EFFECTIVENESS OF PASSIVE COOLING STRATEGIES OF INDOOR THERMAL CONDITIONS FOR TERRACE HOUSE UNDER HOT AND HUMID CLIMATE

NG WAI TUCK

UNIVERSITI TEKNOLOGI MALAYSIA

EFFECTIVENESS OF PASSIVE COOLING STRATEGIES OF INDOOR THERMAL CONDITIONS FOR TERRACE HOUSE UNDER HOT AND HUMID CLIMATE

NG WAI TUCK

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

Razak Faculty of Technology and Informatics
Universiti Teknologi Malaysia

JANUARY 2021

DEDICATION

This thesis is dedicated to my parents, who gave me the breath to open my mind and soul of knowledge.

ACKNOWLEDGEMENT

I started this research five years ago at the age of 48, with very limited knowledge in research. From excitement to lost and back to hope, I wish to express my sincere appreciation and thanks to my research supervisor, Assoc. Prof. Dr. Sheikh Ahmad Zaki bin Shaikh Salim, for his encouragement, guidance, critics and friendship. Without him, I won't be able to complete my research and writing this thesis. I am also very thankful to Professor Dr. Aya Hagishima from Kyushu University, Japan, Professor Dr. Hom Bahadur Rijal from Tokyo City University, Yokohama, Japan, and Dr. Mohd Azuan Zakaria from Universiti Tun Hussein Onn Malaysia, Johor, Malaysia for their guidance, advices and motivation. Without their continued support and interest, this thesis would not have been the same as presented here.

My fellow postgraduate student should also be recognised for their support. My sincere appreciation also extends to all my colleagues and others who have helped at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my family member.

It is also dedicated to my family, my wife Poh Moi, my daughter Jie Yi, and my son Jia Hua who have gave me their full support and encouragement for the last five years along my journey of research.

ABSTRACT

Global warming has caused the air temperature to increase and this has a serious impact on the urban area whereby causing heat wave during the summer in temperate climate area and all year long in tropical region. In Malaysia, heat wave has caused residential buildings especially terrace houses in urban areas to experience thermal discomfort. Passive cooling strategies such as natural ventilation and building retrofit method is proven to be a more effective method to resolve thermal discomfort. Therefore, the objective of this study is to assess the performance of passive cooling with different natural ventilation and building retrofit methods on improving the indoor thermal conditions for terrace house in hot and humid climate conditions. The performance of each method was assessed based on the estimated operative temperature (T_{op}) in the building and compared with American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55, European Standard EN15251, and adaptive thermal comfort equation (ACE) developed from ASHRAE RP-884 database for hot and humid climate. The field measurement to measure the thermal conditions of the house was conducted in two stages in a corner terrace house located in Kuala Lumpur, Malaysia. Climatic data that influenced the T_{op}, such as outdoor and indoor air temperature, relative humidity, outdoor wind velocity, indoor air velocity, indoor globe temperature, and outdoor solar radiation were measured. In the first stage, four types of natural ventilation which were full day ventilation (FV), full day no ventilation (WV), day ventilation (DV), and night ventilation (NV) were adopted to evaluate the performance of different natural ventilation strategies. The measurement was conducted in all rooms on the first floor. In the latter stage, the measurement was carried out in the master bedroom located on the first floor due to its west facing orientation and it being the hottest part in the investigated house. A study of four approaches on natural ventilation combined with different building retrofit methods which are high density polyethylene (HDPE) nets as roof cover, heat insulation above ceiling, and active cooling method with ceiling fan were conducted to analyse how each combination of methods assist in the thermal performance of the room. The results from the first stage showed that the mean indoor temperature under natural ventilation was approximately 27–37 °C, and FV and DV recorded better correlation between outdoor and indoor temperature compared with WV and NV. Although natural ventilation could improve the thermal condition in the room, but it was still not enough to achieve the acceptable indoor thermal condition under relevant international standards. The use of roof cover in the second stage reduced convective heat flux of approximately 70–80% in the attic and 88% in the room. Meanwhile, the mean of daytime air temperature in the room was reduced approximately 1°C. However, the heat insulation layer above the ceiling did not contribute much in improving thermal condition of the room during daytime. Whereas the thermal condition in the room became worse during night time due to the heat trapped by this heat insulation layer. As a conclusion, a roof cover with HDPE nets managed to improve the compliance on ACE hot and humid climate from 38% with only natural ventilation to 48% after a roof cover was added on the roof. Due to the effectiveness of improving the thermal condition in the house, this passive cooling method employing a roof cover with HDPE nets has the potential for further research and to be developed as a passive building retrofit method for low-cost landed houses with roof tiles in Southeast Asia such as in Indonesia and Thailand.

