IMPACT OF BUILDING ENVELOPE MODIFICATIONS ON THE THERMAL PERFORMANCE OF GLAZED HIGH-RISE RESIDENTIAL BUILDINGS IN THE TROPICS

by

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TABLE OF CONTENTS

CHAPTER 3 : RESEARCH METHODOLOGY

CHAPTER 4 : EXPERIMENTAL WORK AND SIMULATION TOOL SELECTION

CHAPTER 5 : SIMULATION RESULTS OF THE BUILDING MODELS

CHAPTER 6 : SUMMARY, CONCLUSION AND RECOMMENDATIONS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION

ABCSE	Australian Business Council For Sustainable Energy
AC	Air Conditioned
ACH	Air Change Per Hour (Air Change Rate)
ASHRAE	American Society Of Heating, Refrigeration and Air-Conditioning Engineers
BABUC	Data Logger for Measuring Physical Quantities Manufactured by LSI
BC	Base Case
BSI	British Standards Institution
CETDEM	Centre for Environment, Technology & Development, Malaysia
CFD	Computational Fluid Dynamics
CLO	Thermal Resistance of Clothing (M^2kw^{-1})
COP	Coefficient of Performance
CP	Coefficient of Performance
DBT	Dry Bulb Temperature (^oC)
DOE	Department of Energy, USA
DSM	Department of Statistical Malaysia
ECDB	Energy Commission Diamond Building
EE	Energy Efficiency
EIA	Energy Information Administration
FSEC	Florida Solar Energy Center
GBI	Green Building Index
GDP	Gross Domestic Product
GEO	Green Energy Office
GFA	Gross Floor Area
GSR	Global Solar Radiation
HVAC	Heating, Ventilating and Air-Conditioning

IAQ	Indoor Air Quality
IEM	Institution of Engineers Malaysia
IES<VE>	Integrated Environmental Solutions <Virtual Environment>
ISO	International Standards Organization
LEO	Low-Energy Office, Malaysia
MBIPV	Malaysian Building Integrated PV project
MEGTW	Ministry of Energy, Green Technology and Water, Malaysia
MET	Metabolic Rate (Wm^{-2})
MMD	Malaysian Metrological Department
MRT	Main Radient Temperature (^oC)
MS_1525	Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings
MSRB	Multi-Storey Residential Building
NV	Naturally Ventilated
OTTV	Overall Thermal Transfer Value
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PTM	Malaysian Energy Centre
RH	Relative Humidity (%)
SC	Shading Coefficient
T_c	Thermal Comfort Temperature (^oC)
T_g	Indoor Globe Temperature (^oC)
T_i	Indoor Air Temperature (^oC)
T_o	Outdoor Temperature (^oC)
TMY	Typical Meteorological Year
TRNSYS	A Transient System Simulation Program
UBBL	Uniform Building By-Law
WFR	Window-to-Floor Ratio (Gross Floor Area)

WWR	Window-to-Wall Ratio (Gross Wall Area)
UNDP	United Nations Development Programme
ZEO	Zero Energy Office

IMPAK PENGUBAHSUAIAN DINDING LUARAN BANGUNAN KE ATAS TINDAKBALAS TERMA BANGUNAN KEDIAMAN TINGGI BERKACA DI IKLIM TROPIKA

ABSTRAK

Terdapat bukti bahawa bangunan perumahan berkaca tinggi yang dibina di iklim panas lembap seperti Malaysia telah mengakibatkan keadaan keselesaan yang tidak dapat diterima dan penggunaan pendingin hawa yang banyak untuk penyejukan. Tenaga digunakan untuk membuang haba yang masuk disebabkan dinding bangunan yang mempunyai keupayaan terma yang rendah. Daripada tinjauan literatur, kaedah pasif merupakan salah satu strategi yang amat berpotensi untuk diaplikasikan pada dinding bangunan di kawasan yang mempunyai radiasi solar yang tinggi dan beriklim panas lembap tropika. Tesis ini mempersembahkan keputusan secara empirikal dan kajian simulasi terhadap tahap pembaikan yang boleh dicapai melalui pengenaan modifikasi terpilih pada dinding luavan bangunan tinggi perumahan berkaca. Melalui kajian rintis dan kajian lapangan secara bersiri dalam keadaan iklim sebenar, telah didapati bahawa pembaikan yang signifikan dapat dicapai pada iklim dalaman sesebuah bangunan dengan mengurangkan WWR, mengaplikasikan pengudaraan semulajadi dan memilih orientasi yang berpatutan. Simulasi menggunakan IES<VE> yang dijalankan pada bangunan “The View Apartments” untuk mengkaji impak kepelbagaian modifikasi terhadap bangunan dari segi orientasi, pelbagai saiz tingkap WWR, pelbagai alat peneduhan dan jenis-jenis kaca telah dijalankan secara berasingan. Keputusan melaporkan bahawa melalui aplikasi strategi kombinasi seperti merendahkan WWR, tambahan peneduhan “egg-crate” dan penggunaan kaca pembalik dapat meningkatkan jumlah jam selesa tahunan dalam keadaan tanpa pengudaraan sebanyak 92%, 142.3% dan 64% dalam keadaan sehari penuh, waktu siang dan waktu malam masing-masing membanding nya dengan keadaan B.C. Walaubagaimanapun, peratusan ini adalah 12.5%, 27.6% dan 5% dalam keadaan adanya pengudaraan. Perlakuan terma tiap modifikasi terhadap iklim dalaman pada hari terpanas juga telah disusun. Peneduhan “egg-crate” didapati pengubahsuaian paling berkesan untuk merendahkan suhu dalaman.

IMPACT OF BUILDING ENVELOPE MODIFICATIONS ON THE THERMAL PERFORMANCE OF GLAZED HIGH-RISE RESIDENTIAL BUILDINGS IN THE TROPICS

ABSTRACT

There are evidences that the new highly glazed high-rise residential buildings being built in the hot-humid climate of Malaysia have inherently produced unacceptable comfort conditions resulting in a greater use of air conditioning systems for cooling. Energy is used to remove substantial amount of gained heat due to poor thermal envelope performance. From the literature, the passive design method is one of the most potential strategies to be applied to the building envelope in the high solar radiation and hot-humid tropical regions. This thesis presents the results of the empirical and simulation studies on the extent of improvement in indoor climate condition by applying selected modifications to the high-rise glazed residential building envelope. Through the pilot study and a series of full scale field measurement studies conducted under real weather conditions, it is found that a significant improvement in indoor climate condition could be achieved by reducing WWR, applying NV and selecting proper orientation. Simulations using IES<VE> were carried out at “The View Apartments” to investigate the effects of different modifications to the building configuration in terms of orientations, different window sizes WWR, varied external shading devices and varied glazing types as separate entities. The results reported that, by applying a combination of strategies such as lowering WWR, adding egg-crate shading devices and using reflective glazed windows, the number of comfortable hours in un-ventilated condition was improved annually by 92.0%, 142.3% and 64.9% in full day, day-time, night-time conditions respectively comparing them to Base Case condition. However, these percentages were 12.5%, 27.6%, and 5.0% in ventilated conditions. The thermal behaviour of each investigated modification to indoor condition during the hottest day has also been ranked. The egg-crate shading device was found to be the best modification to lower the indoor air temperatures.

CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

Architecturally, tropical region is one of the hardest climates to compromise through design (Szokolay, 2008). This is due to the high humidity and day-time temperatures that result in high indoor temperatures exceeding the upper limit of thermal comfort zone for most of the year (Sabarinah, 2008). Since Malaysia is in the tropical region, it is undeniable that buildings are facing numerous problems. Buildings are overheated during the day due to solar heat gain through the building envelope and radiant solar penetration through windows (Rajapaksha et al., 2003). Traditionally, this heat can be removed partly by applying passive design concepts. However, in recent years, the use of electricity for indoor thermal environment control, particularly air-conditioning has become the dominant energy end-use in buildings.

In recent years, Malaysia maintains a high economic growth and therefore, its energy consumption increased dramatically. Commercial and residential buildings alone account for about 13.6% of total energy consumption and 48% of electricity consumption (Al-Mofleh et al., 2009, Lucas, 2003). This means that Malaysia has a strong need and great potential to apply efficient strategies in lowering energy consumption in buildings. Thus, buildings, energy and the environment have become some of the key issues facing the building professions (Azni Zain, 2008). With the increasing population and living standards, energy issue is becoming more and more important today because of a possible energy shortage in the future (Yilmaz, 2007).

According to the Ninth Malaysia Plan 2006–2010, energy conservation culture must be inculcated amongst Malaysians and emphasized in government policies and the buildings should be designed to optimise energy usage. Such resources need to be prudently and carefully utilised. The government is adopting measures to reduce wastage by promoting energy efficient buildings and increasing energy sufficiency throughout the country (Malaysia_Plan, 2006). Therefore, it is necessary to correct and modify the indoor climatic condition especially for those buildings with high glazing area in the façade, which is more sensitive to climatic conditions, by getting the all benefits of passive design concepts. The major feature that can be altered for better energy performance is the envelope design.

The building envelope may be defined as the totality of building elements made up of components, which separate the indoor environment of the building from the outdoor environment (Oral et al., 2004). The construction of the building envelope and selection of its material have a significant effect on a building's thermal performance and accordingly on both energy efficiency and occupant comfort, especially when taking into account the envelope's orientation, windows area, glazing types and shading system. An analysis of the building energy consumption in Hong Kong, Singapore and Saudi Arabia for example gives a result that the building envelope design accounts for 37%, 25% and 43% of the peak cooling load respectively (AL-Najem, 2002, Cheok-Chan, 2008, Lam and Li, 1999).

To limit the amount of heat gain through the building envelope is obviously an important step for reducing the cooling energy consumption. Architects and designers need to understand that the energy demands of a building stems from functions of its design, the quality of the environment in which it is located, and the way in which it is being operated (Salvan, 1999). In other words, building design and climate conditions play a significant role in energy consumption and thermal performance of the building envelope components. To utilize the potential of the thermal performance of building envelope, these characteristics should be identified and properly considered at an early design stage to reduce the energy consumption required to achieve thermal comfort.

The energy consumption in buildings is normally given in terms of the Building Energy Index BEI. The South East Asian Average BEI is 233 kWh/m^2/yr whereby the Malaysian average is 269kWh/m^2/yr, whereby 64% is for air conditioning, 12% lighting and 24% general equipment (Azni Zain, 2008). However, the level for low energy buildings recommended by Green Building Index GBI is between 90-150 kWh/m^2/yr (MS_1525, 2007). To comply with that Malaysian government in 2006 has already built the low-energy office (LEO) building in Putrajaya whose energy intensity is 104 kWh/m^2. The Malaysian Energy Centre (PTM) has also built a zero energy office building (ZEO) in line with global initiatives to reduce environmental pollution (Al-Mofleh et al., 2009). ZEO building is now called green energy office building (GEO) which is officially Malaysia’s first Green Building Index Certified Building since 2009 (GBI, 2011). The government has also included 5% renewable energy usage in its 9th Malaysian plan to encourage the usage of renewable energy to reduce the environmental burden on the atmosphere.

This research is focused on reducing the indoor air temperature in high-rise residential buildings where the major feature of its façade is the glass material which can be altered for better thermal performance. It is commonly known that external environment and the outdoor climate cannot be changed, neither can it be controlled and once the building has already been constructed, little can be done to improve the thermal performance of the building envelope. However, a lot can be done on the early stage of building design. Therefore, this research study concentrated on how thermal performance of the high-rise residential building envelope in tropics could be improved.

This research investigated the effect of the building envelope modifications such as, area ratio of window to wall (WWR), different categories of glazing and several kinds of shading system. The effect of natural ventilation and building orientation is also investigated. Considering these design concepts at the early design stages, it is strongly believed that an acceptable indoor thermal environment could be achieved with low energy consumption.

This is more important in developing countries where energy efficient codes are still being developed. In Malaysia, efforts are currently under way to improvise the Malaysian Green Building Index (GBI) launched in August 2008. Therefore, the expected output of this research is hoped to be of significant contributions and become design guidelines for improving thermal performance of naturally ventilated and un-ventilated high-rise residential buildings in tropical climate.

1.2. STATEMENT OF THE PROBLEM

The rapid development, process of urbanization, and growth of construction industry in tropical developing countries such as Malaysia, have contributed in introducing new high-rise, highly glazed, thermally lightweight residential buildings that are unsuitable to the local hot and humid climate (Byrd, 2008). Many of these buildings have not been designed and operated efficiently, contributing to an overall poor thermal performance of the buildings envelope. Thus, new high-rise residential building became more dependent on artificial means to provide comfortable thermal environment at high energy consumption (Rickwood et al., 2008, Liping et al., 2007, Seung et al., 2004, Bojic et al., 2002, Cheung et al., 2005).

In Malaysia, according to A. Rahman and R. Ismail, Malaysian buildings are consuming about 70% of energy for cooling the indoor environment (Abdul Rahman and Ismail, 2008). However, Azni reported that more than 40% of the energy consumed by Malaysian buildings can be reduced if energy efficiency is practiced and sustainable technologies are applied to building envelope (Azni Zain, 2008). Compared with commercial buildings, research studies on residential buildings are limited and detailed thermal performance data are largely lacking. Another study reported that there are very few studies on facade designs to improve indoor thermal comfort for naturally ventilated residential buildings especially for hot-humid climate (Liping and Hien, 2007). The majority of the previous studies in high-rise residential building envelope performance were carried out in Hong Kong, Singapore, Japan, China and

Taiwan. Few of these studies dealt with large glazed area as the main material for the high-rise residential building façade. However, extremely few studies in this field have been obtained in Malaysia.

