

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

NOOR SYAZWANEE BINTI MD TAIB

A thesis submitted in partial fulfilment of the  
requirements for the award of the degree of  
Master of Philosophy

Malaysia-Japan International Institute of Technology  
Universiti Teknologi Malaysia

JUNE 2022

## **DEDICATION**

*For my better half and family whom I love dearly.*

## ACKNOWLEDGEMENT

I'd like to offer my heartfelt gratitude to my main supervisor, Assoc. Professor Ir. Ts. Dr Sheikh Ahmad Zaki bin Shaikh Salim, for his patience, guidance and critics. I am also very thankful to my co-supervisor Dr Waqas Khalid for his helpful pointers.

I am also indebted to the Malaysia-Japan International Institute of Technology (MJIT) for funding my Masters study. Special thanks to Ts. Dr. Azli Abd Razak and his students Nur Dina Auni and Siti Maisarah for their support in collecting data in Universiti Teknologi MARA (UiTM) in Shah Alam.

My fellow postgraduate students should be thanked for their help as well. My sincere gratitude also goes out to all of my co-workers and those who have helped me on multiple occasions.

## 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  $\pm 2$  °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*  $\pm 2$  °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 sehalu 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 signifikan terhadap suhu keselesaan. Pejabat yang besar dan dihuni 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.

## TABLE OF CONTENTS

	<b>TITLE</b>	<b>PAGE</b>
	<b>DECLARATION</b>	<b>v</b>
	<b>DEDICATION</b>	<b>vi</b>
	<b>ACKNOWLEDGEMENT</b>	<b>vii</b>
	<b>ABSTRACT</b>	<b>viii</b>
	<b>ABSTRAK</b>	<b>ix</b>
	<b>TABLE OF CONTENTS</b>	<b>x</b>
	<b>LIST OF TABLES</b>	<b>xv</b>
	<b>LIST OF FIGURES</b>	<b>xviii</b>
	<b>LIST OF ABBREVIATIONS</b>	<b>xxiii</b>
	<b>LIST OF SYMBOLS</b>	<b>xxv</b>
	<b>LIST OF APPENDICES</b>	<b>xxvii</b>
<b>CHAPTER 1</b>	<b>INTRODUCTION</b>	<b>1</b>
1.1	Research Background	1
1.2	Problem Statement	2
1.3	Research Questions and Objectives	4
1.4	Research Scopes and Limitations	5
1.5	Research Significance	6
1.6	Thesis Structure	6
1.7	Chapter Summary	7
<b>CHAPTER 2</b>	<b>LITERATURE REVIEW</b>	<b>9</b>
2.1	Introduction	9
2.2	Factors Affecting Thermal Comfort	9
2.2.1	Environmental Factors	10
2.2.1.1	Air and Mean Radiant Temperature	10
2.2.1.2	Relative Humidity	10
2.2.1.3	Air Velocity	11

2.2.2	Personal Factors	12
2.2.2.1	Metabolic Rate	12
2.2.2.2	Clothing Insulation	13
2.3	Thermal Comfort Model	14
2.3.1	Heat-balance theory	14
2.3.2	Predicted Mean Vote ( <i>PMV</i> )	16
2.3.3	Predicted Percentage of Dissatisfied ( <i>PPD</i> )	17
2.3.4	Adaptive Model	19
2.4	Indoor Environment Standards	20
2.5	Thermal Comfort in Air-Conditioned Office Buildings	24
2.5.1	Studies in Tropical and Subtropical Climates	24
2.5.2	Comparison of Preferred Temperature and Thermal Comfort	32
2.5.3	Effect of Contextual Factors on Thermal Comfort	32
2.6	Research Gaps	33
2.7	Chapter Summary	34
<b>CHAPTER 3</b>	<b>RESEARCH METHODOLOGY</b>	<b>35</b>
3.1	Overview	35
3.2	Geographical and Climate Description of Study Area	36
3.3	Investigated Buildings	38
3.3.1	Kuala Lumpur	40
3.3.1.1	Kuala Lumpur 1 (KL1)	40
3.3.1.2	Kuala Lumpur 2 (KL2)	44
3.3.1.3	Kuala Lumpur 3 (KL3)	45
3.3.2	Shah Alam	50
3.3.2.1	Shah Alam 1 (SA1)	51
3.3.2.2	Shah Alam 2 (SA2)	54
3.4	Field Study Process	56
3.4.1	Instrumentation	56
3.4.2	Set-point Temperature Conditions	59

3.4.3	Experimental Setup	59
3.4.4	Data Collection Method	61
3.4.5	Questionnaire Survey	67
3.5	Estimation of Thermal Comfort Parameters	69
3.5.1	Thermal Indices	69
3.5.2	Running Mean Outdoor Temperature	70
3.5.3	Absolute Humidity	70
3.5.4	Body Surface Area	71
3.5.5	Predicted Mean Vote and Predicted Percentage of Dissatisfied	72
3.6	Analytical Method	72
3.6.1	Regression Method	73
3.6.2	Probit Method	73
3.6.3	Griffiths' Method	74
3.6.4	Comparison with Related Standards	75
3.6.5	T-test and Analysis of Variance	75
3.7	Chapter Summary	76
<b>CHAPTER 4</b>	<b>EVALUATION OF RESULTS</b>	<b>77</b>
4.1	Introduction	77
4.2	Subjects' Information	77
4.2.1	Demographics Distribution	77
4.2.2	Anthropometric Data	80
4.2.3	Health Conditions	81
4.2.4	Clothing Insulation	82
4.2.5	Metabolic Rate	84
4.3	Outdoor Thermal Conditions	85
4.4	Indoor Thermal Conditions	87
4.4.1	Indoor Temperature	91
4.4.1.1	Indoor Air Temperature	91
4.4.1.2	Indoor Globe Temperature	93
4.4.1.3	Indoor Mean Radiant Temperature	95
4.4.1.4	Indoor Operative Temperature	97