ABSTRAK

Pemanasan global telah menyebabkan suhu udara bertambah di kawasan bandar dan memberi kesan yang serius melalui gelombang haba semasa musim panas di kawasan iklim empat musim dan sepanjang tahun di kawasan tropika. Di Malaysia, gelombang haba telah menyebabkan bangunan kediaman terutamanya rumah teres di kawasan bandar menghadapi ketidakselesaan haba. Strategi penyejukan pasif, seperti kaedah pengudaraan semula jadi dan pengubahsuaian bangunan telah terbukti sebagai kaedah yang lebih berkesan untuk menyelesaikan ketidakselesaan haba. Oleh itu, tujuan penyelidikan ini adalah untuk menilai pencapaian strategi penyejukan pasif dengan beberapa kaedah pengudaraan semula jadi dan kaedah pengubahsuaian bangunan bagi rumah teres di kawasan iklim panas dan lembab. Pencapaian setiap kaedah dinilai berasaskan suhu pengendalian (T_{op}) dalam bangunan dan dibandingkan dengan *American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55, European Standard EN15251*, dan persamaan keselesaan haba penyesuaian (ACE) dibangunkan daripada pangkalan data *ASHRAE RP-884* untuk iklim panas dan lembab. Pengukuran keadaan haba dijalankan dalam dua peringkat di sebuah rumah teres lot tepi terletak di Kuala Lumpur, Malaysia. Data cuaca yang mempengaruhi T_{op}, seperti suhu udara, kelembapan relatif dalaman dan luaran, kelajuan angin luaran dan udara dalaman, suhu globe dan sinaran matahari telah diukur. Pada peringkat pertama, empat kes pengudaraan semula jadi telah dikaji, iaitu pengudaraan sepanjang hari (FV), tanpa pengudaraan sepanjang hari (WV), pengudaraan waktu siang (DV), dan pengudaraan pada waktu malam (NV). Pengukuran telah dijalankan dalam semua bilik di tingkat atas rumah. Pada peringkat kedua, pengukuran hanya dijalankan dalam bilik tidur utama di tingkat atas, dengan alasan bahawa bilik itu menghadap arah barat dan merupakan bilik yang paling panas dalam bangunan itu. Empat kaedah penyelidikan dengan pengudaraan semula jadi digabungkan dengan pelbagai kaedah pengubahsuaian bangunan, iaitu penutup bumbung dengan jaring polyethylene (HDPE) ketumpatan tinggi, penebat haba atas siling, dan cara penyejukan aktif dengan kipas siling telah digunakan untuk mengkaji bagaimana setiap kaedah gabungan dapat memperbaiki prestasi haba dalam bilik. Dapatan kajian daripada peringkat pertama menunjukkan purata suhu dalam bilik di bawah kaedah pengudaraan semula jadi adalah kira-kira 27–37 °C, dan FV dan DV menunjukkan korelasi yang lebih baik antara suhu dalaman dengan luaran dibandingkan dengan WV dan NV. Sungguhpun pengudaraan semula jadi boleh memperbaiki keadaan haba dalam bilik, namun tidak mencukupi untuk mencapai keperluan keadaan haba dalaman di bawah piawaian antarabangsa berkenaan. Penggunaan penutup bumbung pada peringkat kedua dapat mengurangkan fluks haba konveksi sebanyak 70–80% di dalam loteng dan 88% di dalam bilik. Pada masa yang sama, purata suhu udara dalam bilik pada waktu siang telah dikurangkan kira-kira 1°C. Penambahan lapisan penebat haba di atas siling bukan sahaja tidak dapat menyumbang kepada pembaikan keadaan haba dalam bilik pada waktu siang, bahkan keadaan haba dalam bilik menjadi lebih teruk pada waktu malam disebabkan oleh pemerangkapan haba oleh lapisan penebatan haba ini. Apabila keputusan penyelidikan dibandingkan dengan penutup bumbung dengan jaring HDPE dapat memperbaiki pematuhan kepada ACE iklim panas dan lembab, daripada 38% dengan pengudaraan semula jadi sahaja kepada 48% selepas penutup bumbung ditambah di atas bumbung. Disebabkan kecekapan peningkatan keselesaan haba dalam rumah, dan kaedah yang senang untuk membina penutup bumbung dengan jaring HDPE, kaedah penyejukan pasif ini mempunyai potensi untuk penyelidikan masa depan dan dibangunkan sebagai kaedah pengubahsuaian pasif untuk rumah kos rendah dengan atap bumbung di Asia Tenggara, seperti di Indonesia dan Thailand.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	-	Air-Conditioner
ACE	-	Adaptive Thermal Comfort Equation
ACH	-	Air Change Rate Per Hour
ASHRAE	-	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFD	-	Computational Fluid Dynamics
CO_2	-	Carbon-Dioxide
DV	-	Day Ventilation
FV	-	Full Ventilation
FV-R	-	Full Day Free Running Ventilation with Retrofit Roof Cover
FV-R-C	-	Full Day Free Running Ventilation with Roof Cover and Heat Insulation Above Ceiling
FV-R-C-F	-	Full Day Free Running Ventilation with Roof Cover, Heat Insulation Above Ceiling, and Mechanical Ventilation with Ceiling Fan
HDPE	-	High Density Polyethylene
IPCC	-	Intergovernmental Panel on Climate Change
Low-E	-	Low-Emissivity
MJIIT	-	Malaysia-Japan International Institute of Technology
NIR	-	Near Infrared
NV	-	Night Ventilation
PV	-	Photovoltaic
RPM	-	Round Per Minute
UHI	-	Urban Heat Island
UTM	-	Universiti Teknologi Malaysia
WV	-	Without Ventilation

LIST OF SYMBOLS

a	-	Solar absorptivity
AH	-	Absolute humidity (g/kg_{DA})
f	-	Decrement factor
h	-	Convection heat transfer coefficient ($W/m^2 \cdot K$)
q_h	-	Convective heat fluxes (W/m^2)
R^2	-	Coefficient of determination
RH_i	-	Indoor relative humidity (%)
RH_o	-	Outdoor relative humidity (%)
SR	-	Solar radiation (W/m^2)
ΔT	-	Temperature difference (°C)
T_a	-	Air temperature (°C)
T_{ag}	-	Air temperature of air gap (°C)
T_{comfop}	-	Indoor neutral comfort temperature (°C)
T_{csb}	-	Bottom surface temperature of ceiling (°C)
T_{cst}	-	Top surface temperature of ceiling (°C)
T_{eff}	-	Equivalent outdoor temperature (°C)
T_g	-	Globe temperature (°C)
T_i	-	Indoor air temperature (°C)
$T_{i,max}$	-	Maximum daily indoor air temperature (°C)
$T_{i,min}$	-	Minimum daily indoor air temperature (°C)
T_{mrt}	-	Mean radian temperature (°C)
T_o	-	Outdoor air temperature (°C)
$T_{o,max}$	-	Maximum daily outdoor air temperature (°C)
$T_{o,min}$	-	Minimum daily outdoor air temperature (°C)
T_{op}	-	Comfort temperature (°C)
T_{outmm}	-	Daily mean outdoor air temperature (°C)
T_r	-	Attic air temperature (°C)
T_{rc}	-	Surface temperature of roof cover (°C)
T_{rsb}	-	Bottom surface temperature of roof tiles (°C)
T_{rst}	-	Top surface temperature of roof tiles (°C)

T_{wse}	-	External surface temperature of wall (°C)
T_{wsi}	-	Internal surface temperature of wall (°C)
U	-	Thermal transmittance ($W/m^2 \cdot K$)
V_i	-	Indoor air velocity (m/s)
V_o	-	Outdoor wind speed (m/s)

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

Global warming is always a main environmental issue since the industrialization era [1]. It has caused the global air temperature increased 0.85 °C from 1880 to 2012 [2]. Increase of global temperature has a serious impact to the urban area with heat wave during summer in temperate climate region and all year long in tropical region [3]. Heat wave has caused a lot of people died due to heat stroke [4], especially in urban area with high population density and limited outdoor green open space to reduce the impact of heat wave.

In hot and humid regions, such as Malaysia, the average daily air temperature is between 21 °C and 32 °C [5]. According to Malaysian Metrological Department [6], in 2019, the average temperature was 27.63 °C, and was 0.69 °C above normal temperature of 26.94 °C. Furthermore, Malaysia was hit twice by heat wave in 2019 with a recorded maximum daily temperature between 37.1 °C to 38.0 °C. This has triggered the alert level (daily maximum temperature 35 °C to 37 °C) on the temperature in the country. However, as easy solution to the critical condition of the temperature, urban dwellers will choose to stay indoors and switch on the air-conditioner (AC) system to remove heat and maintain indoor thermal environment as well as to fight the heat wave and avoid heat stroke [7, 8]. The adoption of active cooling system by using AC has caused the energy consumption increased rapidly in urban area [9]. Usage of AC is only solving the problem of heat wave, but the increase of electrical energy consumption has caused another environmental issue. Generation of electrical power will increase the emission of carbon-dioxide (CO_2) into the environment and make the global warming issue become worse [3]. This cycle of environmental problem will continue growing like a snowball and need immediate intervention to stop the cycle. A better approach to resolve the thermal issue is by using passive cooling strategy that using minimum energy, such as natural ventilation to remove heat and heat preventive method using building retrofitting strategies to improve indoor thermal conditions and achieve thermal comfort, instead of using AC.

Indoor thermal conditions of a building are affected by the air temperature, surrounding surface temperature, humidity and air movement. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [10] defined thermal environment as the environment conditions that affect a person's heat loss. For a person to feel thermally comfortable, where a person is satisfied with the ambient temperature, ASHRAE [10] defined this as the condition of the mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.