The specific problems that signify the importance of thermal performance research in residential building envelope in Malaysia are as follows:

1. Malaysia has one of the fastest growing building industry in the world (ABCSE, 2005). Minister of Housing and Local Government said that since the 1990s, developers had been building an average of 100,000 homes every year (TheStar, 2009).
2. The population increased from 18.1 million in 1990 to 28.3 million in 2009 (DSM, 2009) which demands an accompanying growth in residential sector to fill up the gap of housing needs.
3. The country generated an average GDP growth of 6.2% per annum from 1991 to 2005. This growth more than doubled average household income from RM1.169 per month in 1990 to RM3, 249 a month in 2004 (Malaysia_Plan, 2006).
4. An improvement of living standards in the past two decades has changed dramatically. People tend to be more accustomed to air-conditioned environments. Thus, people are getting more affluent, air-conditioning system is becoming popular to help in achieving a comfortable internal thermal environment (Byrd, 2008).
5. Internationally, energy consumption of the residential sector accounts for 16–50% of that consumed by all sectors, and it averages approximately 30% worldwide. However, as shown in Figure 1.1 this percentage was 19% in Malaysian residential buildings (Saidur et al., 2007), a significant amount which justifies the need to be studied.
6. The trend of Malaysian residential buildings are now constructed in the new style high-rise buildings which are totally different from the traditional ones. Their external envelopes are covered with large area of glass and concrete (Figures 1.2 and 1.3). This is particularly apparent in urban areas where land is scarce while population is high. As Malaysia is located in the tropics, these modern buildings are exposed to the full impact

of the external temperatures and global solar radiation, which affects the occupants comfort in a negative way.

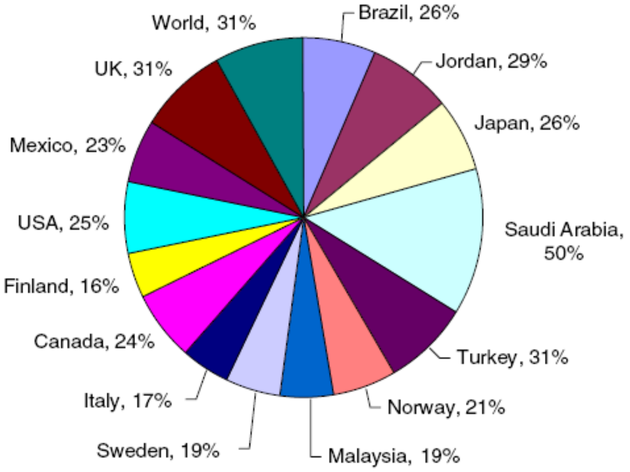

Figure 1.1 Worldwide residential energy consumption
Source: (Saidur, Masjuki et al. 2007)

Figure 1.2 Traditional Malay house

Figure 1.3 New style of high-rise residential building in Kuala Lumpur and Penang

7. Many studies reported that poor indoor comfort of glazed buildings leads to high energy consumption and affects the users' health adversely. In Malaysia, 45% of the average household electricity is consumed by air conditioners to create acceptable indoor environment (CETDEM, 2006). However, applying passive concepts for the building envelope design could lower and save this energy.
8. The Malaysian Standard MS 1525 (Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings) does not elaborate on neither suitable environmental design for high-rise residential buildings nor on its envelope requirements in particular. Subsequently, there is a need for continuous improvement through more extensive studies (Zain et al., 2007).

According to the previously mentioned points, the researcher believes that this study would be of much value in solving the problem of energy consumption in Malaysian residential sector.

1.3. SIGNIFICANCE OF THE STUDY

In Malaysia, nearly half of the electrical energy in residential buildings is used by air-conditioning system to achieve thermal comfort (CETDEM, 2006). The high energy consumption is mostly related to poor thermal performance of building envelope (Manioglu and Yilmaz, 2008). Therefore, a study investigating the thermal performance of building envelope in hot-humid climates of Malaysia will identify the most important thermal design parameters that could be implemented to reduce the dependence on mechanical means and achieve thermal comfort with reduced energy consumption. Moreover, Green Building Index (GBI) introduced design reference guide for residential new construction, which encourages building designers and developers to enhance the buildings to provide a thermally comfortable environment to reduce the use of air-conditioning in residential building, thereby reducing CO^2 emission (GBI, 2010). Thus, this study will be beneficial to architects and housing developers who are energy and environmentally concerns and who would like their designs and housing developments rated “green”.

Consequently, this study will provide general requirements on the proper thermal characteristics of the exterior building envelope that are necessary to achieve thermal comfort at low energy consumption. Therefore, it will contribute to the current efforts of improving Malaysian GBI Code by providing general design guidelines that can be implemented to reduce energy consumption. The study will also be important to home owners who will use the results of this study to improve comfort conditions inside their own houses.

1.4. OBJECTIVES OF THE STUDY

There is a lack of knowledge regarding the overall performance of the high-rise residential building envelope in hot-humid climate of Malaysia. Therefore, the main objectives of the study are:

1. To investigate the thermal performance and the impact of several design modification of the building envelope to the indoor air temperature of naturally ventilated and un-ventilated high-rise residential building in Malaysia.
2. To evaluate each modification in terms of their capability to lower the indoor air temperature.
3. To explore building design potential and ways to enhance indoor thermal condition by introducing new combination strategies for high-rise building envelope that enhance the satisfactory living conditions for residents.
4. To develop design recommendations for thermal performance envelope that improves the indoor air temperature in both ventilated and un-ventilated conditions of high-rise residential building in Malaysia.

1.5. SCOPE OF THE STUDY

The aim of the study is to analyze the most important factors that have a significant effect on building thermal performance and energy consumption of residential building envelope under tropical climate condition. Figure 1.4 presents the scope of this research and the overall framework for a complete building evaluation model. There are many components to overall building evaluation. Therefore, the highlighted boxes are the focus of this research. This research concentrates on building environment as it is shown on (Line 1). Here, glazed residential building is chosen as the studied building imposes the worst problems in terms of thermal environment in the tropics. Within the building environment aspect, the research evaluates the building thermal performance, and addresses the building envelope and system operation (Line 2 and 3). For the building envelope, the research studied the fenestration system as well as its orientation. The evaluation of the operation parameters including the natural ventilated as opposed to un-ventilation conditions are also investigated.

