CHAPTER 1

INTRODUCTION

1.1 Introduction

Recently, the architectural language has given more emphasis to the lightness and the transparency of buildings, heading towards fully glazed building facade (Butera 2005). However, glazed facade is the easiest way for solar radiation to penetrate into buildings and trap the heat indoor. This happens when direct sunlight passes through the glazed facades as a short-wave (radiation) indoors and is absorbed by internal surfaces of buildings. The absorbed sunlight radiation, then, is consequently emitted as a long-wave radiation (heat) resulting in the greenhouse effect (Castro, Labaki *et al.* 2005). This direct sunlight overheats the indoor spaces and contributes 15% to 30% for heat gain (Kimmins 2000).

Although air-conditioning is the easiest way for maintaining indoor air-temperature, it increases the energy consumption for cooling process. In Malaysia, about 57% of energy consumption in the building sector is used for cooling alone (Saidur 2009). With the rise in the energy costs and the increase of the glazing areas in the buildings, there is an increasing demand for alternative inexpensive cooling systems to cater these conflicting requirements. The following points provide an overview of the solar control options for glazing; the single glazing system which is gaining popularity in the tropics. Within this context, the study aims to contribute to the reduction of total solar heat gain by means of sustainable architecture, getting into the potential of Sustainable-Glazed-

Water-Film (hereafter, such a combination would be referred to as “SGWF”) as a solar heat insulation for reducing heat gain through east and west glazed facades in the tropics, Malaysia.

1.2 Towards Sustainable Architecture in the Tropics

There are several definitions of the word ‘sustainability’, yet the most widely agreed upon definition is ‘to maximise the use of renewable resources as building elements’ (Butera 2005). Accordingly, the buildings would achieve sustainability to meet the present needs without compromising the ability of future generations to meet their own needs (Zainazlan Md Zain 2007). Figure 1.1 shows that the sustainable design includes a very large set of issues, and the energy issues are a large subset of all sustainability framework. Apart from this, it is also acceptable that the solar issues are large subsets of the energy issue (Lechner 2009). Therefore, it is recognised that reducing the energy consumption in glazed buildings in the tropics is basically the number one solar control issue.

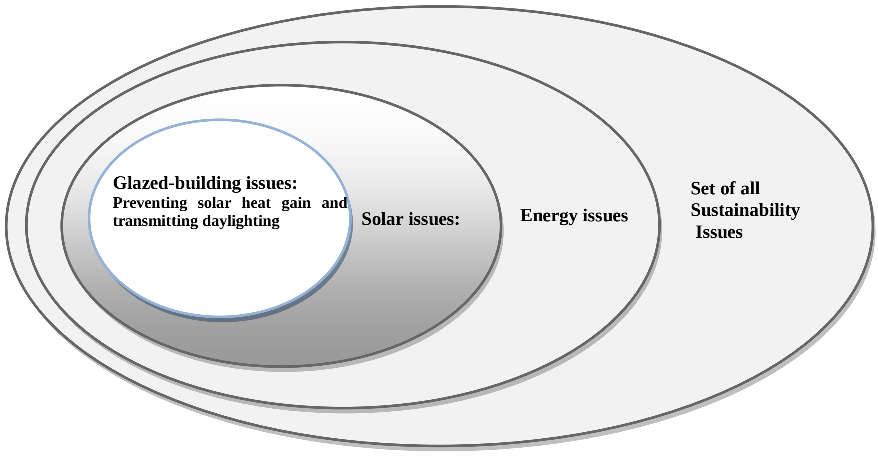

Figure 1.1: The relationship of the issues of sustainability in glazed building (adapted from: Lechner, 2009).

1.3 Passive Solar Control for Glazed Building

There are two means of indicating the total heat gain through glazing; the primary mean is the heat gain due to direct solar radiation, whereas the second means is the heat transfer due to the difference in temperature between ambient and indoor spaces and the difference in temperature between the glazing surfaces.

However, for the tropics the main design guideline is in preventing direct solar radiation from penetrating the building's envelope (Abdullah, Meng *et al.* 2009). Within this context, it is established that the ordinary passive concepts to prevent solar heat gain are: (a) building orientation; (b) shading devices; and (c) insulating glazing.

1.4 Building Orientation and Shading

The intensity of solar radiation beam on building facades varies according to the location, orientation and altitude. The orientation of the facades of certain location of buildings plays a main role to the intensity ratio of solar radiation incidents on the building surfaces (Voss 2007). With respect to the sun path in the tropics, the buildings avoid the east-west orientation, and the ideal building shape is the rectangular along the east-west axis to prevent the solar radiation from entering through the glazing (Yeang, 2006). In Malaysia, it has been reported by Zain-Ahmed (2009) that the maximum of solar radiation which faces vertical walls would vary from 300 Wh/m2 to 250 Wh/m2 throughout the year. This increases the heat gain in indoor spaces.

Notwithstanding the above, the traditional solution besides the proper orientation of the glazing that allows users to control solar gain (Saleh, Kaseb *et al.* 2004) is to install shading devices (Datta 2001; Fairuz and Sia 2004; Gratia and De Herde 2007).

However, by resorting to this solution implies that the shading does not distinguish between daylight (visible range) and heat (infrared range), particularly on the east and west orientations of the tropics. Therefore, the shading is inapplicable unless to block the whole facades. The east and west facades generally receive about 50% more sunshine as opposed to the north and south counterparts (Bansal 1994). This is rightly so that the east and west facades are avoided in the design of tropical buildings following thermal considerations (Zain-Ahmed 2009). However, this is not constantly affordable and acceptable due to the limitations of the land-form and view aspects as well. Based on this premise, the higher performance glazing might be a more appropriate solution to this conflicting problem in glazed building.

1.5 Advanced Glazing

Depending upon the spectral properties of glass type, different glazings have unique characteristics with respect to solar heat gain (Deal, Nemeth *et al.* 1998). When solar energy hits the glass, it is either transmitted, absorbed or reflected away from the glass (Bansal 1994). It has been reported in relation to the case of absorptive glass, in sunny days when part of the solar spectrum is absorbed, the glass warms up to 40°C (Butera 2005), and due to the conductivity of the glass to the thermal energy because of its relatively high k-value and low thickness (Deal, Nemeth *et al.* 1998), the heat eventually passes through a glass surface dissipated to the indoor spaces.

On the other hand, each type of glass has characteristic transmittances to direct solar radiation. For example, in most of the tested cases, radiant energy is transmitted through the surface of clear glass; its short wave infrared transmittance is about 75% and 89% of the visible light (Chow, Li *et al.* 2010). The following is a brief review showing that glazing might be used in the tropical buildings.

1.6 Glazing for Tropical Solar Control

Although glazing allows heat to flow through the skin of the building, glass in the recent years has become popular as a building material in the tropics. This is because of the advancement of glazing technology which allows glazed buildings their chance to be sustainable. In brief, the high performance glass for solar control aspects can be obtained from the basic clear float glass. The solar control glass is categorised into: (a) body tinted glass, (b) insulated glass, (c) solar reflective glass, and (d) low-emissivity glass (Fong and Chong 1999). An ideal glass for tropical regions should be capable of high transmission to visible light at 0.38-0.78µm which accounts for 47% of the incident solar energy, and low transmission of infrared (heat radiation) at 0.78-3µm which carries 46% thereof (Bansal 1994; Muneer 1997).

Tinted single glass with various colours (e.g., green, grey, bronze) is popularly used in the building products in tropical countries like Malaysia, since it is widely manufactured in the country. The particular colour tint could absorb solar radiation and reduce heat, but it is not sufficient to prevent the interior surface from gaining the solar heat, and it reduces light transmittance (Pfrommer, Lomas *et al.* 1995). Within the same context, buildings perform better with low emissivity coating which is applied on clear glass (Erell, Etzion *et al.* 2004). The thin films of low-e have a high transmittance in visible range and very high reflectance in long-wave infrared range (Mohelnikova 2009). This advantage provides the opportunity to control solar heat gain where the variation of temperature between outdoor and indoor is high. In Malaysia, the average difference in temperature between indoor/outdoor was found to be 5°C, according to the field analysis of energy efficient buildings conducted by the author (Qahtan, Keumala *et al.* 2010). This indicates that the problem is mainly the penetration of the short-wave infrared SIR of direct solar beam into the buildings.

The difficulty of this low-emissivity coating in the tropics is that the short wave radiation is still able to penetrate through the glass hitting the indoor surfaces. These surfaces are heated up and remit heat as a long wave radiation which cannot transmit through the low-e glass. This is especially so where the low-e coat effectively traps the long-wave energy within the space (Deal, Nemeth *et al.* 1998). This becomes a disadvantage to the low-e glass in the tropics unless to be compounded with an extra solutions for maximising heat loss. In tropical architecture setting, the direct solar transmittance is the actual factor to be controlled for cooling demands. The approach to solve these requirements is to use the spectrally selective glazing which is applicable in such climate. It has a high visible transmittance while rejecting a great proportion of short wave radiation which is emitted by the Sun (Erell, Etzion *et al.* 2004; Alvarez, Flores *et al.* 2005).

However, all of these glazing systems either provide only a partial response to the problem that faces glazed buildings, by conflicting between visual and thermal comfort or it is not preferable to the clients from economic aspects. For instance, low-e and spectrally selective coated glazing need to be compounded with double glazing for protection reason, in addition to its high production cost (Chow, Li *et al.* 2010). It is evident from a review of the market and through direct contact with manufacturers that tinted glazing is still a popular choice for buildings in Malaysia, especially if it is compounded with passive elements for removing its high body temperature. In addition, there is no large market for a higher performance glazing and have only a few practical applications depending on the imported units.

1.7 Alternative Glazing Systems and Research gap

The most common alternative solutions for controlling solar heat gain in glazed buildings are air and water. The preference of water over air comes from the fact that water has much higher density and much more specific heat than air, where it required a volume of air about 3000 times greater than water to transfer equal amount of heat (Lechner 2009). Moreover, water is one of the continuously renewable natural resources of the world (Gleick 2000), particularly in Malaysia that receives a very high rainfall throughout the year and has not been fully benefited from this (Darus 2009). Aimed at minimising the wastage of rainwater in addition to the low cost of its harvesting system (Amin and Han 2009), the Malaysian Green Building Index (GBI) encourages building designers to implement rainwater harvesting system as passive building elements for cooling demands (GBI 2009).

Therefore, **the gap of this study** lies in the need to maximise the benefits of the alternatives of solar control in glazed-buildings through a sustainable design. It is the challenge of SGWF as an alternative solar control in the east and west facades of glazed office buildings in the tropics. The SGWF is a combination of recycled elements (rainwater) with a low cost single and tinted glazing. The application of the SGWF in this research might benefit from the new green technology, or better known as the "Superhydrophilicty" coat (He and Hoyano 2008). This coat increases the wet-ability and the self-cleaning functions of the glass in the approach of SGWF (Chabas *et al.*, 2010). For example, the TiO_2-coat may perform well in increasing the wet-ability of the glazed façade, in addition to the resistance of TiO_2 to the UV radiation which affects the workspace furniture and finishing (Tuchinda *et al.*, 2006).

1.8 The Research Problem

Based on the above premises, it is established that the main heat gain from the solar radiation occurs through the west and east glazed-facade, which consists of two parts. The first dominating part is related to the short-wave (infrared) solar radiation gain that transmits directly through the glazing. The second part is the long-wave (infrared) radiation transmits indirectly as heat flux from absorbed radiation. However, the research problem raised in this study is the lack of knowledge on the efficient alternative solar control solutions on east and west glazed facades in the tropics. Apart from that, this research examines the possibilities of SGWF in minimising the solar heat gain while maximising the daylighting in the workspace (Figure 1.2).

1.9 Objectives of the Research

In order to respond to the aforesaid problems, this research aims to achieve the following objectives:

(a) To investigate the alternative solar control options for glazing, particularly for east and west orientations, taking into account the types of glazing that is most commonly used for solar control in Malaysia;

(b) To examine the effectiveness of SGWF in reducing solar heat (or far infrared) transmittance through glazed facades; and

(c) To examine the effectiveness of SGWF on absorbing the shortwave solar infrared radiation , and maximising the transmittance of visible light.

(d) To calculate the solar transmittance of SGWF. The transmittance of the entire range of solar radiation; the visible light range and short infrared range.

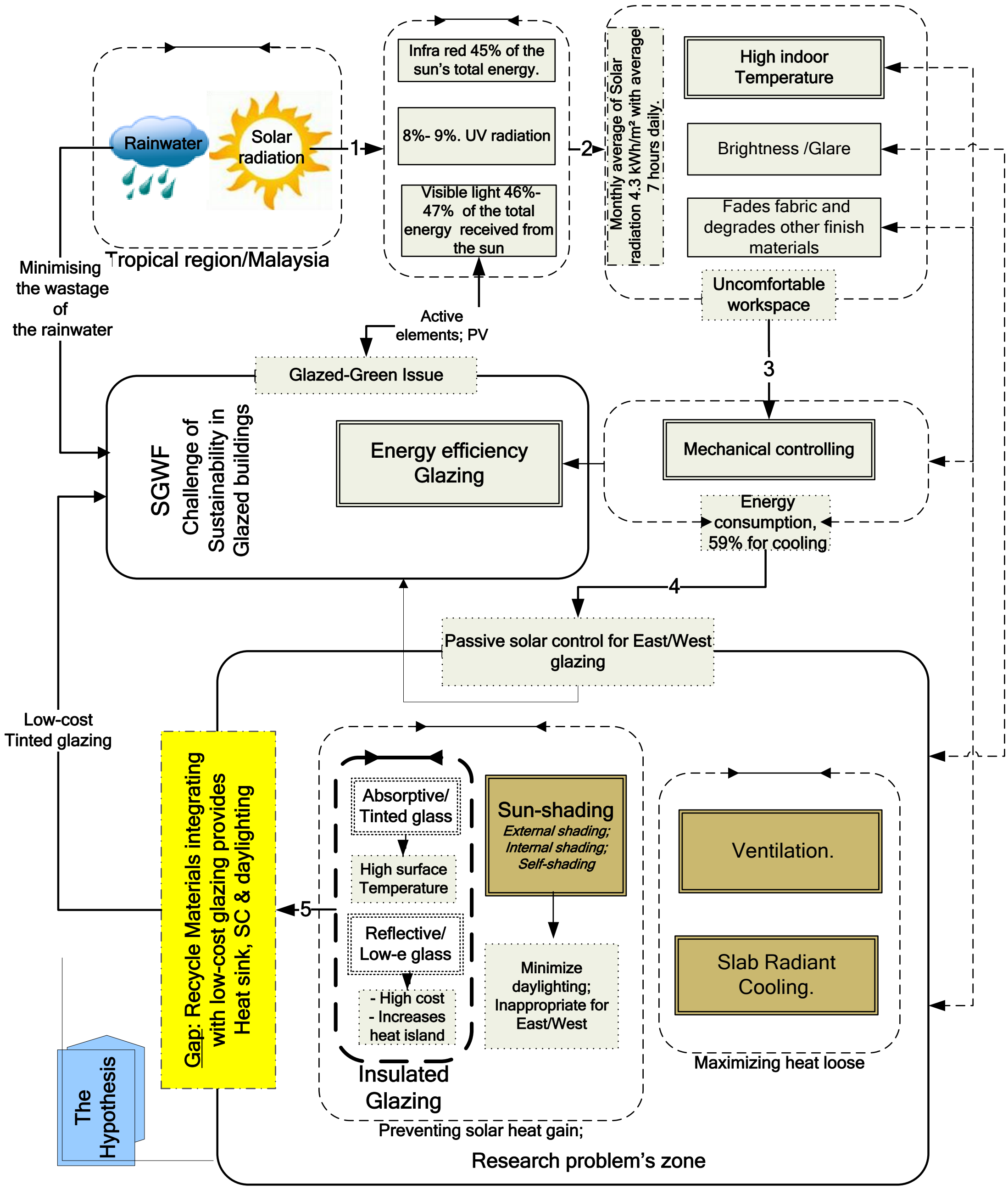

Figure 1.2: The Research Frame Work

1.10 Research questions

Generally, if the SGWF compounds with the low cost single tinted glazing on the east and west glazed-facades, the glazed-buildings could be brought to the sustainable design issue of office buildings in the tropics. However, within the context of the research problem, the research questions might be crystallised as follows:

i. What are the passive solar controls that prove to be the best for east and west glazed facade of mid-rise office buildings in the tropics, Malaysia?

ii. How could SGWF limit solar heat (long-wave) transmittance through glazed facades?

iii. How could SGWF contribute in reducing the transmittance of short-wave infrared (radiation), and increasing the transmittance of visible light?

iv. How far the SGWF is sustainable spectrally selective film?

1.11 Methodology

Based on the research problem and objectives outlined above, as well as the hypothesis of the research, it is concluded that the experimental method is the appropriate way of carrying out an investigation of the solar radiation and thermal performance of the proposed approach; the SGWF. In this study, the configurations of two full-scale rooms, test room and reference room, are designed with respect to the site selected for conducting the experiment. They correspond to the typical dimensions of facade modules used in experiments. However, the design of an experiment would specify the following:

First, the use of a treatment, (or independent variable), which are the water film flow rate, the glass type and the incoming solar radiation intensity. Second, the current thesis work seeks to evaluate the outcome of the treatments (dependent variables), which are the glazing surface temperature, the heat flux through the glazed facades, the indoor air temperature and the indoor vertical solar radiation transmittance. Third, a numerical investigation involves in this study to evaluate the solar optical performance of SGWF.

1.12 Research Design

To achieve the abovementioned, objectives the research was divided into four phases (Figure 1.3). The first phase begins with a brief analysis to the latest 10 years data of the Malaysian climate to determine the characteristics in a specific location and to specify the ideal time for carrying out the third phase of the research. It also consisted of a review to the previous literature: the main aspects of the solar radiation fundamentals of the tropics; the direct and diffused solar radiation; the angle of incidence on the vertical glazed-facade that facing East and West and; the solar heat gain and thermal performance of glazing technology in office building. This phase is documented in Chapters 1 to 3.

The second phase (chapter 4and 5) is given to the field study that is carried out through a photographical documents on the common types of glazing used in office-glazed-buildings. The tropical passive solar control for glazed buildings is reviewed from the practice rather than the literatures. A certified green and glazed-building in Malaysia was selected to be experimentally investigated. The research in this phase also reviews the potential applications of water element as an alternative solar control in glazed-office-buildings in tropics. The research gap and hypothesis will be framed in the end of this phase. The third phase was given to the experimental work that forms the major phase of this study and it is recorded in Chapter 7. The final chapter is Chapter 8, which consists of the conclusions and recommendations.

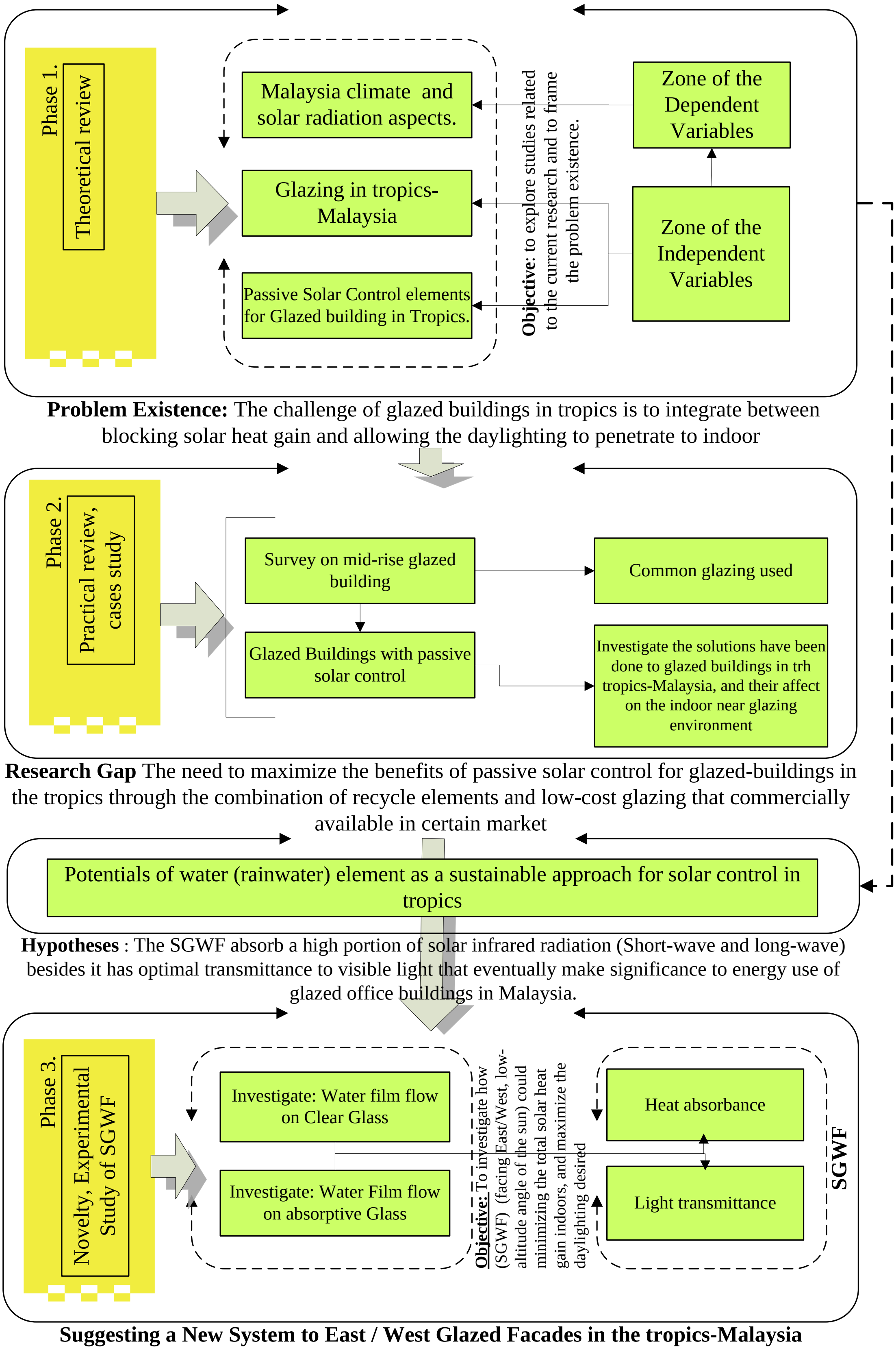

Figure1.3: Flowchart of the study.