Comfortable thermal conditions can be achieved either by active or passive cooling [11]. Active cooling methods are defined as mechanical equipment to satisfy the needs of cooling within a building that not provided by nature. Active methods use electricity and heat as power source. The most used equipment in the residential buildings are fans, evaporative coolers and heat pumps [11]. Meanwhile, passive cooling in building design is an approach that managing heat gain and heat dissipation in a building in order to improve indoor thermal environment and achieve thermal comfort with low or no energy consumption [12]. They work either by removing heat from the building to a natural heat sink (sky, earth, air and water) using natural ventilation or by preventing heat from entering the building (thermal insulation and shading) from external heat sources.

Natural ventilation defined as natural forces (winds and thermal buoyancy force) due to the difference of outdoor and indoor air pressure that drive outdoor air through openings on building envelope. The openings include doors, windows, wind towers, solar chimneys and ventilators [13]. Natural ventilation utilizes onsite energy from the natural environment, combined with the passive cooling features of building components on the building envelope to remove heat from the building [13, 14].

Heat preventive methods in building design is focuses on heat gain control in a building in order to improve the indoor thermal comfort with low or no energy consumption. Prevention of heat gains encompasses all the design techniques and building retrofitting techniques that minimizes the impact of solar heat gains through the building's envelope by installation of heat insulation layer or shading devices [12].

In comparison between active and passive cooling methods on factors of energy consumption, maintenance, retrofitting and required space, passive cooling is found to be the most suitable method for residential buildings [11]. The recommended passive cooling methods are night ventilation, controlled ventilation, shading system, roof coating, building colour and eco-evaporative cooling.

In the previous study on passive cooling [15–19], most of the studies are concentrated in temperate climate regions with moderate annual temperatures, with average monthly temperatures above 10 °C in their warmest months and above -3 °C in their colder months. However, in hot and humid climate regions with a high average daily temperature up to 21 °C to 32 °C and facing serious impact of heat wave issue, very limited studies on how passive cooling can assist in improving indoor thermal conditions can be found [7, 20]. The existing studies in hot and humid climate regions are generally on natural ventilation [7] to remove heat from the building and not on building retrofitting methods that preventing heat from entering the building.

In addition to the passive cooling methods, building types and building forms is also an important factor affecting the thermal performance of the building [21]. Terrace house formed 36.4% of total living quarters in Malaysia *(Population and Housing Census of Malaysia 2010)*, and 47.8% of new launches in Malaysia *(Residential, Commercial and Industrial properties Status report 2018)*. The impact of solar heat gains through building’s envelope is high on terrace house with high ratio of exposure on external wall and roof to the sunlight [22]. In addition, terrace house also facing a low air velocity of 04-0.6 m/s as reported by Kubota and Ahmad [23]. Although terrace houses are one of the common residential building in Malaysia, however, the study is still very limited and required further exploration.

A further investigation on the effectiveness of passive cooling using different building retrofitting methods and natural ventilation strategies to the thermal conditions of terrace houses under hot and humid climate is required. The effectiveness of each passive cooling method was measured by comparing the percentage of compliance of the calculated indoor operative temperature (T_{op}) to the predicted T_{op} under the relevant international adaptive comfort standards. The findings of this type of study will contributed to the improvement of terrace house design and invention of new approach to resolve thermal comfort in terrace house by using building retrofitting methods, instead of conventional passive cooling with natural ventilation approach.

1.2 Problem Statement

As reported by Malaysian Metrological Department annual report, in 2019, the average temperature in Malaysia was 27.63 °C, it was 0.69 °C higher than the normal temperature of 26.94 °C recorded in previous years. In addition to the rise of temperature, Malaysia was hit twice by heat wave in 2019 with a recorded maximum daily temperature between 37.1 °C to 38.0 °C. The recorded extremely high temperature has triggered the alert on the high temperature in the country. The alert level on daily maximum temperature set in Malaysia is 35 °C to 37 °C.

Further to that, the report by United Nations on world energy consumption, electricity contributed 19% of total world energy consumption, and 27% of it was used by households. Space cooling is the fastest growing use of energy in buildings. Another report by International Energy Agency on world energy consumption reported the share of cooling in total energy use in buildings rose from about 2.5% to 6% from 1990 to 2016. In case of a tropical country such as Malaysia, in year 2016, 11% of electricity consumed in residential sector is for space cooling purpose.

This fraction is expected to increase due to the increase of dependency of air-conditioners to achieve thermal comfort accompanied by the economic growth as well as future climate change. The high cost on installation of AC and high energy consumption of this active cooling system is not an environmentally friendly system and not an affordable system to low-income people. On the other hand, considering the persistent gap between rich and poor in developing countries, it is highly likely that low-income people will remain to be exposed to the heat risk elevated by global climate change.

Under these circumstances, to resolve this problem, simple effective and low-cost cooling strategies for residential buildings located in tropical developing countries are strongly needed. Passive cooling strategy without using much energy was the common approach as solution to resolve the high cost and high energy consumption due to active cooling in buildings. Passive cooling strategies that commonly used are provision of cross natural ventilation through the building as cooling agent to remove trapped heat in the building, installation of cool roof to reduce transmission of heat from roof to the building, and provision of shading device on the wall and windows to avoid direct heat transmission from the sunlight to the building.

In recent years, smart-house technologies, which consist of various energy-efficient appliances, roof-top photovoltaic (PV) solar panels, and home energy management systems, have attracted social attention to achieve the energy saving, low carbon, and comfort indoor environment. However, such cutting-edge technologies are still not affordable for most developing countries due to the financial conditions. Although it is already widely known that solar heat gain through the roof is major in low-rise terrace house, and solar shielding of roof should contribute to the reduction of primary heat gain in low-rise buildings, but this common knowledge has not been implemented as affordable design for houses in many developing countries. It is the gap between knowledge in academic community and the construction industry and policy makers.

Therefore, in this research, the main objective is to develop a low-cost passive cooling method that easy to apply to residential buildings in tropical developing countries. The study was conducted through field measurement to collect real data on how the indoor thermal conditions was changed upon application of different natural ventilation strategies and simple building retrofitting methods to the building. The results were compared to the relevant international adaptive comfort standards by comparing the T_{op} in the building. The effectiveness of each passive cooling method was measured by comparing the percentage of compliance of the calculated indoor T_{op}

to the predicted T_{op} under the relevant international standards. ASHRAE defined T_{op} as the uniform temperature of an imaginary black enclosure and air within in which an occupant would exchange same amount of heat by radiation and convection as in the actual non-uniform environment. In building design, T_{op} can be defined as the average of the mean radiant and ambient air temperatures, weighted by their respective heat transfer coefficients. The best performance method with higher compliance with the standards was concluded at the end of this study to introduce a low-cost and easy passive cooling method for residential building in hot and humid climate countries.

1.3 Research Questions

Based on the problems identified in problem statement, the research questions of this study were established as follows:

(a) How different natural ventilation strategies by opening window at daytime and night time affected the operative temperature in terrace house under hot and humid climate?

(b) Will a natural ventilated terrace house required additional building retrofitting method to compliment the thermal conditions?

(c) What is the level of compliance of these passive cooling strategies, when comparing with the relevant international standards on thermal comfort?

1.4 Research Objectives

After summarized the background of the problem and to answer the research questions, three objectives in this research are:

(a) To evaluate the performance on thermal conditions (air temperature, relative humidity, air velocity) of passive cooling with different natural ventilation strategies for terrace house under hot and humid climate.