4.4.1.5	Comparison of Indoor Thermal Indices	99
4.4.1.6	Comparison of Indoor and Outdoor Air Temperatures	103
4.4.1.7	Comparison of Indoor Air Temperature and AC Settings	104
4.5	Indoor Humidity	105
4.6	Indoor Air Velocity	110
4.7	Questionnaire Survey Results	113
4.7.1	Thermal Sensation Vote	115
4.7.2	Thermal Preference and Acceptance	117
4.7.3	Humidity Sensation and Preference	121
4.7.4	Air Movement and Acceptance	123
4.7.5	Overall Comfort	126
4.7.6	Adaptive Actions	127
4.8	Chapter Summary	128
<b>CHAPTER 5</b>	<b>DATA ANALYSIS AND DISCUSSIONS</b>	<b>129</b>
5.1	Introduction	129
5.2	Estimation of Comfort Temperature	129
5.3	Regression Method	130
5.3.1	Probit Method	133
5.3.2	Griffiths Method	138
5.3.3	Predicted Mean Vote and Percentage of Dissatisfied	144
5.3.3.1	Predicted Comfort Temperature	146
5.3.4	Comparison of Comfort Temperatures by All Methods	148
5.3.5	Comparison with Related Standards	149
5.3.5.1	ASHRAE Standard 55 Comfort Chart	150
5.4	Preferred Temperature	152
5.4.1	Probit Method	152
5.4.2	Linear Relationship with Comfort Temperature	154

5.4.3	Preferred Humidity	156
5.5	Effect of Characteristics on Thermal Comfort	157
5.5.1	Effect of Personal Characteristics on Comfort Temperature	157
5.5.2	Effect of Personal Characteristics on Subjective Responses	159
5.5.3	Effect of Building Characteristics on Comfort Temperature	161
5.5.4	Effect of Building Characteristics on Subjective Responses	164
5.6	Chapter Summary	166
<b>CHAPTER 6</b>	<b>CONCLUSIONS</b>	<b>167</b>
6.1	Introduction	167
6.2	Comfort temperature and its relation to standards	167
6.3	Preferred Temperature	168
6.4	Effects of Personal and Building Characteristics on Thermal Comfort	168
6.5	Implications of Study	170
6.5.1	Practical Implications	170
6.5.2	Theoretical Implications	171
6.6	Limitations of Study	171
6.7	Recommendations for Future Research	172
	<b>REFERENCES</b>	<b>173</b>
	<b>LIST OF PUBLICATIONS</b>	<b>233</b>

## LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	The effect of air speed on occupants	11
Table 2.2	Metabolic rate for sedentary activities	12
Table 2.3	Example of a typical clothing ensemble	13
Table 2.4	Existing cooling recommendations for indoor environment in buildings	23
Table 2.5	Thermal comfort studies in office buildings with air-conditioners or mechanical cooling in tropical and subtropical climates	29
Table 3.1	Investigated buildings in Kuala Lumpur and Shah Alam	39
Table 3.2	Details of investigated office in the ten-story KL1 building	41
Table 3.3	Details of investigated office in two-story KL2 building	45
Table 3.4	Details of the investigated offices in KL3	46
Table 3.5	Details of investigated offices in Shah Alam	51
Table 3.6	Specifications of instruments used in field measurement	57
Table 3.7	List of components used in Kuala Lumpur weather station	58
Table 3.8	Number of collected data and measurement duration	61
Table 3.9	Independent t-test of morning and afternoon sessions with $T_a$ and $TSV$	62
Table 3.10	Indoor air temperature variations respective to AC settings used in the investigated buildings	65
Table 3.11	Indoor air temperature for each set-point in investigated buildings	66
Table 3.12	Subjective evaluation scale survey used in this study	68
Table 4.1	Frequency and proportion of gender in studied locations	78
Table 4.2	Descriptive summary of age profile in each studied location	79
Table 4.3	Descriptive statistics of age, height, weight, $BMI$ , and Dubois' body surface area	80
Table 4.4	Proportion of health condition votes during the field study	81

Table 4.5	Descriptive summary of clothing insulation ( $I_{cl}$ ) by gender	83
Table 4.6	Descriptive summary of metabolic rate in each location	84
Table 4.7	Descriptive statistics of outdoor thermal indices during survey days	85
Table 4.8	Summary of indoor thermal environment conditions	88
Table 4.9	Descriptive summary of indoor air temperature	92
Table 4.10	Descriptive summary of indoor globe temperature	94
Table 4.11	Descriptive summary of indoor mean radiant temperature	96
Table 4.12	Descriptive summary of indoor operative temperature	98
Table 4.13	Regression equations of thermal indices	101
Table 4.14	Regression between indoor and outdoor air temperatures	103
Table 4.15	Regression between indoor air temperature and AC settings	104
Table 4.16	Descriptive summary of relative humidity	106
Table 4.17	Descriptive summary of absolute humidity	107
Table 4.18	Descriptive summary of indoor air velocity	111
Table 4.19	Summary of quantified subjective parameters in each study location	114
Table 4.20	Percentage of thermal sensation vote ( $TSV$ ) in each study location based on case studies	116
Table 4.21	Percentage of thermal preference ( $TP$ ) in each location	119
Table 4.22	Percentage of thermal acceptance ( $TA$ ) in each location	120
Table 4.23	Percentage of humidity sensation ( $HS$ ) in each study location	121
Table 4.24	Percentage of humidity preference ( $HP$ ) in each location	122
Table 4.25	Percentage of air movement vote ( $AMV$ ) in each location	124
Table 4.26	Percentage of air movement acceptance ( $AMA$ ) vote in each location	125
Table 4.27	Percentage of overall comfort ( $OC$ ) votes in each location	126
Table 5.1	Linear regression analysis of $TSV$ with indoor operative temperature	131
Table 5.2	Regression equation comparison of past and present studies in AC-operated office buildings	132