On the other hand, ASHRAE Standard 55 and Standard ISO 7730 are currently assuming that thermal sensation is exclusively influenced by four environmental factors i.e. temperature, thermal radiation, humidity and air speed (ASHRAE, 2004, ISO, 2005). However, air temperature is considered as the main and sometimes exclusively considered factor in evaluating building thermal performance (Szokolay, 2008, Ibrahim and M. Hazrin, 2009, Humphreys, 1976a). For example, study by Rohles and Nevins showed that temperature is seven to nine times more important than relative humidity in influencing how men and women felt respectively (Rohles and Nevins, 1971). Therefore, the scope of the thermal performance evaluation of the previous highlighted components on this research was based on the variation between in/outdoor air temperature and ventilation for each building envelope modification.

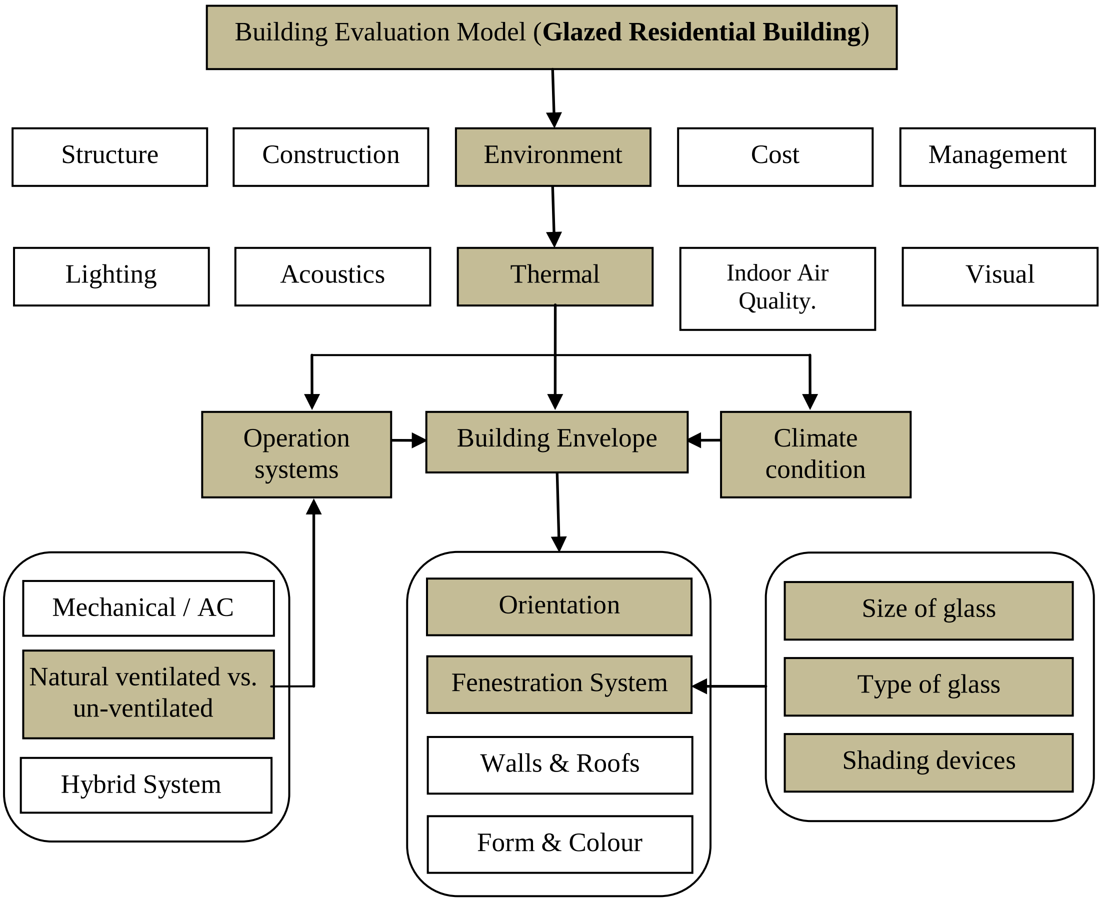

Figure 1.4 Location of research in the body of knowledge
Source: (Author 2009)

1.6. HYPOTHESIS OF RESEARCH

The hypothesis of this research assumes that indoor climate condition can only be improved by the designer through proper selection and integration of the building physical components. Therefore, if the building envelope is efficiently designed, it will result in less dependency on mechanical systems to achieve the desired thermal comfort conditions. The theory of research hypothesis as shown in Figure 1.5 was based on three assumptions as follows:

a) Indoor air temperature (T_i) in glazed building in tropical climate is very high and always above outdoor air temperature (T_o). According to this scenario T_i exceed the upper limit of thermal comfort temperature T_c range especially during day-time hours (Refer to Figure 1.5 a).

b) Implementing different modifications for building envelope configurations have substantial effects on the magnitude of the external heat gains and to the reduction in T_i (Refer to Figure 1.5 b).

c) Further integrating (b) with natural ventilation strategy and optimum orientation will lower T_i to the lowest possible (Refer to Figure 1.5 c).

Therefore, it might not be possible to completely avoid using mechanical systems in tropical climates of Malaysia but the dependence on artificial means to provide a constant thermal comfort can be minimized.

1.7. LIMITATIONS OF THE STUDY

Since the experimental research involves multiple variables and simulation studies, there are limitations and restrictions raised through the research. This research is limited to the following conditions:

1.7.1. BUILDING SAMPLE LIMITATIONS

Initially 6 sample buildings were selected, that exemplify glazed and high-rise residential units in Penang. However, only one building was agreeable to the research. “The View Apartments” was selected and used as the primary case for field data collection and analysis. The reasons of selecting this building were illustrated in section 4.3.1. As a high-rise building, wind direction and pressure will affect indoor ventilation behavior. However, in this study, due to irregularities of wind speed and directions; and limitation of probes, the impact of external wind was not considered.

1.7.2. TECHNICAL LIMITATIONS

a) The instruments field study was conducted for “The View Apartments”, Penang Island. The collected data was used to give a comprehensive picture of the thermal performance of the residential buildings under hot humid climate. However the available data acquisition instrument used had only 4 input channels, which limit the number of thermocouples installed in the investigated units.

