulation, and metabolic rate. AC set point temperature (T_s) of 16℃, 20℃, 24℃ and 28℃ were exposed to the respondents in a group of four to six persons for 45 min for each session. Field study and questionnaire survey at each setting temperatures were performed simultaneously.

1.6 Significance of Research

Based on the thermal environmental measurements and questionnaire survey results, the proposed comfort temperature based on various set point temperatures for the residential buildings will improve the comfort level of indoor spaces and may reduce the energy consumption proportionally. Wise electricity consumption will reduce Malaysia's carbon dioxide emission (Rajamoorthy *et al.*, 2018). Other than that, the identified comfort temperature will represent the guidelines for the tolerable range of setting the temperature for residential buildings equipped with the AC in the living room in Malaysia. Enhanced indoor thermal comfort may improve the occupants' satisfaction to attain environmental sustainability. Therefore, from the health point of view, the optimum satisfaction towards the indoor thermal environment is vital as the thermal conditions may potentially become the cause for the improper function of human physiological processes. It is becoming essential to maintaining thermally comfortable indoor conditions for a healthy indoor living environment and a holistic quality of life in the urban environment.

1.7 Chapter Summary

This chapter briefed the research field study by explaining the background of thermal comfort studies and the problem statement. Then, the research objectives are derived from the research questions, followed by the scope, significance of research, and organization of this thesis. The next chapter presents the literature review to understand the basic theory and current progress on thermal comfort studies.

1.8 Thesis structure

This thesis is coordinated into seven chapters. A brief explanation of the following 7 chapters is as described:

Chapter 1 gives a comprehensive introduction for this field study. It presents the background and identifies problems which lead to research motivation and become the objectives of study. Research scope and significance of study are also discussed in this chapter.

Chapter 2 presents the informative reviews and discussion of the literature review concerning this research. This chapter reviews the adaptive comfort approach that influenced personal thermal comfort. The previous thermal comfort studies conducted in either residential buildings or experimental rooms with AC usage in hot and humid climates are also discussed. Comfort temperatures following thermal comfort in different countries and environments have been analysed critically based on previous studies. The research gaps are also highlighted.

Chapter 3 illustrates and explains the structure of the methodology for this research. The study's area locality, studied buildings, rooms selection, and modification into the living rooms are presented. A comprehensive explanation of the field survey process (i.e., list of equipment used, equipment verification process, equipment installation, research design, preliminary field survey measurement and data collection) for the field survey conducted, is provided. The estimation of thermal

comfort variables from the measured indoor thermal measurements, then extended to data analysis (i.e., regression analysis, Griffiths' method, probit analysis, correlation of thermal parameter, psychrometric chart, and Chi-square test) was presented and discussed.

Chapter 4 presents the analyzed data to achieve the first objective of the research. The sample population based on the socio-demographics of respondents as discovered from the questionnaire survey is presented. Results of the questionnaire survey based on water intake, spend up activities, adaptive actions, and personal factors that affect individual thermal comfort is explained and discussed. The relation of respondents' characteristics (i.e., gender, body mass index, water intake, and clothing insulation) towards the thermal comfort requirement is presented based on the value statistical of significance level (p) from the Chi-square test.

Chapter 5 presents analysis and discussion based on the results of the second objective for the field study research. The analytical methods in estimating comfort temperature based on three analytical methods (i.e., regression analysis, Griffiths' method, and probit analysis) were analyzed and discussed. The comparison of comfort temperature obtained from predicted mean value (*PMV*) and thermal sensation value (*TSV*) is presented. Comparison of comfort temperatures with the local and international standards were explained thoroughly. Also, the relationship of indoor comfort temperature of Griffiths' method and outdoor conditions is presented.

Chapter 6 presents the overall findings and analysis of the third objective for the field study. Comparison of comfort temperature with local and international standards is explained and discussed. Psychrometric chart of the indoor environmental and the applicability to standards is also presented.

Chapter 7 presents concluding remarks and further recommendations of the future works. Research conclusion includes thermal sensation also thermal preference, comfort temperatures, and individual characteristics. The contribution to knowledge, limitations of studies, and potential of future works are also highlighted.

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