Table 5.3	Probit analysis of <i>TSV</i> and indoor operative temperature	134
Table 5.4	Comfort temperature using Griffith's method	139
Table 5.5	Comparison of Griffith's comfort temperature with neutral and comfortable votes	141
Table 5.6	Comparison of comfort temperature with existing studies in the tropics and subtropics offices via Griffiths' method	143
Table 5.7	Estimation of <i>PMV/PPD</i> alongside <i>TSV/APD</i>	144
Table 5.8	Regression analysis of <i>PMV</i> and indoor operative temperature	146
Table 5.9	Comparison of <i>PMV-T<sub>op</sub></i> regression analysis with previous studies in tropical and subtropical climate	147
Table 5.10	Comparison of comfort temperatures with mean indoor operative temperatures	149
Table 5.11	Probit analysis of preferred temperature	153
Table 5.12	Comparison of preferred temperature with existing studies	154
Table 5.13	Regression analysis between preferred and comfort temperature	155
Table 5.14	Probit analysis of preferred humidity	156
Table 5.15	T-test and one-way ANOVA analysis of respondent characteristics on comfort temperature and thermal parameters	158
Table 5.16	T-test and one-way ANOVA analysis of respondent characteristics on subjective votes	160
Table 5.17	T-test and one-way ANOVA analysis of office characteristics on comfort temperature and several thermal comfort parameters	163
Table 5.18	T-test and one-way ANOVA analysis of office characteristics on subjective votes	165

## LIST OF FIGURES

<b>FIGURE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
Figure 2.1	Correlation between predicted percentage of dissatisfied ( <i>PPD</i> ) and predicted mean vote ( <i>PMV</i> ) [13].	18
Figure 2.2	Psychrometric chart for indoor comfort zone taken from the ASHRAE Standard 55 for occupants with ( $1.0 < met < 1.3$ ) and ( $0.5 < clo < 1.0$ ) [14].	21
Figure 2.3	Comfort temperature range in office buildings taken from the CIBSE guideline [68].	22
Figure 3.1	Illustrated summary of the methodology applied in this study.	36
Figure 3.2	Map of field study location (Source: Google Maps (Accessed: 2 July 2020)).	37
Figure 3.3	The annual mean outdoor air temperature and relative humidity in Kuala Lumpur and Shah Alam. Error bars indicate the standard deviation.	38
Figure 3.4	Aerial view of UTMKL campus. Investigated buildings KL1, KL2, and KL3 are highlighted in green boxes (Source: Google Maps (Accessed: 13 August 2020)).	40
Figure 3.5	KL1 building façade.	41
Figure 3.6	Photo of working areas in a) KL1-a and b) KL1-b.	42
Figure 3.7	Layout plan of the interconnecting KL1-a and KL1-b office rooms.	42
Figure 3.8	Photo of a) working areas, and b) layout plan of investigated office on the fourth floor.	43
Figure 3.9	Photo of a) working areas, and b) layout plan of investigated office on the fifth floor.	43
Figure 3.10	KL2 building façade.	44
Figure 3.11	Photo of a) working areas, and b) layout plan of investigated office in KL2 building.	45
Figure 3.12	KL3 building façades.	46
Figure 3.13	Photos of working areas in a) KL3-a, b) KL3-b, c) KL3-c, d) KL3-d, and e) KL3-e.	47
Figure 3.14	Layout plan in a) KL3-a, b) KL3-b, and c) KL3-c.	48

Figure 3.15	Photo of working areas in private office a) KL3-d, and b) KL3-e.	48
Figure 3.16	Layout plan of private office a) KL3-d, and b) KL3-e.	48
Figure 3.17	Photo of a) working areas, and (b) layout plan of KL3-f.	49
Figure 3.18	Aerial view of investigated buildings in Shah Alam. SA1 is highlighted in a yellow ‘L’ perimeter, and SA2 is marked in a blue boundary (Source: Google Maps. (Accessed: 20 August 2020)).	50
Figure 3.19	a) North, and b) west façade of SA1 building.	52
Figure 3.20	Photos of the working areas in SA1-a.	52
Figure 3.21	Layout plan in office SA1-a.	52
Figure 3.22	Photos of working areas in SA1-b.	53
Figure 3.23	Layout plan in SA1-b.	53
Figure 3.24	a) and b) Photo of private offices’ working areas, and c) Layout plan of an average private office in SA1.	54
Figure 3.25	SA2 building façade.	55
Figure 3.26	Photos of working areas in SA2.	55
Figure 3.27	Layout plan in office SA2.	55
Figure 3.28	Instruments used in field measurement. a) TnD TR-77Ui, b) HOBO data logger, c) U12 TMC1-HD sensor, d) 4mm black sphere, and e) Kanomax 6501-G.	56
Figure 3.29	Photo of the weather station on the rooftop of KL1. a) Cup anemometer, rainfall gauge, and pyranometer setup, b) Temperature and relative humidity probe covered in solar radiation shield, and c) Datalogger.	58
Figure 3.30	Photo of a) instruments setup, and b) field measurement setup. The red dotted circle indicates the instrument setup in respondents’ working area.	60
Figure 3.31	Flowchart of field measurement in each set-point condition.	63
Figure 3.32	Photo of AC setting display. a) Prior measurement, and b) During measurement.	64
Figure 4.1	Percentages of gender profile for Kuala Lumpur and Shah Alam.	78
Figure 4.2	Distribution of age based on gender.	79
Figure 4.3	Percentage distribution of health condition votes.	82

Figure 4.4	Distribution of clothing insulation.	83
Figure 4.5	Distribution of metabolic rate.	84
Figure 4.6	Mean values of outdoor temperatures during survey days with 95% confidence intervals.	86
Figure 4.7	Histogram distribution of outdoor air temperature.	86
Figure 4.8	Histogram distribution of indoor air temperature ( $T_a$ ) sorted by set-point conditions.	93
Figure 4.9	Histogram of indoor globe temperature ( $T_g$ ) sorted by set-point conditions.	95
Figure 4.10	Histogram of indoor mean radiant temperature ( $T_{mrt}$ ) sorted by set-points.	97
Figure 4.11	Histogram of indoor operative temperature ( $T_{op}$ ) sorted by case studies and location.	99
Figure 4.12	Mean values of thermal indices with 95% confidence interval for Original, Original $\pm 2$ °C and MS Standard set-points.	100
Figure 4.13	Scatter plot of $T_g$ against $T_a$ with regression lines.	101
Figure 4.14	Scatter plot of $T_{mrt}$ against $T_a$ with regression lines.	102
Figure 4.15	Scatter plot of $T_{op}$ against $T_a$ with regression lines.	102
Figure 4.16	Scatterplot of indoor air temperature against outdoor air temperature for every set-points.	103
Figure 4.17	Scatter plot of AC settings against indoor air temperature.	104
Figure 4.18	Histogram distribution of indoor relative humidity.	108
Figure 4.19	Histogram distribution of absolute humidity.	108
Figure 4.20	Mean values of relative humidity ( $RH$ ) with 95% confidence intervals.	109
Figure 4.21	Mean values of absolute humidity ( $AH$ ) with 95% confidence intervals.	109
Figure 4.22	Scatter plot of absolute humidity ( $AH$ ) against relative humidity ( $RH$ ) with regression lines	110
Figure 4.23	Histogram of indoor air velocity.	112
Figure 4.24	Mean values of air velocity ( $V_a$ ) with 95% confidence intervals.	112
Figure 4.25	Distribution of thermal sensation vote ( $TSV$ ) votes.	117



