THERMAL PERFORMANCE OF SHADED RECESSED WALL FAÇADE OF A CELLULAR OFFICE SPACE IN JOHOR BAHRU, MALAYSIA

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DEDICATION

I dedicate this thesis to Almighty Allah for His infinite mercies throughout the study. The thesis is also dedicated to my immediate family for missing each other for too long, their encouragement, support and regular prayers.

ACKNOWLEDGEMENT

My first and utmost gratitude goes to Allah “subhanahu wa ta’ala” for His sustenance, guide and protection throughout the study. For without that, this thesis wouldn’t have been completed.

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ABSTRACT

Direct solar insolation on unshaded facade causes severe overheating of the indoor environment in a tropical climate, and this would reduce the performance and efficiency of task carried out in the office. External shading strategies have been identified as one of the passive design strategies to mitigate indoor thermal effect in the tropics. As an option, additional design strategy such as recesses on facades, and shade buildings provide exterior projected shading devices. However, literature on studies related to on the recessed wall facade (RWF) are limited particularly in Malaysia. In this study, the influence of RWF on the indoor thermal conditions of an office space in Malaysia was investigated. Three RWF types (vertical, horizontal and punched-hole) recessed facade were investigated and compared with unshaded facade (UF). The thesis aims to investigate the potentials of applying RWF shading strategies to improve thermal performance by reducing the harsh indoor environmental conditions of office spaces in Johor Bahru, Malaysia. The research design employed an exploratory survey to identify RWF types in Malaysia. Further investigation was conducted using the integrated environmental solution-virtual environment (IES<VE>) simulation software. The results showed that deeper depth, punched-hole recessed façade type and RWF with insulation performed better with all the thermal parameters such as indoor air temperature, indoor relative humidity, indoor solar heat gain and indoor surface temperature. While the comparison evaluated between RWF types and exterior shading device (ESD) revealed the possibility of using RWF as an alternative to ESD. The findings revealed some effect of thermal performance of the RWF shading strategy on office space through the series of simulations. The results showed the shading strategies which provide a solar gain reduction ranging from 53.7% to 64.8%, invariably reduced the percentage of harsh indoor thermal conditions. Similarly, the minimum, maximum and average indoor air temperature reduction of 1.44 °C, 2.09°C and 1. 83 °C respectively were recorded. Surface temperature reduction was from 1.0% to 7.4% while the relative humidity was brought down and maintained AT a favourable mean value of not more than 55% within the comfort zone by horizontal recessed (HR) and punched-hole recessed (PHR). Therefore, these findings offer valuable information tool with RWF shading option to building sector stakeholders through various design models with various thermal performance levels.