(b) To assess the performance on thermal conditions (air temperature, relative humidity, air velocity) of passive cooling with different building retrofitting methods for terrace house under hot and humid climate.

(c) To analyse the indoor thermal comfort level of the proposed passive cooling strategies based on international adaptive comfort standards.

1.5 Research Scope

Literature reviews on previous research on passive cooling and building retrofit for residential buildings was performed. Field measurement was conducted in a two-storey terrace house in Kuala Lumpur, Malaysia in tropical region with hot and humid climate. The measurement was conducted in two stages. In the first stage, four natural ventilation strategies: without ventilation, full ventilation, day ventilation and night ventilation were studied to evaluate the thermal performance of the house based on the operative temperature. First stage was conducted for four weeks from February to March 2018 to measure air temperature, globe temperature, relative humidity, air velocity in the house; besides surface temperature of ceiling, roof and external wall were measured. Simultaneously, outdoor air temperature, relative humidity and wind speed were measured. Operative temperature was calculated based on the measured data to check on the compliance to the international adaptive comfort standards. In later stage with building retrofitting methods, four cases with different combination of building retrofitting strategies were studied. The same parameters of measurement were carried out for 14 weeks from September to December 2018 and followed by the same study on compliance of operative temperature to international adaptive comfort standards.

1.6 Significance of Research

The findings of this study provide data towards future house design with passive cooling strategies by adopting different ventilation modes and building retrofitting. The findings can be applied to a terrace house design, and particularly to window design, to control natural ventilation in residential buildings. Furthermore, a low cost and low technology passive cooling method using building retrofitting was proposed. This method of passive cooling will benefit landed low cost houses in hot-humid regions, especially from developing countries, such as Malaysia, Indonesia and Thailand. Besides that, at remote area without electricity to use fan or air-conditioner, roof cover is an effective passive cooling method to be applied.

1.7 Organization of Thesis

This thesis was compiled in seven chapters.

Chapter 1 introduces the thesis with an overview to the thesis, problem background, problem statement, research questions, research objectives, research scope, significance of research, and organization of the thesis.

In Chapter 2, a review on the literature related to this research topic. particularly on passive cooling on residential buildings, various types of air ventilation, and building retrofitting method. At the end of this chapter, research gap was identified.

Chapter 3 describes the research methods applied in this research. The location, details and climatic description of the investigated house were mentioned. Field measurement process including preparation of equipment, setup of equipment, stages of data collection, and method of data analysis were comprehensively explained.

Chapter 4 presents the results from stage 1 measurement on natural ventilation strategies and follows by discussion on findings from the analysis of the data. The indoor and outdoor thermal conditions of the investigated house under different natural ventilation strategies were analysed, compared and discussed. Furthermore, vertical profile of indoor air temperature under natural ventilation and mixed-mode ventilation were compared. Influence of surface temperature on indoor air temperature was analysed. Stage 1 was summarised based the first objective of this research.

Chapter 5 presents the results from stage 2 measurement on four cases with different combination of natural ventilation, building retrofitting methods, and active cooling method. The indoor and outdoor thermal conditions of the investigated master bedroom under different cases were analysed, compared, and discussed. Relationship between indoor and outdoor air temperature, comparison between indoor and outdoor thermal conditions, comparison on vertical temperature profile under different building retrofitting methods, and effect of roof cover on indoor thermal environments were analysed and discussed. Based on the summary, this chapter summarised the achievement of second objective of this research.

Chapter 6 presented the analysis and discussion of this research on different natural ventilation strategies and building retrofitting methods in comparison to relevant international standards using adaptive comfort standards. The percentage of compliance from each strategy and method was discussed. The achievement on the third objective of this research was discussed at the end of this chapter.

Chapter 7 summarise the research outcomes and conclusions drawn. The significance contribution and application of the findings are discussed. Finally, future works from this research were proposed.

REFERENCES

1. Abram NJ, Helen V, Tierney JE, Evans MN, Nicholas P. Early onset of industrial-era warming across the oceans and continents. Nature. 2016;536:411–8.
2. United Nations. Climate Change [Internet]. 2018. Available from: http://www.un.org/en/sections/issues-depth/climate-change/
3. Mccarthy MP, Best MJ, Betts RA. Climate change in cities due to global warming and urban effects. Geophysical Research Letters. 2010;37:1–5.
4. Center for Climate and Energy Solutions. Heat Waves and Climate Change [Internet]. [cited 2019 Aug 25]. Available from: https://www.c2es.org/content/heat-waves-and-climate-change/
5. MyGOV - Malaysia Information | Climate [Internet]. [cited 2020 Oct 29]. Available from: https://www.malaysia.gov.my/portal/content/144
6. Annual Report 2019 Malaysian Metrological Department. Vol. 51. 2019.
7. Kubota T, Chyee DTH, Ahmad S. The effects of night ventilation technique on indoor thermal environment for residential buildings in hot-humid climate of Malaysia. Energy and Buildings. 2009;41(8):829–39.
8. Imessad K, Derradji L, Messaoudene NA, Mokhtari F, Chenak A, Kharchi R. Impact of passive cooling techniques on energy demand for residential buildings in a Mediterranean climate. Renewable Energy. 2014;71:589–97.
9. Tewari M, Salamanca F, Martilli A, Treinish L, Mahalov A. Impacts of projected urban expansion and global warming on cooling energy demand over a semiarid region. Royal Meteorological Society. 2017;426:419–26.
10. ANSI/ASHRAE Standard 55-2013: Thermal environmental conditions for human occupancy. United States of America: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2013 p. 431–9.
11. Oropeza-Perez I, Østergaard PA. Active and passive cooling methods for dwellings: A review. Renewable and Sustainable Energy Reviews. 2018;82(September 2017):531–44.
12. Samuel DGL, Nagendra SMS, Maiya MP. Passive alternatives to mechanical air conditioning of building: Areview. Building and Environment. 2013;66:54–

64.

13. Atkinson J, Chartier Y, Pessoa-Silva CL, Jensen P, Li Y, Seto W-H. Concepts and types of ventilation [Internet]. World Health Organization; 2009 [cited 2019 Sep 26]. Available from: https://www.ncbi.nlm.nih.gov/books/NBK143277/

14. Ardalan Aflaki, Norhayati Mahyuddin, Zakaria Al-Cheikh Mahmoud MRB. A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. Energy and Buildings. 2015;101:153–62.

15. Zingre KT, Yang E, Pun Wan M. Dynamic thermal performance of inclined double-skin roof : modeling and experimental investigation. Energy [Internet]. 2017;133:900–12. Available from: http://dx.doi.org/10.1016/j.energy.2017.05.181

16. Grygierek K, Ferdyn-Grygierek J. Multi-objectives optimization of ventilation controllers for passive cooling in residential buildings. Sensors (Switzerland). 2018;18(4).