Figure 4.26	Distribution of thermal preference ( <i>TP</i> ) and thermal acceptability ( <i>TA</i> ) votes.	118
Figure 4.27	Distribution of humidity sensation ( <i>HS</i> ) and humidity preference ( <i>HP</i> ) votes.	123
Figure 4.28	Distribution of air movement vote ( <i>AMV</i> ) and air movement acceptance ( <i>AMA</i> ) votes.	125
Figure 4.29	Percentage distribution of overall comfort ( <i>OC</i> ) votes.	127
Figure 4.30	Percentage of adaptive actions.	128
Figure 5.1	Scatter plot of <i>TSV</i> against indoor operative temperature. The black regression line represents the overall data.	131
Figure 5.2	Proportion of <i>TSV</i> votes with indoor operative temperature in Original set-point.	135
Figure 5.3	Proportion of <i>TSV</i> votes with indoor operative temperature in Original $-2$ °C set-point.	135
Figure 5.4	Proportion of <i>TSV</i> votes with indoor operative temperature in Original $+2$ °C set-point.	136
Figure 5.5	Proportion of <i>TSV</i> votes with indoor operative temperature in MS Standard set-point.	136
Figure 5.6	Proportion of <i>TSV</i> votes with indoor operative temperature of combined data.	137
Figure 5.7	Proportion of comfortable votes with relevant studies.	138
Figure 5.8	Griffiths' comfort temperatures of each set-point with 95% confidence intervals.	140
Figure 5.9	Griffiths' comfort temperatures of combined data with 95% confidence intervals.	140
Figure 5.10	Scatter plot of <i>PPD</i> against <i>PMV</i> .	145
Figure 5.11	Scatter plot of <i>APD</i> against <i>TSV</i> .	145
Figure 5.12	Scatter plot of <i>PMV</i> against $T_{op}$ in each set-points. Black regression line represents combined data.	147
Figure 5.13	Scatter plot of <i>TSV</i> and <i>PMV</i> against indoor operative temperature.	148
Figure 5.14	Comparison of estimated comfort temperatures with relevant standards.	150
Figure 5.15	Psychrometric chart based on ASHRAE Standard 55-2017 graphic comfort zone.	151
Figure 5.16	Proportion of preferred temperature of combined data.	153

Figure 5.17	Scatterplot between preferred temperature ( $TP =$ no change) and Griffith's comfort temperature with regression line.	155
Figure 5.18	Proportion of preferred humidity.	156

## 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 Percentage 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

$\Delta T$	-	Temperature difference (°C)
$a$	-	Griffiths' constant
$A_d$	-	Dubois body surface area (m <sup>2</sup> )
$AH$	-	Absolute humidity (g <sub>v</sub> /kg <sub>da</sub> )
$C$	-	Convective heat transfer per unit area (W/m <sup>2</sup> )
$D$	-	Diameter (m)
$e$	-	Euler's number
$\mathcal{E}$	-	Emissivity
$E$	-	Evaporative heat loss per unit body surface area (W/m <sup>2</sup> )
$f_{cl}$	-	Clothing area factor
$h$	-	Body height (m)
$h_c$	-	Convective heat transfer coefficient (W/m <sup>2</sup> K)
$I_{cl}$	-	Clothing insulation (clo)
$K$	-	Conductive heat loss per unit area (W/m <sup>2</sup> )
$L$	-	Energy loss to environment per unit area (W/m <sup>2</sup> )
$M$	-	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 <sup>2</sup> )
$Q_d$	-	Dry heat exchange (W/m <sup>2</sup> )
$R_v$	-	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 <sup>2</sup> )
$T_a$	-	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 <sup>2</sup> )
$w$	-	Body weight (kg)

## LIST OF APPENDICES

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
Appendix A	Instrument Verification Testing	185
Appendix B	Preliminary Measurement	219
Appendix C	Respondents Consent Form	221
Appendix D	Questionnaire Survey	222

# 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 ( $\pm 10.4$ ) 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.

## REFERENCES

1. The Japan Refrigeration and Air Conditioning Industry Association (JRAIA). World Air Conditioner Demand by Region [Internet]. The Japan Refrigeration and Air Conditioning Industry Association. 2019. Available from: [https://www.jraia.or.jp/english/World\\_AC\\_Demand.pdf](https://www.jraia.or.jp/english/World_AC_Demand.pdf)
2. Rodriguez CM, D'Alessandro M. Indoor thermal comfort review: The tropics as the next frontier. *Urban Clim* [Internet]. 2019;29(April):100488. Available from: <https://doi.org/10.1016/j.uclim.2019.100488>
3. Boranian AP, Zakirova B, Sarvaiya JN, Jadhav NY, Zhang Z, Pawar P. *Building Energy Efficiency: R&D Roadmap*. Singapore; 2013.
4. Hassan JS, Zin RM, Majid MZA, Balubaid S, Hainin MR. Building energy consumption in Malaysia: An overview. *J Teknol*. 2014;70(7):33–8.
5. Doan Q Van, Kusaka H, Ho QB. Impact of future urbanization on temperature and thermal comfort index in a developing tropical city: Ho Chi Minh City. *Urban Clim* [Internet]. 2016;17:20–31. Available from: <http://dx.doi.org/10.1016/j.uclim.2016.04.003>
6. Santamouris M, Cartalis C, Synnefa A, Kolokotsa D. On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings - A review. *Energy Build*. 2015 Jun 3;98:119–24.
7. Wu Z, Li N, Wargocki P, Peng J, Li J, Cui H. Field study on thermal comfort and energy saving potential in 11 split air-conditioned office buildings in Changsha, China. *Energy* [Internet]. 2019;182:471–82. Available from: <https://doi.org/10.1016/j.energy.2019.05.204>
8. Alajmi AF, Baddar FA, Bourisli RI. Thermal comfort assessment of an office building served by under-floor air distribution (UFAD) system - A case study. *Build Environ* [Internet]. 2015;85:153–9. Available from: <http://dx.doi.org/10.1016/j.buildenv.2014.11.027>
9. Kaushik A, Arif M, Tumula P, Ebohon OJ. Effect of thermal comfort on occupant productivity in office buildings: Response surface analysis. *Build Environ* [Internet]. 2020;180(November 2019):107021. Available from: <https://doi.org/10.1016/j.buildenv.2020.107021>