ABSTRAK

Insolasi suria secara langsung pada fasad yang tidak terlindung menyebabkan pemanasan persekitaran dalaman yang teruk dalam iklim tropika, dan ini akan menurunkan prestasi dan kecekapan tugas yang dilakukan di pejabat. Strategi teduhan luaran telah dikenal pasti sebagai salah satu strategi reka bentuk pasif untuk mengurangkan kesan haba dalaman di kawasan tropika. Sebagai pilihan, strategi reka bentuk tambahan seperti relung pada fasad menjadi peneduh bangunan yang berfungsi kepada alat teduhan unjuran luaran.Walau bagaimanapun, kajian mengenai unjuran dalaman dinding fasad (RWF) adalah terhad terutamanya di Malaysia. Dalam kajian ini, pengaruh RWF terhadap keadaan termal dalaman ruang pejabat di Malaysia telah dikaji. Tiga jenis RWF (menegak, mendatar dan lubang- tebukan) diselidiki dan dibandingkan dengan fasad tidak berlindung (UF). Tesis ini bertujuan untuk mengkaji potensi bagi mengaplikasi strategi teduhan RWF untuk meningkatkan prestasi termal dengan mengurangkan situasi tidak menyenangkan pada persekitaran dalaman ruangan pejabat di Johor Bahru, Malaysia. Ini diikuti dengan tinjauan penerokaan untuk mengenal pasti jenis IWF di Malaysia. Kajian lebih lanjut dilakukan menggunakan perisian simulasi integrated environmental solution-virtual environment (IES <VE>). Hasil kajian menunjukkan bahawa kedalaman yang lebih besar, jenis pembukaan fasad berlubang dan RWF dengan penebat menunjukkan prestasi yang lebih baik dengan semua parameter termal seperti suhu udara dalaman, kelembapan relatif dalaman, penambahan haba solar dalaman dan suhu permukaan dalaman. Sementara perbandingan yang dinilai antara jenis RWF dan Alat Teduhan Luaran (ESD) menunjukkan kemungkinan menggunakan RWF sebagai altematif untuk ESD. Hasil penemuan menunjukkan beberapa kesan prestasi termal dari strategi peneduhan RWF pada ruang pejabat melalui beberapa siri simulasi. Hasil menunjukkan strategi teduhan dapat mengurangkan kenaikan tenaga suria antara 53.7% hingga 64.8%, yang dapat mengurangkan peratusan keadaan termal yang tidak menyenangkan. Begitu juga, bacaan minima, maksima dan purata suhu udara berkurang sebanyak 1.44 ° C, 2.09 ° C dan 1.83 ° C telah direkodkan. Pengurangan suhu permukaan adalah dari 1.0% hingga 7.4% sementera kelembapan relatif dapat diturunkan dan dilaraskan pada nilai min tidak melebihi 55% kadar zon selesa oleh Unjuran Dalaman Melintang (HR) dan Unjuran Dalam Berlubang (PHR). Oleh itu, penemuan ini menawarkan maklumat yang berharga dengan pilihan teduhan RWF bagi pihak berkepentingan melalui pelbagai reka bentuk dengan pelbagai tahap prestasi termal.

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ΔT	-	Temperature difference
A	-	Surface area
Af	-	The area of fenestration
At	-	The gross area of the walls
Aw	-	The area of opaque wall
c	-	Specific heat capacity
CF	-	The solar correction factor
Cp	-	The specific heat capacity of air at constant pressure
d	-	Mean relative error index of agreement
D	-	Depth of overhang
E	-	Illuminance at a point of an area
Ep	-	Environmental Parameter
f shd	-	The diffuse sky shading factor for the surface
HF	-	Floor to floor height
Hfen	-	Fenestration height
I glob	-	The total solar flux (W/m2) on the horizontal plane
I hglob	-	The total solar flux (W/m2) on the horizontal plane,
Ibeam	-	The solar flux
Idir	-	The direct solar flux (W/m2) incident on the surface glass for particular orientation
Igdiff	-	The diffuse ground solar flux (W/m2) incident on the surface
Ihdiff	-	The diffuse sky solar flux (W/m2) on the horizontal plane
Isdiff	-	The diffuse sky solar flux incident on the surface
It	-	Solar intensity falling on the surface K
K	-	Thermal conductivity (W/mK)
L sky(β)-		The long-wave radiation received directly from the sky
Lg(β)	-	The long-wave radiation received from the ground
L	-	The characteristic length of the surface
L	-	Wall thickness
ɵ	-	The angle of incidence