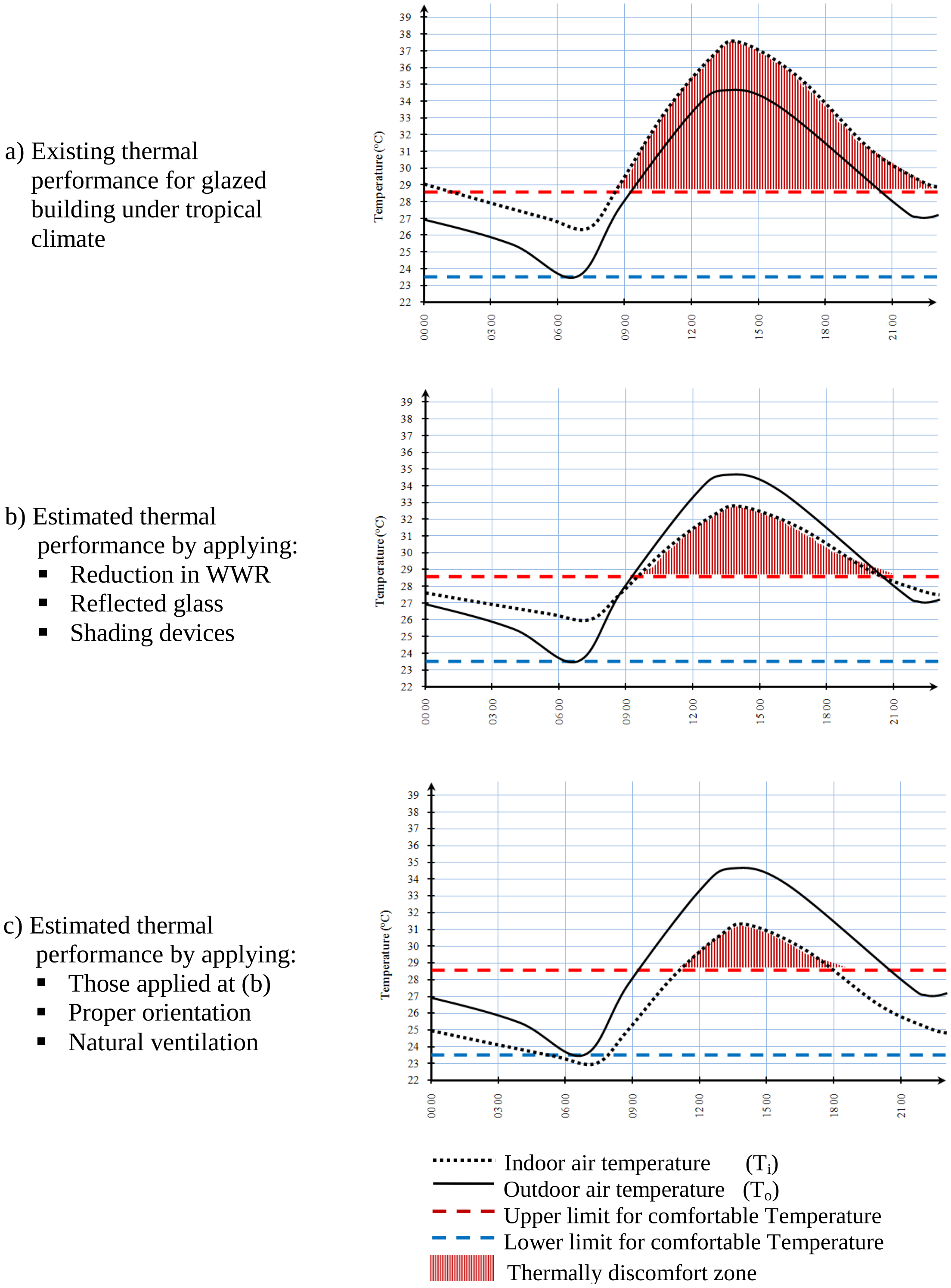

Figure 1.5 a), b) and c) Concepts flow of study hypothesis.
Source: (Author 2009)

b) Although there are many thermal modelling programs in market, simulations were confined to just Ecotect and Integrated Environmental Solutions <Virtual Environment> IES<VE> which were being purchased by the university for academic research purposes. IES<VE>and Ecotect programs were thoroughly tested and calibrated for use in the research. However, some technical limitations arose while using these softwares, which required co-operation between the researcher and the software's support staff to overcome.

1.7.3. TIME AND ACCESS LIMITATIONS

The field study was carried out in the view units for a limited time of three consecutive months during mid April to mid July 2009 agreed and allowed by the owner of the residential complex. This period is considered as a part of the hottest climate period. Not all orientations can be analyzed in fieldwork, because of the limited access to the three units have been taken as case studies and depending also on their designs. Nevertheless, enough data were collected for understanding the thermal performance of real buildings and for successful calibration with the simulation software.

Despite the obstacles and the limitations mentioned previously, but the search should still be carried out to provide design guidelines and design strategy recommendations that maintain comfort conditions while reducing building energy use.

1.8. ORGANIZATION OF THE STUDY

The dissertation is presented in six chapters. **Chapter 1**, provides the introduction to the study by providing a relevant background, presents the problem statement, study objectives, hypothesis, as well as the scope and limitations of the research.

Chapter 2, reviews the previous research conducted in this area, which provides a basis for the development of this study. The discussion includes the basic principles of building thermal behaviour and an assessment of the building envelope components in thermal performance and energy cooling requirements. Effects of orientation and natural ventilation as passive techniques are also discussed.

Chapter 3, discusses the methodology applied to this study. It describes the experimental work as well as the basis for the selection of the simulation model, and outlines the detailed simulation scheme adopted by the study for analysis.

Chapter 4, discusses the concept, components and procedures involved in the pilot study to evaluate the experiment in small scale model. Field work and simulation analysis for the pilot study is presented in this chapter. Second part of this chapter provides the experimental work in full scale case study of "The View Apartments". The effect of building envelope components in indoor air temperature in both naturally ventilated and un-ventilated conditions are also investigated.

Chapter 5, discusses the case study modeling and calibration using IES<VE> tool. This chapter explains the influence of improved and modified building envelope on indoor thermal performance in a different ventilated condition. Moreover, the evaluation of the results are analyzed annually as well as during the hottest day to achieve maximum thermal comfort requirements.

Chapter 6, summarizes the research results, and presents general design recommendations for integrating passive concepts according to weather condition, upper limit of thermal comfort requirement and user's time schedule to save energy in residential buildings in hot and humid climates. It also suggests future research that may be build on the outcome of this study.

CHAPTER 2: LITERATURE REVIEW

2.1. INTRODUCTION

The development of building evaluation systems must begin with an understanding of the factors which influence thermal performance and energy consumption. This literature review includes an overview of the role played by residential building loads, an assessment of the previous research that tested the various properties of envelope components as well as the previous research that has tested the different options to improve indoor environment in various residential buildings in hot humid climate of South Asian countries.

There are many experimental and numerical research studies conducted in some tropical hot and humid climates such as in Taiwan, Singapore, Hong Kong, Saudi Arabia, Indonesia, Thailand and Malaysia to investigate the impact of building envelope on internal thermal performance and its impact on energy consumption. However, there is only a limited amount of research literature on residential building envelope through the climate responsive design requirements to achieve better thermal performance of the high-rise residential building envelope in hot and humid climate.