CHAPTER 2

CLIMATE OF MALAYSIA

2.1 Introduction

Climate has a significant effect on a building's performance, therefore the climate parameters need to be understood in order to formulate the proper design[1] of the second and third phases of this research (field study and experimental stages). The relevant climate data of the needed weather parameters in this chapter has been measured for the recent 10 years (daily average 1999 to 2008) and 5 years, from 2004 to 2008, by the meteorological station located in an area where the experiment and field study are conducted (Subang Jaya Meteorological Station, Latitude: 03° 07'_N, Longitude: 101° 33'_E). The following points represent a brief analysis with respect to these parameters: solar radiation, air temperature, humidity, rainfall, cloud cover and wind speed.

2.2 Solar Radiation

The rotation of the earth around its own axis determines the daily and annual position of the Sun, which affects the solar radiation intensity falling on the buildings. The position of the Sun is determined by the altitude and its azimuth angles. Figures 2.1 and 2.2 illustrates the positions of the Sun over Malaysia where the site is 03° 07' north latitude, and for latitude 3.1, 0.0 of the experiment's site which has been identified for the

[1] The accurate minutes of the weather data adopted for analysis will be measured during the period of the case studies investigation and conducting the experiment.

purpose of this research. The longest day, 22nd June indicating summer solstice, the over head Sun is over the tropic of cancer that receives the largest amount of solar radiation. It is the longest day of Malaysia since its site is 03° 07' north latitude.

Global solar radiation feature in Malaysia varies significantly throughout the day. The monthly average of solar radiation in Kula Lumpur’s Subang station is 4.3kW/m², with the monthly sunshine duration ranging from 4.5 to 6.6 hours. Table 2.1 shows that the high solar radiation increases during the months of February to March and August to October where the position of the Sun is almost over the equator, while the low solar radiation occurs throughout the months of November to January, with the minimum of 4.0 kW/m² which was recorded in December.

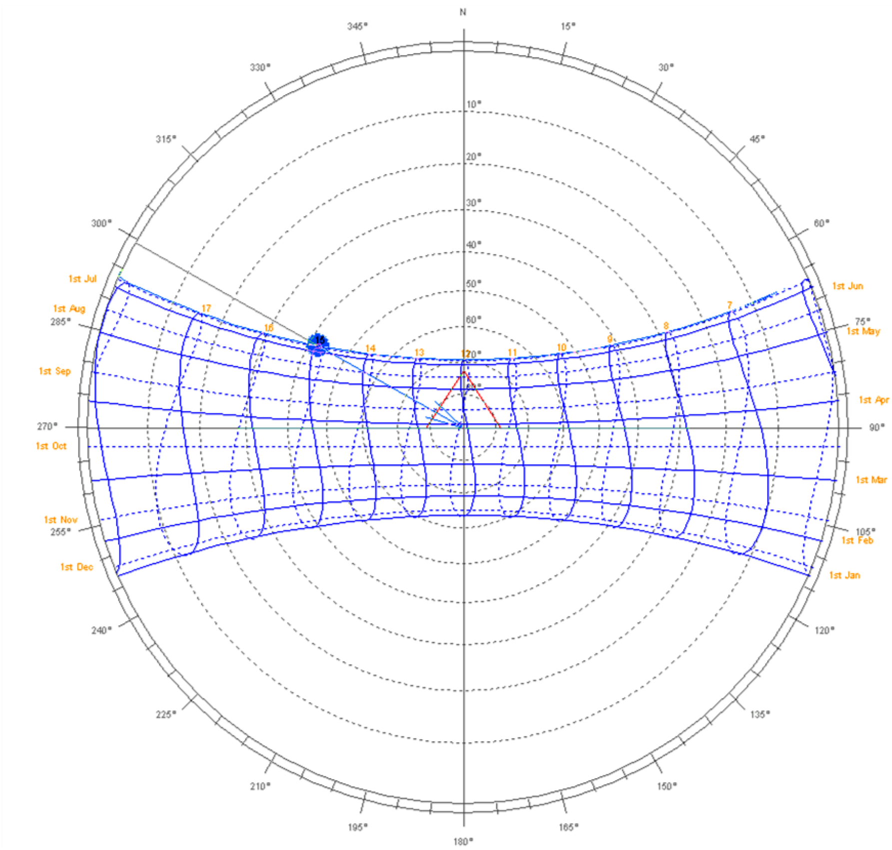

Figure 2.1: Sun path diagram of 22nd of June, Kuala Lumpur (Author-Suntool)

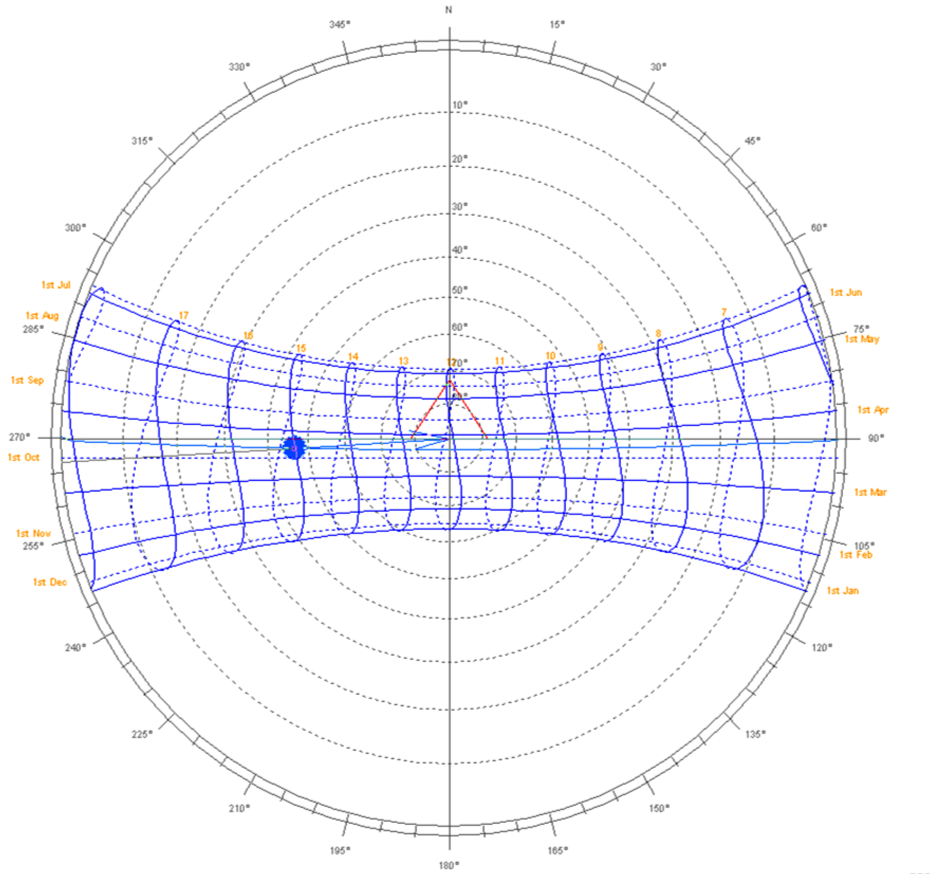

Figure 2.2: Sun path diagram of 21st March, Kuala Lumpur (Author-Suntool)

Table 2.1: Monthly average of solar radiation and sunshine hours for Kuala Lumpur, Malaysia (Subang Jaya Meteorological Station throughout the years 2004 to 2008)

Month.	Solar radiation kW/m²	Monthly sunshine duration (hours)
Jan.	4.2	5.8
February [2]	4.5	6.6
March	4.6	6.5
April	4.2	6.2
May	4.1	6.1
Jun	4.3	6.2
July	4.3	6.0
August	4.5	5.9
September	4.5	5.2
October	4.5	5.3
November	4.2	4.5
December	4.0	4.9
Average	4.3	5.8

Table 2.2 and Figure 2.3 summarises the hourly average of solar radiation of three particular days, the 22nd December and 21st March being the shortest days and 22nd

[2] February and March (5years data)of tropical climate of Malaysia show the long duration of daily sunshine hours with high value of solar radiation intensity. This pattern suggested as an ideal time of conducting the experiments related to solar radiation.

June being the longest day in Malaysia. Although, the Sun shone almost equally on the east and west as shown on Figures 2.3 and 2.4, the air temperature was observed to be higher in the afternoon confirming that the west facades receive more solar loads than east facades. This result makes the west glazed facade as an optimal orientation for examining the impact of the alternative passive solar control. This study will adopt testing rooms to windows facing west.

Table 2.2: Hourly solar radiation (kW/m²) for the longest and shortest days (average throughout the years 2004 to 2008, Subang Jaya Meteorological Station)

Hour. Days	7	8	9	10	11	12	13	14	15	16	17	18	19
21st March	0.03	0.73	2.43	4.56	6.24	6.7	6.25	5.73	3.98	1.83	1.48	0.04	0.00
22nd June	0.1	0.7	2.9	3.7	5.3	6.5	6.0	3.34	1.82	0.9	0.5	0.1	0.00
22nd December	0.1	1.2	3.0	4.8	5.6	5.5	4.7	4.7	4.0	2.7	0.7	0.2	0.0

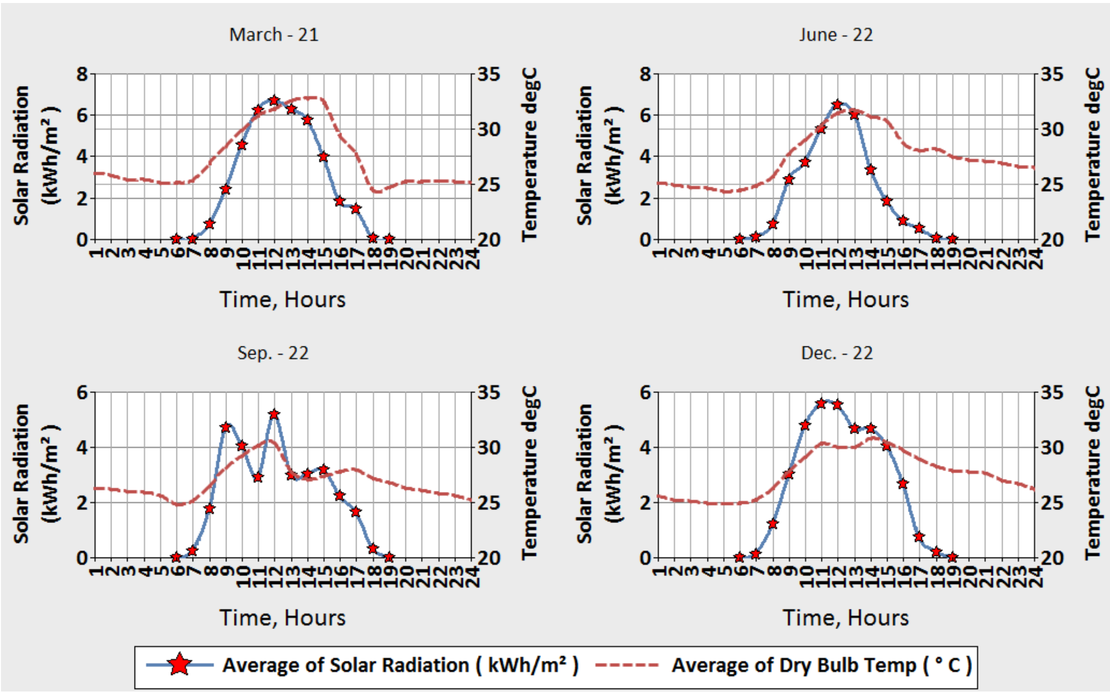

Figure 2.3:Hourly Average DBT with its relation to the solar radiation kW/m2, in particular days; the shortest and longest days (2004 to 08 average, Subang Jaya Meteorological Station)

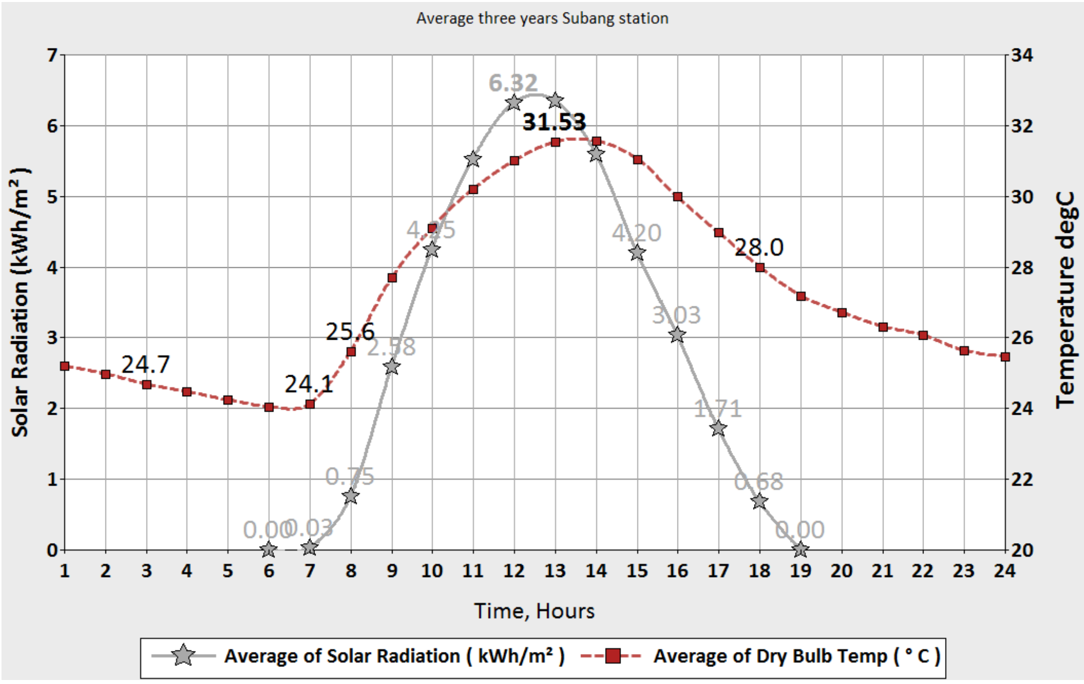

Figure 2.4: Hourly average of solar radiation (kWh/m²) (2004 to 2006, Subang Jaya Meteorological Station)

2.3 Rainfall

Rainfall in Malaysia generally occurs between the months of October to March. Table 2.3, Figures 2.5 and Figures 2.6 show the total rainfall for 5 years in Subang Jaya. It illustrates that rain falls for the entire year with a total monthly rainfall exceeding 200mm for eight to nine months in a year.

Table 2.3:Monthly sum of rainfall intensity for the year 2004 to 2008, recorded by the Subang Jaya Meteorological Station

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Total
Rainfall (mm)	374.8	161.6	554.2	325.4	87.4	202.8	108.4	194.4	174.4	413.8	477.2	203.6	3188.6

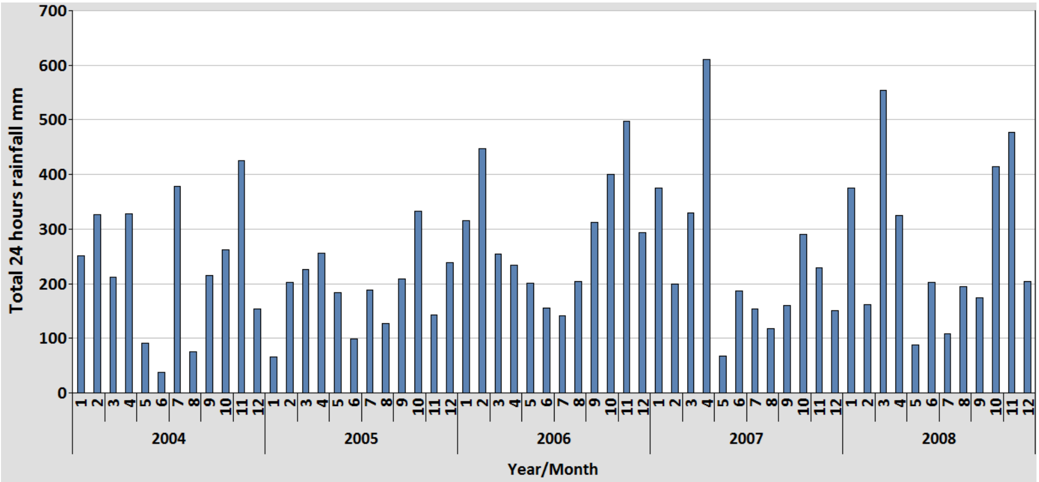

Figure 2.5:Monthly total rainfall mm, 2004 to 2008, Subang Jaya Meteorological station.

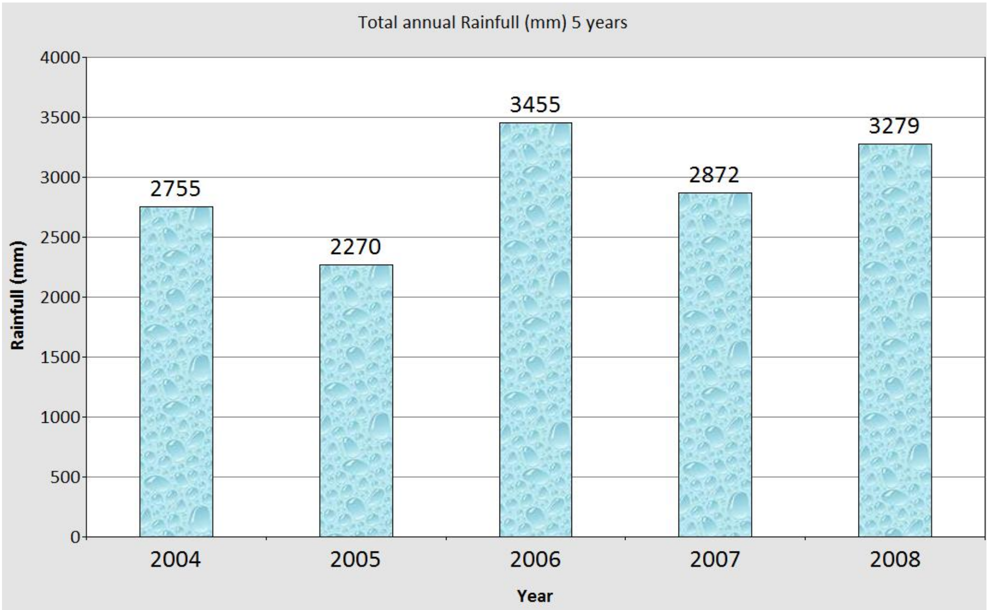

Figure 2.6:Annual total rainfall mm, 2003 to 2008, Subang Jaya Meteorological station

2.4 The Malaysian Sky Condition

Malaysia has abundant sunshine but it is however very rare to have a clear day. The hourly cloud cover in Subang Jaya as shown in Figure 2.7 is between 6 to 7 oktas, with a mean value of 7 oktas monthly (see Figure 2.8) throughout the period of 1999 to 2008. However, identifying the Malaysian sky condition has been reported by Zain-Ahmed *et* *al.* (2002) as to conclude that the sky is of the average or intermediate type. Figure 2.9 describes the sky type with a frequency of occurrence of 14.0% is overcast and the vast majority of the time of 85.6% is predominantly intermediate (2.3% intermediate overcast, 66.0% intermediate mean and 16.3% intermediate blue), whereas the sky is never cloudless.

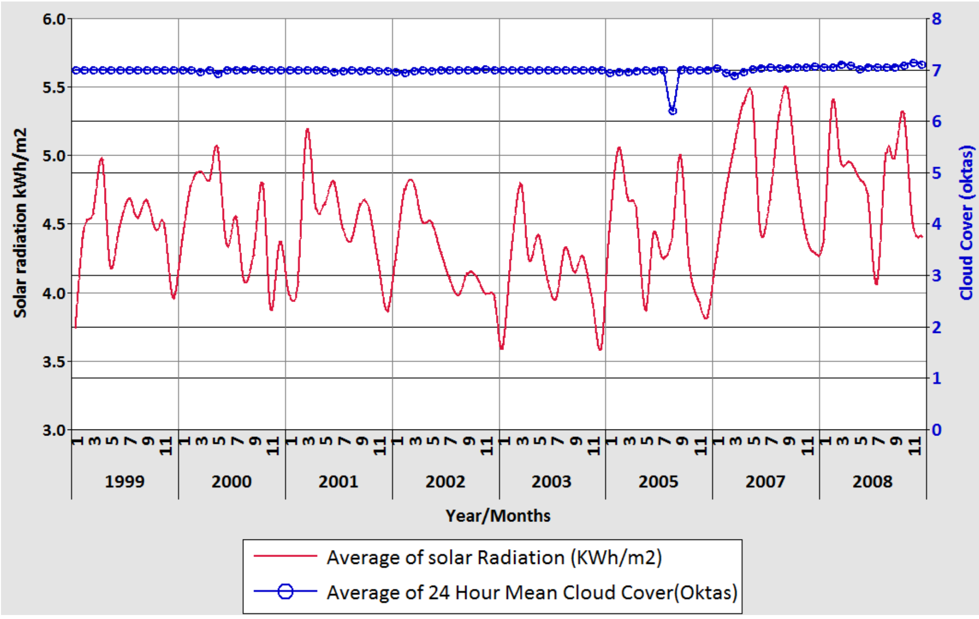

Figure 2.7:Cloud cover and solar radiation, average monthly to 8years (Subang Jaya Meteorological Station).

