FULLY ENCLOSED VEGETATED COURTYARD IN HOT HUMID TROPICS

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A thesissubmitted in partial fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Architecture)

Faculty of Built Enviroment and Surveying
Universiti Teknologi Malaysia

MAY 2020

DEDICATION

To God be the glory for great things He has done. This thesis is specially dedicated to the Almighty God who owns everything and has seen me through the ups and downs so far in the journey of life.

To my beloved wife, daughter, and sons, for understanding the many years, I was away, thanks. To God be the glory.

ACKNOWLEDGEMENT

This thesis was done under the supervision of my main supervisor, Assoc. Prof. Dr Lim Yaik Wah and co-supervisor Dr Doris Toe Hooi Chyee. I would like to thank them for their constructive criticism. I am so much thankful, for your commitment to sparing your time to go through the manuscript and corrected it. Also, I want to thank my former supervisor Prof. Dr Dilshan Remaz Ossen for inspiring me to initiate this research area. I am sincerely grateful sir.

I am indebted to the management of Nuhu Bamalli Polytechnic, Zaria Kaduna State, Nigeria for granting me study leave to pursue this programme. Great commendation goes to the Tertiary Education Trust Fund (TETFund), for their immense support and intervention in making my study in Malaysia a reality. My appreciation goes to the entire members of Redeemed Christian Church of God (RCCG) power palace Skudai, Johor, Malaysia. I would like to appreciate the following people: Dr Oladukun Goke, Dr Amos Danladi, Dr Solomon Zakka, Dr Bruno Lot Tanko, Arc Joshua Abimaje, Dr Markus Bulus, Dr J D Shagaya, Dr Simon Gumbaro Peter, Mr Bulus Ibrahim, Mr Timothy Gandu and Dr Gimba Dogara, my flatmate, and many that have contributed in one way or the other to make this thesis a success. I thank you all for your love and support. My gratitude goes to my uncle, Hon. Danazumi Modi Kissabo as my encourager and role model, the entire extended family members and the entire Chori community for your prayers and support.

I sincerely thank my beloved wife ('Sweetheart' as I usually called her), Gloria Modi, and my children, Blessed, Wehnom, and the princess of the house Himiedah, for their endurance, support, encouragement, and prayers during this journey. Salamatu, you are a wonderful sister and a friend. My father, and a friend late Mallam Musa Zango Modi, death refuse you to see the final destination of my career as your son. Rest in peace father.

I thank and give all the glory and honour to God Almighty for his protection during the journey. My sincere prayer is that the knowledge acquired will be beneficial to the entire community and humanity.

ABSTRACT

Vegetation is considered a prominent strategy to improve the overall thermal performance of a courtyard. Most tropical fully-enclosed courtyard buildings are characterised with vegetation, but empirical studies on its effects remain to be limited. This study aims to examine the thermal performance of a fully-enclosed vegetated courtyard in hot, humid tropical weather, in order to develop design strategies for enhancing its performance. Field measurements and computer simulations using Envi-met V4.2 software and Rayman Pro 2 model were carried out to measure parameters such as air temperature, mean radiant temperature, and physiological equivalent temperature. Field measurements were conducted on a fully-enclosed courtyard building in the Raja Zarith Sofiah library, Universiti Teknologi Malaysia, for validation against computer simulations. In addition, five courtyard ratios comprising 1:1:1, 1:2:1, 1:3:2, 1:2:2, and 1:3:3, were selected and simulated with different leaf area density (LAD) values, namely, 0.93 LAD with example of melaleuca leucadendron (ml), 7.9 LAD with example of Mesua ferrea (mf), and 9.7 LAD with example of ficus benjamina (fb), whereby the percentage of the vegetated area was 25%, 50%, and 75% respectively. East-West orientation was used for courtyard ratios of 1:1:1, 1:2:2, 1:3:3, 1:2:1 and 1:3:2. This is because the East-West orientations are the worst scenarios, as they are the most exposed to solar radiation compared to the North-South, Northwest-Southwest and Northeast-Southwest orientations for the courtyard. The results reveal that 9.7 LAD (fb) recorded the highest average temperature reduction of 1.2°C, followed by 7.9 LAD (mf), with an average air temperature reduction of 0.71°C, and 0.93 LAD (ml), with an average air temperature reduction of 0.34°C. Finally, the study identified the quantity and type of LAD for effective shading and evapotranspiration cooling process during the hottest hours. Besides, the cooling effects were more significant with a larger percentage of LAD. The findings from this research serve as design strategies for the effective use of vegetation to enhance courtyard thermal performance.