17. Alam M, Sanjayan J, Zou PXW, Ramakrishnan S, Wilson J. Evaluating the passive and free cooling application methods of phase change materials in residential buildings: A comparative study. Energy and Buildings [Internet]. 2017;148:238–56. Available from: http://dx.doi.org/10.1016/j.enbuild.2017.05.018

18. Pisello AL, Castaldo VL, Fabiani C, Cotana F. Investigation on the effect of innovative cool tiles on local indoor thermal conditions: Finite element modeling and continuous monitoring. Building and Environment [Internet]. 2016;97:55–68. Available from: http://dx.doi.org/10.1016/j.buildenv.2015.11.038

19. Schelbach S. Developing a method to improve the energy efficiency of modern buildings by using traditional passive concepts of resource efficiency and climate adaptation. International Journal of Sustainable Development and Planning. 2016;11(1):23–38.

20. Khalid W, Zaki SA, Rijal HB, Yakub F. Investigation of comfort temperature and thermal adaptation for patients and visitors in Malaysian hospitals. Energy and Buildings [Internet]. 2019;183:484–99. Available from: https://doi.org/10.1016/j.enbuild.2018.11.019

21. Taleghani M, Kleerekoper L, Tenpierik M, Van Den Dobbelsteen A. Outdoor

thermal comfort within five different urban forms in the Netherlands. Building and Environment [Internet]. 2015;83:65–78. Available from: http://dx.doi.org/10.1016/j.buildenv.2014.03.014

22. Kubota T, Chyee DTH. Potential of passive cooling techniques for modern houses in the tropical climate of malaysia - Analysis of the indoor thermal environment for various ventilation strategies. International Journal of Ventilation. 2010;9(1):11–24.

23. Kubota T, Ahmad S. Wind Environment Evaluation of Neighborhood Areas in Major Towns of Malaysia. Journal of Asian Architecture and Building Engineering. 2006;(May):199–206.

24. Global warming of 1.5 °C [Internet]. Intergovernmental Panel on Climate Change. 2019. Available from: https://www.ipcc.ch/sr15/

25. World Health Organization. Information and public health advice: heat and health [Internet]. [cited 2020 Jan 5]. Available from: https://www.who.int/globalchange/publications/heat-and-health/en/

26. Chenvidhya T, Seapan M, Parinya P, Wiengmoon B, Chenvidhya D, Songprakorp R, et al. Investigation of power values of PV rooftop systems based on heat gain reduction. In: 8th Reliability of Photovoltaic Cells, Modules, Components and Systems Conference. SPIE - The International Society for Optical Engineering; 2015.

27. Osório GJ, Shafie-Khah M, Carvalho GCR, Catalão JPS. Analysis application of controllable load appliances management in a smart home. Energies. 2019;12(19):1–24.

28. Al Essa MJM. Home energy management of thermostatically controlled loads and photovoltaic-battery systems. Energy [Internet]. 2019;176:742–52. Available from: https://doi.org/10.1016/j.energy.2019.04.041

29. Taleb HM. Using passive cooling strategies to improve thermal performance and reduce energy consumption of residential buildings in U.A.E. buildings. Frontiers of Architectural Research [Internet]. 2014;3(2):154–65. Available from: http://dx.doi.org/10.1016/j.foar.2014.01.002

30. Harkouss F, Fardoun F, Biwole PH. Passive design optimization of low energy buildings in different climates. Energy [Internet]. 2018;165:591–613. Available from: https://doi.org/10.1016/j.energy.2018.09.019

31. Macias M, Gaona JA, Luxan JM, Gomez G. Low cost passive cooling system

for social housing in dry hot climate. Energy and Buildings. 2009;41:915–21.
32. Rabani M, Madessa HB, Nord N. A state-of-art review of retrofit interventions in buildings towards nearly zero energy level. Energy Procedia [Internet]. 2017;134(1876):317–26. Available from: https://doi.org/10.1016/j.egypro.2017.09.534
33. Ma Z, Cooper P, Daly D, Ledo L. Existing building retrofits: Methodology and state-of-the-art. Energy and Buildings. 2012;55:889–902.
34. Synnefa A, Santamouris M, Akbari H. Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. Energy and Buildings. 2007;39(11):1167–74.
35. Borderon J, Virgone J, Cantin R. Modeling and simulation of a phase change material system for improving summer comfort in domestic residence. Applied Energy [Internet]. 2015;140:288–96. Available from: http://dx.doi.org/10.1016/j.apenergy.2014.11.062
36. Saffari M, de Gracia A, Fernández C, Cabeza LF. Simulation-based optimization of PCM melting temperature to improve the energy performance in buildings. Applied Energy [Internet]. 2017;202:420–34. Available from: http://dx.doi.org/10.1016/j.apenergy.2017.05.107
37. Dabaieh M, Wanas O, Hegazy MA, Johansson E. Reducing cooling demands in a hot dry climate: A simulation study for non-insulated passive cool roof thermal performance in residential buildings. Energy and Buildings [Internet]. 2015;89:142–52. Available from: http://dx.doi.org/10.1016/j.enbuild.2014.12.034
38. Pisello AL, Cotana F. The thermal effect of an innovative cool roof on residential buildings in Italy: Results from two years of continuous monitoring. Energy and Buildings [Internet]. 2014;69:154–64. Available from: http://dx.doi.org/10.1016/j.enbuild.2013.10.031
39. Pisello AL, Rossi F, Cotana F. Summer and winter effect of innovative cool roof tiles on the dynamic thermal behavior of buildings. Energies. 2014;7(4):2343–61.
40. Benhammou M, Draoui B, Hamouda M. Improvement of the summer cooling induced by an earth-to-air heat exchanger integrated in a residential building under hot and arid climate. Applied Energy [Internet]. 2017;208(September):428–45. Available from:

https://doi.org/10.1016/j.apenergy.2017.10.012
41. Son MH. Field evaluation of reflective insulation in south east Asia. Open Engineering. 2017;352–62.
42. Michael A, Demosthenous D, Philokyprou M. Natural ventilation for cooling in Mediterranean climate : a case study in vernacular architecture of Cyprus. Energy & Buildings. 2017;144:333–45.
43. Bayoumi M. Improving natural ventilation conditions on semi-outdoor and indoor levels in warm-humid climates. Buildings. 2018;8(6):1–15.
44. Santamouris M, Sfakianaki A, Pavlou K. On the efficiency of night ventilation techniques applied to residential buildings. Energy and Buildings [Internet]. 2010;42(8):1309–13. Available from: http://dx.doi.org/10.1016/j.enbuild.2010.02.024
45. Maragogiannis K, Kolokotsa D, Maria EA. Study of Night Ventilation Efficiency in Urban Environment: Technical and Legal Aspects. Environmental and Climate Technologies. 2011;6(1):49–56.
46. Psomas T, Heiselberg P, Lyme T, Duer K. Automated roof window control system to address overheating on renovated houses: Summertime assessment and intercomparison. Energy and Buildings [Internet]. 2017;138:35–46. Available from: http://dx.doi.org/10.1016/j.enbuild.2016.12.019
47. Teh KS, Yarbrough DW, Lim CH, Salleh E. Reflective insulation for energy conservation in south east Asia. IOP Conference Series: Earth and Environmental Science. 2017;63(1).
48. Koenders SJM, Loonen RCGM, Hensen JLM. Investigating the potential of a closed-loop dynamic insulation system for opaque building elements. Energy and Buildings [Internet]. 2018;173:409–27. Available from: https://doi.org/10.1016/j.enbuild.2018.05.051
49. Stazi F, Tomassoni E, Di Perna C. Super-insulated wooden envelopes in Mediterranean climate: Summer overheating, thermal comfort optimization, environmental impact on an Italian case study. Energy and Buildings [Internet]. 2017;138:716–32. Available from: http://dx.doi.org/10.1016/j.enbuild.2016.12.042
50. Hudobivnik B, Pajek L, Kunič R, Košir M. FEM thermal performance analysis of multi-layer external walls during typical summer conditions considering high intensity passive cooling. Applied Energy. 2016;178:363–75.