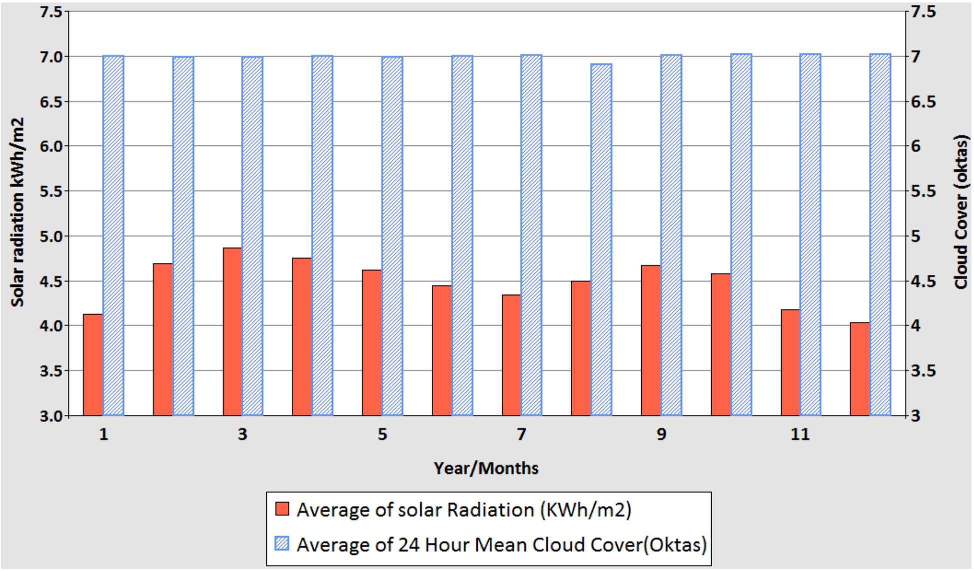

Figure 2.8:Monthly cloud cover and solar radiation (average10 years Subang Jaya Meteorological Station)

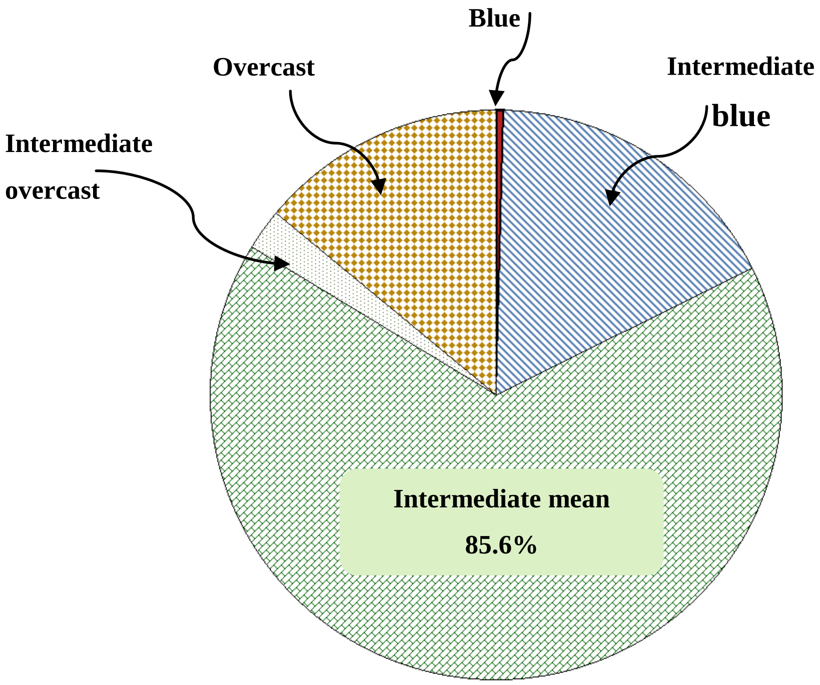

Figure 2.9: Annual occurrences of different sky types at Subang Jaya, Malaysia (source: Zain-Ahmed *et al.*, 2002)

2.5 Air Temperature Data

There are no large variations in temperature during the daytime of the year, the variation significantly accurse throughout the day. As illustrated on the Figures 2.10 and 2.11, the mean monthly temperature varies not more than 1.4°C from the mean average 27.0 which was found in November to 28.4°C in May. From the analysis throughout the years 2004 to 2008 in Subang Jaya as shown in Figure 2.12, the average hourly dry bulb temperature in a day varies with approximately 7.4°C difference in February and March (32.2°C at 1.00pm to 24.8°C at 6.00am). Whereas the difference in air-temperature between the daytime and night-time which was recorded in November and December is 6.5°C (varies from 24.0°C at 6.00am to 30.5 °C during the daytime at about 1.00pm).

Figure 2.12 shows also that the afternoon hours are higher in temperature than the morning. This means a study focusing on the passive solar control to the critical position should examine the west glazing for optimum thermal performance. The hourly dry bulb temperature for the months March, June and December are demonstrated in Figure 2.13.

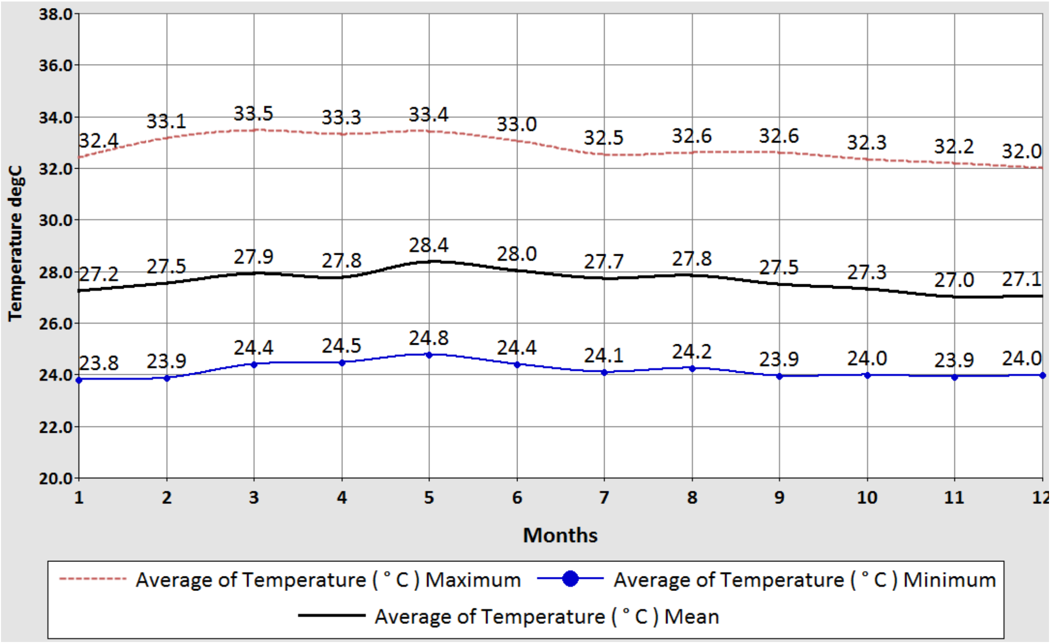

Figure 2.10:Monthly temperature variation (average 10 years, Subang Jaya)

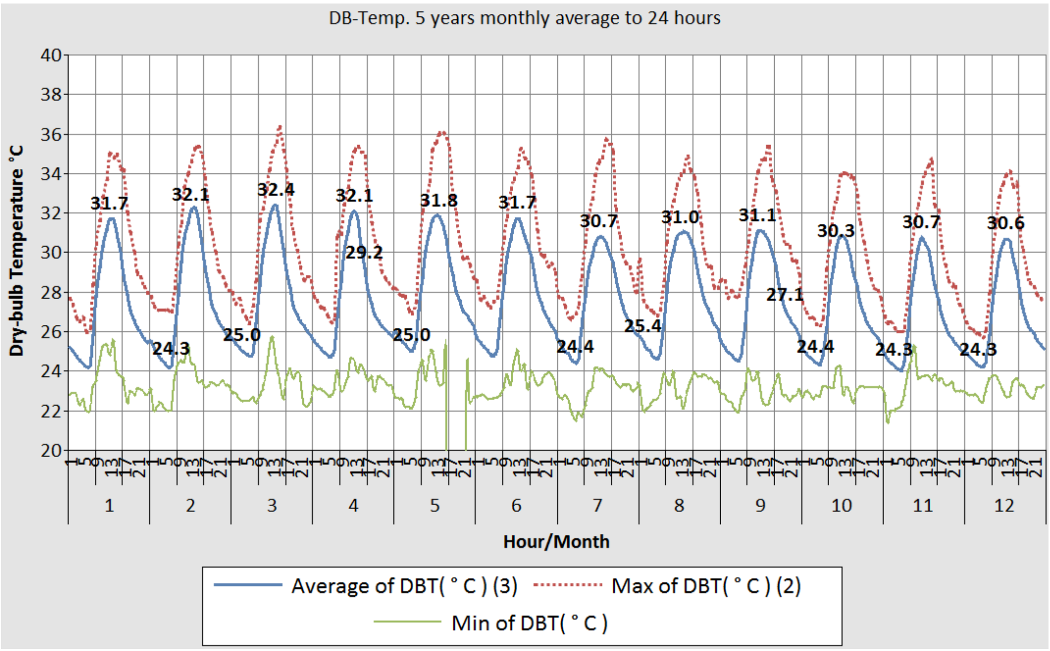

Figure 2.11:Monthly average to 24 hours. The maximum of air temperature occurred during the month of March (Subang Jaya, 2004 to 2008)

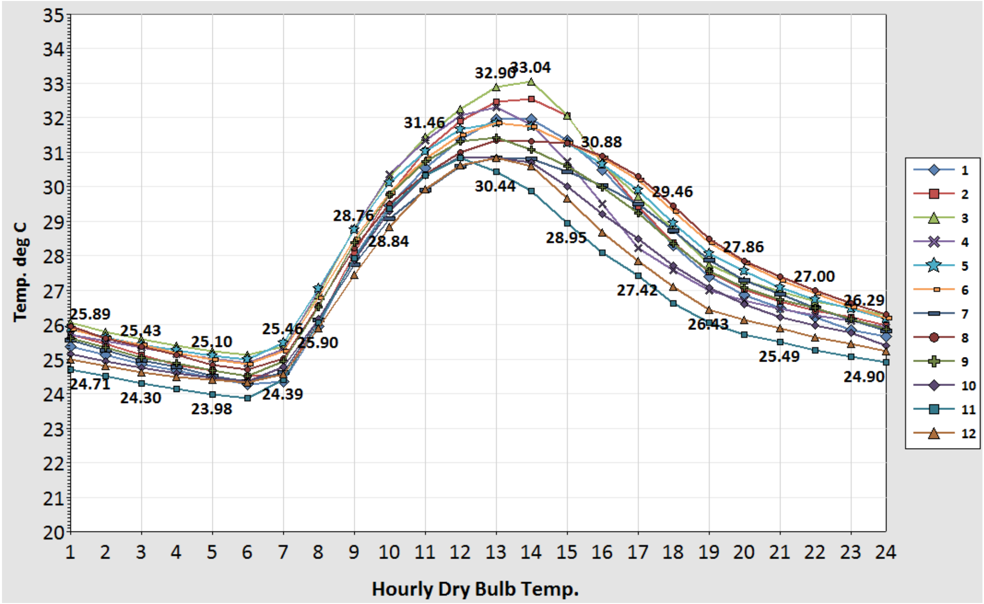

Figure 2.12:Average hourly dry bulb temperature in a day (Subang Jaya, 2004 to 2008)

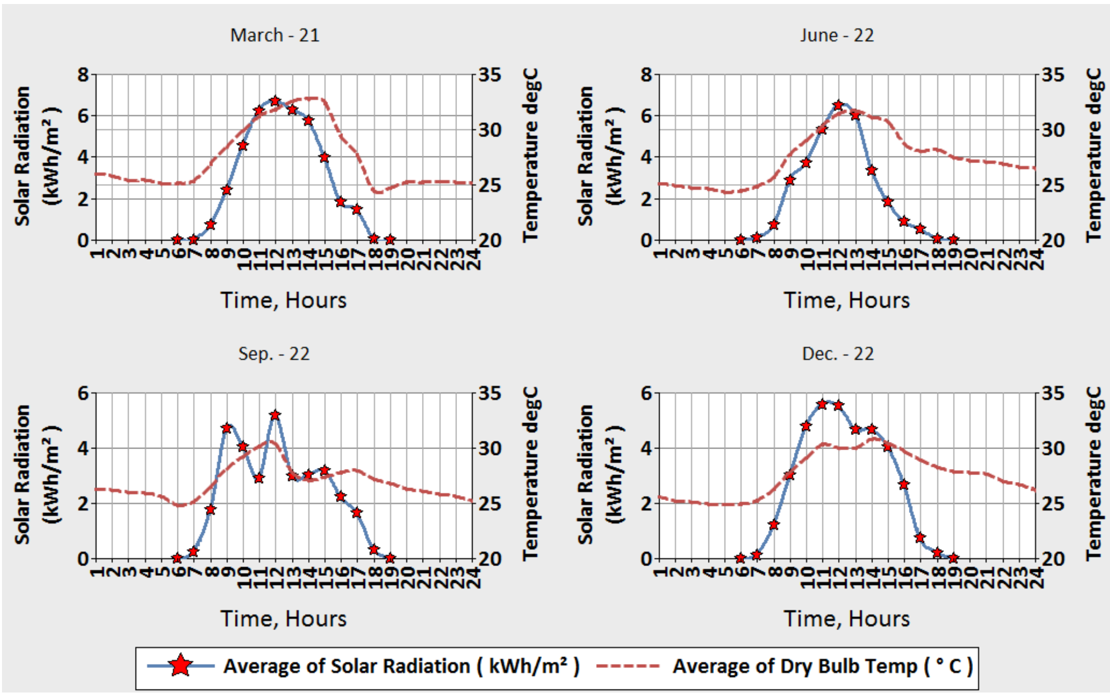

Figure 2.13:Average hourly dry bulb temperature with its relation to solar radiation kWh/m2, in particular days; shortest and longest day (Subang Jaya, 2004 to 2006)

2.6 Relative Humidity

Due to the large body of water surrounding the Peninsular Malaysia, the relative humidity is uniformly high throughout the year. According to the data from Subang Jaya Meteorological Station, the mean monthly relative humidity falls within 75% to 82%, varying from month to month. The difference in the monthly relative humidity varies from a minimum of about 3% to a maximum of about 7%. The mean relative humidity varies from a low 75% in August to a high level of only 82% in November. Figure 2.14 gives an idea about the relation between relative humidity and dry bulb air temperature in a period of 10 years which was recorded by Subang Jaya Meteorological Station.

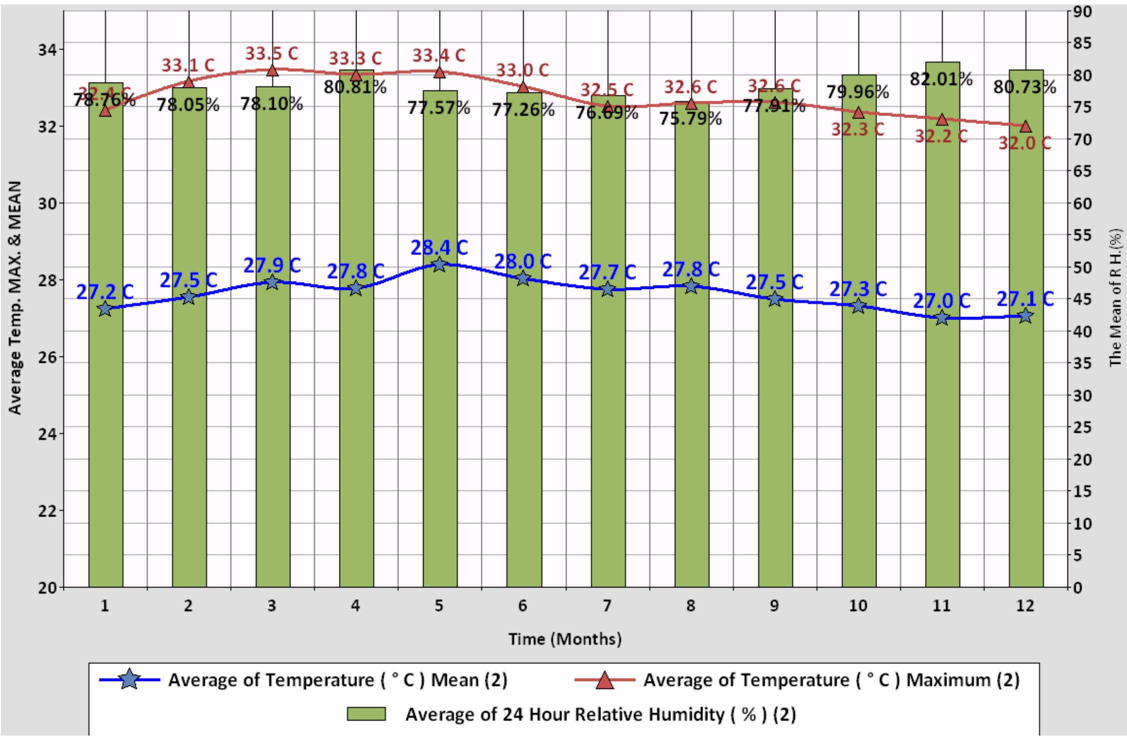

Figure 2.14:Monthly average of relative humidity and its relation to average temperature (for the period 10 years at Subang Jaya Meteorological Station)

2.7 Wind Speed

The mean surface winds that blow over the Peninsular Malaysia are generally mild, with the maximum value speed of 8.8 m/s as shown in Figures 2.15 and 2.16. While the maximum mean speed is about 1.9 m/s, minimum mean is 0.1m/s. For the recent 10 years, as illustrated in Figures 2.15 and 2.16, the maximum mean of wind speed occurs in March and April, as well as September and October, with no large difference throughout the entire year. The hourly wind speed as was measured by the author at the rooftop of the 8th storey of a building in Kuala Lumpur with 10 minutes intervals for February and March in 2010 is as illustrated in Figure 2.15. It reveals that the hourly maximum mean speed reaches to 3.9 which is often associated with the rainfall. Table 2.4 and Figure 2.16 show that the wind direction in Kuala Lumpur is mainly from the north-west to the south-west throughout the year, as shown in the wind roses. Meanwhile, Figure 2.17 shows the monthly wind speed for 10 years as recorded at the Subang Jaya Meteorological Station.

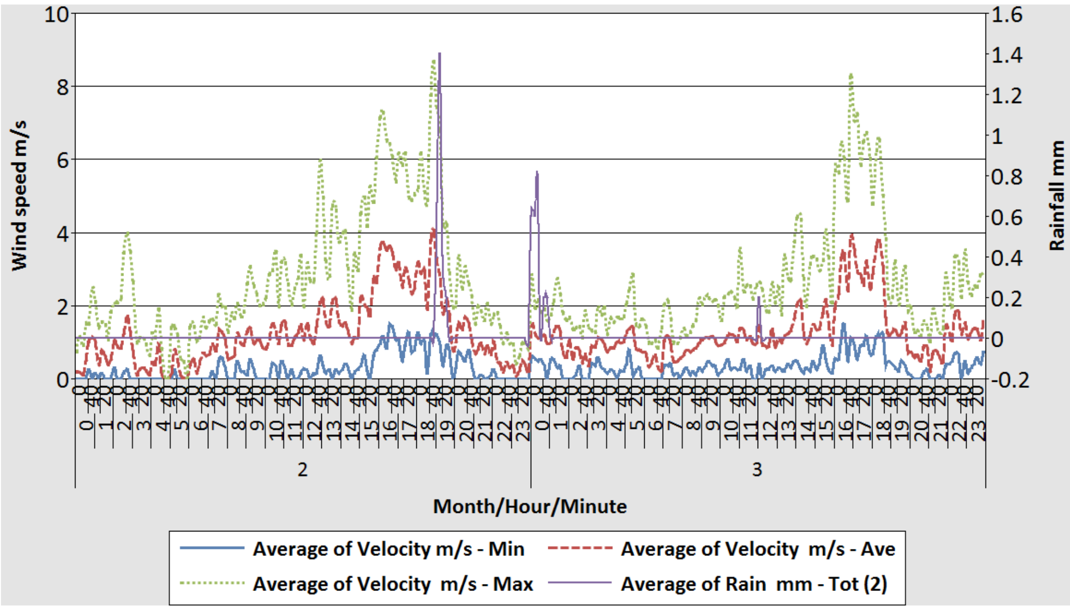

Figure 2.15:Hourly wind speed measured at University of Malaya

Table 2.4 Wind flow over Peninsular Malaysia (Ismail, 1996)

Duration	Types of wind	Affected area
November December	north-east Monsoon (Strong, together with heavy rain)	The whole of peninsular Malaysia East coast of peninsular Malaysia
April May	Transitional period (Weak and variable)	The whole of peninsular Malaysia
June July September October	south-west monsoon (Not as strong as the north-east) Southerly wind (Light wind)	Northern part of peninsular Malaysia Southern part of peninsular Malaysia below latitude 5°N
October November	Transitional period (Weak and variables)	The whole of peninsular Malaysia

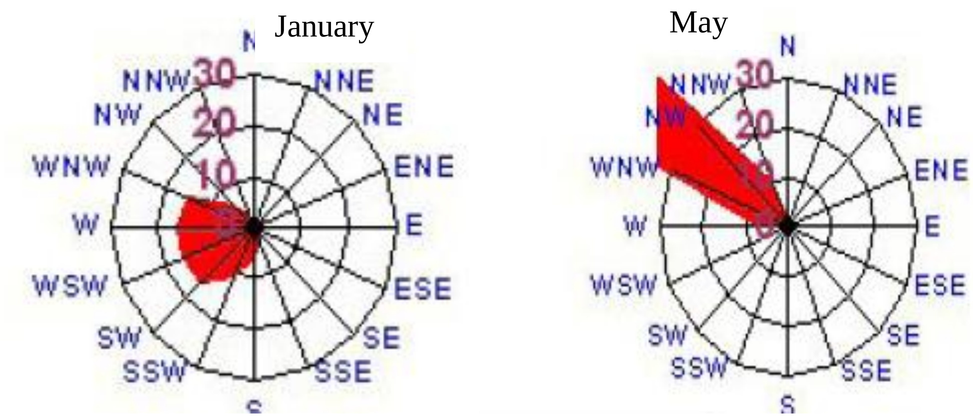

Figure 2.15:Wind direction is mainly from the north-west to the southwest throughout the year Kuala Lumpur wind rose (Ahmad *et al.*, 2007).

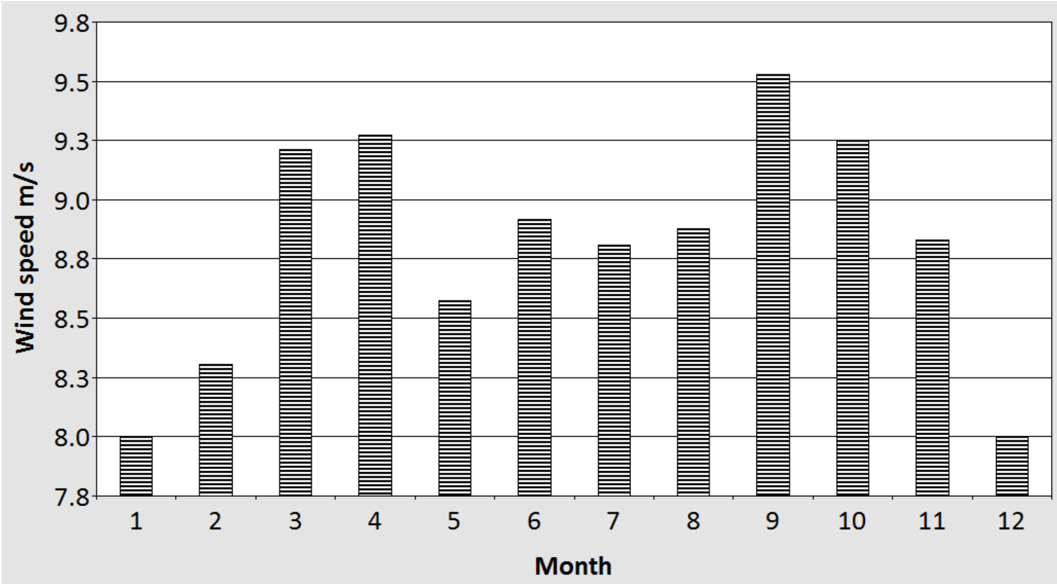

Figure 2.16:Monthly wind speed for 10 years as recorded at Subang Jaya Meteorological Station

2.8 Summary

With respect to the Malaysian climate, by adopting the case of Subang Jaya Meteorological Station, the database of the climate has been taken from this station for the latest 10 years, assuming a change in the climate after the tsunami which occurred in 2004. It is to represent the climate of the Klang-Valley where the location of the case studies and the site of the experiments of this research were carried out.