10. Frontczak M, Wargocki P. Literature survey on how different factors influence human comfort in indoor environments. *Build Environ*. 2011 Apr;46(4):922–37.
11. Fisk WJ, Black D, Brunner G. Changing ventilation rates in U.S. offices: Implications for health, work performance, energy, and associated economics. *Build Environ* [Internet]. 2012;47(1):368–72. Available from: <http://dx.doi.org/10.1016/j.buildenv.2011.07.001>
12. Lan L, Wargocki P, Wyon DP, Lian Z. Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance. *Indoor Air*. 2011 Oct;21(5):376–90.
13. Fanger PO. Thermal comfort. Analysis and applications in environmental engineering. *Therm Comf Anal Appl Environ Eng*. 1970;
14. American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE). *Thermal Environmental Conditions for Human Occupancy*. Atlanta; 2017.
15. Brager, G.S. and RJ de D. Center for the Built Environment UC Berkeley. *Energy Build*. 1998;45–9.
16. Damiani SA, Zaki SA, Rijal HB, Wonorahardjo S. Field study on adaptive thermal comfort in office buildings in Malaysia, Indonesia, Singapore, and Japan during hot and humid season. *Build Environ* [Internet]. 2016;109:208–23. Available from: <http://dx.doi.org/10.1016/j.buildenv.2016.09.024>
17. Humphreys MA, Fergus Nicol J. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy Build*. 2002;34(6):667–84.
18. Indraganti M, Ooka R, Rijal HB, Brager GS. Adaptive model of thermal comfort for offices in hot and humid climates of India. *Build Environ* [Internet]. 2014 Apr;74:39–53. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0360132314000055>
19. Khalid W, Zaki SA, Rijal HB, Yakub F. Investigation of comfort temperature and thermal adaptation for patients and visitors in Malaysian hospitals. *Energy Build* [Internet]. 2019;183:484–99. Available from: <https://doi.org/10.1016/j.enbuild.2018.11.019>
20. Mustapa MS, Zaki SA, Rijal HB, Hagishima A, Ali MSM. Thermal comfort and occupant adaptive behaviour in Japanese university buildings with free



- running and cooling mode offices during summer. *Build Environ* [Internet]. 2016;105:332–42. Available from: <http://dx.doi.org/10.1016/j.buildenv.2016.06.014>
21. Mustapa MS, Zaki SA, Ali MSM, Rijal HB. Investigation of thermal comfort at different temperature settings for cooling in university building. *J Mech Eng*. 2017;SI 4(4):123–34.
  22. He M, Li N, He Y, He D, Song C. The influence of personally controlled desk fan on comfort and energy consumption in hot and humid environments. *Build Environ*. 2017;123:378–89.
  23. Indraganti M, Boussaa D. An adaptive relationship of thermal comfort for the Gulf Cooperation Council (GCC) Countries: The case of offices in Qatar. *Energy Build* [Internet]. 2018;159:201–12. Available from: <http://dx.doi.org/10.1016/j.enbuild.2017.10.087>
  24. Tewari P, Mathur S, Mathur J, Kumar S, Loftness V. Field study on indoor thermal comfort of office buildings using evaporative cooling in the composite climate of India. *Energy Build* [Internet]. 2019;199:145–63. Available from: <https://doi.org/10.1016/j.enbuild.2019.06.049>
  25. Department of Standard Malaysia. MS 1525:2014: Energy efficiency and use of renewable energy for non-residential buildings - Code of practice. 2014;
  26. Wu Z, Li N, Wargocki P, Peng J, Li J, Cui H. Field study on thermal comfort and energy saving potential in 11 split air-conditioned office buildings in Changsha, China [Internet]. Vol. 182, *Energy*. Elsevier Ltd; 2019. 471–482 p. Available from: <https://doi.org/10.1016/j.energy.2019.05.204>
  27. Fang Z, Zhang S, Cheng Y, Fong AML, Oladokun MO, Lin Z, et al. Field study on adaptive thermal comfort in typical air conditioned classrooms. *Build Environ* [Internet]. 2018;133(February):73–82. Available from: <https://doi.org/10.1016/j.buildenv.2018.02.005>
  28. Shahzad S, Rijal HB. Preferred vs neutral temperatures and their implications on thermal comfort and energy use: Workplaces in Japan, Norway and the UK. *Energy Procedia* [Internet]. 2019;158:3113–8. Available from: <https://doi.org/10.1016/j.egypro.2019.01.1007>
  29. Shahzad S, Brennan J, Theodossopoulos D, Calautit JK, Hughes BR. Does a neutral thermal sensation determine thermal comfort? *Build Serv Eng Res Technol*. 2018;39(2):183–95.