2.2. THERMAL PERFORMANCE FOR CLIMATE RESPONSIVE DESIGN

Climate responsive design is part of an environmental approach to building development called ecological sustainable design. Therefore, it combines the study of climate, biology and building design to enhance living conditions and reduce energy consumption (Hyde and Woods, 2000). With the advent of the energy crisis there was a renewed interest in those aspects of architecture which contributed to thermal comfort in a building without (or with minimum) expenditure of energy (Sodha et al., 1986). This research addresses the most important factors that determine thermal performance in buildings, which cover the weather data of Georgetown, building envelope components and its orientation as well as natural ventilation. The following is a brief theoretical description of the effect of these elements on indoor thermal environment.

2.2.1. CLIMATIC CONDITIONS IN HOT-HUMID CLIMATE (MALAYSIA)

From the knowledge of sun earth relationship, one would therefore expect the equatorial region to be the hottest and as one moves away from equator towards the poles, it gets steadily cooler (Sodha et al., 1986). Malaysia, lying in the equatorial region, consists of Peninsular Malaysia and a part of Borneo Island, and together they make a total of 328,600 km^2 of land area. Since the peninsular has the major population (76%), the present study is aimed in this area (Ali et al., 2010). Peninsular Malaysia as shown in Figure 2.1 is situated between 1^{o}N and 7^{o}N latitude. Most towns in the peninsular experience high temperature and humidity throughout the year without remarkable variations. The diurnal temperature range is of minimum 23–27^{o}C and maximum 30– 34^{o}C. The average difference is 6.7^{o}C – 8.3^{o}C with annual RH value ranges from 74 - 90% (MMD, 2009, Heerwagen, 2004). However, there is a seasonal climatic change, which is dominated by the monsoons. The monsoons represent significant changes in the wind conditions and rainfalls.

Figure 2.1 Map of Malaysia
Source: (U.S. Central Intelligence Agency, 2000).

2.2.2. AMBIENT CLIMATIC CONDITIONS OF PENANG

Climate data has been presented for the selected city of Georgetown, which is located in Latitude +5.3°N and Longitude +100.3°E and Time zone +8. The data is constructed in graphs and charts which map the climatic situation of the city covering the complete yearly cycle. The data presented are those which influence the building design, which includes average temperature, humidity, solar radiation and sunshine hours, wind and air movement.

2.2.2.1. Temperature

Georgetown has an equatorial climate. It is uniformly warm and humid throughout the year. There are no particular hot or cold seasons as such. The diurnal temperature range of minimum 23–24°C and maximum 30– 33°C (MMD, 2009). The latest climatic updates in Georgetown temperature is shown in Figure 2.2.

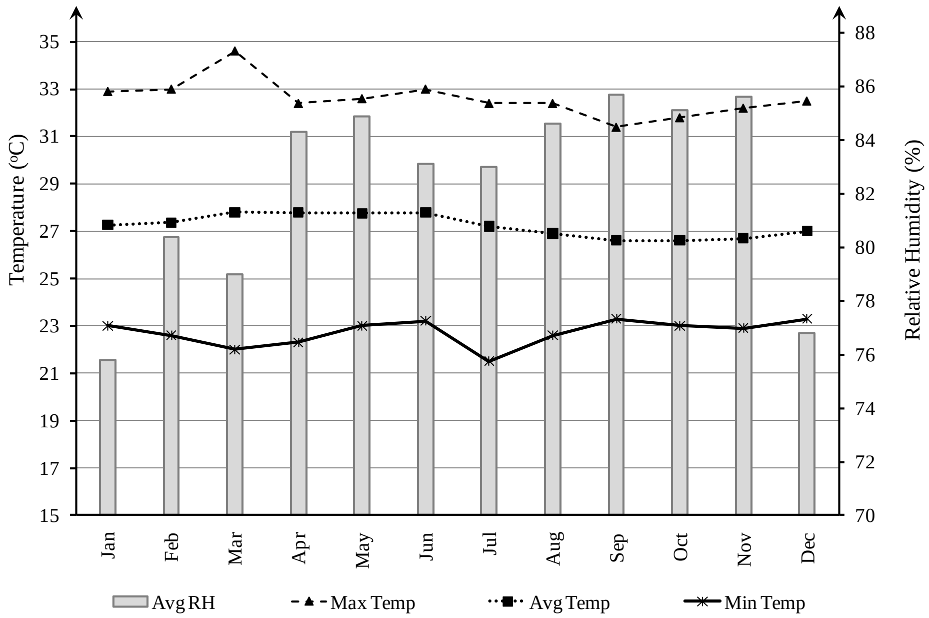

Figure 2.2 Maximum, minimum, average dry bulb temperature and average relative humidity in Georgetown

(Source: Weather Tool Software, average of 30 years data)

2.2.2.2. Humidity

The annual rainfall is evenly distributed throughout the year. The relative humidity ranges from 74 – 86%. September to November may be considered the wettest months (MMD, 2009).

2.2.2.3. Solar Radiation

As a maritime country close to the equator, Malaysia has abundant sunshine and thus solar radiation. On the average, Malaysia receives about 6 hours of sunshine per day. The cloud cover limits sunshine substantially and thus solar radiation. Hu and Lim investigated solar radiation and sunshine duration for a total of 14 stations in Peninsular Malaysia. The study found that the pattern of global solar radiation follows somewhat in accordance with that of the rainfall pattern (Hu and Lim, 1983). Figure 2.3 shows most parts of Malaysia recorded 16.4 to 21.7 MJm^2 of daily solar radiation. The lowest solar radiation below 16 MJm^2 per day was recorded over southern part of Johore. On the other hand, some places in Penang together with and eastern division of Sabah had higher daily solar radiation of more than 22.0MJm^2 (Malaysia MMD, 2009).

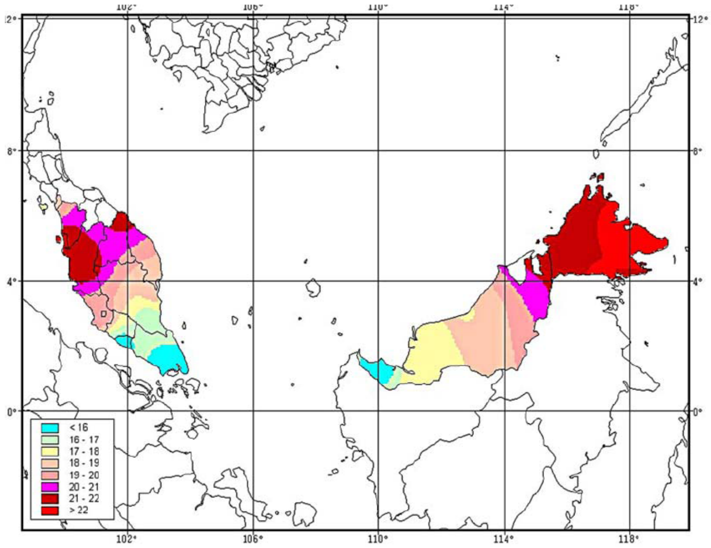

Figure 2.3 Mean Daily Solar Radiation (MJm-2), Malaysia

Source: (Malaysia MMD, 2009)