Q	-	Heat flow into the air mass
Q	-	Total heat transfer
qb	-	Total solar gain (heat flow per unit area)
Qc	-	Conduction heat flow rate
Qg	-	The heat conduction through glass windows
Qs	-	The solar radiation through glass windows
Qw	-	The heat conduction through opaque walls
R	-	Thermal Resistance
R	-	Correlation coefficient
R2	-	Coefficient of determination
Rso	-	Outside surface resistance
RH_o	-	Outdoor Relative Humidity
SC	-	The shading coefficient
SF	-	The solar factor
SG_o	-	Outdoor Solar Gain
SHGC	-	Solar heat gain coefficient
ST_o	-	Outdoor Surface Temperature
ß	-	The inclination of the surface
T	-	Solar transmittance
T	-	Temperature
T_o	-	Outdoor Temperature (°C)
TDeq	-	The equivalent temperature difference
Tp	-	Thermal Performance
Ts	-	The mean surface temperature
Tsky	-	sky temperature in Kelvin (K)
Tsur	-	temperature of the exposed building surface (K)
Tα	-	The air temperature
U	-	Thermal Transmittance
UF	-	Unshaded Facade
Uf	-	The U-value of fenestration
Uw	-	The U-value of opaque wall
Vd	-	The air volume
W	-	The heat flux λ is the density of the solid (kg/m2k)

α - The solar altitude

α - The solar absorptivity of the opaque wall

δT - Temperature differences

δt - Time differences

θ - The angle

ρ - Conductivity of the solid

$\rho\alpha$ - The air density

δ - Stefan-Boltzmann constant

ε - Emissivity

λ - Thermal conductivity

ρ - density porosity

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Buildings consume between 40-45% of gross national energy demand globally (Wells et al., 2018; Attia et al., 2017; Zhang and Wang, 2016; Hassan et al., 2014; Quarmby, 2013). Large percentage of that energy goes to thermal controls, including heating, ventilation and air conditioning (HVAC) (Harish and Kumar, 2016). The measure of the energy required for HVAC depends on the building design, thermal performance, and climatic suitability. A lot of the energy required can be minimised by suitable configuration of facade fenestrations, but particularly, the control of direct solar radiation and use of shading strategies.

The essential climatic factors that affect thermal condition of buildings are; air temperature, solar radiation, relative humidity, mean radiant temperature and prevailing winds (air velocity) (Mirrahimi et al., 2016; Al Yacouby et al., 2011; Szokolay, 2008). The tropical climate experiences severe condition of overheating by solar radiation, which leads to increase in cooling load due to occupant’s thermal comfort demand.

Consequently, the initial requirement for an architect who designs climatic responsive buildings, is knowledge of solar heat gain. Furthermore, there is also the need to determine suitable strategy for controlling the undesirable solar radiation (Pereira and Turkienikz, 2001; Kirimtat et al., 2016). An essential strategy of designing solar shading in buildings is having the knowledge of the sun’s position and path throughout the year in relation to the building structure (Baker and Steemers, 2014; DeKay and Brown, 2013).

According to Liping and Hien (2007), the indoor thermal comfort of a building can be determined by the thermal performance of facade to a large extent, ranking second to the local climatic characteristics. There are proven facade design strategies that provide optimum modifier to achieve better indoor thermal comfort with minimum energy usage. They include the thermal property of construction materials, window sizes, shading, building orientations, and effective ventilation strategies (Liping and Hien, 2007).

Architects and engineers have significant roles to play in reducing cooling and heating loads through the design of buildings (Heywood, 2012). The role is played by using exterior shading strategies on building facades. It has been identified as one of the essential criteria a building designer can use to achieve that design goal (Halawa et al., 2017). Much literature has shown that, good façade shading design is one of the most effective strategies for minimising solar transmission into buildings (Pacheco et al., 2012; Sadineni et al., 2011; Tzempelikos and Athienitis, 2007). Various exterior shading devices have been used for providing shade expected to reduce, not only cost of energy demand, but also to improve thermal comfort of occupants. However, there is a need for innovative and multiple shading strategies for sustainable development in architecture.

In achieving shading against direct effect of solar radiation on buildings, Kamal (2010) listed five strategies. They include shade by; use of facade recesses, use of fixed or dynamic exterior blinds or louvers, and orientation of the building. There is also permanent or transient shading provided by surrounding buildings, screens or vegetation. The last one is shading of roofs by rolling reflective canvas, earthen pots and vegetation. His study concluded that comfort level of the indoor would be improved by using any or more of these strategies.