ABSTRAK

Proses vegetasi dianggap sebagai strategi utama untuk meningkatkan prestasi pelesapan haba di halaman dalam bangunan. Kebanyakan halaman dalam bangunan tinggi mempunyai ciri-ciri sesuai untuk vegetasi, tetapi kajian empirikal tentang kesan pelesapan haba masih terhad. Kajian ini mengkaji prestasi pelesapan haba di halaman dalam bangunan beriklim tropika lembab yang panas untuk membangunkan cadangan reka bentuk untuk meningkatkan prestasinya. Ukuran bacaan dan simulasi komputer menggunakan perisian Envi-met V4.0 dan Rayman Pro 2 dilakukan untuk mengukur parameter seperti suhu udara, suhu purata sekeliling, dan suhu setara fisiologi. Ukuran bacaan dijalankan di kawasan halaman dalam bangunan Perpustakaan Raja Zarith Sofiah Universiti Teknologi Malaysia, sebagai validasi pengukuran hasil simulasi komputer. Di samping itu, lima nisbah halaman yang terdiri dari; 1: 1: 1, 1: 2: 1, 1: 3: 2, 1: 2: 2, dan 1: 3: 3 telah dipilih dan disimulasikan dengan indeks tumbuh-tumbuhan (LAD) yang berbeza iaitu 0.93 LAD dengan contoh maleueuca leucadendron (ml), 7.9 LAI dengan contoh mesua ferrea (mf), dan 9.7 LAD dengan contoh ficus benjamina (fb); yang mana peratusan kawasan vegetasi adalah 25%, 50% dan 75%. Orientasi Timur-Barat telah digunakan dengan nisbah 1: 1: 1, 1: 2: 2, 1: 3: 3, 1: 2: 1 dan 1: 3: 2. Ini adalah kerana orientasi Timur-Barat melibatkan senario yang paling buruk kerana ianya lebih terdedah kepada cahaya matahari berbanding dengan orientasi Utara-Selatan, Barat Laut-Barat Daya dan Timur Laut-Barat Daya. Kajian mendapati bahawa 9.7 LAD (fb) mencatatkan pengurangan purata suhu tertinggi sebanyak 1.2°C, diikuti oleh 7.9 LAD (mf) dengan pengurangan purata suhu udara sebanyak 0.71°C, dan 0.93 LAD (ml) dengan pengurangan purata suhu udara sebanyak 0.34°C. Kajian ini juga telah mengenal pasti kuantiti dan indeks vegetasi (LAD) bagi teduhan dan proses evapotranspirasi yang efektif pada waktu yang paling panas. Kesan penyejukan juga lebih berkesan dengan peratusan vegetasi (LAD) yang lebih tinggi. Hasil penemuan kajian ini boleh memberikan cadangan reka bentuk untuk penggunaan vegetasi yang berkesan untuk meningkatkan prestasi pelesapan haba di kawasan halaman dalam bangunan.

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LIST OF ABBREVIATIONS

LAI	-	Leaf Area Index
LAD	-	Leaf Area Density
PET	-	Physiological Equivalent Temperature
MRT	-	Mean Radiant Temperature
AT	-	Air Temperature
AR	-	Aspect Ratio
SSI	-	Solar Shadow Index
CTTC	-	Cluster Thermal Time Constant
ET	-	Evapotranspiration
GA	-	Genetic Algorithm
PSO	-	Particle Swarm Optimization
ET_C	-	Evaporation Time
K_c	-	Crop coefficient
T	-	Temperature Range
NE-SW	-	Northeast-Southwest orientation
NW-SE	-	Northwest-Southeast orientation
N-S	-	North-South orientation
E-W	-	East-West orientation
ml	-	malaleuca leucadendron
mf	-	mesua ferrea
fb	-	ficus benjamina
CFD	-	Computational Fluid Dynamics
UTM	-	Universiti Teknologi Malaysia
RMSE	-	Root Mean Square Error
d	-	Degree of agreement

LIST OF SYMBOLS

k	-	kelvin
%	-	percentage
°C	-	Degree centigrade
3D	-	3 Dimension
1D	-	1 Dimension
m	-	metre
m/s	-	Metre per second
g/kg	-	Gram per kilogram
h	-	height
l	-	length
w	-	width

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Many studies have shown that globalization has caused environmental pollution, carbon emission, climate change, increasing energy demand and inadequate natural resources (Behrens et al., 2007; Inglesi-lotz and Dogan, 2018; Rasul and Sharma, 2016; Wang et al., 2018). Over 30% of carbon emission, which is the main attribute of climate change, reflected on the quality of thermal performance the buildings exhibit (Wang et al., 2018). Therefore, it is necessary to conduct studies to improve the thermal performance of buildings. In this context courtyard as a building component is one of the sustainable strategies to checkmate the thermal performance and improve the microclimate of the building. The adoption of the courtyard in buildings solves many problems such as privacy, comfort and less energy usage. In addition, the courtyard provides daylight, natural ventilation and thermal performance. Meir et al. (1995) believe that applying courtyard structures as a microclimatic modifier is considered in many decades.