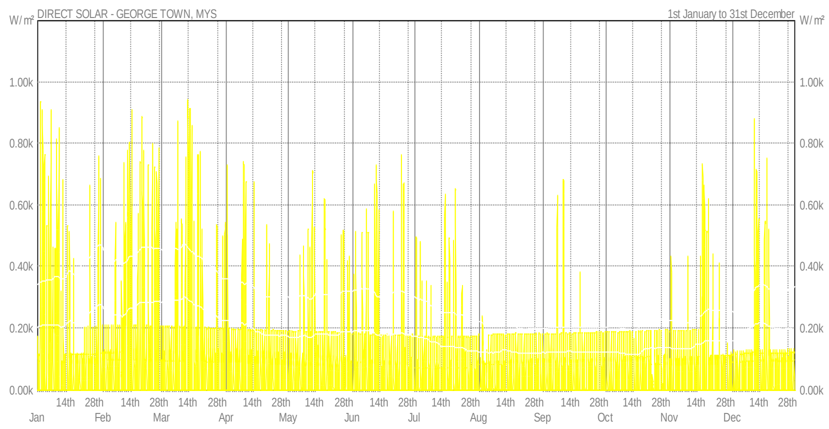

Figure 2.4 Direct Solar Radiation, Penang

(Source: Weather Tool Software, average of 30 years data).

2.2.2.4. Air Velocity and Wind Direction

The mean surface winds over peninsular Malaysia are generally mild, with the mean speed of about 1.5 m/s, and a maximum speed of less than 8 m/s. The main direction is varied (Refer to Figure 2.5). The hourly speeds are high during the day, and the calm periods which vary from 16% to 50%, mostly occur at night. The wind conditions are favourable for the adoption of natural ventilation (Ismail, 1997).

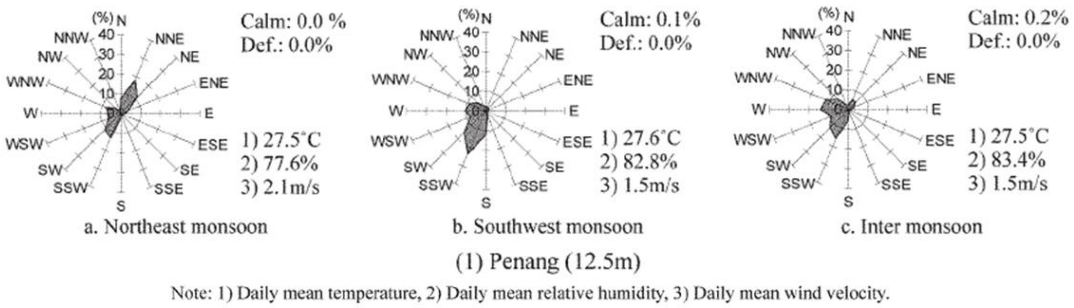

Figure 2.5 Wind rose and climate summary in Penang

Source: (Kubota and Supian, 2006)

2.2.3. THE INDOOR THERMAL ENVIRONMENT

A building is usually required to provide an indoor environment that can be maintained within certain limits as required by the occupants. A thermal comfort environment is a condition that is neither too warm nor too cold, or thermal neutral in which the strain on the body's thermal regulatory system is minimal (Gwilliam and Jones, 2002). Many people believe that the quality of the thermal environment can be evaluated simply by measuring the air temperature (the dry-bulb temperature). However, this is far from accurate (Al-Rubaih, 2008). There are many factors that can influence occupants thermal comfort in built environment including indoor air temperature, air humidity, air movement, mean radiant temperature (MRT), as well as occupants' activity level (measured in METs), clothing level (measured in CLO), age and sex (Meredith, 2004).

2.2.3.1. A Definition of Thermal Comfort

One of the simplest definitions of thermal comfort is given by Givoni, who explained that thermal comfort could be defined as the range of climatic conditions considered comfortable and acceptable to humans (Givoni, 1998). Thermal comfort is also defined in both ASHRAE Standard 55 and ISO Standard 7730 as: that condition of mind which expresses satisfaction with the thermal environment (ASHRAE, 2004, ISO, 2005). Therefore, the term 'thermal comfort' describes a person's psychological state of mind and is usually referred to in terms of whether someone is feeling too hot or too cold.

2.2.3.2. Previous Thermal Comfort Studies in Hot-Humid Climate

It is important to understand the thermal comfort expectations in tropical climate in order to design a proper building envelope that contributes in environmental and energy efficiency. Several thermal comfort studies in hot humid climates have been conducted to develop a database of the thermal environment and subjective responses of the people living in these climates. ASHRAE standard 55 on “Thermal environmental conditions for human occupancy" gives 26°C as an upper limit of comfortable temperature (ASHRAE, 2004). However, many old and new studies assert that it is reasonable to assume that people living in unconditioned buildings in hot developing countries are acclimatized to higher temperatures and/or humidities (Givoni, 1992, Busch, 1992,- Milne and Givoni, 1979, Humphreys, 1976b, Wong and Khoo, 2003, Ellis, 1952b). A summary of thermal comfort literature review in tropical countries are illustrated as follows.

a) **Malaysia:**

A study in a controlled climate chamber involving 130 university students aged between 18-24 conducted in 1993 (Abdul Shukor and Young, 1993). All subjects were engaged in light activity of 1.0 met and clothes of 0.5 Clo value. The air velocity was 0.1 m/s and relative humidity 50%. The result showed that the neutrality temperature was 28.2°C. On the other hand, Sabarinah and Steven (2007) reported that, the comfort band for Malaysia for all building types is between 23.6 and 28.6°C. Another study suggested that, the occurrence of thermal comfort in Malaysia could be achieved below 28.69°C (Zain et al., 2007).