Previous studies have indicated that the depths of shading devices also affect its thermal performance (Al-Tamimi and Fadzil, 2011; Wong and Li, 2007; Ossen, 2005). There are three primary forms of shading devices widely studied; horizontal overhang, vertical fins and egg-crate. These shading devices have resemblance with recessed wall façade (RWF) as illustrated in Figure 1.1 (Santos et al., 2016). However, research in the aspect of RWF is minimal. It is within this premise that, the study investigates thermal performance of recessed wall façade shading of cellular office space in the tropics. Parameters of orientations and various recess depths were used, by assuming they have less thermal bridging and more ability to modify the thermal condition of the indoor space.

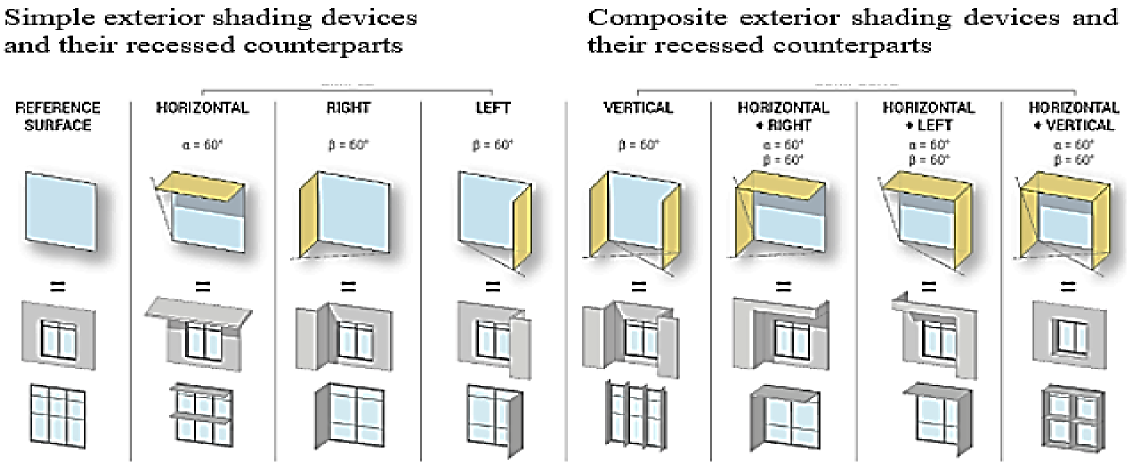

Figure 1.1 Exterior Shading Devices and their Alternative Recessed Wall Facades Source: (Santos et al., 2016)

1.2 Problem Statement

In Malaysia, the exposure of building façade, constituted of windows and walls, to the sun, allows heat from solar radiation, causing increased energy demand for cooling due to high temperature and other environmental parameters (Al-Tamimi and Fadzil, 2011; Sosa, 2007). A study by Chan (2004), indicated that air-conditioning of a tropical office building in Malaysia, consumed the highest total energy of 64%. Corroboratively, Saidur (2009) found that in Malaysia, air conditioning systems and lighting consumed 57% and 19% of energy consumption in buildings, respectively. The consumption was reflected in Malaysian buildings using a cumulative of 48% of the electricity produced in the country (Chua and Oh, 2011). As indicated by Energy Commission Malaysia (2016), energy consumption record of 2013 showed a high percentage of 32.7% of total energy utilised in the country to be, by commercial buildings. The reason was that, commercial buildings in a hot-humid climate like Malaysia have been regularly installed with air conditioning and mechanical ventilation strategies to support and improve indoor thermal space. In most cases, these strategies expend the most energy among all other building services (Kwong et al., 2014).

On common outcome of those studies has been that, there is a need for reduction of the indoor thermal condition in Malaysia by application of passive design such as solar shading strategies. It has been ascertained that the application of innovative passive design of buildings has the advantage of reducing total energy by lowering the harsh environmental condition of space (Omer, 2008). Similarly, to meet the set sustainability targets for the building sector; there is a need for continued development of new building concepts, technologies and materials (Loonen et al., 2016). These concepts can further improve the thermal performance of buildings while enhancing the indoor environmental condition.