The solution to the issue of thermal performance focused on finding effective passive strategies. The outcome of this step that the designers became more aware of traditional strategies that depend on non-mechanical methods, in order to improve the comfortable atmosphere. For an example in hot-dry and warm-humid zones cooling is a priority than heating, for this demand many elements support natural techniques applied in these buildings for many decades, such as courtyards, mashrabiyya, wind towers and ventilation tunnel (Allen G. Noble, 2007; Rajapaksha et al., 2003; Zain, 2012). Rajapaksha et al., (2003) in their study focused on the cooling techniques around the building, they found that in warm-humid regions, vernacular design techniques involved elements in providing a cooling environment such as courtyard, building orientation, shading device, while in the United State of America, a ventilation tunnel is accessible in the region. In Middle Eastern countries mashrabiyya and ventilation through water elements used in a humid area, whereas in the tropics they used courtyard.

This research will focus on the vegetated courtyard as an element that provides cooling to the building. The significant role that is played by the courtyard in building design of many regions as shown in warm and humid weather (Ghaffarianhoseini, Berardi, & Ghaffarianhoseini, 2015; Muhaisen, 2006). The elements of the courtyard have unique advantages in hot and humid climates as passive cooling systems, which can cool the building and offers the thermal comfort for users' (Kubota et al., 2017; Sadafi et al., 2011). After many attempts of examining courtyard, designers started to introduce the benefit of the courtyard on the early stage of building design, especially in green building and offer the best techniques that are compatible with the building elements to gain significant microclimatic and thermal impact of the courtyard (Rajapaksha & Hyde, 2002; Paula et al., 2014; Zamani et al., 2018). The fully enclosed courtyard buildings are commonly used within the hot humid climate for commercial or residential purposes.

However, during the construction or building refurbished, the elements of the courtyard as landscaping and water features could add to the building environment without changing the structure of the existing building. Various efforts (Kubota et al., 2014; Rajapaksha, Nagai, & Okumiya, 2003; Sadafi et al., 2011; Zakaria, Kubota, & Toe, 2015) conducted field measurement or computer simulation, in order to improve thermal performance in the buildings by incorporating courtyards as a passive cooling technique. Therefore, the purpose of the study is to develop design strategies to enhance the thermal performance of vegetated fully enclosed courtyard for hot humid tropics.

1.2 Problem Statement

There is lack of studies of courtyard in the tropics especially Malaysia (Ghaffarianhoseini et al., 2015; Sadafi et al., 2011). In general, the size and design of the courtyard have a significant influence on its performance (Almhafdy et al., 2013). The performance of the courtyard can be optimized by considering the building shape and the heat gain control strategy (Kim et al., 2012). The causes of discomfort in the courtyard microclimate quality in the Tropics are the high power of solar radiation throughout the year and the low wind speed (Ghaffarianhoseini et al., 2015; Yu and Hien, 2009). These possible issues increases the air temperature and the heat related parameters, (for example, the mean radiant temperature, physiological equivalent temperature) in the courtyard (Ghaffarianhoseini et al., 2015). This heat associated parameter is also extended to an indoor environment that leads to increased cooling loads and energy consumption (Ghaffarianhoseini et al., 2015; Kubota et al., 2014; Rajapaksha and Hyde, 2002; Sadafi et al., 2011). The concept of courtyard microclimate as it relates to the tropics is crucial as with the climate characteristics of Malaysia which caused the global temperature during the daytime to be between 20°C to 32°C. While during the night it reduces from 27°C to 21°C, with a relative humidity of around 75% to 90% and never went down under 60% (Yunis, 2016). Therefore, residential and non-residential building are subjected to significant cooling necessities due to the high intensity of heat passing from the courtyard building to the external envelope (Kubota *et al.*, 2014; Zakaria *et al.*, 2015; Kubota *et al.*, 2017). The residential and non-residential buildings rely on the mechanical cooling system to gain indoor thermal comfort, thereby leading to increased energy consumption.