30. Rupp RF, Vásquez NG, Lamberts R. A review of human thermal comfort in the built environment. *Energy Build* [Internet]. 2015;105:178–205. Available from: <http://dx.doi.org/10.1016/j.enbuild.2015.07.047>
31. Rupp RF, Kim J, de Dear R, Ghisi E. Associations of occupant demographics, thermal history and obesity variables with their thermal comfort in air-conditioned and mixed-mode ventilation office buildings. *Build Environ* [Internet]. 2018;135(March):1–9. Available from: <https://doi.org/10.1016/j.buildenv.2018.02.049>
32. Havenith G, Griggs K, Qiu Y, Dorman L, Kulasekaran V, Hodder S. Higher comfort temperature preferences for anthropometrically matched Chinese and Japanese versus white-western-middle-European individuals using a personal comfort / cooling system. *Build Environ* [Internet]. 2020;183(August):107162. Available from: <https://doi.org/10.1016/j.buildenv.2020.107162>
33. Hoyt T, Arens E, Zhang H. Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. *Build Environ* [Internet]. 2015;88:89–96. Available from: <http://dx.doi.org/10.1016/j.buildenv.2014.09.010>
34. Mui KW, Wong LT, Fong NK. Optimization of indoor air temperature set-point for centralized air-conditioned spaces in subtropical climates. *Autom Constr.* 2010 Oct;19(6):709–13.
35. Lu S, Wang W, Lin C, Hameen EC. Data-driven simulation of a thermal comfort-based temperature set-point control with ASHRAE RP884. *Build Environ* [Internet]. 2019;156(December 2018):137–46. Available from: <https://doi.org/10.1016/j.buildenv.2019.03.010>
36. Gauthier S. The role of environmental and personal variables in influencing thermal comfort indices used in building simulation. *Proc BS 2013 13th Conf Int Build Perform Simul Assoc.* 2013;2320–5.
37. de Dear RJ, Brager GS. Developing an adaptive model of thermal comfort and preference. *ASHRAE Trans.* 1998;104(Pt 1A):145–67.
38. Lin Z, Deng S. A study on the thermal comfort in sleeping environments in the subtropics-Developing a thermal comfort model for sleeping environments. *Build Environ.* 2008;43(1):70–81.
39. Hensen JLM. Literature review on thermal comfort in transient conditions. *Build Environ.* 1990;25(4):309–16.

40. Roy Choudhury AK, Majumdar PK, Datta C. Factors affecting comfort: human physiology and the role of clothing. *Improv Comf Cloth*. 2011 Jan 1;3–60.
41. Dryden IGC. *The efficient use of energy*. Butterworth-Heinemann; 2013.
42. Tredre BE. Assessment of mean radiant temperature in indoor environments. *Occup Environ Med*. 1965;22(1):58–66.
43. Li H. Impacts of Pavement Strategies on Human Thermal Comfort. *Pavement Mater Heat Isl Mitig*. 2016 Jan 1;281–306.
44. Wolkoff P, Kjærgaard SK. The dichotomy of relative humidity on indoor air quality. *Environ Int*. 2007;33(6):850–7.
45. Nicol F. Adaptive thermal comfort standards in the hot-humid tropics. *Energy Build*. 2004;36(7):628–37.
46. Rijal HB, Humphreys M, Nicol F. Adaptive thermal comfort in Japanese houses during the summer season: Behavioral Adaptation and the Effect of Humidity. *Buildings*. 2015;5(3):1037–54.
47. Luo M, Zhou X, Zhu Y, Sundell J. Revisiting an overlooked parameter in thermal comfort studies, the metabolic rate. *Energy Build* [Internet]. 2016;118:152–9. Available from: <http://dx.doi.org/10.1016/j.enbuild.2016.02.041>
48. Gagge AP, Burton AC, Bazett HC. A practical system of units for the description of the heat exchange of man with his environment. *Science* (80- ). 1941;94(2445):428–30.
49. Humphreys MA. Classroom Temperature, Clothing and Thermal Comfort--A Study of Secondary School Children in Summertime. *Building Research Establishment Current Paper 22/74*. Repr from *Build Serv Eng*. 1974;41:191–202.
50. Humphreys MA. Clothing and the outdoor microclimate in summer. *Build Environ*. 1977;12(3):137–42.
51. Parsons KC. The effects of gender, acclimation state, the opportunity to adjust clothing and physical disability on requirements for thermal comfort. *Energy Build*. 2002;34(6):593–9.
52. ISO. *ISO 7730: 2005: Ergonomics of the Thermal Environment. Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria*. International Standards Organization Geneva; 2005.

53. Nicol F, Roaf S. Pioneering new indoor temperature standards: the Pakistan project. *Energy Build.* 1996;23(3):169–74.
54. Liu W, Yang D, Shen X, Yang P. Indoor clothing insulation and thermal history: A clothing model based on logistic function and running mean outdoor temperature. *Build Environ* [Internet]. 2018;135(December 2017):142–52. Available from: <https://doi.org/10.1016/j.buildenv.2018.03.015>
55. Doherty TJ, Arens EA. Evaluation of the physiological bases of thermal comfort models UC Berkeley Indoor Environmental Quality ( IEQ ) University of California. *ASHRAE Trans.* 1988;94(January 1988).
56. Parsons K. *Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort, and performance.* CRC press; 2014.
57. Hausladen G. *Climate design: solutions for buildings that can do more with less technology.* Birkhauser; 2005.
58. McNall PE, Ryan PW, Rohles FH, Nevins RG, Springer WE. Metabolic rates at four activity levels and their relationship to thermal comfort. *ASHRAE Trans.* 1968;74(1).
59. Forgiarini Rupp R, Ghisi E. Predicting thermal comfort in office buildings in a Brazilian temperate and humid climate. *Energy Build* [Internet]. 2017;144:152–66. Available from: <http://dx.doi.org/10.1016/j.enbuild.2017.03.039>
60. Salam A, Rakshit D, Pun M, Babu S, Sarvaiya JN, Kumar DEVSK, et al. Evaluation of thermal comfort criteria of an active chilled beam system in tropical climate : A comparative study. *Build Environ* [Internet]. 2018;145(June):196–212. Available from: <https://doi.org/10.1016/j.buildenv.2018.09.025>
61. Markus TA, Morris EN, Reed PA. *Buildings, climate and energy.* Pitman London; 1980.
62. Djongyang N, Tchinda R, Njomo D. Thermal comfort: A review paper. *Renew Sustain Energy Rev.* 2010;14(9):2626–40.
63. Oseland NA. Predicted and reported thermal sensation in climate chambers, offices and homes. *Energy Build.* 1995;23(2):105–15.
64. Nicol JF, Humphreys MA. Thermal Comfort As Part of a Self-Regulating System. *Build Res Pr.* 1973;1(3):174–9.
65. De Dear R, Brager G, Donna C. Developing an adaptive model of thermal comfort and preference. Final Report ASHRAE RP-884. *ASHRAE Trans*