The work of Ling *et al.* (2007) indicated that vertical building envelop such as facades of buildings, are critical to the impact of solar radiation. It acted as strong motivation for subsequent studies to investigate effects of shading devices and their impacts on the thermal condition of a space and energy use (Faisal and Aldy, 2016; Santos et al., 2016; Kamal, 2010; Aksit, 2010). However, there are limited empirical studies on their effects on various types of thermal environmental factors such as solar gain, indoor relative humidity and air temperature (Al-Tamimi and Fadzil, 2011). These factors are important because they are mostly the causes of severe thermal condition in buildings. A study by Rashid and Ahmed (2009) agreed that, temperature is one of the critical measures of human thermal comfort. Therefore, lowering it improves thermal comfort.

Exterior shading devices (ESD) can also reduce severe indoor thermal condition of a space by a reasonable percentage depending on the type, material, configuration and orientation (Lau et al., 2016; Bellia et al., 2014). However, some of their weaknesses have been identified. There are the problems of anchorage, façade aesthetic distortion, and the structural attachment of the device, which results in thermal bridge (Totten et al., 2008). According to Hassan and Arab (2014), recessed wall, balcony, attached roof and roof overhang are typical shading elements in a traditional architectural style that prevent sunlight from penetrating into the indoor space. Therefore, the use of building forms for shading was identified as ideal. Among the shading forms are recesses of façade with window(s). Building design and construction should therefore consider the significant impact of solar radiation on building thermal and energy performance (Maestre et al., 2013).

The application of recessed wall facades (RWF) has been given less consideration by researchers, despite its perceived advantage of having less thermal transfer. This study examines various types of RWF with different orientations, depths and insulation. Four solar shading depths of 0.3m, 0.6m and 0.9m were used in the study carried out by Wong and Li (2007), and were found to be effective in reducing cooling load. This study, therefore, adopts the same wall recess depths of Wong and Li (2007). Thus, experimental measurements were conducted followed by building performance simulation using integrated environmental solution-virtual environment (IES<VE>) tool.

The results of this study would afford mitigation of the harsh thermal conditions of indoor environment of buildings in Malaysia. Furthermore, the outcome of this study would make vital information available for the building sector stakeholders. Among the stakeholders are; architects, urban planners, building engineers, green building assessors, building owners, estate valuers, facility managers, façade manufacturers, and policymakers.

1.3 Research Gap

Many studies on sustainable building design revealed that, passive design strategies such as exterior shading on building façades, could significantly diminish the cooling load in tropical buildings. Conversely, most external shading devices are protruded in nature; for example, vertical fins, horizontal overhang, and horizontal louvres. Hence, they possess some limiting factors ranging from structural anchorage of the devices to façade aesthetic distortion. Therefore, if not correctly handled, there would have been high chances of thermal bridging in the building as a result of the construction material types used in most exterior shading devices (ESD). The thermal bridging is a result of the high thermal conductivity of the materials used in the construction of many ESD components (Theodosiou et al., 2017).

Consequently, the use of building forms that would be self-shading, like recessed wall façade, was recommended, as they could lower the effect of solar radiation in the buildings (Ogunshote, 2011; Arif, 2010). Good façade shading is an effective passive design strategy for improving thermal performance and energy consumption of tropical buildings (Mirrahimi et al., 2016; Othuman Mydin et al., 2014). Shading devices could significantly decrease the cooling load of tropical buildings by a magnitude between 23% and 89% (Al Yacouby et al., 2011; Dubois and Blomsterberg, 2011). It should be understood that, the reduction is dependent on the type of shading device used, the building orientation, and the climate.