Most of the courtyard in the tropics, especially Malaysia as keenly observed, much vegetation are planted, as it is believed that vegetation moderate the microclimate. This moderation is based on the principle of shading and evapotranspiration, also provide a better microclimate that is thermally comfortable (Ghaffarianhoseini et al., 2015; Toe and Kubota, 2013). However, this vegetation that is planted in the tropical courtyard has limited empirical studies related to the thermal performance of the vegetation within the courtyard. Therefore, there is a need to address this issue (Ghaffarianhoseini *et al.,* 2015; Sadafi *et al.,* 2011). One of the advantages of planting vegetation in the tropical courtyard is to shade the wanted space that will thus decrease solar radiation inside the tropical courtyard. Aside from that, it likewise makes evapotranspiration cooling impact which is where water is exchanged from land to the atmospheric level and transpiration from plants so as to cool the outdoor and it is believed that it affects the indoor condition (Scott *et al.,* 1999; Makaremi *et al.,* 2012). Therefore, the types and quantity of vegetation for the thermal performance of a fully enclosed courtyard for enhancing the environmental condition for a fully enclosed courtyard building in Malaysia is desired.

Fully enclosed courtyard building in Malaysia is usually used for a school building, student hostel, and offices (Ismail, Mohd Saman, & Hassim, 2014; Jamaludin, Hussein, Mohd Ariffin, & Keumala, 2014). Fully enclosed courtyard building is located everywhere within Malaysia especially as a public building, but limited attention was given on the studies of a fully enclosed courtyard (Ghaffarianhoseini et al., 2015; Jamaludin, Hussein, & Tahir, 2018). The need for this study is based on the passive design principles to improve the thermal performance of the fully enclosed courtyard building, this is in accordance with the issues of sustainability.

1.3 Research Gap

The literature that is related to courtyard studies focuses on the microclimatic functions of the courtyard, thermal functions, and some combined the microclimatic and thermal functions of courtyards (Zamani et al., 2018). Many researchers study the microclimatic effect of open spaces such as the courtyard(Paula et al., 2014; Taleghani et al., 2014; Yang Zhao et al., 2013). Microclimatic and thermal functions are procedures that improve the performance of outdoor thermal comfort of the courtyard (Kubota *et al,.* 2017; Zamani *et al.,* 2018). Taleghani (2014) concluded that the courtyard offers a comfortable microclimate in comparison to other buildings (Sadafi *et al.,* 2011). In another study, Ratti et al. (2003) opined that the courtyard serves as protection from the sun in some places and sun collectors in other places.

Thermal performance of courtyard was analysed by Aldawoud (2008), Moonen et al. (2011), Muhaisen (2006), Muhaisen & Gadi (2006) and Safarzadeh & Bahadori (2005). Whereas vegetation effect was analysed in some studies: (Ghaffarianhoseini et al., 2015; Haggag et al., 2014; Mangone et al., 2014; Park et al., 2012; Shashua-Bar et al., 2011). Past studies were directed on the courtyard and their impacts, the majority of these studies were focused on hot-dry climate. Studies on courtyard building in the tropics are limited because the focus on buildings in Malaysia is based on terraced houses and high rise buildings. (Almhafdy et al., 2013; Ghaffarianhoseini et al., 2015; Kubota et al., 2014, 2017; Rajapaksha et al., 2003; Tablada and Blocken, 2005; Zakaria and Kubota, 2014).

The performance of courtyard with vegetation demonstrates a positive response to thermal comfort, for instance, Shashua-Bar et al. (2011) demonstrates that trees provide more outdoor air temperature reduction compare to shading meshes and grass Taleghani et al. (2014) studied on three heat mitigation scene, their findings demonstrate that addition of vegetation and water pool in the courtyard lead to a reduction in mean radiant temperature and air temperature. In another study, Mangone and Linden (2014) conceived that the presence of vegetated courtyard was found to be more effective in reducing the energy consumption and carbon emission of the building than just the vegetation shade canopy. This implies that the vegetated courtyard does not only provide shade, but it provides evapotranspiration that is a combination of evaporation and transpiration and this tends to reduce energy consumption in terms of air temperature, mean radiant temperature and physiological equivalent temperature. Ghaffarianhoseini et al. (2015) also attest in their study and their findings affirmed that abundance vegetation in the courtyard can achieve an acceptable level of thermal comfort for the tropics and may enjoy the courtyard by its user for a long duration of daytime even during noontime. Also, Toe and Kubota (2015), affirmed that vegetation is attributed to the moderation of the courtyard microclimate of Chinese shophouse in Melaka, Malaysia. The application of vegetation in the courtyard shows positive results toward enhancing the microclimate of a courtyard; most studies are conducted in the hot-arid climate, only few that were done in the tropical climate.