51. Pisello AL. Experimental analysis of cool traditional solar shading systems for residential buildings. Energies. 2015;8(3):2197–210.
52. Omar I, Virgone J, David D, Corre O Le. Energy saving potential with a double-skin roof ventilated by natural convection in Djibouti. Energy Procedia [Internet]. 2017;140:361–73. Available from: https://doi.org/10.1016/j.egypro.2017.11.149
53. Abuseif M, Gou Z. A review of roofing methods: construction features, heat reduction, payback period and climatic responsiveness. Energies. 2018;
54. Zingre KT, Pun M, Khian S, Boo W, Toh T, Yen I, et al. Modelling of cool roof performance for double-skin roofs in tropical climate. Energy [Internet]. 2015;82:813–26. Available from: http://dx.doi.org/10.1016/j.energy.2015.01.092
55. Januševičius K, Streckiene G. Solar assisted ground source heat pump performance in nearly zero energy building in Baltic countries. Environmental and Climate Technologies. 2013;11(1):48–56.
56. Yan H, Yang L, Zheng W, He W, Li D. Analysis of behaviour patterns and thermal responses to a hot-arid climate in rural China. Journal of Thermal Biology [Internet]. 2016;59:92–102. Available from: http://dx.doi.org/10.1016/j.jtherbio.2016.05.004
57. Staszczuk A, Wojciech M, Kuczyński T. The effect of floor insulation on indoor air temperature and energy consumption of residential buildings in moderate climates. Energy. 2017;138:139–46.
58. Zhang K, Zhao D, Yin X, Yang R, Tan G. Energy saving and economic analysis of a new hybrid radiative cooling system for single-family houses in the USA. Applied Energy [Internet]. 2018;224(April):371–81. Available from: https://doi.org/10.1016/j.apenergy.2018.04.115
59. Abdallah ASH. A new design of passive air condition integrated with solar chimney for hot arid region of Egypt. International Journal of Environmental Science and Technology [Internet]. 2019;16(6):2611–8. Available from: https://doi.org/10.1007/s13762-018-1804-x
60. Maciel ACF, Carvalho MT. Operational energy of opaque ventilated façades in Brazil. Journal of Building Engineering [Internet]. 2019;25(April):100775. Available from: https://doi.org/10.1016/j.jobe.2019.100775
61. Hasan MI, Noori SW. A study of the potential of using the Earth to air heat

exchanger for cooling and heating of residential buildings in Iraq. Heat Transfer - Asian Research. 2019;48(8):3902–27.

62. Lapisa R, Karudin A, Rizal F, Krismadinata, Nasruddin. Passive cooling strategies in roof design to improve the residential building thermal performance in tropical region. Asian Journal of Civil Engineering [Internet]. 2019;20(4):571–80. Available from: https://doi.org/10.1007/s42107-019-00125-1

63. Hassan AS, Ramli M. Natural Ventilation of Indoor Air Temperature : A Case Study of the Traditional Malay House in Penang. American J of Engineering and Applied Sciences. 2010;3(3):521–8.

64. Mohamed MF, King S, Behnia M, Prasad D. A study of single-sided ventilation and provision of balconies in the context of high-rise residential buildings. 1954;1954–61.

65. Jamaludin AA, Hussein H, Mohd Ariffin AR, Keumala N. A study on different natural ventilation approaches at a residential college building with the internal courtyard arrangement. Energy and Buildings [Internet]. 2014;72:340–52. Available from: http://dx.doi.org/10.1016/j.enbuild.2013.12.050

66. Micallef D, Buhagiar V, Borg SP. Cross-ventilation of a room in a courtyard building. Energy and Buildings [Internet]. 2016;133:658–69. Available from: http://dx.doi.org/10.1016/j.enbuild.2016.09.053

67. Varela-Boydo CA, Moya SL. Inlet extensions for wind towers to improve natural ventilation in buildings. Sustainable Cities and Society [Internet]. 2020;53(November 2019):101933. Available from: https://doi.org/10.1016/j.scs.2019.101933

68. Grigoropoulos E, Anastaselos D, Nižetić S, Papadopoulos AM. Effective ventilation strategies for net zero-energy buildings in Mediterranean climates. International Journal of Ventilation. 2017;16(4):291–307.

69. Evola G, Gagliano A, Marletta L, Nocera F. Controlled mechanical ventilation systems in residential buildings: Primary energy balances and financial issues. Journal of Building Engineering [Internet]. 2017;11(December 2016):96–107. Available from: http://dx.doi.org/10.1016/j.jobe.2017.04.010

70. Al-Obaidi KM, Ismail M, Abdul Rahman AM. A comparative study between unvented and vented attics powered by the hybrid turbine ventilator in Malaysian houses. International Journal of Sustainable Energy.

2016;35(2):148–60.

71. Shahdan MS, Ahmad SS, Hussin MA. External shading devices for energy efficient building. IOP Conference Series: Earth and Environmental Science. 2018;117(1).

72. Nagahama T, Sato T, Harima T, Shimizu J. Optical properties and field test results of spectrally-selective solar control window film that enables not increasing downward reflection. Energy and Buildings [Internet]. 2017;157:176–83. Available from: https://doi.org/10.1016/j.enbuild.2017.01.037

73. Kachkouch S, Ait-nouh F, Benhamou B, Limam K. Experimental assessment of thermal performance of three passive cooling techniques for roofs in a semi-arid climate. Energy & Buildings [Internet]. 2018;164:153–64. Available from: https://doi.org/10.1016/j.enbuild.2018.01.008

74. Lee KR, Seong JH, Han YK, Lee WH. Comparison of rooftop surface temperature and indoor temperature for the evaluation of cool roof performance according to the rooftop colors in summer: Using thermal infrared camera mounted on UAV. Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography. 2019;37(1):9–18.

75. Dominguez A, Kleissl J, Luvall JC. Effects of solar photovoltaic panels on roof heat transfer. Solar Energy [Internet]. 2011;85(9):2244–55. Available from: http://dx.doi.org/10.1016/j.solener.2011.06.010

76. Taylor ST, Persily AK, Burge H, Daynard R, Fanger PO, Fickes EA, et al. Ventilation for Acceptable Indoor Air Quality. 1999;1999:404–636.

77. Sustainable Schools - Ventilation and Ventilation Systems [Internet]. 2019 [cited 2019 Sep 26]. Available from: https://www.dgsapps.dgs.ca.gov/DSA/SustainableSchools/sustainabledesign/ieq/iaq/ventilation.html

78. Wind ventilation and cross ventilation | BUILD [Internet]. 2019 [cited 2019 Sep 26]. Available from: https://build.com.au/wind-ventilation-and-cross-ventilation

79. Ismail M, Malek A, Rahman A. Stack ventilation strategies in architectural context : a brief review of historical development. International Journal of Recent Research and Applied Studies. 2012;11(May):291–301.