Klang-Valley represents a hot and humid tropical region. The highest hourly mean in air temperatures were found in March with 32.4°C at 1.00pm. Whereas the highest daily average mean was 28.7°C in March as well. Sunshine hours are between 4.5 and 6.6 hours daily with an average daily solar radiation 4.3 kW/m² and the highest value of 4.6 kW/m² occurs in the month of March.

In relation to the survey and experimental day, it is showed that in order to select typical hot and sunny days in the tropics, February and March are the ideal months to do so, following the high intensity in solar radiation. In addition to the position of the sun which is almost overhead the tropical countries in these months, this reduces the errors of the measurement values in the experiment model, where the solar radiation hits the two rooms equally throughout the whole day. To continue measuring in April to July is possible, but the accuracy in the data values in both rooms is reduced, unless to have enough space between the two tested rooms so that no shade of one room is laid on the other. Apart from that, August and October are also possible time periods to carry out the investigation of the glazed buildings.

The wind surface speed over peninsular Malaysia is generally mild. This supports the indication that it cannot be relied upon for cooling purposes especially for the case of glazed buildings.

Finally the climate of Malaysia is not extreme where the outdoor air temperature is not very high and the sunshine occurs time to time with a daily mean of cloud cover of 7oktas. However, the passive elements for glazed buildings should match the fact of tropical sky conditions. The fixed solutions, such as very advanced glazing systems, could lead to extra cost and its installation being impractical. Based on this premise, apart from review the previous literatures on passive solar control for glazing, this research would investigate the existing passive elements of glazed-buildings through selected several case studies in the Kalang Valley area. The aim of this investigation is to examine the matching of the passive concepts to the actual condition of tropical sky. Moreover, if the rainfall in the entire year is considered, verily, the water element is the appropriate alternative for such a climate where it is easy to get and to run during sunshine hours and stop when there is no sunlight.

CHAPTER 3

SOLAR CONTROL FOR GLAZED BUILDINGS IN THE TROPICS

3.1 Introduction

In order to understand the solar control against the energy flows through the glazing skin, it is required to understand the concepts of the solar radiation and energy spectrum that contribute to heat gain. The basic definitions to solar energy and the way in which it contributes to heat gain, as well as the performance of glazing against the direct solar energy and the passage of long-wave through glazing, are all described in this chapter. This chapter reviews basic solar gain control and heat transfer fundamentals with respect to glazing performance and the common glazing types in the tropics, Malaysia.

3.2 Solar Radiation Fundamentals

Solar radiation, basically, provides information on how much solar energy hits a surface at a location on the earth during a particular time (Elminir, Areed, & Elsayed, 2005). The following section gives a review on the mean fundamentals of the solar radiation.

3.2.1 Solar Geometry

The rotation of the earth around its own axis determines the daily and annual position of the Sun. This is required to calculate the solar radiation intensity falling on the surfaces of the buildings and also to predict the sun's beam direction to calculate the shading devices needed (Bansal, 1994b). Figure 3.1 and Table 3.1 demonstrate the position of the Sun and its incident angles. The position of the Sun is determined by the altitude and its azimuth. The solar altitude h_S is expressed as the angle between the sun's beam and the horizontal, and is used to draw the Sun's beam in section. An azimuth is the angle between the south or the north, and the projection of the beams on horizontal. It is used to draw the sun's beam in plan (Davies, 2004).

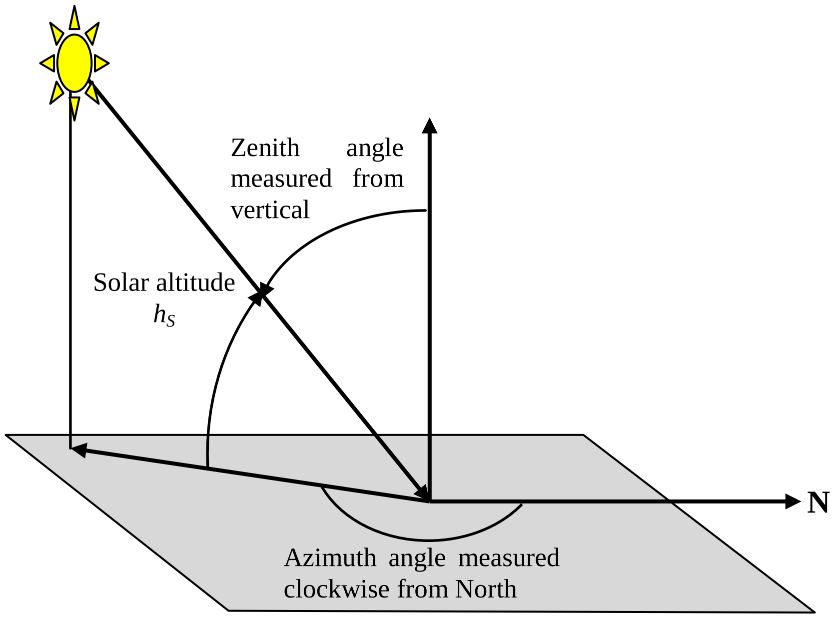

Figure 3.1:The Varying Solar Angles (source: modified from Bansal (1994b))

Table 3.1:The Altitude and azimuth angles, 21st March, Kuala Lumpur, orientation 0.0° (source: Author by Sun-tool)

Local time	Azimuth	Altitude h_S
7:30	90.4°	2.4°
8:00	90.8°	9.9°
9:00	91.7°	24.8°
10:00	92.9°	39.8°
11:00	94.8°	54.8°
12:00	99.1°	69.6°
13:00	123.3°	83.9°
14:00	108.6°	79.6°
15:00	97.2°	64.9°
16:00	94.1°	50.0°
17:00	92.5°	35.0°
18:00	91.4°	20.1°
19:00	-90.5°	5.1°

3.2.2 Diffuse and direct solar radiation

Another important aspect of the solar radiation is the ratio of diffuse and direct radiation which is received by the earth's surface. It is important to know the beam of solar light (direct radiation) and diffuse radiation differently in addition to their total solar radiation. This helps to understand the solar energy performance in order to balance between preventing direct beams and allowing sufficient daylight into glazed buildings. Direct sunbeam can be simply blocked out by shading devices (Tzempelikos and Athienitis, 2007), particularly when the designer avoids the east and the west sun's low angle. On the other hand, the diffuse radiation might have a large impact on the glazed buildings (Edwards and Lake, 1965), especially in the tropical region which is close to the equator and faces a very high degree of diffuse radiation (Morrison, 1992). This situation results in the glazed buildings to resort to alternative and passive solar control elements in the tropics.

However, the absolute global radiation incident on a horizontal surface can be used to estimate the diffuse and beam components of the radiation. The "diffuse fraction regressions" (Vijayakumar *et al.*, 2005) and the "neural network NN model" are used to predict diffuse fractions in hourly and daily scales (Elminir *et al.*, 2007; (Paoli, Voyant, Muselli, & Nivet, 2010).

3.2.3 Intensity of solar radiation

When sunlight passes through atmosphere to reach the earth's orbit, the intensity (solar constant) fluctuates between 1350 and 1440 W/m^2 during the year (Bansal, 1994b) depending on the distance of the earth from the Sun.

Many climate factors affect the incoming intensity of the solar radiation, such as: the thickness and the composition of the atmospheric, the location of the Sun in the sky, as well as the actual conditions of the sky (Mingfang, 2002). The intensity of the clear sky with direct radiation is more than the intensity of the diffuse radiation on cloudy days (Paoli, et al., 2010).

3.2.4 Solar radiation spectrum

The intensity of solar radiation varies in different wavelengths. It ranges from the shortwave ultraviolet (UV) radiation at 0.20 – 0.38 µm, forming a small part of the total solar energy, which is about 8% to 9% of the solar beam that reaches to the earth's surface (Davies, 2004). The visible radiation is at 0.38 – 0.78 µm, which forms 46%. The remaining 46% goes to the near infrared ranging from 0.78 – 25 µm [1] (Elminir *et al.*, 2007, Muneer, 1997). The fourth part, that of long-wave or far-infrared radiation represents the reradiated energy from ground surfaces spanning from 3µm to 50µm (3000nm to 5000nm) (Wasley and Utzinger, 1996) (Figure 3.2).

All visible wavelengths are absorbed by a rough black surface, whereas the clear glass permits almost all visible radiation to pass through (Wasley and Utzinger, 1996). Ultraviolet (UV) radiation of wavelength less than 320 nm is absorbed by the upper atmosphere hence protecting the earth's surface from the harmful radiation. The portion of UV which reaches the earth's surfaces transfers through clear glass and fades fabric and degrades other finishing materials of indoor spaces (Fisette, 1998). The significant part with respect to the passive solar control of glazed buildings is the infrared (heat) radiation. It is highly recommended that the tropical buildings should prevent indoor spaces from the passage of infrared radiation.

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[1] This range of near infrared (0.78 – 0.25 µm) will be adopted throughout this research.

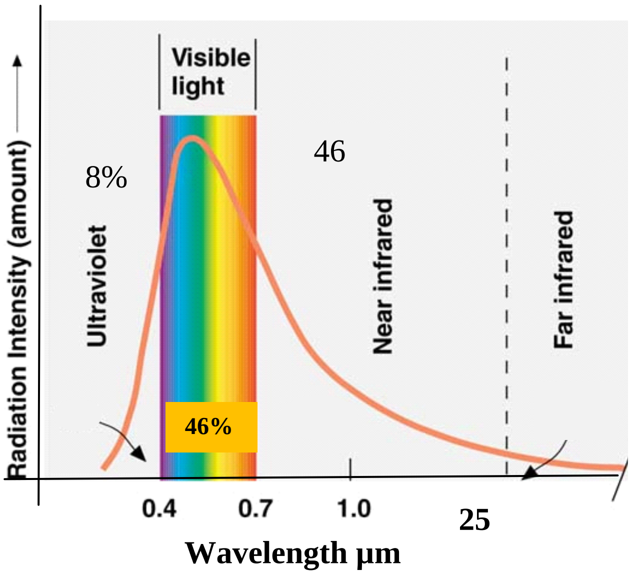


Figure 3.2:The solar spectrum at the Earth's atmosphere, (modified from Button and Waldron (1993))

3.2.5 Solar radiation on horizontal surface

The solar radiation can be defined by two angles, the altitude angle and the azimuth angle of the Sun at a particular site. The altitude h_S is the angle between the sun's beams and the horizontal, and the azimuth is the angle between the south (or north, according to convention) and the projection of the sun's beams on the horizontal (Davies, 2004) (refer to Figure 3.1). The estimation and calculation of the solar intensity of direct solar beam can be achieved as follows (Bansal, 1994b; Mingfang, 2002):

$$I = I_0 P^{1/\mathrm{Sin}\, h_s} \qquad (3.1)$$

Where I is the direct solar radiation intensity on the surface which is perpendicular to the incident direction of sunlight (W/m^2), I_0 is the solar constant (W/m^2), P is the atmospheric transparency and h_S is the solar altitude angle.

The horizontal surface (roof) of the buildings receives the longest duration of sunshine from the sunrise to the sunset. The intensity of the solar radiation on the horizontal surfaces can be expressed in form of the formula (1), as follows:

$$I^{-} = I \sin h_S \tag{3.2}$$

Where I^{-} is the direct solar radiation intensity on the horizontal surface (W/m^2).

3.2.6 Solar radiation on vertical surface

On a vertical and a slope surface, the total solar radiation is a sum of the direct beam, the diffuse radiation and the reflected one from the neighbouring surfaces. The relative intensity of direct solar beam on the vertical surface, could be shown in the equation (1), is:

$$I^{\perp} = I \cos h_S \tag{3.3}$$

Where $I^{\perp}$ is the direct solar radiation intensity on the vertical surface (W/m^2). If the inclination of the plane is taken as 90°, therefore cos h_S becomes zero.

3.3 Solar heat gain through glazings

There are two means of indicating the total solar heat gain through glazings: first, the heat gain due to the direct solar radiation τ_e. Whereas, the second means is the internal heat transfer q_i, including the irradiative heat and conductive heat gain: $SHG_{total} = \tau_e + q_i$ (Manz, 2004). The second portion, however, occurs because of the difference in the temperature between the ambient and the indoor spaces and the difference in the temperature between the glass surfaces (Kuehn, 2005). The following gives a review of the two portions of the total solar heat gain.

3.3.1 Direct solar radiation on glazings (or "near infrared")

When solar beam meets the glass, it is either transmitted, absorbed or reflected away from the glass (Bansal, 1994a). This depends on the spectral properties of the glass, where the different types of glass have unique characteristics with solar energy (Deal *et al.*, 1998). For example, most of the solar energy is transmitted through the surface of clear glass, its transmittance in part of short-wave infrared is about 75% and 89% of the visible light (Chow *et al.*, 2010). Therefore, an ideal glass for tropical regions should be the one with a high transmission to visible light, which is at 0.38-0.78μm, and low transmission to infrared (heat radiation), which is at 0.78-3μm (Muneer, 1997, Bansal, 1994b). Figure 3.3 experimentally determines the total amount of solar energy passing through a 3mm sheet clear glass taken as a reference.

3.3.1.1 Estimating of the shade coefficient

Shading Coefficient (SC) is commonly used to estimate the solar heat gain through glazings (Li and Lam, 2000). The SC is the ratio of the solar energy transmission through a specific glazing relative to the solar energy for standard glass (3mm clear sheet glass) under the same condition. The SC is expressed as a number between 0 and 1. The lower a glass' SC, the less solar heat it transmits (Deal *et al.*, 1998; Hassall, 1977).

The AIRAH[2] in the "Design Application manual DA91" provides formulas for calculating the SC which determines the amount of solar gain for single glazing (Fig.3.3) (Mason and Kingston, 2010):

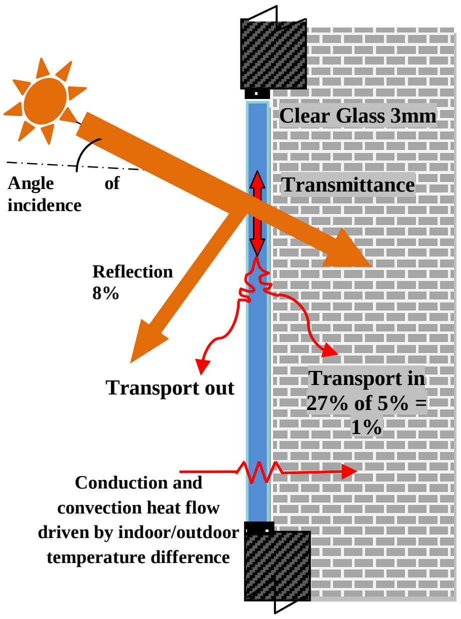
$$SC=(0.4\alpha+\tau)/0.884 \qquad (3.4)$$

[2] AIRAH: Australian Institute of Refrigeration, Air Conditioning and Heating

Where: α is the glass absorption coefficient

τ is the glass transmission coefficient.

0.4 is the proportion of the absorbed heat that is transmitted inwards. *It is assumed to be the ratio of the outside film coefficient divided by the sum of the inside and outside film coefficient."*



Reflectance	r	(0.08) 8%
Absorbance	b	(0.05) 5%
Transmittance	t	(0.87) 87%
Total		(1.0)100%

Figure 3.3: Solar reflection, transmission and absorption: standard 3mm clear sheet glass (Hassall, 1977).

The assumed air velocity is a very significant factor with regards to the inside and outside film coefficients. It is to determine the solar gain through glazings (Mason and Kingston, 2010).

ASHRAE[3] assumes the outside wind speed of 2.8m/s while 0.0m/s to the inside[4] (Colliver and Jarnagin, 2005). This wind speed makes change to the formula (3.4) :

[3] ASHRAE: American Society of Heating, Refrigerating and Air-conditioning Engineers.

[4] The ASHRAE assumption of the wind speed will be chosen for examining the SC of the "SGWF" in the experimental stage of this research work, since the test rooms are enclosed and the air velocity inside the rooms will be assumed of 0.0.

$$SC = (0.34\alpha+\tau)/0.884 \quad (3.5)$$

The SC of a given film such as SGWF is the product of the shading coefficients of the sheet of glass and water film:

$$SC_{SGWF} = SC_g \times SC_w \quad (3.6)$$

3.3.1.2 Solar Heat Gain Coefficient SHGC

The amount of the total solar heat gain (UV, visible and infrared radiation) that passes through a glazing is usually evaluated in terms of Solar Heat Gain Coefficient (SHGC) or sometimes called “g-value” (Li and Lam, 2001). The SHGC has replaced the SC as the standard indicator of a glazing's shading ability. It is expressed as a number between “0” and “0.87” instead of “0” and “1” for SC. The lower a glazing's SHGC, the less solar heat it transmits (Deal *et al.*, 1998). In Malaysia, a tropical country with a hot humid climate, the ideal glazing is the one with low SHGC. According to ASHRAE (2008), in warm climates for the north and the south glazed facades the sellected SHGC Should be ideally of no more than 0.35, and the east and west glazed-facades should be selected for no more than 0.25. For calculating the SHGF Pedrini, (2003) defined the following formula:

$$SHGC = \tau_s + N_i \,.\, \alpha_s \quad (3.7)$$

Where: τ_s = solar transmittance of fenestration system, N_i = inward-flowing fraction of absorbed radiation (according to equation (3.4) N_i= 0.4) and α_s = solar absorption of a single-element.

Moreover, according to the National Fenestration Rating Council (NFRC) the consistent results of SHGC are obtained by measurement at laboratories. Whereas the hourly measurements produce low consistent values of SHGC particularly if the measured values of solar irradiance below 500 W/m² (Pedrini, 2003).

However, to calculate the hourly SHGC, Li and Lam (2001) developed an approach based on the solar angle and the clearness index (K_t). The clearness index is one of the solar engineering concepts. "*It gives more information about the atmospheric characteristics of solar stations in addition to the degree of solar energy potential of stations and their surrounding areas*" (Sahin *et al.*, 2001).

The hourly SHGC for the horizontal surface in W/m^2, according to Li and Lam (2001) is:

$$SHGC_h = H_h(\tau_b + N_i\alpha_b) + D_h(\tau_d + N_i\alpha_d) \quad (3.8)$$

For the vertical surface, the hourly SHGC is given as:

$$SHGC_v = H_v(\tau_b + N_i\alpha_b) + I_v(\tau_d + N_i\alpha_d) \quad (3.9)$$

$$H_v = \left({H_h}/{\sin\alpha}\right)\cos\theta \quad (3.10)$$

$$I_v = G_v - H_v \quad (3.11)$$

Where:

τ_b, the transmittance of the reference glazing for direct beam radiation,

α_b, absorptance of the reference glazing for direct beam radiation,

τ_d, transmittance of the reference glazing for diffsuse radiation,

α_d, absorptance of the reference glazing for diffsuse radiation,

D_h, hourly diffuse radiation on the plane of the horizontal glazing (W/m2),

H_h, hourly direct beam radiation on the plane of the horizontal glazing (W/m2),

N_i, inward flowing fraction of the absorbed radiation,

I_v, the sum of the hourly diffuse and reflected radiation on the plane of the vertical glazing (W/m2),

G_v , measured hourly global radiation on the plane of the vertical glazing (W/m2), and

H_v hourly direct beam radiation on the plane of the vertical glazing (W/m2).

3.3.2 Heat transfer through the glazing (or "far infrared")

When the sunbeam and diffused radiation energy hit the outer glazing surface, a portion of this energy is absorbed by the glazing and re-emits as long-wave energy inwards (Chowdhury and Cortie, 2007). This forms another important portion of the total heat gain through glazings. The transfer of this long-wave infrared takes place from the outdoor ambient to the indoor space through the glazings by three methods of heat transfer: conduction, convection and radiation. The radiation absorbed within the glazings will flow as a heat energy as follows: conduction and convection to the ambient air, conduction and convection due to a temperature difference between indoors and outdoors, and radiant heat exchanges with the internal surfaces and other heat sources/sinks in the room (Underwood and Yik, 2004; Pal *et al.*, 2009). This movement of the heat energy on the glazing is affected by several physical parameters (Mason and Kingston, 2010): the inside air temperature, the inside air velocity, the effective room radiant temperature, the effective room emissivity, the outside air temperature, the direct solar radiation, the outside wind speed, the effective sky radiant temperature, and the effective sky emissivity. The following paragraphs serve to define the three mechanisms of heat transfer through the glazing, i.e. conduction, convection and radiation.

3.3.2.1 Conductive heat

In term of glazing, the heat conduction is the *"flow of energy across a glass sheet due to thermal diffusion between molecules"* (Deal *et al.*, 1998). Because the glazing used in the buildings are typically thin sheets, and the thermal conductivity of the glass (k)[5] is relatively high compared with that of other materials (refer to Table 3.2), the glass by then is a good conductor of thermal energy (Underwood and Yik, 2004). Noted that a material that is a good insulator (low k-value) or very thick (large L) suppresses heat transfer. With the glazing, the thermal resistance is often ignored for calculating the heat transfer through. Using the *Fourier's law* to address the one dimensional heat flow through a single glass pane at the right angles to the surface, the formula is (Moss, 2007; Hauser, 1994) :

$$Q = \frac{k\Delta t}{L} = \frac{k}{L}.(t_1 - t_2) W/m^2 \qquad (3.12)$$

Where: k (W/mK) is the thermal conductivity

Δt (°C) is temperature difference across the faces of the glass pane.