Similarly, previous studies in the tropics revealed that, exterior shading strategies could significantly reduce the solar radiation effects on the openings and windows than the interior shading devices (Ossen et al., 2005; Givoni, 1998; Hassan, 1996; Olgyay, 1957). Some previous related studies on thermal performance and shading strategies are briefly analysed in Table 1.1 below.

Table 1.1 Related previous studies on thermal performance and shading strategies

Author and Year	Study Method	Variables																	Remarks
		Design								Performance/Environmental Factors									
		Recessed wall facade	Orientation	Shading Depths	Exterior shading devices	Window wall Ratio	Inclined wall shading	Building geometric shape	Façade texture	Indoor Air Temperature	Solar heat gain	Relative humidity	Solar power incidence	Daylighting	Surface temperature	Cooling energy	Indoor thermal comfort	Thermal performance	
Wong and U (2007)	Simulation		√	√	√	√													Study that specified depths of ESD
Chia Sok Ling et al. (2007)	Survey & Simulation		√				√			√	√								Solar insolation reduction by building geometry & orientation
Aksit (2010)	Simulation	√	√	√					√		√								Façade texture study
Kamal (2010)	Literature review	√	√	√	√	√		√			√			√		√			Recommended the use of RWF as shading strategy
Al-Tamimi and Fadzil (2011)	Simulation		√	√	√	√				√	√						√	√	Study on EST with air temperature
Hassan and Arab (2014)	Simulation	√	√							√					√		√	√	Terrace building & RWF sunlight penetration
Santos et al. (2016)	Simulation		√	√	√	√										√		√	ESDs & their relative RWF
Faisal and Aldy (2016)	Theory/qualitative		√		√	√					√		√			√			Typology of building shading elements
(Shaik et al., 2016)	Simulation		√	√	√			√			√					√		√	Window overhang shading for passive cooling
(Saifelnasr, 2016)	Mathematical framework		√	√	√						√		√						Chart to Determine the Dimensions of a shading device
Present Study	Exploratory survey, Measurement & Simulation	√	√	√	√					√	√	√	√		√		√	√	RWF thermal performance

1.4 Research Questions

The following research questions will be addressed in this thesis:

(i) What are the types of recessed wall façade (RWF) applicable in Malaysian building designs, and their thermal performance, with regards to different orientations as compared with unshaded façades?

(ii) What are the impacts of various types of RWF on thermal performance, with regards to various recessed depths, orientations and the effect of wall insulation on them?

(iii) How does the thermal performance of RWF differ from that of exterior shading devices (ESD) in terms of air temperature, relative humidity, solar gain and surface temperature?

(iv) What are the thermal performance abilities of the three types of RWF with regards to various recessed depths and orientations?

1.5 Aim and Objectives of the Research

This research aims to investigate the potentials of applying recessed wall façade (RWF) shading strategies, in the improvement of. thermal performance, and to reduce the harsh indoor environmental conditions of an office space in the tropical climate of Johor Bahru, Malaysia. The specific research objectives are as follows: -

(i) To explore the types of RWF applied in Malaysian buildings and their thermal reduction ability in comparison with an unshaded facade.

(ii) To investigate the thermal performance potentials of various RWF types with regards to various recessed depths, orientations and the effect of wall insulation application on them.

(iii) To examine the thermal performance capabilities of various types of RWF and the ESD regarding indoor air temperature, indoor relative humidity, indoor solar gain and façade surface temperature.

(iv) To provide design recommendation and comparing thermal performance ability of the three types of RWF with regards to various recessed depths and orientations.

1.6 Scope and Limitation

This research focused on the thermal performance of RWF. Although, lowering the solar thermal effect on the building could significantly affect daylighting and visual performance, that was excluded from the scope of this study.

The office building was selected for this study because of its growing utilisation in Malaysia. Additionally, it was because the critical thermal periods are within the office occupancy period of between 8 am and 6 pm. The day time temperature when the offices are in use is higher than the nighttime temperature when occupants are at home. The purpose of shading is to block the effect of solar radiation, hence, the need for indoor environmental thermal quality control design.