Most of these fully enclosed courtyard buildings are large and have vegetation, but there are limited empirical studies associated with the performance of the fully enclosed courtyard with vegetation (Jamaludin et al., 2014). Therefore, a gap in knowledge is identified, and there is a need to bridge the gap. This study intends to bridge the gap in knowledge.

1.4 Research Hypotheses

The study hypothesizes that the thermal performance of a fully enclosed courtyard in a tropical climate can be improved by:

(i) Optimum courtyard configuration and orientation can be determined through shading from solar radiation.

(ii) Appropriate Leaf Area Index (LAI) quality and quantity of vegetation can be used to achieve shading and evapotranspiration cooling effects.

(iii) Thermal performance of fully enclosed courtyard can be improved by introducing appropriate Leaf Area Index (LAI) quality and quantity of vegetation.

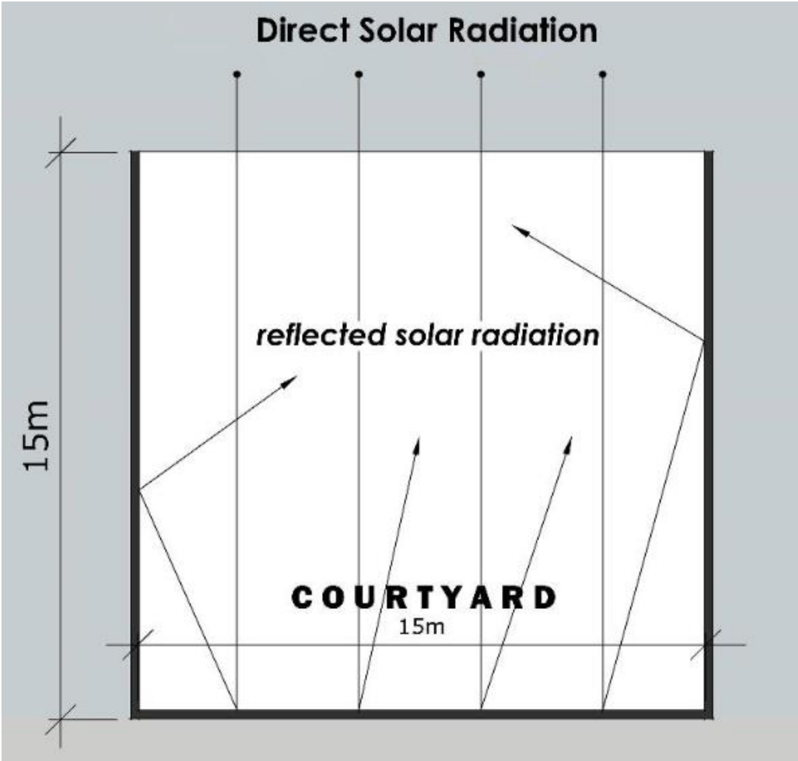

Figure 1.1 Courtyard height, width, direct and reflected solar radiation

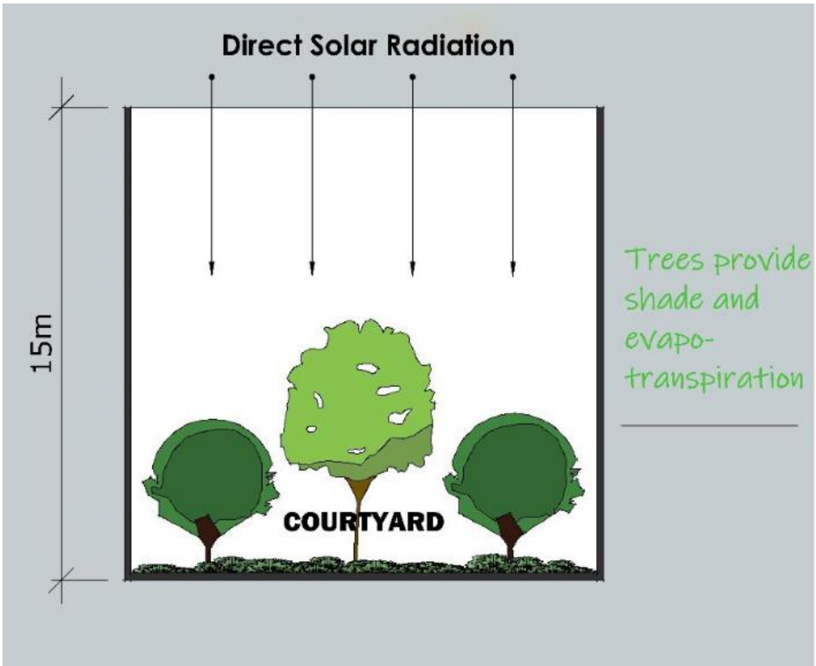

Figure 1.2 Courtyard environment with trees and grass to provide shade and evapotranspiration.