80. Cross Ventilation in House Designs for Natural Passive Air Flow | HubPages

[Internet]. [cited 2019 Sep 26]. Available from: https://hubpages.com/living/Cross-Ventilation-in-House-designs-for-Natural-Passive-Air-Flow

81. Lai D, Qi Y, Liu J, Dai X, Zhao L, Wei S. Ventilation behavior in residential buildings with mechanical ventilation systems across different climate zones in China. Building and Environment [Internet]. 2018;143(May):679–90. Available from: https://doi.org/10.1016/j.buildenv.2018.08.006
82. Khan N, Su Y, Riffat SB, Biggs C. Performance testing and comparison of turbine ventilators. Renewable Energy. 2008;33(11):2441–7.
83. Al-Obaidi KM, Ismail M, Abdul Rahman AM. A review of the potential of attic ventilation by passive and active turbine ventilators in tropical Malaysia. Sustainable Cities and Society [Internet]. 2014;10:232–40. Available from: http://dx.doi.org/10.1016/j.scs.2013.10.001
84. Nejat P, Jomehzadeh F, Abd. Majid MZ Bin, Mohd Yusof MB, Zeynali I. Windcatcher as sustainable passive cooling solution for natural ventilation in hot humid climate of Malaysia. IOP Conference Series: Materials Science and Engineering. 2019;620:012087.
85. Sun Control and Shading Devices | WBDG - Whole Building Design Guide [Internet]. [cited 2019 Nov 3]. Available from: https://www.wbdg.org/resources/sun-control-and-shading-devices
86. Kisilewicz T, Fedorczak-Cisak M, Barkanyi T. Active thermal insulation as an element limiting heat loss through external walls. Energy and Buildings. 2019;205.
87. Somasundaram S, Chong A, Wei Z, Thangavelu SR. Energy saving potential of low-e coating based retrofit double glazing for tropical climate. Energy and Buildings [Internet]. 2020;206:109570. Available from: https://doi.org/10.1016/j.enbuild.2019.109570
88. Boafo FE, Ahn JG, Kim SM, Kim JH, Kim JT. Fenestration refurbishment of an educational building: Experimental and numerical evaluation of daylight, thermal and building energy performance. Journal of Building Engineering [Internet]. 2019;25(May):100803. Available from: https://doi.org/10.1016/j.jobe.2019.100803
89. Bitaab M, Hosseini Abardeh R, Movahhed S. Experimental and numerical study of energy loss through double-glazed windows. Heat and Mass

Transfer/Waerme- und Stoffuebertragung. 2019;
90. Friess WA, Rakhshan K. A review of passive envelope measures for improved building energy efficiency in the UAE. Renewable and Sustainable Energy Reviews. 2017;72(November 2016):485–96.
91. Ichinose M, Inoue T, Nagahama T. Effect of retro-reflecting transparent window on anthropogenic urban heat balance. Energy and Buildings [Internet]. 2017;157:157–65. Available from: https://doi.org/10.1016/j.enbuild.2017.01.051
92. Inoue T, Shimo T, Ichinose M, Takase K, Nagahama T. Improvement of urban thermal environment by wavelength-selective retro-reflective film. Energy Procedia [Internet]. 2017;122:967–72. Available from: https://doi.org/10.1016/j.egypro.2017.07.447
93. Toe DHC, Kubota T. Comparative assessment of vernacular passive cooling techniques for improving indoor thermal comfort of modern terraced houses in hot-humid climate of Malaysia. Solar Energy [Internet]. 2015;114:229–58. Available from: http://dx.doi.org/10.1016/j.solener.2015.01.035
94. Taylor APR. A comparative analysis of a white-roof installation during a New Zealand autumn and winter. International Journal of Sustainable Building Technology and Urban Development. 2016;7(1):52–60.
95. Osma-Pinto G, Ordóñez-Plata G. Measuring factors influencing performance of rooftop PV panels in warm tropical climates. Solar Energy [Internet]. 2019;185(April):112–23. Available from: https://doi.org/10.1016/j.solener.2019.04.053
96. Muhammad-sukki F, Ramirez-iniguez R, Abu-bakar SH, Mcmeekin SG, Stewart BG. An evaluation of the installation of solar photovoltaic in residential houses in Malaysia : past, present, and future. Energy Policy [Internet]. 2011;39(12):7975–87. Available from: http://dx.doi.org/10.1016/j.enpol.2011.09.052
97. Malaysia SEDA. Go solar and save on your electricity bill [Internet]. 2019 [cited 2019 Jun 23]. Available from: http://www.seda.gov.my/2019/05/go-solar-and-save-on-your-electricity-bill/
98. Department of Statistics Malaysia Official Portal [Internet]. 2017 [cited 2019 Aug 15]. Available from: https://www.dosm.gov.my/v1/index.php?r=column/cthemeByCat&cat=120&b

ul_id=RUZ5REwveU1ra1hGL21JWVlPRmU2Zz09&menu_id=amVoWU54UTl0a21NWmdhMjFMMWcyZz09

99. Mistriotis A, Hemming S, Waaijenberg D. Plastic nets in agriculture: a general review of types and applications. Applied Engineering in Agriculture. 2008;24(6):799–808.

100. Soni P, Salokhe VM, Tantau HJ. Effect of screen mesh size on vertical temperature distribution in naturally ventilated tropical greenhouses. Biosystem Engineering. 2005;92(4):469–82.

101. Pérez-Andreu V, Aparicio-Fernández C, Martínez-Ibernón A, Vivancos J-L. Impact of climate change on heating and cooling energy demand in a residential building in a Mediterranean climate. Energy [Internet]. 2018 Dec;165:63–74. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0360544218317754

102. Kubota T, Chyee DTH, Ahmad S. The effects of night ventilation technique on indoor thermal environment for residential buildings in hot-humid climate of Malaysia. Energy and Buildings. 2009;41(8):829–39.

103. Krzaczek M, Florczuk J, Tejchman J. Field investigations of stack ventilation in a residential building with multiple chimneys and tilted window in cold climate. Energy & Buildings. 2015;103:48–61.

104. Yang T, Clements-Croome DJ. Natural ventilation in built environment. Vol. 10, Sustainable Built Environments. Springer Science; 2013. 394–424 p.