There are several types of usable spaces in office buildings; cubicle offices, closed plan offices, open plan offices, waiting rooms, meeting rooms, and pantries among others. The type of space chosen for this study was limited to cellular office space. The reason was that, cellular office space has more critical thermal conditions than other types of office spaces, due to the limited volume of space that could enhance high indoor heat generation. Ventilation is not the focus of this study therefore, was not investigated. The study focused on an area of RWF, in order to improve current office building façades and provide subtitude to exterior shading device, through the use of three types of RWF, to enhance the thermal performance of office space.

The design variables the study focused on were exterior shading strategy and adoption of three types of RWF with fixed WWR of 18%. That was adopted from the base case office building since it is within the acceptable openings (Alibaba, 2016; Al-Tamimi et al., 2011). Depths of 0.3m, 0.6m and 0.9m were used, as demonstrated by Wong and Li (2007). The forms of shading strategy are used, not only as building form shading, but could also yield a better result than the conventional shading devices. Application of insulation on the wall of best performing RWF types were tested to ascertain thermal performance. Other design variables such as, wall thickness, components materials, paints, room areas and volumes, glazing types and pane, which could affect the potentials of the RWF, were not considered.

The determination of appropriate models of various RWF types with their implications was necessary for comparison with other shading devices. Therefore, IES<VE> computer simulation method was used for building energy model (BEM) to assess the thermal performances of various RWF model to ascertain their potentials in shading. However, a qualitative study that is accompanied by other subjective human factors and behaviours was not considered in this study.

The area of study was limited to tropical climate condition of Malaysia. Therefore, the climatic data employed study, was that of Singapore due to its closeness to Johor Bahru, the case study city. Environmental thermal parameters used were; indoor air temperature, indoor relative humidity, indoor solar gain and façade surface temperature. They were used for the significant role they play in indoor thermal condition of an environment (Mirrahimi et al., 2016; Al Yacouby et al., 2011; Szokolay, 2008).

1.7 The Significance of the Research

In Malaysia, office buildings consumed huge amount of electrical energy through mechanical means to achieve a conducive indoor environment for occupants. This high energy use is due to the improper consideration of the thermal performance of the building envelope. Therefore, this study aims at examining the thermal performance of shaded window with recessed façade for Malaysian office buildings in hot and humid tropical climate. It identifies significant thermal design variables of both the recessed wall façade and environmental parameters used to minimise over-dependence on mechanical cooling system. Further, the aim is to achieve indoor thermal comfort with minimal energy consumption. It is believe that the result of this study would reduce the harsh thermal conditions of the indoor environment of buildings in Malaysia. It is also believed that the outcome of this study would make vital information available for building sector stakeholders. These include architects, urban planners, building engineers, green building assessors, building owners, estate valuers, facility managers, façade manufacturers, and policymakers.

This study is highly significant to building designers, engineers and urban planners. It will also provide basic requirements to be considered and met in designing recessed façade window shading for better thermal performance and indoor thermal comfort. The strategy will result in a reduction of cooling load demand, consequently leading to low consumption of energy. The results of various simulation models will provide additional guide, along side the present Malaysia Standard (MS: 1525) and Green Building Index (GBI).

It will be beneficial to all countries within the tropical climate, most especially those in the hot and humid climate. It will serve as guide on implementation for energy reduction in buildings, thereby contributing to lowering and mitigation of climate change challenges. Building sectors stakeholders and most especially architects will also find the results useful in preparing their design and planning toward achieving good indoor thermal conditions for their clients.

1.8 Thesis Organization

This thesis is organized into five chapters. Chapter One presents an introduction of the subject and focus of the study. It discusses the research questions, research gap, and objectives. The scope and limitations were also presented. The significance of the research and the overall thesis organisation was also explained in the chapter.