L (m) is thickness of the glass pane.

t_1 (°C) is temperature at the hot end

t_2 (°C) is the temperature at the cold end

Table 3.2:Thermophysical properties of some building materials (Bansal, 1994b)

Material	Thermal conductivity W/mK	Specific heat capacity Wh/kgK
Aluminium	165	0.25
Constriction steel	60	0.13
Normal concrete	2.1	0.24
Solid brick	0.50 – 0.96	0.24
Glass	0.8	0.19 – 0.26
Wood	0.13 – 0.20	0.66
Water	0.60	1.2

5 *What is called the k-value of construction materials in the U.S., is called λ-value in Europe. What is called U-value in the U.S., used to be called k-value in Europe.*

3.3.2.2 Convective heat

Heat convection occurs between a solid and a liquid, or a solid and a gas, when a molecules move freely and independently at different temperatures. The convection heat transfers by means of the conduction and the bulk motion of liquid (Deal *et al.*, 1998). The motion of the liquid might be forced or freely flow. Forced convection is made with the aid of a prime mover, such as pumping the water to flow inside the heat exchanger pipes. Free convection relies on natural force such as water film flow down a vertical surface, where its effectiveness in heat transfer relies on (Moss, 2007): the velocity of the water film over the surface, where heat transfer is usually higher for forced convection than for natural convection, the magnitude of the temperature difference between the water film and the surface, the size and the shape of surface and its position in space.

The mathematical relationship to calculate the amount of heat convection is given in the following formula:

$$Q = h_c \times (t_1 - t_2) \qquad (3.13)$$

Where: h_c , the convective heat transfer coefficient.

3.3.2.3 Radiant heat

A simple definition of heat radiation is the exchange of electromagnetic waves between surfaces of different temperatures (Hauser, 1994). The main difference between the heat radiation exchange and the heat convection and conduction is that radiation does not require an exchange medium. However, every surface is emitting radiant heat. For example, the glass in the buildings absorbs, reflects or transmits a part of the heat energy when its temperature is above absolute zero (Moss, 2007). The formula that illustrates a flux radiated from the surface is (Hauser, 1994):

$$Q = \varepsilon \times C_s \left(T_0 / 100 \right)^4 \quad (3.14)$$

Where: ε Emissivity

C_s Radiation constant for black bodyes (=5.67 W/m2k4)

T_0 Absolute temperature of surfaces (k)

All surfaces in the buildings emit heat radiation, the heat radiation exchanges between the warmer surface 1 and the cooler surface 2 is given by this formula (Hauser, 1994) :

$$Q_{1\rightarrow 2} = \varphi_{1\rightarrow 2} \times \varepsilon_1 \times \varepsilon_2 \times C_s \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right] \quad (3.15)$$

The factor $\varphi_{1\rightarrow 2}$ is the radiator depends on the relative position of the two surfaces.

$$\varphi_{1\rightarrow 2} = \frac{1}{\pi \times A_1} \int A_1 \int A2 \frac{\cos\beta_1 \cos\beta_2}{S^2} \, dA_1 \mathrm{d}A_2 \quad (3.16)$$

3.3.2.4 Light to Solar Gain Ratio LSG

Light to solar gain (LSG) is the ratio of visible light transmittance (VT) to the solar heat gain coefficient (SHGC). It measures the ability of glazings to admitted light without the overload of solar heat gain. It measures the efficiency of glazing under solar radiation in transmitting visible light region while blocking infrared (or heat) (Nagamedianova *et al.*, 2011). However, the high LSG value behind the glazing means the more daylight in the room with less heat gain, which is shown in the following formula:

$$LSG = \frac{VT}{SHGC} \quad (3.17)$$

Hence, the ideal alternative solution for glazing might be the one that enhances the efficiency of the glazing through the factor of LSG, which is characterized the performance of glazing vis-à-vis solar heat gain in glazed buildings (Gueymard and DuPont, 2009).

3.3.2.5 Heat sink

The cooling effect of a heat sink can result from a cold liquid or from the mass of the building itself. Often the massive structure of a building acts as a heat sink (Lechner, 2009). In hot humid tropics, heat sinks might be used to enhance the rate of heat flux with a great heat capacity from the indoor to the outdoor, either under forced or natural convection. The application of this concept in buildings is found when the spaces are cooled by the chilled water running inside pipes which are located in the building's slab or the metal ceiling to enhance heat loss. As the chilled water flows through the pipes, it transfers cooling capacity to the slab, thereby cooling it with the floor slab acting as a heat sink system. Another application of heat sink that could be practical for the tropics is forcing air convection to increase the air exchange rate with the ambient to lower the office temperature (Figure 4.4). The mechanism is to use high air exchange rates at night when the ambient temperature is low to create a cooled building structure which during the day acts as a heat sink to the solar gain through (James and Bahaj, 2005).

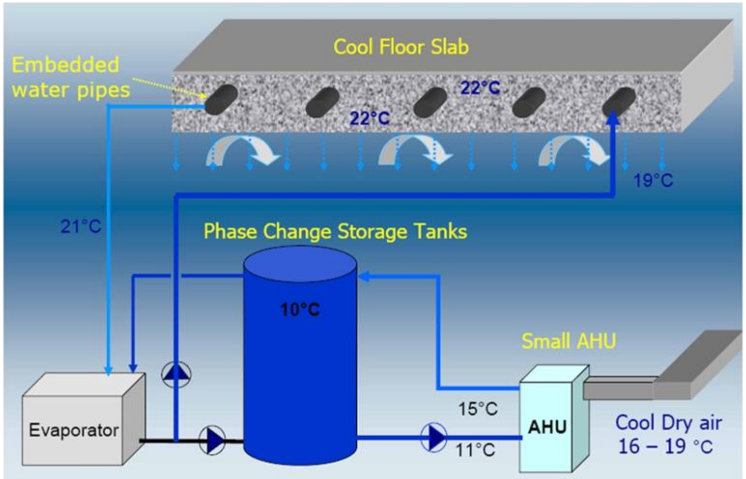


Figure 3.4:Chilled water tubes are embedded into the floor slabs acting as a heat sink, in GEO building

3.3.2.6 The green house effect

Glass allows short-wave solar radiation to transmit but disallows long-wave radiation transmission. This phenomenon is known as the green house effect (Moss, 2007). As the direct sunbeam strikes the glass, a short-wave solar radiation passes through the glass. When the transmitted short-wave hits surfaces inside the space, it is absorbed and warms up the objects that begin to emit long-wave radiation which cannot escape through the typical glass resulting in the rise of the indoor temperature (West, 2001).

In the tropics, increasing the heat loss through glazing by this means can be obtained if the glass is treated to absorb this long-wave radiant energy. The water flow or air flow over the glass might control the indoor climate by cooling down the surfaces of the glass, absorbing the heat and evaporating it away. However, in the tropics like in Malaysia, before thinking how to increase the heat loss through the glazing, it is very important to avoid infrared radiation as much as possible in order to minimize the greenhouse effect.

3.4 Passive solar control for glazed building in tropics

The solar radiation beams, as stated above can be broken into three electromagnetic waves, ultraviolet with 6% of the energy, visible light on average 48%, and shortwave or near-infrared part of the spectrum with 46%. However, to reduce the effect of solar radiation heat in the tropics, it is very important to avoid the infrared radiation as much as possible instead of introducing the air-conditioning system for maintaining indoor thermal comfort. The air-conditioning system is the easiest decision to be taken for controlling solar loads, but this leads to the increase in energy consumption in addition to emission of the greenhouse gases.

However, by introducing the appropriate alternative passive solar control is the right decision to be taken in the early stages of designing buildings, particularly for office buildings that are the main application for passive solar control elements (Voss, 2007). In general, solar control might be split into two groups. First is to prevent direct solar radiation through the glass area and the heat gain through building envelops from penetrating to the workspaces (Chan, Riffat, & Zhu, 2010; Abdullah *et al.*, 2009), whereas the second group is to maximize the heat loss from workspace by means of heat sink, such as, cooling building surfaces, introducing an ample air movement or radiant system that are capable of reducing the indoor air temperature (Vangtook, 2005). However, the following section of the study provides a review of advanced passive solutions that are suitable for glazed buildings in the tropics: the sun shading devices and the glazing technology.

3.4.1 Shading devices and east/west orientation

Glazed buildings need to keep solar radiation out of the whole building envelop by means of the "envelop shading system". This system firstly prevents the building from the penetration of direct solar radiation, and secondly reduces the temperature of the glazing surfaces so that the heat conduction indoors is decreased (Yu *et al.*, 2008).

In related to the glazing, several studies have been conducted on the shading as a passive strategy to control solar heat gain. They mainly focused on: (a) fixed or movable sun-shading devices, either external or internal, that control solar loads and at the same time allow light and some view to the outdoors. The efficiency of this system depend mainly on the slat tilt angle, reflective material and the colour (Bessoudo *et al.*, 2010; Agarwal and Verma, 1977; van Moeseke *et al.*, 2007; Tzempelikos, 2008; Simmler and Binder, 2008); (b) compound the shading devices with double glazing systems, focusing on the efficiency of the colour and the position of the shading devices to achieve high reflectance values inside the double glass pane resulting in minimisation of heat gain ((Baldinelli, 2009; Gratia and De Herde, 2007; Breitenbach *et al.*, 2001) and (c) building shape towards the self-shading, where it has been found by Capeluto (2003) that self-shading results in similar performance of using high-performance low-emissivity glazing on vertical facades.

In general the decision to implement shading devices on glazed facades in Malaysia should take into account the Malaysian sky condition. Referring to Chapter Two, the sky is mostly cloudy and sometimes clear (Zain-Ahmed, 2009). Therefore, the shading devices for the buildings with the entire glass facades are difficult to be controlled without conflicting between the heat and the light, especially the fixed external shading devices during the cloudy times. Internal shading devices are much better in terms of its non-exposure to wind loads and air pollution, lower production and maintenance costs (Voss *et al.*, 2007) and the ease of use which allows users to control over solar gain and obtain light during cloudy hours, but it also acts as heat traps indoor.

The north and the south glazing might easily be shaded by horizontal overhang. While the east and the west glazed facades are challenging to be effectively shades, their shading devices must be external and vertical in order to be effective (Askar *et al.*, 2001). As illustrated in Figure 3.5, screen walls and vertical fins elements could effectively help block low-altitude sun beam by completely shading the glazings during the sunshine but they eliminate the glazing characteristics. In addition, it is not easy to remove the devices during the cloudy times to obtain the desires lightings. The east and the west facades receive about 50% more sunshine than the north and the south (Bansal, 1994). Therefore, the glazing on the east and the west walls are avoided in the tropical buildings' design for thermal considerations (Zain-Ahmed, 2009). But this is not constantly affordable and acceptable due to the limitation of the land-form, day-lighting and viewing aspects. However, with the traditional shading devices, the east and the west glazed facades are more difficult to be adapted, whereby the mostly used solution would be the reflective or the absorptive glazing. The following section will discuss the common solar control glazing systems used in the tropics, particularly in Malaysia.

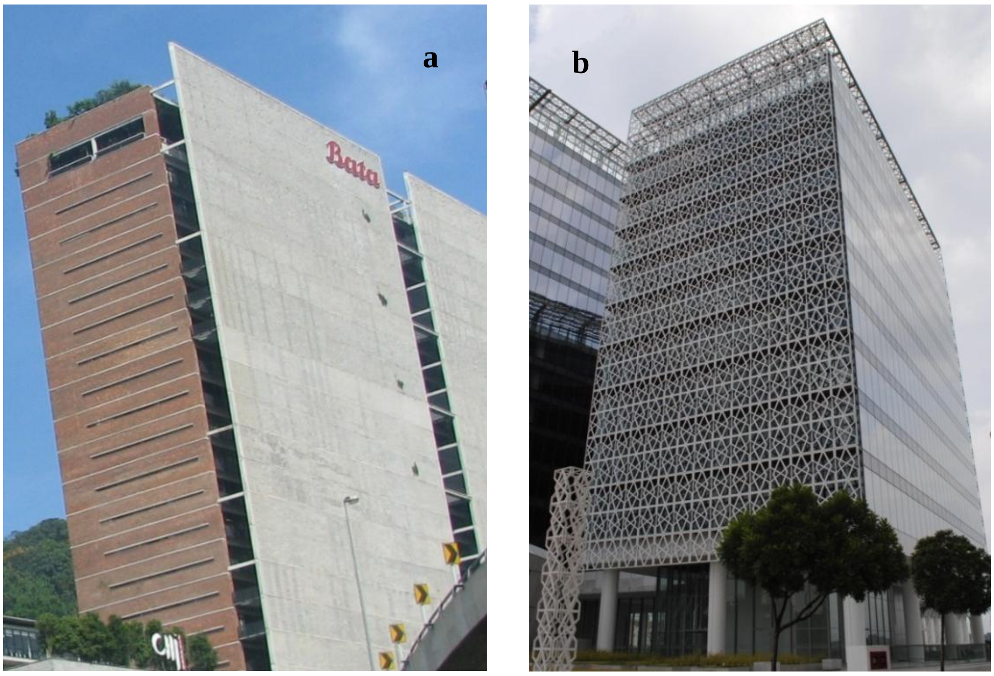


Figure 3.5: The east and the west shading devices: (a) Wall Fence, PJ Trade Centre and (b) Screen Wall, Putrajaya

3.4.2 Glazing technology in the tropics

Glass usage in buildings of the tropics, with hot-humid climate, as in Malaysia, causes a higher indoor temperature which usually requires an air conditioning system in order to succeed in providing thermal comfort in the workspace. This increases the energy consumption particularly in the office buildings. Therefore, glazing is strongly preferred in order to satisfy the occupants in their workspace by obtaining the desired natural light and outside view (Menzies and Wherrett, 2005). The perfect glazing for the tropical region should be the one that has the ability to block the infrared radiation and transmit the visible light (Castro *et al.*, 2005).

The glazing might be classified according to many aspects: the manufacturing process, such as the float glass, tempered glass; and the glass pane properties, such as the optical properties and the thermal properties. All of these can be single or double glazing units. In the design guide for glass architecture in the tropics, Fong and Chong (1999) reviewed the common types of glass used in the architectural applications in such regions, covering the laminated architectural glass with its wide applications, and the higher solar performance glass, including body tinted glass, insulating glass, solar reflective glass, low-emissivity glass and spectrally selective glass.

Nevertheless, this study focuses on the single higher solar performance glass that is gaining popularity as a building material in Malaysia, as in the country of the tropics (Table 3.3 and Table 3.4). This study aims to understand in which ways the glazing might be better used for solar heat control in the tropics.

3.4.2.1 Clear glass

Clear glass is applicable for the cold and the moderate climate due to its higher transmittance to visible and near-infrared radiation in addition to its absorbance to far-infrared radiation (Wasley and Utzinger, 1996). In the tropics, clear glass is completely not advisable, especially on the east and the west facades which is exposed to the high intensity of the direct solar radiation. However, the clear float glass can be modified to obtain the higher solar performance glass by taking advantage of the modifications in transmission, the reflection and the absorption properties (Button and Waldron, 1993).

Table 3.3: The characteristics of glasses available in Malaysia, Pilkington products (MSG, 2009)

Product	Nominal Glass Thickness		Visible Light[2]			Total Solar Energy[2]			U-Factor[5]						Solar Heat Gain Coeffi-cient[7]	Shading Coeffi-cient[8]
			Trans-mittance[3]	Reflectance[4] %		Trans-mittance[3]	Reflect-ance[4]	UV Trans-mittance[2]	U.S. Summer		U.S. Winter		European[6]			
	in.	mm	%	Outside	Inside	%	%	%	Air	Argon	Air	Argon	Air	Argon		
Pilkington Uncoated Float Glass																
Optifloat Clear	3/32	2.5	90	8	8	86	8	75	0.95	–	1.05	–	5.9	–	0.87	1.00
	1/8	3	90	8	8	84	8	72	0.94	–	1.04	–	5.8	–	0.86	0.99
	5/32	4	89	8	8	81	7	68	0.94	–	1.04	–	5.8	–	0.84	0.97
	3/16	5	89	8	8	80	7	65	0.93	–	1.03	–	5.8	–	0.83	0.96
	1/4	6	88	8	8	77	7	62	0.93	–	1.02	–	5.7	–	0.81	0.94
	5/16	8	87	8	8	73	7	57	0.92	–	1.01	–	5.7	–	0.79	0.91
	3/8	10	86	8	8	70	7	54	0.91	–	1.00	–	5.6	–	0.77	0.88
	1/2	12	84	8	8	64	6	49	0.89	–	0.98	–	5.5	–	0.73	0.84
	5/8	16	83	8	8	59	6	45	0.88	–	0.97	–	5.4	–	0.70	0.81
	3/4	19	81	7	7	55	6	41	0.86	–	0.95	–	5.3	–	0.67	0.78
Optifloat Grey Tint	1/8	3	61	6	6	59	6	35	0.94	–	1.04	–	5.8	–	0.69	0.8
	3/16	5	50	6	6	48	5	26	0.93	–	1.03	–	5.8	–	0.62	0.71
	1/4	6	43	5	5	40	5	20	0.93	–	1.02	–	5.7	–	0.57	0.66
	5/16	8	33	5	5	31	5	14	0.92	–	1.01	–	5.7	–	0.50	0.59
	3/8	10	28	5	5	26	5	11	0.91	–	1.00	–	5.6	–	0.47	0.55
	1/2	12	19	4	4	17	4	7	0.89	–	0.98	–	5.5	–	0.42	0.49
Optifloat Bronze Tint	1/8	3	68	6	6	65	6	37	0.94	–	1.04	–	5.8	–	0.73	0.84
	3/16	5	59	6	6	55	6	28	0.93	–	1.03	–	5.8	–	0.67	0.77
	1/4	6	53	5	5	49	5	23	0.93	–	1.02	–	5.7	–	0.62	0.72
	5/16	8	44	5	5	39	5	16	0.92	–	1.01	–	5.7	–	0.56	0.65
	3/8	10	39	5	5	34	5	13	0.91	–	1.00	–	5.6	–	0.53	0.61
	1/2	12	29	5	5	25	4	8	0.89	–	0.98	–	5.5	–	0.47	0.55
Optifloat Blue-Green Tint	1/4	6	75	7	7	48	5	31	0.93	–	1.02	–	5.7	–	0.62	0.72
	5/16	8	70	7	7	40	5	25	0.92	–	1.01	–	5.7	–	0.57	0.66
	3/8	10	67	6	6	36	5	21	0.91	–	1.00	–	5.6	–	0.54	0.63
EverGreen High-Performance Tint	1/8	3	76	7	7	49	6	27	0.94	–	1.04	–	5.8	–	0.62	0.72
	3/16	5	73	7	7	42	5	21	0.93	–	1.03	–	5.8	–	0.58	0.67
	1/4	6	66	6	6	33	5	14	0.93	–	1.02	–	5.7	–	0.51	0.60
Arctic Blue High-Performance Tint	5/32	4	65	6	6	45	5	31	0.94	–	1.04	–	5.8	–	0.60	0.69
	1/4	6	55	6	6	34	5	22	0.93	–	1.02	–	5.7	–	0.52	0.61
	3/8	10	39	5	5	20	5	12	0.91	–	1.00	–	5.6	–	0.43	0.51
SuperGrey High-Performance Tint	1/8	3	25	5	5	23	4	6	0.94	–	1.04	–	5.8	–	0.45	0.52
	3/16	5	12	4	4	11	4	2	0.93	–	1.03	–	5.8	–	0.37	0.44
	1/4	6	9	4	4	8	4	1	0.93	–	1.03	–	5.7	–	0.35	0.41

Table 3.4:Characteristics of low-e glass, imported to Malaysia. (MSG, 2009)

Pilkington Eclipse Advantage™ Reflective Low-E Glass Outer Lite (#2 Surface)																
Eclipse Advantage Clear	1/4	6	66	22	27	56	17	28	0.53	–	0.67	–	3.8	–	0.61	0.71
Eclipse Advantage Grey	1/4	6	32	9	26	29	8	10	0.53	–	0.67	–	3.8	–	0.41	0.48
Eclipse Advantage Bronze	1/4	6	40	11	26	35	9	11	0.53	–	0.67	–	3.8	–	0.46	0.53
Eclipse Advantage Blue-Green	1/4	6	56	17	27	35	10	16	0.53	–	0.67	–	3.8	–	0.45	0.53
Eclipse Advantage EverGreen	1/4	6	49	14	26	23	8	7	0.53	–	0.67	–	3.8	–	0.37	0.43
Eclipse Advantage Arctic Blue	1/4	6	41	11	26	24	8	11	0.53	–	0.67	–	3.8	–	0.37	0.44
Pilkington Solar E™ Solar Control Low-E Glass (#2 Surface)[9]																
Solar E Solar Control Low-E	3/32	2.5	61	7	9	47	8	51	0.49	–	0.65	–	3.7	–	0.55	0.64
	1/8	3	60	7	9	46	7	47	0.49	–	0.65	–	3.6	–	0.53	0.62
	5/32	4	60	7	9	44	7	44	0.49	–	0.64	–	3.6	–	0.52	0.61
	3/16	5	60	7	9	44	7	45	0.49	–	0.64	–	3.6	–	0.52	0.61
	1/4	6	60	7	9	42	7	41	0.49	–	0.64	–	3.6	–	0.51	0.59
	5/16	8	60	8	9	41	7	40	0.48	–	0.63	–	3.6	–	0.50	0.58

3.4.2.2 Tinted glazing (heat absorbing glazing)

The essential character of the tinted glass is to produce a high ratio of absorption to the selected parts of the solar radiation spectrum by the tint material that is created with adding metal oxides to the base glass (Compagno, 2002). Although the surface temperature of the tinted glass might be as high as 50 °C (Erell *et al.*, 2004), two thirds of this absorbed heat reradiates the outdoors leading to the reduction in the heat gain indoors. A disadvantage of this tinted glass, besides its high temperature, is the decreasing of the light by blocking some of the visible spectrum. The “light/heat ratio” is a relationship to express both light transmission and total heat transmission through the glazing, for example 72/62, 6mm green body tinted glass (Button and Waldron, 1993).

The ranges of tinted glass available in the tropics, according to “NSG[6] Group’s literature” are green, blue, bronze and grey. Green-tinted glass is achieved by adding iron oxide in the glass and is preferable due to the high transmittance in visible light. While grey and bronze-tinted glasses are the most widespread tint colours used for reducing both glare and heat(U.S. DOE, 1994), the grey-tinted glass is obtained by adding nickel oxide, and bronze-tinted glass is produced by adding selenium (Compagno, 2002). Although the tinted glass absorbs the solar heat, some heat still passes indoors by radiation and conduction, which suggest the need to omit for other glazing properties.

3.4.2.3 Heat Reflective glazing

Heat reflective glazing is the most effective glazing for reducing solar loads, and can be combined with clear or tinted float glass. The reflectivity is achieved by coating the glass with a thin layer of metal oxide on a single side of the glass, to further reduce the SC which leads to reducing heat transfer (Fong and Chong, 1999). The advancement in the reflective glazing with a special invisible metal oxide film is called low-e glazing.

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[6] Nippon Sheet Glass NSG/Pilkington is one of the largest glass companies in the world. In 1971 Malaysian Sheet Glass MSG was established, and by 2004 MSG was wholly owned by NSG.