Another survey conducted and measured the indoor environmental parameters to study and determine the comfort conditions of college students in their naturally ventilated classrooms in Shah Alam. A mean temperature of 29.8°C and mean air movement of 0.27 m/s were experienced by the subjects at average 65% humidity. The neutrality temperature calculated was 27.4°C (Abdul Rahman and Kannan, 1997).

b) **Singapore:**

A study conducted in Singapore involving 98 students showed that the acceptable comfort zone was 27.6°C at 70% relative humidity and 27.9°C at 35% relative humidity (De Dear et al., 1991a). However, a field study was conducted in classrooms in Singapore to assess their thermal conditions during the students' lesson hours. The result shows that the acceptable temperatures ranged from 27.1 to 29.3 °C, implying that the ASHRAE standard 55 is not applicable in the free-running buildings in the local tropical climate. A neutral temperature of

28.8 °C was found to be in good agreement with the result of other recent studies in Singapore (Wong and Khoo, 2003).

c) Thailand:

A study in Bangkok conducted during the hot season in April and wet season in July involving more than 1100 office workers responded to a questionnaire.The study compared naturally ventilated offices with air conditioned ones. Results from these studies showed that people in tropical regions could tolerate warmer temperature than predicted by comfort models and ASHRAE 55-1995 standards. The study shows that, based on 80% of Thailand workers being satisfied, the upper limit of the comfortable temperature can be as high as 28^{o}C for people in air-conditioned buildings, and 31^{o}C in naturally ventilated buildings (Busch, 1992).

d) Indonesia:

A field study conducted in Jakarta involving 596 office workers working in seven multi-storey office buildings which consisted of a naturally ventilated, a hybrid and five air conditioned. The neutrality temperature was 26.4°C which was 2.5°C higher than those recommended by ISO and ASHRAE (Karyono, 2000).

e) Hawaii:

A study conducted a survey of 3544 students and teachers in 29 naturally ventilated and air conditioned class rooms in Hawaii. The study found that, naturally ventilated class room occupants accept a wide operative temperature range (22.0 – 29.5^{o}C). Besides that, strong air velocity can increase the rate of convective and evaporative heat loss from the human skin to the environment (Kwok, 1998).

2.2.3.3. Previous thermal comfort studies in residential buildings

a) Malaysia:

Based on the literature review, there are limited studies on thermal comfort in Malaysia before the 1990s. However, since 1990's with the increase of energy usage in commercial sector, more research has been conducted in the area of thermal comfort to find means to provide comfortable indoor environments to reduce energy consumption and costs. Studies have shown that an increase in temperature indoor setting of 1.5°C gave 15.8% energy saving (Abdul Rahman and Kannan, 1997, Zainal and Keong, 1996).

A study of comfort (using software code TAS) was conducted on apartment units in medium rise housing block in the Klang Valley area. The results show that these units are uncomfortable especially during the day-time (Sabarinah, 2005). In addition, several studies have been undertaken by researchers in Malaysia in relation to thermal comfort in residential buildings (Abdul Shukor and Young, 1993, Zain et al., 2007, Sabarinah and Steven, 2007). The main scope of these studies was to find the neutral temperature according to the country's tropical climate. Findings revealed a higher comfort temperature in comparison with those recommended by international standards where in naturally ventilated buildings the upper range of comfort could be stretched with the aid of higher natural air movement. Summary of the results are illustrated in Table 2.1.

b) Singapore:

A study conducted field experiments in both naturally ventilated high rise residential buildings and air conditioned buildings in Singapore. The neutral temperatures of subjects in the naturally ventilated building and air-conditioned buildings were 28.5 and 24.2 °C respectively (De Dear et al., 1991c). Other studies in Singapore showed that the acceptable temperatures range from 27.1 to 29.3 °C, implying that the ASHRAE standard 55–92 is not applicable in the free-running buildings in the local climate (Feriadi et al., 2003, Wong et al., 2002).

c) Thailand:

A study carried out a thermal comfort survey in Bangkok, Thailand which covered 1377 residents while physically taking measurement simultaneously in air-conditioned and naturally ventilated residential buildings. The results showed that the comfort temperatures for Thai people in residential buildings are 25.0°C with the range of 22.5°C to 27.5°C (90% acceptability) for air-conditioned buildings and 28.0°C with the range of 25.5°C to 30.5°C (90% acceptability) for natural ventilation buildings (Rangsiraksa, 2006).

d) Indonesia:

Feriadi and Wong (2004) conducted an extensive field survey in residential buildings in Indonesia, 525 sets of data had been gathered. The results showed that under hot and humid tropical climate of Indonesia, people prefer environment condition at 26°C and 29.2°C in A/C and naturally ventilated spaces respectively.

2.2.3.4. Summary on thermal comfort study

A comparative analysis of all the previous thermal comfort studies done in South East Asia made and concluded that people living in the warm and humid tropical countries prefer similar neutral temperatures around 25-30°C. In comparison to ASHRAE standard 55 and ISO standard (ISO, 1994, ASHRAE, 2004) recommended temperature of 23-26°C, these figures are 2-4°C higher. Over all, a summary of the neutral temperatures and comfort ranges of subjects in the hot-humid regions is shown in Table 2.1.

28.6^{o}C has been taken as an upper limit of the comfort temperature for this research evaluation based on the following criteria:

- The previous thermal comfort studies in general and in residential building in particular (Refer to Table 2.1) especially in Malaysian climate.
- The calculation method of the thermal comfort zone for Georgetown climate based on mathematical equation showed in appendix B.

Table 2.1 Thermal comfort research for naturally ventilated buildings and air-conditioned buildings in Malaysia and the South East Asia Region

Researcher & Year Published	Location	Type of Building	Type of Study	No. of Subjects	RH%	Temp. of Comfort (°C)
(Webb, 1952)	Singapore		Field Study	16		26.2
(Ellis, 1952a)			Field Study	5211		26.1-30.0 NV
(Ellis, 1953)			Field Study	118		22-25.5 A/C
(De Dear et al., 1991a)			Thermal Chamber	32		25.4 A/C
(De Dear et al., 1991b)			Thermal Chamber	98	35	27.6 NV
(De Dear et al., 1991c)		High-Rise Resdi	Field Study	583		28.5 NV
(Wong et al., 2002)		High-Rise Resdi				28.9
(Salleh, 1989)	Malaysia	terrace housing				26.1
(Zainal and Keong, 1996)		Factory				33
(Zain et al., 2007)		Residential				23.69 - 28.69
(Abdul Shukor and Young, 1993)	Penang , Malaysia	Residential			50	28.2
(Zainal and Keong, 1996)	Johor Baru, Malaysia	Factory			18-75	26
(Abdul Rahman and Kannan, 1997)	Shah Alam, Malaysia	Classrooms			54 -76	27.4
(Sabarinah and Steven, 2007)	Kuala Lumpur	Medium-Rise Resdi				23.6-28.6
(Sh. Ahmad and Ibrahim, 2003)	Shah Alam, Malaysia	Classrooms				27.6
(Sabarinah, 2005)	klang valley Malaysia	Residential				26.1
(Busch, 1992)	Bankok, Thailand	Offices	Field Study	1100		28.5 ET(NV2) 27.4 ET*
(Khedari et al., 2000)	Thailand	Classrooms			70-80	27.2 at 0.2 m/s 28.3 at 0.5 m/s 30.3 at 1.0 m/s 31.2 at 1.5 m/s
(Santosa, 1986)	Indonesia	Residential				27.4
(Karyono, 2000)			Field Study	596		26.7 to (NV+AC)

2.3. PASSIVE DESIGN STRATEGIES IN BUILDINGS

Passive design is known as climate adapted design or climate responsive design. It is an approach to building design that uses the building architecture to minimize energy consumption and improve thermal comfort. The building form and thermal performance of