- [Internet]. 1997;104(Part 1):1–18. Available from: [https://escholarship.org/uc/item/4qq2p9c6.pdf%5Cnhttp://escholarship.org/uc/item/4qq2p9c6.pdf%5Cnhttp://repositories.cdlib.org/cedr/cbe/ieq/deDear1998\\_ThermComPref](https://escholarship.org/uc/item/4qq2p9c6.pdf%5Cnhttp://escholarship.org/uc/item/4qq2p9c6.pdf%5Cnhttp://repositories.cdlib.org/cedr/cbe/ieq/deDear1998_ThermComPref)
66. Cena K, De Dear R. Thermal comfort and behavioural strategies in office buildings located in a hot-arid climate. *J Therm Biol* [Internet]. 2001 [cited 2022 Feb 27];26(4–5):409–14. Available from: <https://researchers.mq.edu.au/en/publications/thermal-comfort-and-behavioural-strategies-in-office-buildings-lo>
  67. European Committee for Standardization (CEN). Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. EN 15251. 2007;
  68. Chartered Institution of Building Services Engineers (CIBSE). Environmental design: Guide A. CIBSE Guide A. 2006. 336 p.
  69. Humphreys M. Outdoor Temperatures and Comfort Indoors. *Batim Int Build Res Pr*. 1978;6(2):92.
  70. Auliciems A. Towards a psycho-physiological model of thermal perception. *Int J Biometeorol* [Internet]. 1981 Jun [cited 2022 Feb 27];25(2):109–22. Available from: <https://pubmed.ncbi.nlm.nih.gov/7019105/>
  71. Humphreys MA, Rijal HB, Nicol JF. Updating the adaptive relation between climate and comfort indoors; new insights and an extended database. *Build Environ* [Internet]. 2013;63:40–55. Available from: <http://dx.doi.org/10.1016/j.buildenv.2013.01.024>
  72. McCartney KJ, Fergus Nicol J. Developing an adaptive control algorithm for Europe. *Energy Build*. 2002;34(6):623–35.
  73. International Organization for Standardization (ISO). Energy performance of buildings — Methods for expressing energy performance and for energy. 2017;
  74. 2019 EN 16798-1: Energy Performance of Buildings—Ventilation for Buildings—Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics—Module M1-6. European Committee for Standardization Brussels, Belgium; 2019.
  75. Khovalyg D, Kazanci OB, Halvorsen H, Gundlach I, Bahnfleth WP, Toftum J,

- et al. Critical review of standards for indoor thermal environment and air quality. *Energy Build* [Internet]. 2020;213:109819. Available from: <https://doi.org/10.1016/j.enbuild.2020.109819>
76. Fukawa Y, Murakami R, Ichinose M. Field study on occupants' subjective symptoms attributed to overcooled environments in air-conditioned offices in hot and humid climates of Asia. *Build Environ* [Internet]. 2021;195(March):107741. Available from: <https://doi.org/10.1016/j.buildenv.2021.107741>
  77. Tsay YS, Chen R, Fan CC. Study on thermal comfort and energy conservation potential of office buildings in subtropical Taiwan. *Build Environ* [Internet]. 2022;208(June 2021):108625. Available from: <https://doi.org/10.1016/j.buildenv.2021.108625>
  78. Aryal A, Chaiwiwatworakul P, Chirarattananon S, Wongsuwan W. Subjective assessment of thermal comfort by radiant cooling in a tropical hot humid climate. *Energy Build* [Internet]. 2022;254:111601. Available from: <https://doi.org/10.1016/j.enbuild.2021.111601>
  79. De Vecchi R, Candido C, de Dear R, Lamberts R. Thermal comfort in office buildings: Findings from a field study in mixed-mode and fully-air conditioning environments under humid subtropical conditions. *Build Environ*. 2017;123:672–83.
  80. Sikram T, Ichinose M, Sasaki R. Assessment of Thermal Comfort and Building-Related Symptoms in Air-Conditioned Offices in Tropical Regions : A Case Study in Singapore and Thailand. 2020;6(November):1–16.
  81. Zhao Z, Houchati M, Beitelmal A. An Energy Efficiency Assessment of the Thermal Comfort in an Office building. *Energy Procedia* [Internet]. 2017;134:885–93. Available from: <https://doi.org/10.1016/j.egypro.2017.09.550>
  82. López-Pérez LA, Flores-Prieto JJ, Ríos-Rojas C. Adaptive thermal comfort model for educational buildings in a hot-humid climate. *Build Environ* [Internet]. 2019;150(December 2018):181–94. Available from: <https://doi.org/10.1016/j.buildenv.2018.12.011>
  83. Maykot JK, Rupp RF, Ghisi E. A field study about gender and thermal comfort temperatures in office buildings. *Energy Build*. 2018;178:254–64.
  84. Wu T, Cao B, Zhu Y. A field study on thermal comfort and air-conditioning