3.4.2.4 Low-e glazing

Low emissivity (low-e) glass has special coatings that reflect invisible long wave radiation passing through glazing. The coatings are almost invisible metal oxide that can reduce the emissivity of the surface of the glass from e ~ 0.87 to e ~ 0.04, thus reflecting back 65% to 96% of long-wave radiation, resulting in reduced infrared radiation up to 20%, without affecting the transmittance of visible light (Compagno, 2002). Low-e coating is mostly compounded with double glazing for both reasons of protection and to increase the efficiency of blocking long-wave infrared radiation (Figure 3.6). There are two types of low-e coatings that are developed and used in the market namely the hard coat (*pyrolithic-coated)* reflective glazing or soft coat (*sputtering-coated)* reflective glazing.

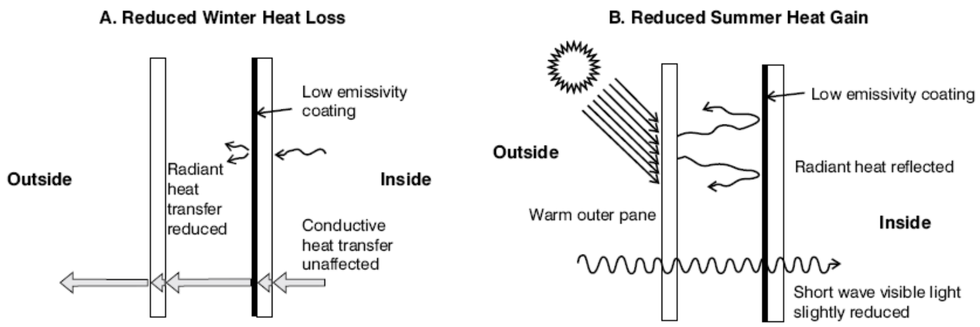


Figure 3.6:The performance of low-e glazing that reduces radiant heat transfer (long-wave infrared) (U.S. DOE, 1994)

a) Soft coat/ Sputtered

The most common low-e coating is sputtered, which is achieved by applying silver and anti-reflective coating. The coating is applied to the glass by vacuum deposition to the glass surface, creating a soft coat that should be protected within double glazing unit, on the surface facing the air pace (Woolley and Kimmins, 2002).

b) Hard-coat/ Pyrolytic

The pyrolytic (hard coat) reflective glazing is a very thin layer of metallic oxides applied online during the basic manufacture (Deal *et al.*, 1998) . The coating has the advantages of hardness and durability so that it can be used on single glazing (Button and Waldron, 1993). The metal oxide creates the colour of the glazing and the variation of colour intensity is affected by the thickness of the glass pane (Fong and Chong, 1999). Generally, this glazing shows a high luminous transmission, and are not so efficient for the infrared protection and the coated surface should face the exterior for obtaining high thermal reflectivity (Castro *et al.*, 2005).

In summary, as mentioned above, highly reflective coating that was developed in 1970 and became available in the market around 1980, is now becoming popular in certain countries that experience extreme winter (Figure 3.7). In the tropics, with hot humid, as in Malaysia where the difference in temperature between the outside and the inside is not high, the heat (long infrared) exchange between the outdoor and the indoor is not high. The main contributor to interior heat loads is the direct solar radiation that contain near-infrared light passing through the low-e glazing to the indoor absorbs by the interior surfaces then re-emitted from the surfaces as a long-wave infrared. The said infrared cannot escape to the outdoors forming what is called the greenhouse effect, resulting in the increased indoor temperature.

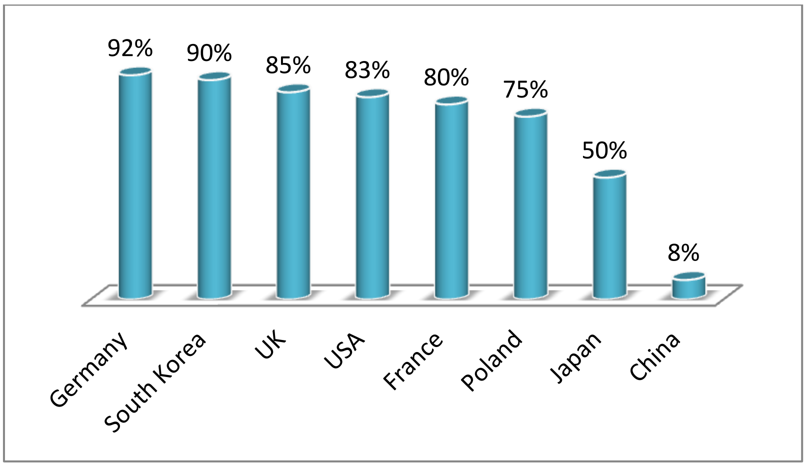
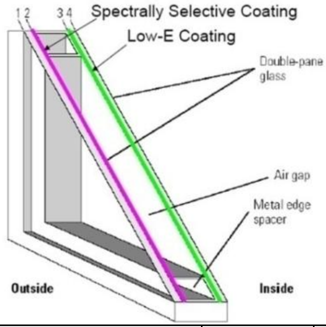


Figure 3.7:Low-E Glass Penetration Rate in Major Countries where climates are cold in winter (Research In China, 2010).

3.4.2.5 Spectrally selective glazing

Improvements in the glazing efficiency might be obtained by applying the low-e coating that reflects the long-wave infrared radiation. However, in the tropics, the priority is given to the reflection of the short-infrared radiations, which are still able to penetrate into low-e coat. The success of glazing in the tropics lies in the concept that transmits the visible light and reflects out the short-wave infrared radiation. The low-e coating has been enhanced to the low-e spectrally selective coatings that combine the best qualities of tinted glazing, reflective glazing and low-e glazing (DOE, 1998; Menzies and Wherrett, 2005; Alvarez *et al.*, 2005; Ma *et al.*, 2008).

Thus, the SHGC of the glazing becomes low resulting in the reduced heat gain more than heavily tinted bronze and gray glazing. The visibility to light is also high making it advantageous for daylighting (Erell *et al.*, 2004; Woolley and Kimmins, 2002). Although, the spectrally selective glazing might be the appropriate choice for the tropics, there are still some disadvantages which may cause a drawback in the practice of this glazing in the tropics. It needs to be compounded with double glazing for protective purposes and its relatively high production cost (Figure 3.8).



Description	Heat %	Light %	U-Value W/m^2k
Single glass	85	85	6
Double spectrally selective, low-e and gas filled	25	50	1

Figure 3.8:Double glazing system, integrating low-e and spectrally selective glazing in GEO Building, a certified green office building in Malaysia (Source: PTM).

3.4.2.6 New glazing systems

There is still a possibility to implement more glazing systems in the offices for obtaining the comfort in the workplace, such as switchable glazing system, inert gas-filled double glazing and angular selective coatings (Nitz and Hartwig, 2005; Sottile, 2005; Compagno, 2002; Reppel and Edmonds, 1998). But these glazing systems are not dealt with in this research. However, double skin glazed-facade and tilted glazing systems will be discussed in Chapter Four as a part of field observation and the analysis of green glazing practices in the tropics, Malaysia.

3.4.2.7 Discussion on the recommended glazing in the tropics

The differentiation of glazing performance in terms of the relationship between light transmittance and heat transfer, the light to heat ratio is illustrates in Figure 3.9. For example: (point a) is a Suncool HP Brilliant 50, with VLT of 51% and SHGC of 26%, the VLT/SHGC ratio is 1.96. (Spectrally selective, allowing light, blocking heat), whereas the Optifloat Clear (point b), with VLT of 81% and SHGC of 73%, the VLT/SHGC ratio is 1.11, (only slightly spectrally selective).

However, the review of the glazing states that the glazing either provides only a partial response to the solar loads by conflicting between the visual and the thermal comfort. Or it is not preferable to the clients from the economic aspects. As the low-e and spectrally selective coated glazing need to be compounded with double glazing for protection reasons, in addition to its relatively high production cost. However, although the spectrally selective glazing that has a high visible transmittance and low SHGC appeare to be the applicable glazing for the tropics, it has been found from a review of the market and through direct contact with manufacturers that tinted glazing is still a popular choice for buildings in Malaysia, whereas no large market exists for a higher performing glazing that has only a few practical applications depending on the imported units.

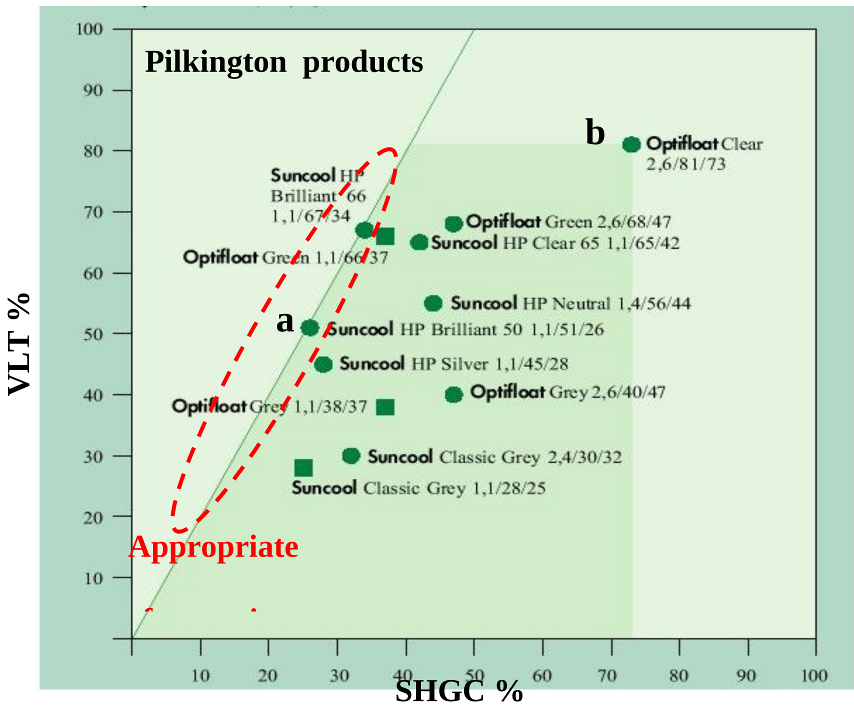


Figure 3.9:Different glazing performance, the light/heat ratio. (Source: modified from Button and Waldron, 1993)

3.5 Summary

This chapter describes the concepts of the solar radiation and energy spectrum that contribute to the heat gain through the glazing. There are two means of indicating the total heat gain through the glazing: primary the heat gain due to the direct solar radiation, whereas the second is the heat transfer due to the difference in temperature between the ambient and the indoor spaces and the difference in temperature between the glass surfaces. However, most of the solar radiation is transmitted through the surface of clear glass, particularly on the east and the west glazing orientations. Where, short wave infrared transmittance is about 75% and 89% of the visible light. Therefore, an ideal glass for the tropical regions should be that one with a high transmission to visible light, at 0.38 to 0.78µm that accounts 47% out of the incident solar energy, and low transmission to infrared (heat radiation), at 0.78 to 3µm that carrying 46% out of the incident solar radiation.

Heat convection that occurs between a solid and a liquid, or a solid and a gas, transfers by means of the conduction and the bulk motion of a liquid over the surface, where its effectiveness in the heat transfer relies on: velocity of the water film over the surface (heat transfer is usually higher for forced convection than for natural convection), magnitude of the temperature difference between the water film and the surface, and the size and the shape of the surface and its position in space.

In hot humid tropics, heat sinks concept might be used to enhance the rate of the heat flux with a great heat capacity from the indoor to the outdoor, either under forced or natural convection. The application of this concept in the buildings is found when the chilled water flows inside pipes that are located in the building slab or the metal ceiling to enhance the heat loss. As the chilled water flows through the pipes, it transfers cooling capacity to the slab, thereby cooling it, with the floor slab acting as the heat sink system. Another application of the heat sink which could be practical for the tropics, is forcing air convection to increase the air exchange rate with the ambient to lower the office temperature. A water film flowing down over the glazed facades might be a new application for improving the glazing performance against the solar radiation and the increased heat loss in the tropics by conveying the thermal energy indoor towards the heat sink (glazing) and then releasing the heat to the air or by means of the bulk motion of the water film over the surface of the glazing.

In the tropics, solar loads are a serious buildings' problem to be solved. The traditional solution that allows users to control solar gain, besides the proper glazing orientation, is to install shading devices, but this does not distinguish between the daylight and the heat, particularly on the east and west orientations of the tropics where the solar altitude is low and the horizontal shading is inapplicable unless by blocking the whole facades. The east and the west facades are generally avoided in the tropical buildings' design for thermal considerations, but this is not constantly affordable and acceptable due to the limitation of the land-form and view aspects as well.

Using absorptive (tinted) glazing is the common way of reducing solar radiation but it also reduces the transmittance of light into the workspace. The advanced low-e coating has been enhanced to the low-e spectrally selective coatings that combine the best qualities of tinted, reflective and low-e glazing. Yet, the low-e spectrally selective glazing is applicable for the tropics from the solar heat performance; the drawback is the high manufacture cost which makes it not preferable to the clients from economic aspects.

CHAPTER 4

THE CHALLENGES OF THE GLAZED BUILDINGS IN THE GREEN ERA IN THE TROPICS

4.1 Introduction

This Chapter covered a field analysis to explore the tropical passive solar control and alternative cooling for glazed buildings in Kalang Valley, Malaysia, giving emphasis to the mid-rise office glazed-buildings. Photographical documentaries of office- glazed-buildings for standing on the common types of glazing used are illustrated. Five certified green and glazed-buildings in Malaysia were selected to be experimentally investigated. Relying on the theoretical literatures of the passive solar control in the above Chapters and the field review in this Chapter, the research gap will be framed in the end of this chapter.

4.2 Glazing in architecture.

The world from as far back as the first century AD has known that the glass and the architecture are standing together (Watkin, 2005). The transparency of the glass among the building materials, gives the unique character to the glazing of transmitting light and connecting the outside with the inside. The significant example of the early glazed workspace was made with a wide glass panes supported by a thin framework of steel, is the Fagus factory in Germany (Figure 4.1). It was designed in 1911 by the architect

Walter Gropius (Fong and Chong, 1999). In the early of 1914, Paul Scheerbart, the Germany utopian poet, summarized the significance of glass architecture as followed:

> *Glass Architecture which will let the sunlight and the light of the moon and stars shine into the room, not through a couple of windows but, as nearly as possible through whole walls, of coloured glass.* (Button and Waldron, 1993).

After 1970s, in response to the energy crisis, the glazed building design focused on minimizing the energy for maintaining the indoor comfort, and gave more emphasis to the prevention of solar heat gain by increasing the glazing insulation with a highly reflective coating *e.g.*, low-e coating which was developed in 1970 and become available in the market around 1980s (Deal *et al.*, 1998). By then, the architectural language has been pushed towards fully glazed envelopes while reducing the unwanted solar heat gains for the hot or warm climate.

Figure 4. 1The Fagus factory in Germany, the early glazed facade in 1911

However, the light and transparency of the glass architecture are suitable for moderate climate which always introduces light into the interior spaces and holds the solar heat within the spaces (Kim and Kim, 2003). But in the tropics, glass architecture was primarily not for the environmental issue, it was mostly an issue of aesthetics (El Demery, 2010). However, recently with the development of glass architecture, the glazed buildings have been encouraged and found expression in the tropics, especially the office buildings which operate during the sunshine hours. In this context observation studies on glazed buildings in Malaysia will be conducted.

4.2.1 Survey on Mid-rise glazed-office-buildings in Klang-Valley

In this research, the "mid-rise” is defined as the buildings with 5 – 20 storeys (Yuen, 2005). However, the office buildings are an index of the economic activity of social, technological, and financial progress to the countries. In hot-humid climate of the tropics, the competition to involve the latest material in the construction of the office buildings, such as glass, is often driven by status and prestige rather than the environmental control (Bahaj *et al.*, 2008).

This study summarises that the glasses and the glazing systems are common materials for office buildings in Malaysia. The advantages are that: the glazing is faster in construction, thinner structure to reduced building dead-loads and increase floor area, water tight and lighter than other materials. However, the photographs (refer to appendix B, Figure B.1 to B.4) of the conventional office-glazed-buildings in Klang-Valley show that almost all of the glass types on the buildings envelop are tinted glasses with the variation of the tint’s colour. This is in addition to some projects which use mirror reflective glazing. Moreover, it is shown that the main problem is the exposure of glazed facades to the solar radiation, while the buildings are, completely, depending on the mechanically air-conditioning for maintaining the high indoor temperature. However, with respect to the section above, the need to carefully select the kind of glazing in office building in tropics arose.

4.2.2 Buildings and Energy consumption

Architectural design has an important impact on the energy efficiency and sustainability of the society. Building design loses its sustainability with the implementation of the air conditioning systems (Laar and Grimme, 2002). The obvious cases are the fully glazed buildings that rely on the air-conditioning system for sustaining its workspaces. As a result, the buildings make direct effect on energy consumption (Rijal *et al.*, 2007) which can be observed all over the tropical region. For instance, in Florida-USA, the total energy which is used in the buildings is 47% of the total energy, whiles the consumption of the same sector in Brazil is 42% of the electricity energy (Laar and Grimme, 2002).

The effects of buildings industry on energy consumption in the tropical region of Southeast Asia can be similarly observed. For example, in Singapore it is 59% for the air-conditioning and 7% for the lighting. In Thailand, it is also 59% for the air-conditioning and 21% for the lighting. In Indonesia, the air-conditioning takes 51% and the lighting 14%, while in Malaysia 57% is owed to the air-conditioning and 19% to the lighting (Saidur, 2009; Zain-Ahmed, 2008). The building industry in Malaysia is one of the fastest growing in world (Zain-Ahmed, 2009). With respect to energy consumption, the buildings might be classified into residential and non-residential buildings.

In Malaysia, the commercial buildings is the second largest user of the energy that has been found accounting for about 32% of the total energy used in the country (Oh and Chua, 2010). Offices that are one of the fastest growing sectors in the building industry, typically consume about 21% of the total commercial energy use (Saidur, 2009). The energy consumption in offices is 10–20 times of that in the residential sector (Yang *et al.*, 2008). The energy consumption in the buildings is typically described by Building Energy Index (BEI). The building energy index of Malaysia is 296 k/Wh/m^2/year (Zain-Ahmed, 2009). The average energy consumption of office buildings in Malaysia is summarized in table 4.1.

Table 4.1:Energy consumption in the Malaysian buildings (%) (Zain-Ahmed, 2008)

	Residential	Hotels	Shopping Complexes	Offices
Lighting	25.3	18.0	51.9	42.5
Air-Conditioning	8.3	38.5	44.9	**51.8**
Total	33.6	56.5	96.8	94.3

4.2.3 Energy efficient design in the tropics

There are several recommendations for employing the renewable energy in non-residential buildings. For example, in the Malaysian standards MS1525:2007, the buildings are recommended to employ the passive strategies for solar control and environmental cooling (Malaysia, 2007; Yeang, 2006). However, the passive solar control elements are so important to efficiently reduce the energy use in the office buildings (Voss *et al.*, 2007), where it has been found that if sustainable design is applied to the buildings, the reduction in the energy consumption reaches to more than 40% (Zain-Ahmed, 2009). Improving energy efficiency in the buildings would not only reduces energy consumption, it would also contribute to reduce carbon dioxide (CO2) emission which is one of the main causes of the global warming (Saidur, 2009). It is the scope and intent of this thesis work to focus on the sustainable design of the office buildings in the tropics and in more specific the glazed-office buildings in the country of Malaysia.

4.3 Potentials of green design for glazed buildings in Kalang-Valley, Malaysia

Generally, the glazing for the workspace is light and transparent, which is useful to the occupants' health (Aboulnaga, 2006). But the problem is that glazing increases the thermal loads indoor (Miyazaki *et al.*, 2005), resulting in the effect of the occupant's comfort and the increase of the energy consumption for cooling. According to the World Green Building Council, the buildings industry is one of the greatest contributors to global warming that were universally found accounting for 33%of carbon dioxide emissions, 30-40 % of the world's energy consumption and 40-50 % of raw materials (Kerr, 2008). Yet, there are signs that this is starting to change through the concepts of sustainable and green buildings.

However, sustainability means the maximizing of the use of renewable resources as building elements (Butera, 2005). This helps the buildings to meet the present needs without compromising the ability of the future generations to meet their own needs (Zain *et al.*, 2007). On the other hand, green buildings according to the United States Green Building Council (USGBC) is "*one that have significantly reduced or eliminated negative impacts on the environment and the occupants"(USGBC, 2009).* To apply this definition on glazing, there is a challenge for the glazed-buildings to be green or sustainable (Butera, 2005). However, most of the developing nations intend in the environmentally sensitive architecture. They are supporting the future growth of green buildings particularly in the office buildings sector. For example, Malaysia's Green Building Index (GBI) for non-residential building was developed in 2009 to promote the design and the construction of green buildings for the Malaysian-tropical climate (GSB, 2009).

4.3.1 Green building index

Malaysia's Green Building Index (GBI) for non-residential buildings bases on six criterias (Table. 4.2) to promote the design and the construction of green buildings for the tropics. The measurement rating system for the certification of the green buildings in Malaysia are: energy efficiency, indoor environmental quality, sustainable site planning and management, material and resources, water efficiency and innovation (GBI, 2009)

Table 4.2: Summary of GBI rating system (adapted from GBI(2010)

part	Item	Maximum point	Score
1	Energy efficiency	35	22
2	Indoor environmental quality	21	21
3	Sustainable site planning & Management	16	14
4	Material & resources	11	10
5	Water efficiency	10	6
6	Innovation	7	7
Total		100	80
Green building index classification:		≥ 90 points	Platinum
		80 to < 90 points	Gold
		70 to < 80 points	Silver
		50 to < 70 points	Certified

4.3.2 Glazed and Green certified office buildings in Malaysia

In the tropical climate like Malaysia, solar radiation is considered as a serious variable to be controlled for achieving the sustainability or green in the non-residential buildings. A few glazed buildings in the tropics, Malaysia are placed in or around this concept. The current research in this stage explores the alternative solar controlling on the glazed buildings in Kalang-Valley.

4.3.2.1 The G-Tower building, Kuala Lumpur

The G-Tower (integrated offices and hotel, as in Figure 4.2) building has been certified with Green Mark Gold status, given by the Singapore Building and Construction Authority BCA Green Mark. The design of the building facades orient east and west are not entirely glazing. But in particular the south and the north facades appear as glazed facades. The green building features that were implemented in G-Tower aim to improve the following:

- Energy efficiency,
- Water efficiency- and has a rain water harvesting system,
- Indoor environmental quality and environmental management,
- Green planting throughout the building to improve the air quality. Figure 4.3,

- Energy efficient chilled water centralised air conditioning,
- Low e-glass for lower heat transmission, and
- Environmental-friendly materials used throughout the building. The old timber decking has been used as the floor and the wall finishing. Figure 4.4.