Chapter Two reviews the literature and theories, divided into four key sections. The first section reviews the energy consumption and climatic thermal condition of Malaysia. The second section reviews the role of façade in building design. The third section presents heat transfer in buildings. This section discourses about the three modes of heat transfer and how their adverse effect can be prevented against tropical climate buildings. The fourth section discusses issues in the tropical envelope of buildings.

Chapter Three is divided into two sections. The first section presents the methods of thermal analysis. The second section explains the thesis methodology, including an exploratory survey of recessed wall façade that resulted in discovering recessed wall façade typologies. This section also presents validation of Integrated Environment Solution Virtual Environment (IESVE) simulation tools after experimental field measurement with Apache computer simulation modelling.

Chapter Four investigates the impact of various recessed wall façade types on thermal performance using IESVE computer simulation. The results are analysed according to the thermal performance of various typologies with regards to the configurations. The summary of the general performances of the design variables is highlighted.

Chapter Five presents the overall review of the research objectives and research questions. This chapter also concludes the principal findings of the thesis as a design recommendation for the thermal performance of tropical recessed wall office buildings. Lastly, this chapter also suggests future research to complement with this thesis findings. The research framework is shown in Figure 1.2.

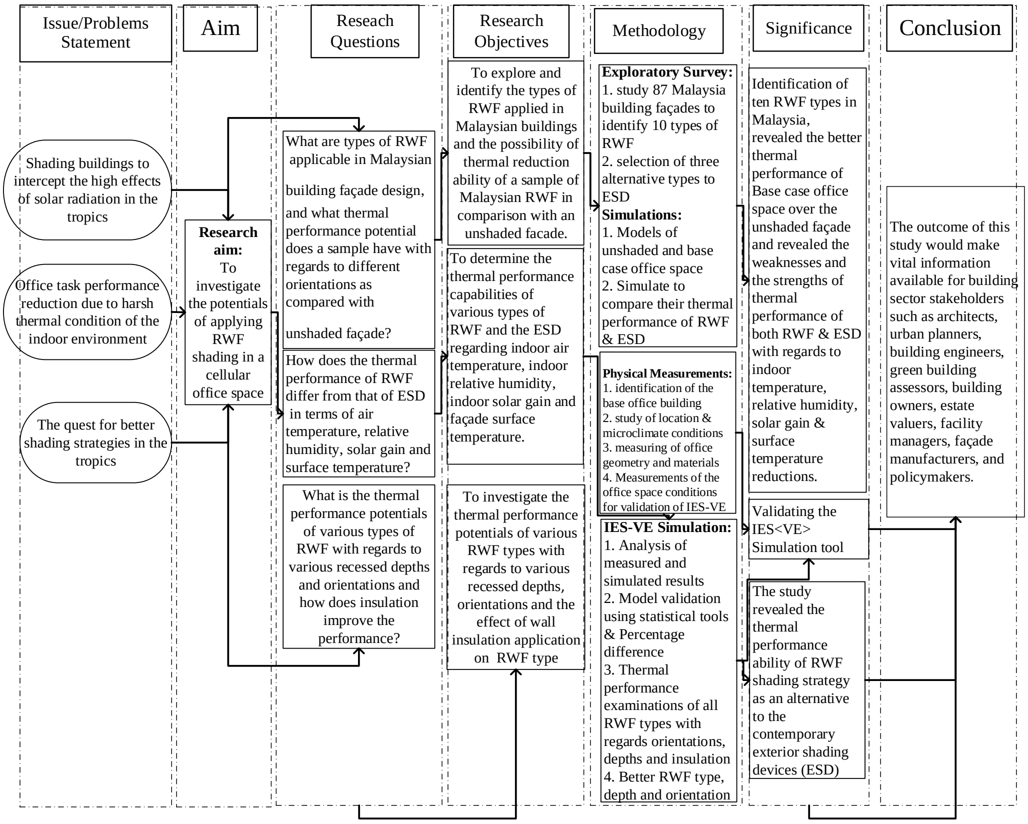

Figure 1.2 Research Framework

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