105. European Committee for Standardization. DS/EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Geneva: International Standard Organization [Internet]. 2007;54. Available from: http://sd.ds.dk.globalproxy.cvt.dk/Viewer?ProjectNr=M204572&Status=60.61&VariantID=&Page=0

106. Toe DHC, Kubota T. Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot-humid climates using ASHRAE RP-884 database. Frontiers of Architectural Research [Internet]. 2013;2(3):278–91. Available from: http://dx.doi.org/10.1016/j.foar.2013.06.003

107. Suruhan Tenaga Malaysia. National energy balance 2016 [Internet]. 2016. Available from: http://meih.st.gov.my/documents/10620/9a9314a1-cf11-4640-

a9de-3b31f336a416
108. Residential, commercial and industrial properties status report 2018. Malaysia: Pusat Maklumat Harta Tanah Negara, Jabatan Penilaian dan Perkhidmatan Harta, Kementerian Kewangan Malaysia; 2018.
109. Lee YY, Lee YH, Mohammad S, Shek PN, Ma CK. Thermal characteristics of a residential house in a new township in Johor Bahru. Institute of Physics (IOP) Conference Series: Materials Science and Engineering. 2017;271(1).
110. Hooff T Van, Blocken B, Timmermans HJP, Hensen JLM. Analysis of the predicted effect of passive climate adaptation measures on energy demand for cooling and heating in a residential building. Energy. 2016;94:811–20.
111. Swarno HA, Zaki SA, Yusup Y, Ali MSM, Ahmad NH. Observation of diurnal variation of urban microclimate in Kuala Lumpur, Malaysia. Chemical Engineering Transactions [Internet]. 2017;56:523–8. Available from: http://www.aidic.it/cet/17/56/088.pdf
112. UAC Berhad. UCO-Supeflex [Internet]. 2019 [cited 2019 Jun 6]. Available from: http://uac.com.my/wp-content/uploads/2017/08/UCO-Supeflex.pdf
113. Kabre C. A new thermal performance index for dwelling roofs in the warm humid tropics. Building and Environment [Internet]. 2010;45(3):727–38. Available from: http://dx.doi.org/10.1016/j.buildenv.2009.08.017
114. Saidur R, Hasanuzzaman M, Hasan MM, Masjuki HH. Overall thermal transfer value of residential buildings in Malaysia. Journal of Applied Sciences. 2009;9(11):2130–6.
115. Department of Standards Malaysia. Malaysian Standard energy for residential buildings - Code of practice. Malaysia; 2017.
116. Seong Aun C. Green Building Index – Ms1525. 2009.
117. Pyranometer CMP11 Instruction Manual. Kipp & Zonen; 2016.
118. Zakaria MA, Kubota T, Chyee Toe DH, Ahmad MH. Full-scale experiment on energy-saving modifications for urban houses in hot-humid climate of Malaysia. PLEA Conference Proceedings: Design to Thrive. 2017;III.
119. Cui S, Cohen M, Stabat P, Marchio D. CO2 tracer gas concentration decay method for measuring air change rate. Building and Environment. 2015;84:162–9.
120. ANSI/ASHRAE Standard 62.1-2010: Ventilation for Acceptable Indoor Air Quality. ASHRAE United States of America: American Society of Heating,

Refrigerating and Air-Conditioning Engineers; 2010.
121. Thermal comfort in ASHRAE fundamentals handbook (SI). United States of America: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); 2005.
122. Krüger E. Estimation of relative humidity for thermal comfort assessment. Proceedings of the Seventh International IBPSA Conference Building Simulation. 2001;2:765–72.
123. Muzathik A. Potential of Global Solar Radiation in Terengganu, Malaysia. International Journal of Energy Engineering [Internet]. 2013;3(January 2013):130–6. Available from: http://www.researchgate.net/publication/259479366_Potential_of_Global_Solar_Radiation_in_Terengganu_Malaysia/file/72e7e52c144b87b365.pdf
124. Sendanayake S, Miguntanna NP, Jayasinghe MTR. Predicting solar radiation for tropical islands from rainfall data. Journal of Urban and Environmental Engineering. 2015;9(2):109–18.
125. Bevilacqua P, Mazzeo D, Bruno R, Arcuri N. Experimental investigation of the thermal performances of an extensive green roof in the Mediterranean area. Energy and Buildings [Internet]. 2016;122:63–79. Available from: http://dx.doi.org/10.1016/j.enbuild.2016.03.062
126. EnergyPlus (US Department of Energy). Engineering Reference. EnergyPlus, US Department of Energy; 2019. p. 119.
127. Al-Saud KA. Measured versus calculated roof peak sol-air temperature in hot-arid regions. 2009;21(1):1–7.
128. ASHRAE Handbook Fundamentals. ASHRAE; 2017.
129. Monier concrete roof tiles [Internet]. 2019 [cited 2019 Jul 6]. Available from: https://www.monier.com.au/products/concrete-tiles/elabana
130. Toe DHC, Kubota T. Comparative assessment of vernacular passive cooling techniques for improving indoor thermal comfort of modern terraced houses in hot-humid climate of Malaysia. Solar Energy [Internet]. 2015;114:229–58. Available from: http://dx.doi.org/10.1016/j.solener.2015.01.035
131. Zaki SA, Fadhilah N, Hanip M, Hagishima A, Yakub F. Survey of Resident Behaviour Related to Air Conditioner Operation in Low-Cost Apartments of Kuala Lumpur. Chemical Engineering Transactions. 2018;63:259–64.
132. Kubota T, Zakaria MA, Abe S, Toe DHC. Thermal functions of internal

courtyards in traditional Chinese shophouses in the hot-humid climate of Malaysia. Building and Environment [Internet]. 2017;112:115–31. Available from: http://dx.doi.org/10.1016/j.buildenv.2016.11.005

133. Kontoleon KJ, Bikas DK. The effect of south wall's outdoor absorption coefficient on time lag, decrement factor and temperature variations. Energy and Buildings. 2007;39(9):1011–8.

134. Osman NA, Tafara M, Sunarti N, Kamarudin SS. Feasibility Study Into Implementation of Solar Energy in Inti International. 2nd Regional Conference on Campus Sustainability: Capacity Building in Enhancing Campus Sustainability. 2015;(July):217–33.

135. Mohammad ST, Al-Kayiem HH, Aurybi MA, Khlief AK. Measurement of global and direct normal solar energy radiation in Seri Iskandar and comparison with other cities of Malaysia. Case Studies in Thermal Engineering [Internet]. 2020;18(January):100591. Available from: https://doi.org/10.1016/j.csite.2020.100591

136. Masumi O, Hirofumi N. How to measure temperature accurately (1) Making an aspirated radiation shield for air temperature measurement. The Society of Agricultural Meteorology of Japan. 2010;2–6.

LIST OF PUBLICATIONS

Journal with Impact Factor

1. **N. Wai Tuck**, S.A. Zaki, A. Hagishima, H.B. Rijal, M.A. Zakaria, F. Yakub. (2018). Effectiveness of free running passive cooling strategies for indoor thermal environments: Example from a two-storey corner terrace house in Malaysia. *Building and* Environment, 160. https://doi.org/10.1016/j.buildenv.2019.106214. **(Q1, IF: 5.379)**

2. **N. Wai Tuck**, S.A. Zaki, A. Hagishima, H.B. Rijal, F. Yakub. (2019). Roof cover as an effective building retrofit for thermal comfort in residential buildings in Malaysia with a hot–humid climate. *Building and Energy*. (manuscript submitted on 29 November 2019)

Patent Filling

Title: Shaded Roof
Application No: PI 2018704320
Filling Date: 14 November 2018

Conference Proceedings

1. **N. Wai Tuck**, S.A. Zaki, A. Hagishima, F. Yakub, M.A. Zakaria. (2018). Field measurement of indoor thermal environments in a two-storey corner terrace house in hot-humid climate. In *The 4th International Conference on Low Carbon Asia (ICLCA 2018)* (73-78).

2. **N. Wai Tuck**, S.A. Zaki, A. Hagishima, H.B. Rijal, M.A. Zakaria, F. Yakub. (2018). Investigation of indoor thermal environments in a typical two-storey corner terrace house in Malaysia. In *The 5th International Seminar on Tropical Eco-Settlements*.