- Building height: 30 storey
- Building type: Office and hotel
- Glass used: double glazing blue tint with low-e coat
- GBI rating: Gold

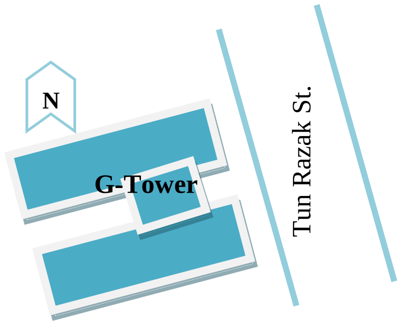


Figure 4.2: G-Tower building, north facades 2009

Figure 4.3: G-Tower, the green planting throughout the building to improve air quality

Figure 4.4: G-Tower, the recycle timber used for wall decorating.

4.3.2.2 The Securities Commission building, Kuala Lumpur

The Securities Commission building (Figures 4.9- 4.12), the winner of the ASEAN Energy Awards (2001), is constructed in an eight-storey office building with double skin glazed facades (Hong *et al.*, 2007). Its design is based on implementing passive building elements which improve the building's envelop with less energy for cooling and lighting. The 18-meter deep of plan holds the offices with natural daylight entering from both sides; the double skin glazed facade and the atrium.

The double skin glazed facades compound two layers of glass with a 1.2m gap. The external is 12 mm thick low-e tinted green glass and the internal is 8 mm thick green glass. The "recycled" cooled air from the office space is exhausted at the ceiling levels into the glazing cavity. The air gap acts as a cool buffer zone keeping the solar heat out of the workspaces and eliminates the condensation on the glass surface. Within the double skin facade, shading devices are used, both horizontal louvers and vertical blinds. An automatic vertical blinds controlled by solar cell, prevents the workspace from the direct solar radiation especially on the east and the west facades. In addition, the overhanging roof structures provide the shading particularly for the upper two levels.

However, the sustainable characteristics of the design of the Securities Commission building were summarized by Shafii (2006) and Shafii *et al.* (2006) in the following points:

- An effective building shell,
- Environmental responsiveness,
- Energy efficient of design both in the passive and the active concepts,
- A flexible work space,

• Provide a healthy working environment, and

• Environmental friendly.

The disadvantages of the glazing system in the case of the Securities Commission building are that the low-emissivity glass on the facade is not highly reflective. It absorbs a high portion of the solar heat by conducting and trapping the heat inside the cavity forming the greenhouse effect. Although “recycled” cooled air from the office space is emptied into this glazing cavity, the greenhouse phenomenon increases the outer surface temperature of the inside glass units compared to its inner surface temperature, which causes glass breaking (Refer to Figure 4.8). This is in addition to other disadvantages such as the higher construction cost, the reduction of the rentable office space as the gap between the two glasses is 1.2m in this particular case, besides the additional maintenance and operational costs.

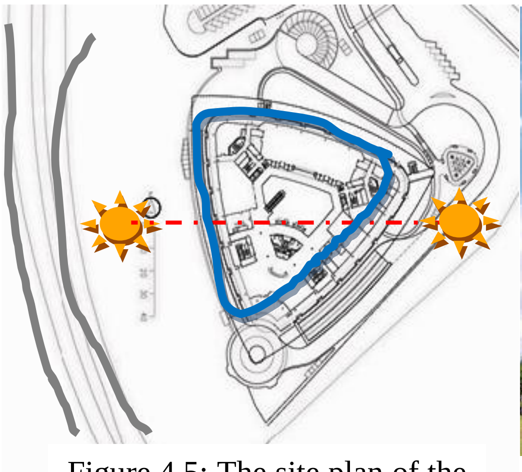


Figure 4.5: The site plan of the Securities Commission Building, (Kasturi, 2006)

Figure 4.6: Perspective view for the Securities Commission Building

Figure 4.7: The glazing cavity which is a buffer and service route, the shading devices also illustrated

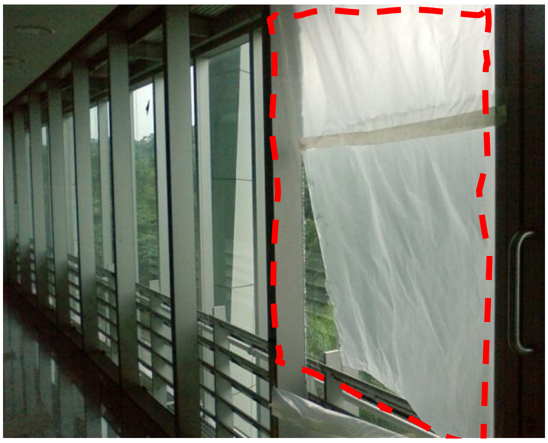


Figure 4.8: View from the lift lobby towards the west double skin showing the braking glass due to the temperature differences

4.3.2.3 The Menara Mesiniaga building, Subang Jaya

The Menara Mesiniaga was the winner of Aga Khan Award for Architecture in1995 (Al-Kodmany, 2010). It is located in Subang Jaya, Selangor and was constructed as a fifteen-storey office building. The Mesiniaga building has experienced a shading system for preventing glazed facades from the direct solar radiation. All glazing facing the east and the west have external louvers to reduce the solar heat gain while the north and the south have unshaded glazing to enhance daylighting indoors (Figure 4.9), and it also has a ventilation system to maximise the heat loss. Nevertheless, the vertical landscaping that spirals upwards the facades, is the most sustainability feature to improve the air quality and provide the occupants with the sense of connection to the nature (Refer to Figure 4.10). Zain-Ahmad (2000), reported that the Mesiniaga's occupants suffered from glare effects especially in workspaces facing the west, so the owners replaced the original glazing with dark blue tinted glass.

Figure 4.10: View of the vertical landscaping

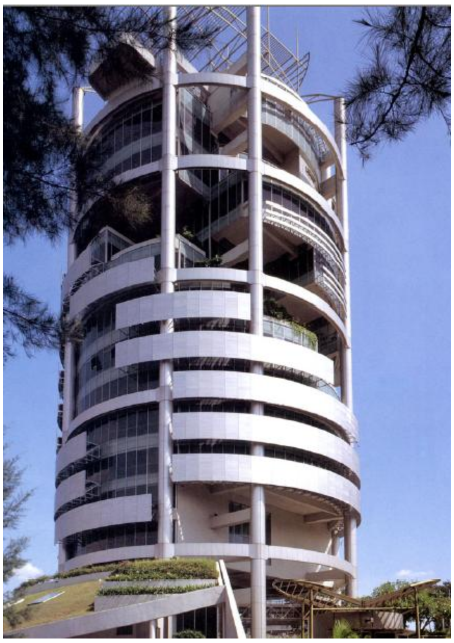


Figure 4.9: North-west view of the Menara Mesiniaga with

4.4 A Case Study to Assess the Workspace Thermal Performance of glazed building in the tropics, Malaysia [1]

4.4.1 Introduction

The objective of this stage is to explore the tropical passive solar control of glazed buildings from the practical point rather than the literatures. The study summarizes the passive solar controls that have been practised in the green-glazed-building in the Klang-Valley and investigates its near-glazing workspace. It is to examine to which extent the implemented elements lead to the control of the solar heat gain. If the results are positive, this indicates that the goal of the green-glazed-building is achieved and the implemented passive features are recommended. It is significant that this thesis work relies on the theoretical and the practical points in order to crystallize and frame the research gap that needs to be filled. The study will measure the near glazing environment of the buildings, in terms of the outdoor/indoor dry bulb temperature, the

[1] This section of the Chapter four has been published and cited in this study as: (Qahtan *et al.*, 2011)

glass surface temperature, the heat flux through glazing, the outdoor/indoor air movement and the lux and the solar radiation.

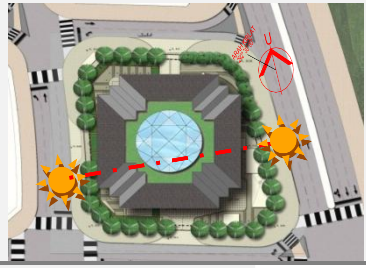
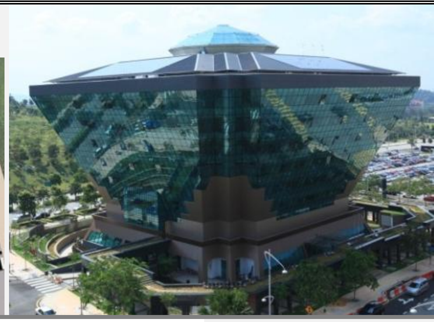
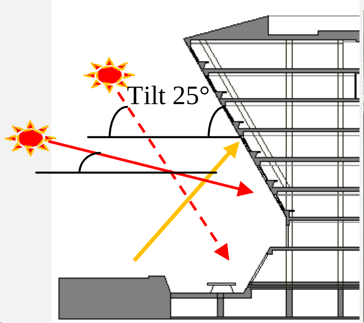
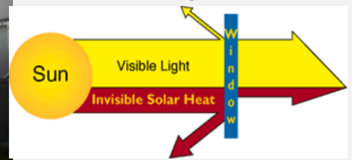
4.4.2 The Building and Passive Solar Control Elements

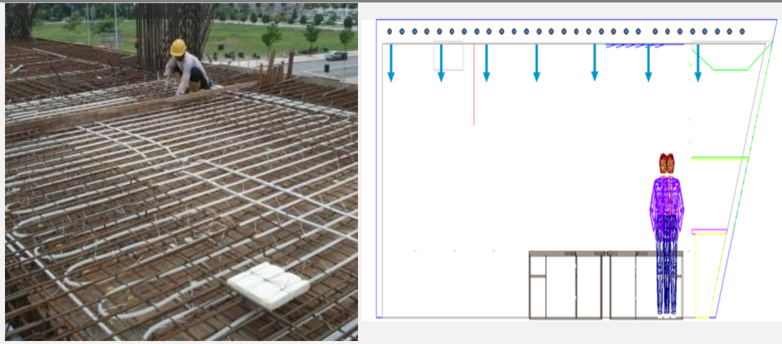
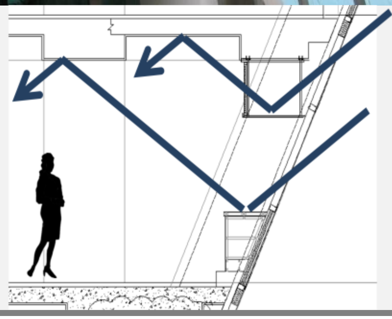
In Malaysia, as mentioned in Chapter 3, about 57% of the energy consumption in the buildings sector is used for cooling; this is why the passive solar control elements are so important to efficiently reduce the energy use in the offices. In order to explore the appropriate solar control strategies for the tropics, the Energy Commission Diamond building in Putrajaya was chosen for several reasons:

a) The Energy Commission Diamond building has achieved the highest rating of Malaysian GBI; the "platinum" in addition to the Green Mark "platinum" status, given by the Singapore BCA Green Mark;
b) The building represents one of the mid-rise glazed buildings in Klang-Valley;
c) The building geometrical configuration exposes the glazed facades directly to solar radiation;
d) A unique case where the glasses are tinted green integrated with spectrally selective coat that reflects near-infrared radiation.
e) The building employs self-shading with 25° tilt angle of the facade which guarantees that the north and the south facades are fully self-shaded during the hottest mid-day hours. It also helps to reduce the solar impact by 41% on the east and the west tilting facades (Reimann, 2010).

The result of the building walkthrough study showed that the passive solar control strategies have been split into two groups. The first group demonstrated on how it is preventing the direct solar radiation through the glass area and the second was how it is maximizing the heat loss from the workspace. Table 4.2 summarised the solar control strategies in the green-glazed-buildings of the tropics.

Table 4.2
Summary of the passive solar control elements which are employed in the ST Diamond building

Passive solar control elements			Details
Preventing the solar heat loads	Building shape and orientation	The intensity of the solar radiation beam incident on the building envelop surfaces varies according to the location, orientation and tilt. The orientation of the envelop surfaces of certain location of the building plays a main role towards the intensity ratio of the solar radiation incidents on this surfaces (Voss,2007). For the ST Diamond building, the site is tilted 16° from the north. Figure 4.11,a on the left: The site view.Figure 4.11,b on the right: The north-west view of the ST Diamond building (Reimann, 2010).	 
	Shading	• Self-shading: the facades are slanted 25° downward and inward to provide fully self-shaded to the north and the south facades during the hottest mid-day hours. This helps to reduce the solar impact by 41% on the east and the west facades. • Fixed blinds: the upper part of the glazing compounds with louvers to reduce the window ratio, and to control the glare. The blinds also provide for controlling the direct solar particularly on the east and the west as illustrated on the figure on the right. • Automated atrium blind: to balance between the desired daylighting and the solar heat gain.	Figure 4.12,a (Left): Self-shading facades from the direct sun-beam (Reimann, 2010). Figure 4.12,b (Right): Fixed louvers and blinded to reduce the glazing ratio  
	Building insulation and glazing	This is to indirectly reduce the heating of the workspace. The building with well design to the envelope through the implemention of high insulation levels can be prevented from the solar heat gain and made more sustainability for reducing the maximum indoor temperatures (Cheng, 2005). In this case the glazing used is highly insulated with low-e spectrally selective coat that has low SHGC and high VL transmittance. The glazing reflects almost the near-infrared radiation and allows for cool light to transfer. The green roof is another feature; it plays the role of green insulation to the building.	 Figure 4.13,a: The green roof provides an insulation to the ST Diamond building  Figure 4.13,b: Spectrally selective performance

Passive solar control elements			Details
Maximizing the heat loss	Radiant cooling	The ST Diamond building incorporates the floor slap cooling for radiant cooling to enhance the heat loss and help to maintain the indoor thermal comfort with increased energy efficiency. The pipes are impeded in concrete slap. Chilled water runs through the pipes so the floor slab acts as a radiant cooling system.	 Figure 4.14: About 40% of the cooling is delivered by floor slab cooling (Source: IEN Consultants)
Other sustainable features	• Rain water harvesting: The system is located on the roof. The rainwater saved is 35.2% of the rainwater storage capacity and the water is used for toilet flushing and irrigation. Water film: clear water pumps on the glazing of the main entrance and flows down to be recycled. It is used to cool down the glass surface. Where the water film reduces the glazing surface temperature up to 14C if the glazing exposed to direct solar radiation (Qahtan et al., 2011) • • PV panels on the roof are to provide 10% of the energy needed in the building. • Daylighting: the ST Diamond building is 50% lit with natural light.		 Figure 4.15: The water film flows down the glass at the ST Diamond building entrance  Figure 4.16: Diffuse light is redirected into the workspace by light-shelf and window sill (Reimann, 2010)

4.4.3 Methodology

The methodology of this study stage was based on the physical measurement of the buildings environment to investigate the effectiveness of the passive solar strategies in controlling the total solar gain in the near-glazing-workspace. The study was carried out in the months of July and August which is considered amongst the hot-sunny months in the tropics.

However, the instrumentation and field measurement process were as follows: “Babuc/M” data logger for indoor and “Skye” data logger for outdoor logging with a number of sensors (Refer to Figure 4.17 – 4.21), outdoor/indoor dry-bulb temperature, glass surface temperature, heat flux probe, air movement, solar radiation both vertical and horizontal global and lux meter were all connected to the data logger. The outdoor sensor was placed on the roof of the building. The indoor sensors were stationed on a tripod located at about 1.0 m above the floor level, with about 1 m away from the glazing. The readings of each sensor were recorded by the logger at 5-minutes interval for 24 hours duration. Manual readings were recorded from the thermometer’s readings, the mini-hygrometer and the infrared thermometer, to compare with the initial readings of the sensors in order to minimize errors.

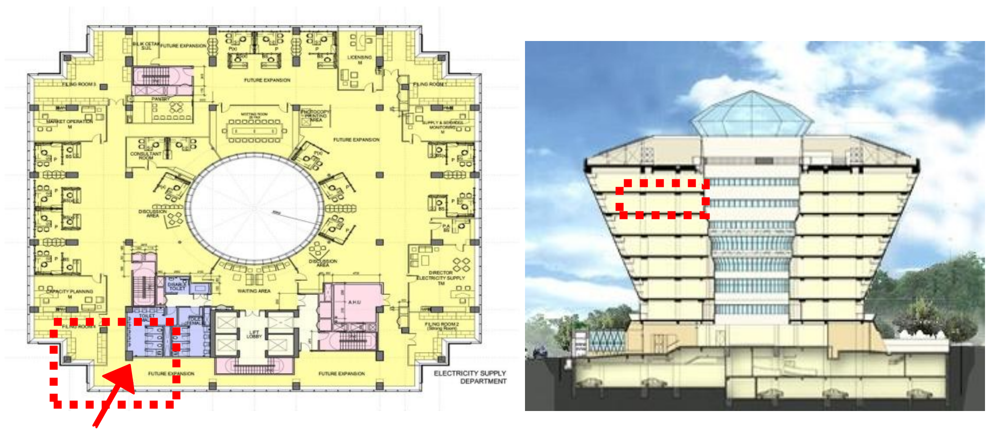


Figure 4.17: ST Diamond building (a) plan of the level four, (b) section

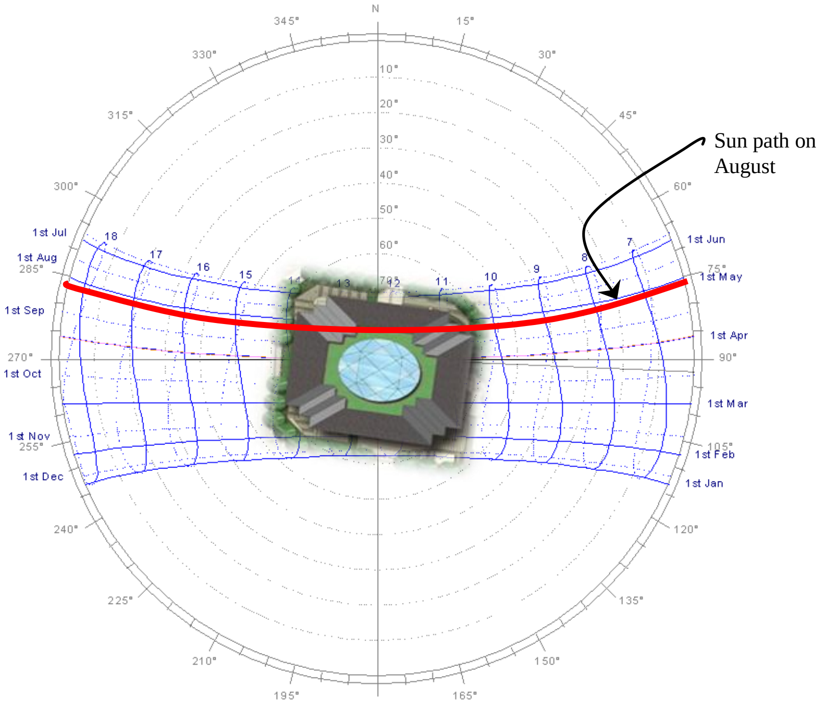


Figure 4.18: Sun paths on the ST Diamond Building site of the measuring

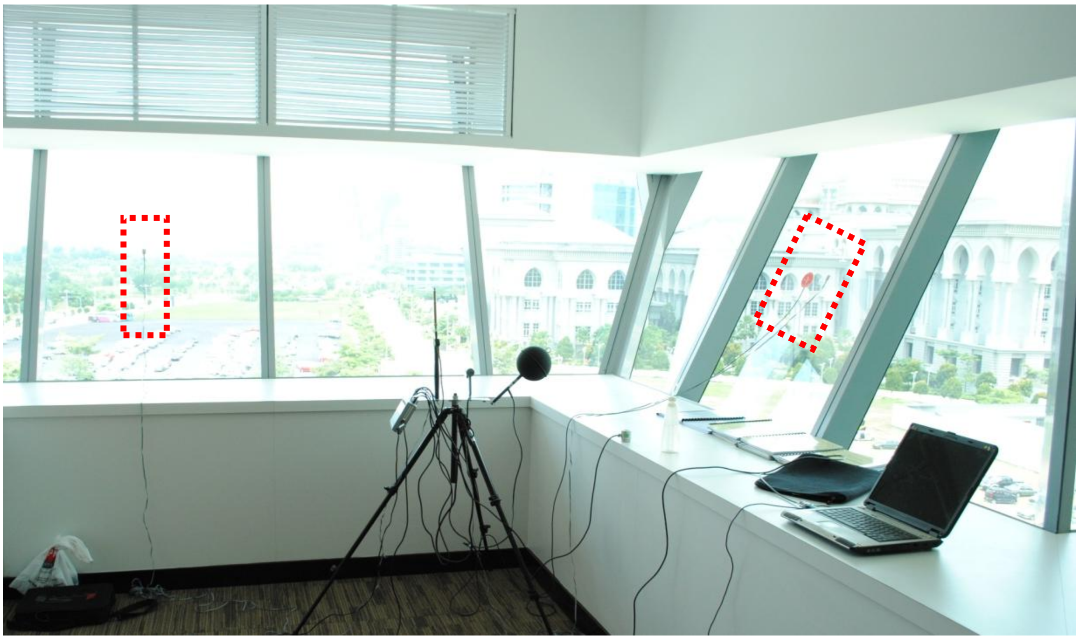


Figure 4.19: Setting up the measurements in ST Diamond Building

Figure 4.20: Set up of the indoor Data logger

Figure 4.21: Set up of the outdoor data logger

4.4.4 Results and discussion

As summarised in Table 4.3, the average peak indoor air temperature (indoor dry-bulb) of 7 working days of August was 23.4°C. This peak value was recorded at 17:00h, when the outdoor temperature was 30.5°C. The difference between outdoor and indoor at that time was of 7.6°C. While on the non-working days (4 days in August) the average peak indoor air temperature was 25.4 °C at 14:00h and also at 15:00h. The outdoor air temperatures at those times were 31.9°C and 29.8°C respectively. The difference, therefore, was found of 6.5°C from the indoor to the outdoor. However, referring to the Table 4.3, the average daily temperature values of working / non-working days and show difference between the two configurations of approximately 1.5°C higher in the non-working days than the working days. This is due to the cooling systems that were operated during the working hours.