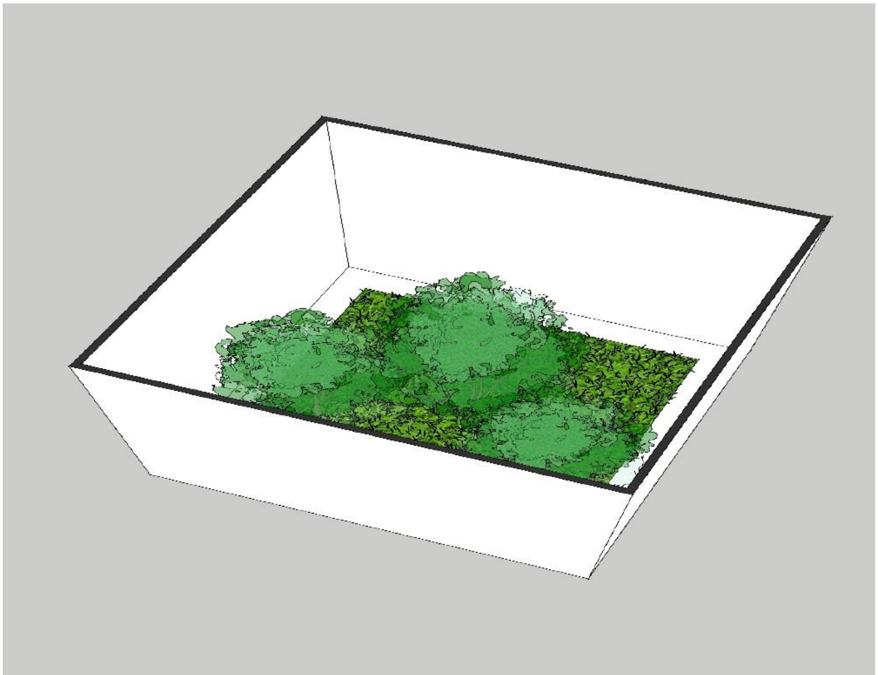

Figure 1.3 3D of Courtyard environment with trees and grass to provide shade and evapotranspiration

Figure 1.1 explain the propositions that the courtyard with the height of 15m is exposed to direct sunlight. The height (15m) is selected due to the fact that most courtyards within Malaysia have similar height and within the range of 10m – 15m (Jamaludin et al., 2014), also refers to as low rise building (Ismail *et al.,* 2014; Jamaludin *et al.,* 2014; Bulus *et al.*, 2017). The sunlight is reflected from the floor, walls and in all direction, thereby making the courtyard microclimate to be uncomfortable. Orienting the courtyard in a different orientation (N – S; E – W; NE – SW; NW – SE) will enhance the shading effect of the courtyard thereby improving the courtyard microclimate.

Figure 1.2 and 1.3 explain the proposition that by introducing the trees with grass the direct sunlight is blocked by providing shades and evapotranspiration cooling effect from the trees leaves thereby improving the courtyard microclimate.

1.5 Research Aim and Objectives

The research aim is to examine the thermal performance of a fully enclosed vegetated courtyard in a hot humid climate in order to develop design strategies for enhancing the thermal performance of courtyards.

The objectives of this research are:

(a) To assess the environmental conditions of the fully enclosed courtyard in the hot humid tropics.

(b) To examine the effect of configuration and orientation on the thermal performance of fully enclosed courtyards in a hot humid tropics.

(c) To evaluate the quantity and types of vegetation in the form of leaf area density (LAD) that will enhance the thermal performance of fully enclosed courtyards in the hot humid tropics.

(d) To develop design strategies for enhancing the thermal performance of fully enclosed courtyards in a hot humid tropics.

1.6 Research Questions

The literature review showed that vegetation has the potential of enhancing the courtyard microclimate positively. Therefore, the following research questions are formulated in order to understand the hypotheses.

(i) What are the environmental conditions of a fully enclosed courtyard in a hot humid tropics?

(ii) What is the effect of configuration and orientation on the thermal performance of a fully enclosed courtyard in a hot humid tropics?