- energy use in an office building in Guangzhou. *Energy Build.* 2018;168:428–37.
85. Shahzad S, Calautit JK, Hughes BR, Satish BK, Rijal HB. Patterns of thermal preference and Visual Thermal Landscaping model in the workplace. *Appl Energy.* 2019;255(February).
  86. Hwang RL, Cheng MJ, Lin TP, Ho MC. Thermal perceptions, general adaptation methods and occupant’s idea about the trade-off between thermal comfort and energy saving in hot-humid regions. *Build Environ.* 2009;44(6):1128–34.
  87. Chow TT, Fong KF, Givoni B, Lin Z, Chan ALS. Thermal sensation of Hong Kong people with increased air speed, temperature and humidity in air-conditioned environment. *Build Environ.* 2010 Oct 1;45(10):2177–83.
  88. Lan L, Lian Z, Liu W, Liu Y. Investigation of gender difference in thermal comfort for Chinese people. *Eur J Appl Physiol* [Internet]. 2008 Mar [cited 2022 Mar 1];102(4):471–80. Available from: <https://pubmed.ncbi.nlm.nih.gov/17994246/>
  89. Byrne NM, Hills AP, Hunter GR, Weinsier RL, Schutz Y. Metabolic equivalent: one size does not fit all. *J Appl Physiol* [Internet]. 2005 Sep [cited 2022 Mar 1];99(3):1112–9. Available from: <https://pubmed.ncbi.nlm.nih.gov/15831804/>
  90. Indraganti M, Humphreys MA. A comparative study of gender differences in thermal comfort and environmental satisfaction in air-conditioned offices in Qatar, India, and Japan. *Build Environ* [Internet]. 2021;206(March):108297. Available from: <https://doi.org/10.1016/j.buildenv.2021.108297>
  91. Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World map of the Köppen-Geiger climate classification updated. *Meteorol Zeitschrift.* 2006;15(3):259–63.
  92. Malaysian Meteorological Department. *MetMalaysia* [Internet]. 2019 [cited 2021 May 28]. Available from: <https://www.met.gov.my/index.php>
  93. Google Map. Malaysia [Internet]. 2020 [cited 2020 Feb 2]. Available from: <https://www.google.com/maps/place/Malaysia/@4.1143706,100.5550206,5z/data=!4m5!3m4!1s0x3034d3975f6730af:0x745969328211cd8!8m2!3d4.210484!4d101.975766>
  94. Google Earth. UTM Kuala Lumpur [Internet]. 2020 [cited 2020 Aug 13]. Available from: [https://www.google.com.my/maps/place/UTM+Kuala+Lumpur/@3.1732889,](https://www.google.com.my/maps/place/UTM+Kuala+Lumpur/@3.1732889)

- 101.7190992,17z/data=!4m5!3m4!1s0x31cc37e8de0a443f:0x9e772d5b7ac66d27!8m2!3d3.1729407!4d101.7209231
95. Mcneil S, Bulletin T, Zealand N. The Thermal Properties of Wool Carpets. Tech Bull AgResearch, Christchurch, New Zealand [Internet]. 2016;(March). Available from: [www.agresearch.co.nz](http://www.agresearch.co.nz)
  96. Google Earth. Universiti Teknologi MARA Shah Alam [Internet]. 2020 [cited 2020 Aug 20]. Available from: <https://www.google.com.my/maps/place/Universiti+Teknologi+MARA+Shah+Alam/@3.0697294,101.5014839,17z/data=!3m1!4b1!4m5!3m4!1s0x31cc528b5e947345:0xe8520627500cb672!8m2!3d3.069724!4d101.5036726>
  97. TWC Product and Technology LLC. Local Weather Forecast, News and Conditions | Weather Underground [Internet]. 2021 [cited 2019 Oct 31]. Available from: <https://www.wunderground.com/>
  98. Wang D, Chen G, Song C, Liu Y, He W, Zeng T, et al. Experimental study on coupling effect of indoor air temperature and radiant temperature on human thermal comfort in non-uniform thermal environment. Build Environ [Internet]. 2019;165(August):106387. Available from: <https://doi.org/10.1016/j.buildenv.2019.106387>
  99. Chui AC, Gittelsohn A, Sebastian E, Stamler N, Gaffin SR. Urban heat islands and cooler infrastructure – Measuring near-surface temperatures with hand-held infrared cameras. Urban Clim. 2018;24:51–62.
  100. Oliveira AVM, Raimundo AM, Gaspar AR, Quintela DA. Globe Temperature and Its Measurement: Requirements and Limitations. Ann Work Expo Heal. 2019;63(7):743–58.
  101. Cash TF. Encyclopedia of Body Image and Human Appearance. Vols. 1–2, Encyclopedia of Body Image and Human Appearance. Elsevier Inc.; 2012.
  102. Zaki SA, Damiati SA, Rijal HB, Hagishima A, Abd Razak A. Adaptive thermal comfort in university classrooms in Malaysia and Japan. Build Environ [Internet]. 2017;122:294–306. Available from: <http://dx.doi.org/10.1016/j.buildenv.2017.06.016>
  103. American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE). 2005 ASHRAE Handbook: Fundamentals. S.I. ed. Atlanta GA.: ASHRAE; 2005.
  104. Nevins R. Temperature-Humidity Chart for Thermal Comfort of Seated Persons.



- ASHRAE Trans., 1966;72:283–91.
105. Finney DJ. Probit Analysis, Cambridge University Press. J Pharm Sci. 1971;
  106. Griffiths ID. Thermal comfort studies in buildings with passive solar features, field studies. Rep to Comm Eur Community. 1990;35.
  107. Griffiths ID, McIntyre DA. Sensitivity to temporal variations in thermal conditions. Ergonomics. 1974;17(4):499–507.
  108. Nicol F, Jamy GN, Sykes O, Humphreys M, Roaf S, Hancock M. A survey of thermal comfort in Pakistan toward new indoor temperature standards. Final Rep to Overseas Dev Adm Publ by Oxford Brookes Univ Sch Archit UK. 1994;
  109. Nicol F, Humphreys M. Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. Build Environ [Internet]. 2010;45(1):11–7. Available from: <http://dx.doi.org/10.1016/j.buildenv.2008.12.013>
  110. Azmi MY, Junidah R, Siti Mariam A, Safiah MY, Fatimah S, Norimah AK, et al. Body mass index (BMI) of adults: Findings of the Malaysian Adult Nutrition Survey (MANS). Malays J Nutr. 2009;15(2):97–119.
  111. Makaremi N, Salleh E, Jaafar MZ, GhaffarianHoseini AH. Thermal comfort conditions of shaded outdoor spaces in hot and humid climate of Malaysia. Build Environ [Internet]. 2012;48(1):7–14. Available from: <http://dx.doi.org/10.1016/j.buildenv.2011.07.024>