(iii) What is the effect of the quantity and types of vegetation on the thermal performance of a fully enclosed courtyard in a hot humid climate?

How can the performance of a fully enclosed courtyard in hot humid tropics be enhanced using vegetation?

1.7 The significance of the Study

The significance of this study lies on the increasing architects, landscape architects, and designers' awareness on the importance of manipulating quantity and types of vegetation on the thermal performance of the courtyard at the design stage to improve the courtyard microclimate condition. The effects of quantity and type of vegetation on the thermal performance of the courtyard study might add theoretical knowledge to the existing literature.

Furthermore, the study can help the architect, landscape architect, and designer by providing methods for improving the investigation of the courtyard microclimate and its impact on the sustainability design. The importance of this study could help the researchers to analyse their results better, the vegetated courtyard and the sustainability design phenomenon would be better understood. A better quantity and types of vegetation could reduce undesirable solar radiation. Thus, help to improve the climatic condition of the courtyard microclimate, and in turn, this will help in reducing the energy consumption of courtyard buildings and create a thermally healthy environment. The relationship between the fully enclosed vegetated courtyard environment and indoor is based on the principle of shading from the vegetation that blocked the solar radiation. By convection and radiation the indoor would also be affected thereby reducing the heat gain and the indoor temperature thereby providing better indoor thermal condition.

1.8 Research Scope and Limitation

This study focusses on the impact of the quantity and types of vegetation on the fully enclosed courtyard with 15 metres high wall in a hot humid climate. The environmental microclimate factors, for example, air temperature, mean radiant temperature, and the physiological equivalent temperature was identified as the primary parameters of the study. It prompts the investigation of the quantity and types of vegetation on the thermal performance to improve the fully enclosed courtyard microclimate, which thus influence the indoor condition of the fully enclosed courtyard. One week from 11th – 17th July 2017 was chosen for checking, gathering the climatic data from the fully enclosed courtyard at Raja Zarith Sofiah Library, Universiti Teknologi Malaysia. In any case, data on a typical sunny day on 16th July 2017 was picked to be utilized as input for simulation and details analysis to demonstrate the investigation.

The present research was numerically conducted utilizing a free professional climate and urban environment analysis software program that is intended to simulate the aim and objectives of the investigation which is Envi-met 4.2 and Rayman pro 2 model. The investigation had utilized the numerical method for the following reason.

Firstly, field measurement was led in a genuine existing fully enclosed courtyard building (Raja Zarith Sofiah Library Universiti Teknologi Malaysia) so as to have an underlying idea on the impact of the courtyard microclimate contrasting with the outdoor environment.

Also, it is an extremely exhausting task to look at the stated objectives as the complexity of planting and nurturing the types of vegetation to be utilized in the research; it will take time. Consequently, the study proposes that the investigation is numerically conducted. Thirdly, the minor irregularity of data could happen during field measurement; sensor probes sensitivity may sometimes need adjustment-a limited sensor such as solar radiation probe which in turn relies on the simulation data instated.

This study focuses on quantifying the benefits of fully enclosed vegetated courtyard on its thermal performance. The study also considered the grass cover as part of the vegetation alongside with the Leaf Area Density (LAD) of the trees adopted. Also, due to the inadequate database the leaf area density (LAD) in Malaysia, the selected leaf area density, LAD in this research is adopted from the previous study by Shahidan (2011)

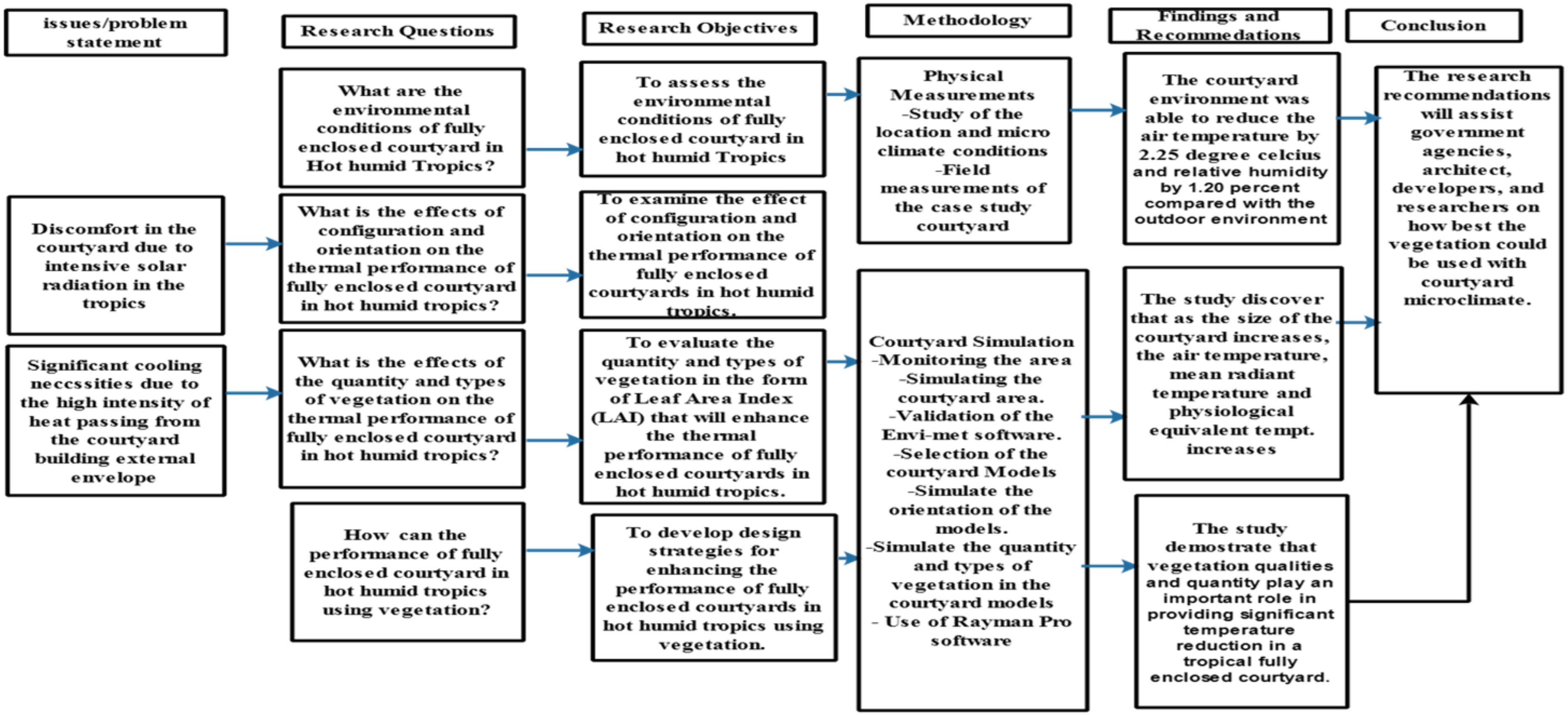

Figure 1.4 Research flow chart

1.9 Thesis Organisation

Chapter one: introduces the concept of passive design in the building, in which courtyard is one. It discusses the issue of the study, the research gap, the research question, research aim and objectives. In addition, further discussion on the scope and the limitation of the current study, the significance was presented. Thesis organisation and the summary of the thesis are also presented.

Chapter two reviews the history of the courtyard in Malaysia, courtyard vernacular building and types of the courtyard. It further reviews the general overview of the courtyard, this involves courtyard and ventilation, courtyard and environment, thermal comfort in the courtyard, thermal performance and courtyard, courtyard forms and geometry, courtyard and orientation. The concept of the vegetated courtyard was reviewed. This chapter also discusses the different climate region, including the hot humid tropical climate, Malaysia location and its urban climate that influences the study.

Chapter three describes the methodology of the study. The different methods that were employed in outdoor studies were reviewed in this chapter. It also discusses the appropriate method for the current study, the compatible software model and a general overview of the selected software. It illustrates the case study and the field measurement procedures. Validation and evaluation of the software are presented in this chapter. It discusses the procedure to achieve objective one. The simulation procedure to achieve objective two, the input data for the simulation and the output data from the simulation was presented. It further discusses the procedure to achieve objective three, this involves the selection of the vegetation for the simulation.

Chapter four: This chapter covers the results of the comparative analysis study that focus on air temperature, mean radiant temperature and physiological equivalent temperature reduction on thermal performance of vegetated fully enclosed courtyard. It further presents the result and discussion on examining the effect of orientation on the basis of the air temperature, mean radiant temperature and physiological equivalent temperature of the selected courtyard ratio. The chapter also presents result and discussion on evaluating the quantity and types of vegetation that will enhance the performance of fully enclosed courtyard considering also air temperature, mean radiant temperature and physiological equivalent temperature.

Chapter five: discusses the conclusion of the thesis. Additionally, the results of developing the design strategies for enhancing the thermal performance of a vegetated fully enclosed courtyard was presented. This chapter also provides recommendation and potential research for future studies, advice, and suggestions for architects, landscape architects, planners, and developers are included.

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