Table 4.3: Summary of the hourly average temperature for working-days and the non-working days in July and August

Parameters/Hourly average		8	9	10	11	12	13	14	15	16	17	Average daily
Working-days	Outdoor Temp.	26.1	28.0	29.9	30.9	32.3	32.0	31.4	31.1	30.4	30.5	30.2
	Indoor-Temp.	22.5	22.4	22.6	22.8	23.1	23.2	23.2	23.3	23.3	23.4	23.1
	Glass surface Temp. (West)	25.1	26.5	28.3	29.6	31.3	31.4	31.2	30.9	30.4	32.8	30.0
	Glass surface temp.(South)	25.1	26.7	28.7	30.0	31.5	31.8	31.5	31.1	30.2	29.7	29.5
Off-days	OutdoorTemp	24.8	27.0	29.0	30.5	31.9	32.1	32.3	31.9	29.8	28.7	29.7
	Indoor-Temp.	23.4	23.7	24.1	24.5	24.9	25.2	25.4	25.4	25.4	25.1	24.7
	Glass surface temp. (West)	24.9	26.8	28.9	30.9	32.5	33.0	33.2	32.9	31.3	29.8	30.2
	Glass surface temp. (South)	24.9	27.2	29.7	31.8	33.2	33.7	33.8	33.2	31.3	29.2	30.6

Figure 4.22 shows the differences between the indoor and the outdoor temperatures near glazing for the whole measuring days. It is shown that the peak difference between the indoor-outdoor air temperatures vary from 9.8°C to 8.0°C. The feed back showed the indoor air temperatures remain within the Malaysian Standard of 22 to 26 °C of air-conditioning workspace. The highest indoor air temperatures were noticed on the non-working days, from 31st of July to 1st of August and 14th to 15th of August. This happened because of the air-conditioning was not operating to maintain the indoor thermal level. The results of non-working days give a clear perception about the performance of the passive solar control elements that have been successfully employed in ST Diamond building.

Figure 4.23 illustrates all the measured days with the relationship between the solar radiations falling on the vertical west glazing of the ST Diamond building, and the increase of the temperature of its glass surface that results in the heat transmittance indoors. The low value of heat flux remains entering indoors during the entire period of measurements with average of -4.0W/m2. There is an exception to a few working days which found with sudden increase in heat flux inwards, exceeded the range of the sensor that is (±50W/m2). This increase in the heat conduction indoors happens due to the increase of the glazing surface temperature. This is confirmed by the results of the cloudy days when the difference of the temperature between the outdoor and the indoor was less than 0.5°C. The heat flux was found balanced on glass surface.

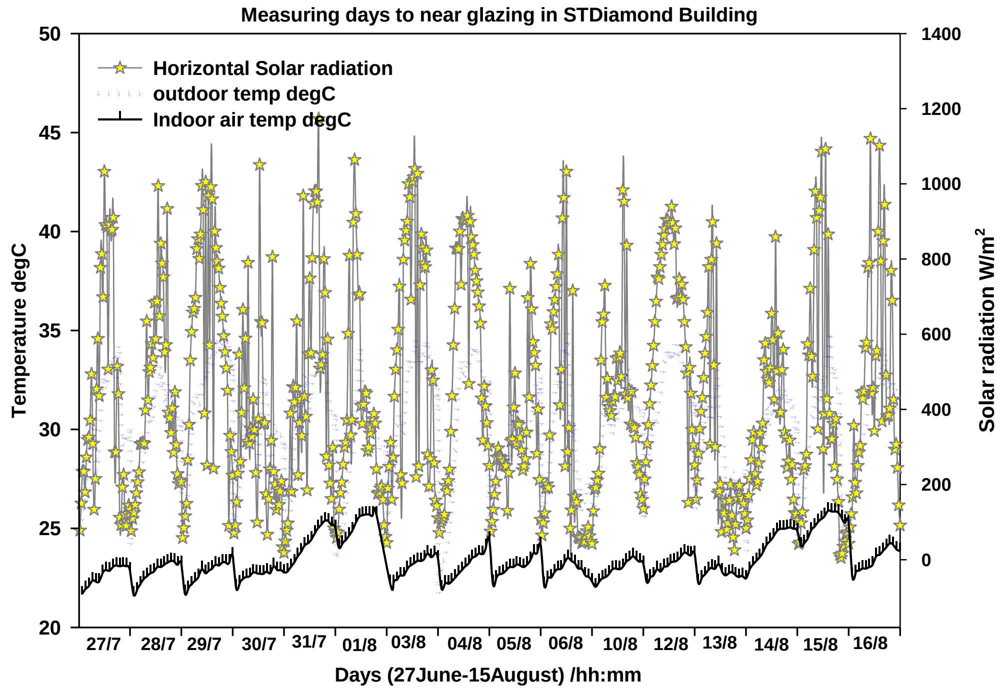


Figure 4.22: The differences between the indoor and the outdoor temperatures near glazing

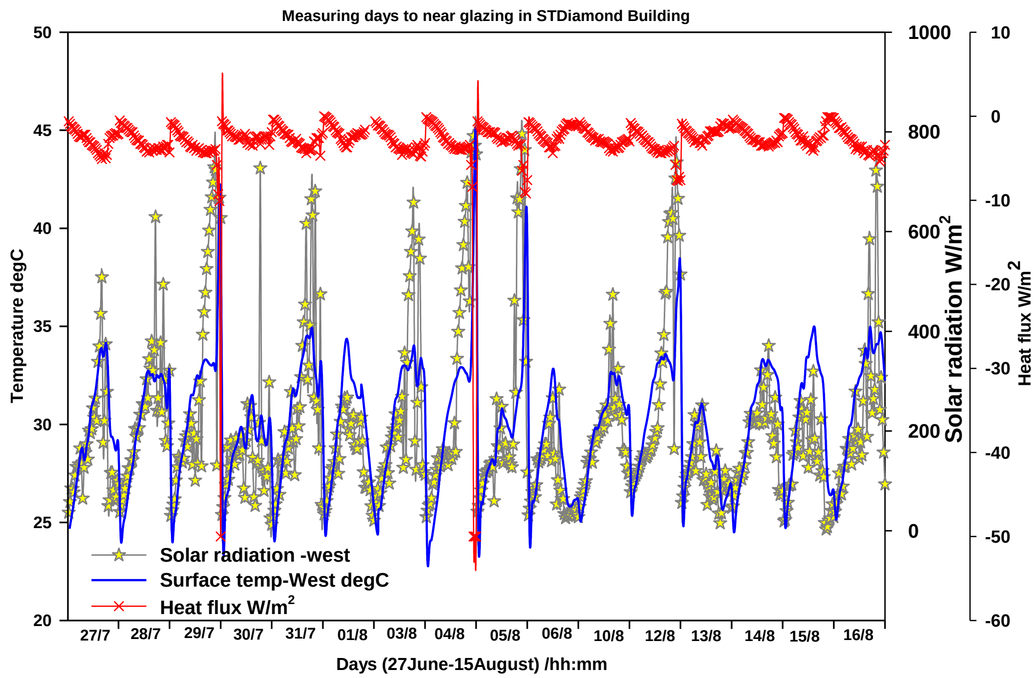


Figure 4.23: The relationship between the direct solar radiation, the glazing surface temperature and the heat flux values for all measuring days in ST Diamond Building.

Figure 4.24 shows the measuring results on the 4th and the 5th of August during working hours. The highest surface temperatures were recorded on these two days. On the first day, the surface reached to 44°C at 18:20h. It is when the outdoor temperatures and the vertical solar radiations were 31.7 °C and 688W/m2 respectively. The heat flux through the glazing skin also increased inwards due to the increase in the glazing surface temperature. It reached to the maximum[2] of -50W/m^2. On the second day, the 5th of August, the heat flux peak remained at (-10.3) although the glazing surface temperature reached 40°C. This is due to the short period of exposing the glazing surface to the solar beam if compared to the previous day, the 4th of August.

Although in the month of August the Sun's position is about the overhead of the ST Diamond building with slightly slating on the north (refer to Figure 4.18 and 4.11,a), Figure 4.24 shows that the surface temperature of the south-glazing is higher than the west-glazing for five hours from 11am to 4pm, with difference of about 1°C. This is because of the south glazing which was exposed to the reflective solar radiation from the exposed surrounding from the morning until the midday hours. On the other hand, the west facade of the ST Diamond building was not totally exposed to the direct solar radiation because of the neighbouring buildings shade its west façade.

Figure 4.25 shows the result on two non-working days. Although the mechanical controlling was not operating during the measuring of these two non-working days, the indoor air temperature kept within the comfort range of the Malaysian workspace. The maximum indoor air temperature which was recorded is 26°C at 14:10h on 15th of August, when the glazing surface temperature reached to about 36.0 °C, the outdoor

[2] The value of -50W/m^2 was recorded as an error due to the exposure of the sensor to the high intensity of the direct solar beam. The heat flux sensor ranges from (-50) to (50), which means that any measurements exceeding this value, the error will be noted.

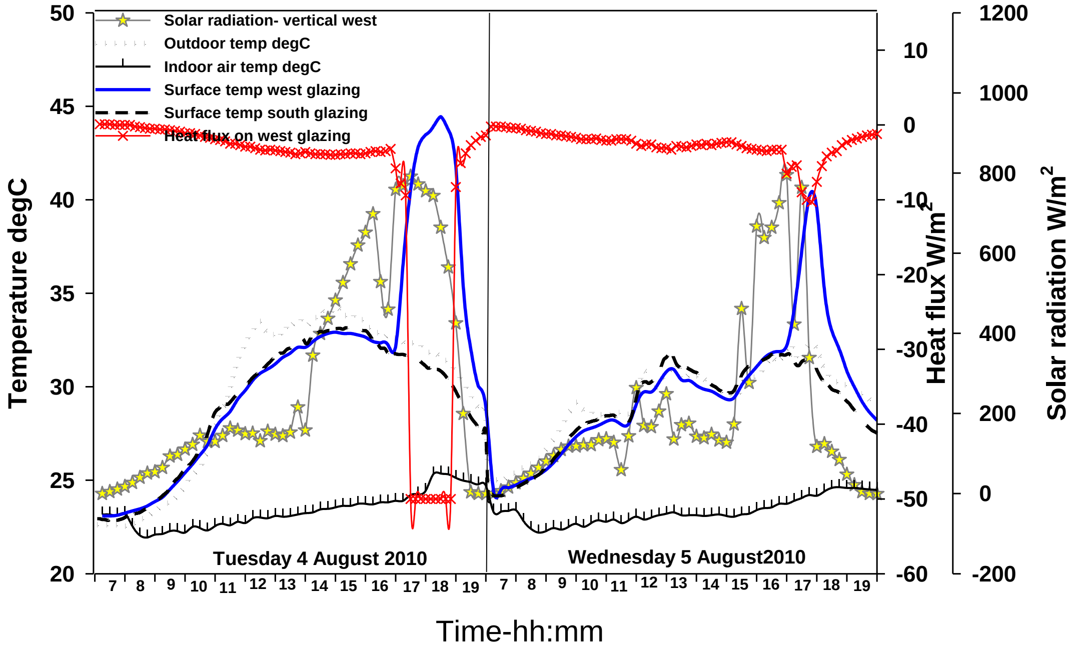


Figure 4.24: Measurement results during working days

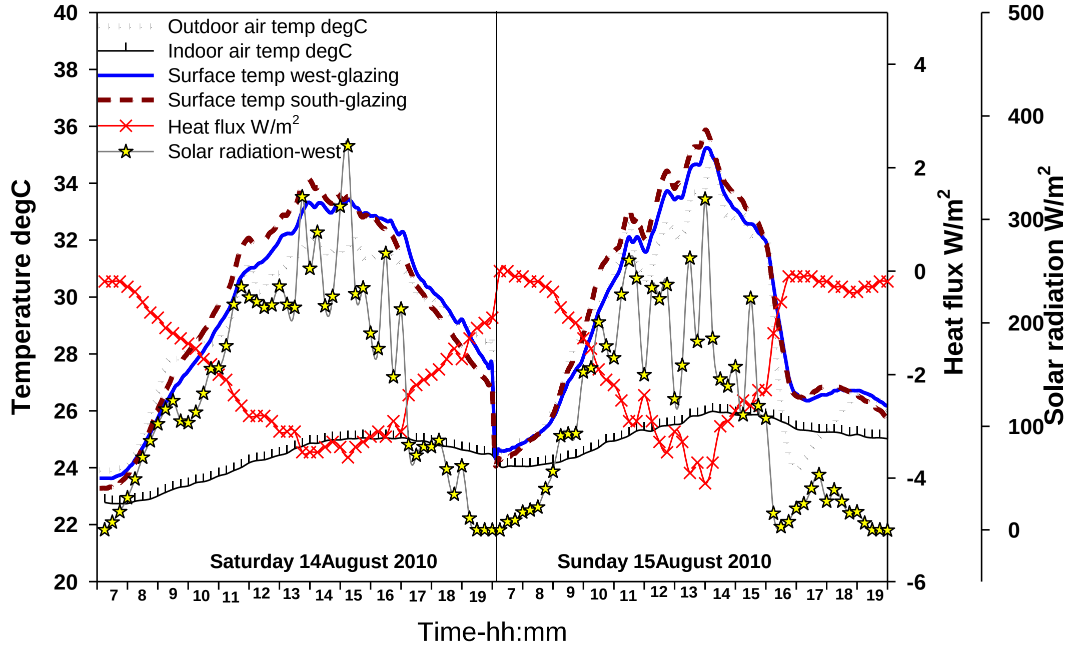


Figure 4.25: Measurement results during non-working days

temperature was of 34.5°C and the vertical solar radiation was of 319.7W/m2. At 17:25h, although the surface temperature was 34.0C° and the outdoor temperature was

30.9 C°, it became lower than the values at 14:10h, where the heat flux value was noted transferring insides with a peak value of -4.7W/m2. This is because of the increase of the direct solar intensity with low angle that hits the glass surface. This indicates the lack of the effectiveness of the passive solar control used in the buildings for controlling the direct solar radiation on the east and the west facades. It is useful to notice that during the measurement of non-working days, there were no high solar intensity hitting the buildings, especially on the west facades. The sky condition during the measurement of this case showed that was very hard to find clear sky condition for accurate results relating to the investigation of the passive solar control. This also indicates that any alternative solution for controlling solar radiation should take into account the type of the sky in the tropics, Malaysia.

4.4.5 Conclusion

It is important to note that the examined workspace was not exposed to the high solar intensity, particularly the measured facades during the months of the investigation; July and August. This is because of the Sun's position during the measurement period. However, the study concluded that the strategies which were employed in the ST Diamond building have been proven to be effective in controlling the solar heat gain through glazing, which in turn led to reduce the energy consumption for controlling the solar heat loads.

In the tropics, such as Malaysia, the indoor thermal loads mainly occur due to the direct solar radiation, therefore self-shading or upside-down pyramid shape of the glazed building is recommended for the tropical climate if the roof of the building is designed to prevent the direct solar radiation. However, the experiment results near the west glazed-facades show that although the glazing is highly insulated with spectrally-selective reflected coat, the glazing surface temperature still showed a high value resulting in the heat flux inwards. This increases the indoor temperature near glazing. It is recommended to do measurement on this building during the extreme sunny months, which were found for Malaysia to be in February and March, to stand on the accurate results of the building performance against the direct solar loads particularly on the east and the west facades.

4.5 Chapter Summary

It appeared from the survey on the glazed buildings in the Klang-Valley and a review of the market and through direct contact with the manufacturers that tinted glazing is still a popular choice for the buildings in Malaysia, whereas no large market exists for a higher performing glazing that has only a few practical applications depending on the imported units.

It is the scope and intent of this thesis to avoid the use of expensive glazing in order to achieve a good thermal performance. It is to focus on the sustainable design for glazed buildings in the tropics and in more specific in the country of Malaysia. The orientation, the inner and the outer shading devices and the window size are also capable for solar control, but they are not applicable for east and west facades in the tropics, therefore, sizing window and shading devices are not dealt with in this research.

It is concluded from the field analysis that the double skin facades are not suitable for tropical climate due to the overheating of glazing cavity during the Sun shine forming what is called the “green house effect” that causes the transfer of the heat indoors. This is in addition to other disadvantages such as the higher construction cost, the reduction of the rentable office space, besides the additional maintenance and operational costs. It has been noted during the building walkthrough that several inner glass panes of duble glazing facade shuttered due to the “green house effect” that increases the outer surface temperature of the inside glass pane, while the inner surface is cooled due to its exposure to the air-conditioning system.

For the climate of the tropics where the heat gain mainly occurs because of the direct solar radiation, the self-shading is appropriate for the two orientations; the north and the south. The observation results of the west glazing shows that although the glazing is highly insulated with spectrally-selective coat, the glazing surface temperature is high, this influences the increase of the indoor temperature.

Passive solar control elements are important to efficiently reduce the energy use in the office buildings, where it has been found if sustainable design is applied to the buildings, the reduction in the energy consumption reaches to more than 40%. Figure 4.26 shows the passive solar control for the glazing in the tropics.

4.6 Research gap

From all of the above Chapters and the results of the field study in this Chapter, the current research recognizes the following research gap:

- There is still a room for employing an alternative and passive solar control to glazing on the east and west orientation. The recycle resource such as the water elements (rain-water) which is locally available in Malaysia and not fully benefit from, is a choice to be investigated.
- The Malaysian sky condition is very rare to be clear sunny. This is because of the changeability of the tropical sky during the day. It is represented by an intermediate sky. However, the passive solar control that does not put the nature of the local climate into account will be considered as an increase in the building operation cost without deriving full benefits from it. The solution recommended is

that one compound with low cost glazing and be flexible for application when necessary (sunny times) and omit when it is not required. The non-residential buildings are recommended to employ rain water harvesting as a passive strategy for solar control and environmental cooling.

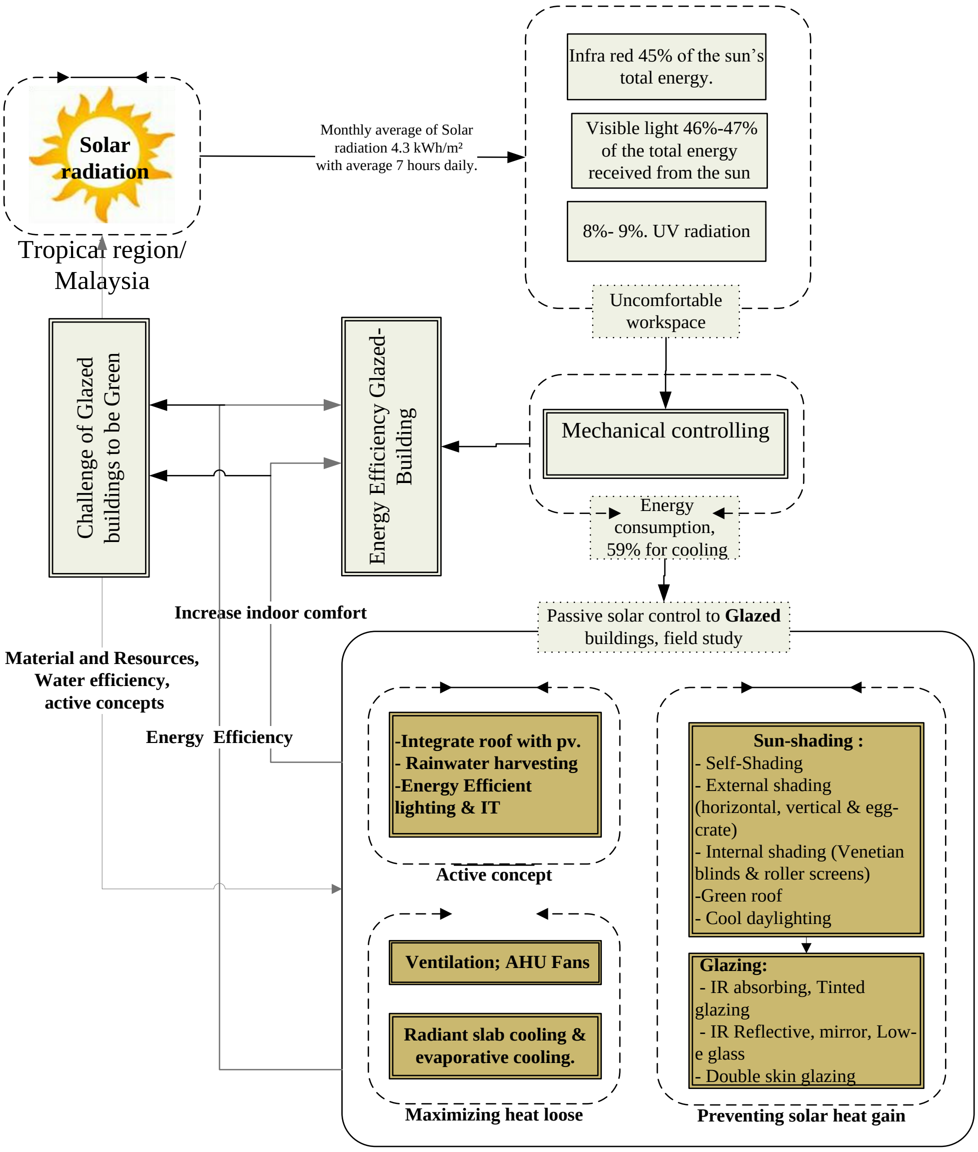


Figure 4.26: The passive solar control options for the glazing in the tropics.

CHAPTER 5

THE POTENTIALS OF WATER AS A SUSTAINABLE SOLAR GAIN CONTROL FOR GLAZED-BUILDINGS IN THE TROPICS

5.1 Introduction

To preserve comfort and to reduce cooling loads, it is important to apply the natural solar protections that are generally used on the external face of glazing since they lower direct radiation from reaching the internal ambient (Datta, 2001). However, the objective of this chapter is to review the potential applications of water element in the buildings, and the behaviour of water-film under the solar radiation on the glazed-facades. The discussion provides a theoretical view toward the research hypothesis on the effectiveness of SGWF as a natural solar control to the east and the west glazed facades of the workspace in the tropics.

5.2 Rainwater harvesting systems

Rainwater harvesting is a technology which has been used for thousands of years (AbdelKhaleq and Ahmed, 2007). It has evolved and is being commonly used in many environmental applications by collecting and storing rainwater from rooftops, land surfaces or rock catchments (Helmreich and Horn, 2009; Yuan, Fengmin, & Puhai, 2003). For rooftops rainwater harvesting, the system consists of its catchment area, a treatment facility, a storage tank, a supply facility and piping (Han and Mun, 2007). This system is adopted mainly in building supplies water for non-potable use such as toilet flushing, and it is used as an alternative source of potable water (Amin and Han, 2009). However, in this research, the rainwater harvesting is to be implemented for flushing as “glazed water film” to investigate the reduction of the penetration of the solar heat gain by blocking some of the infrared and cutting off the thermal bridges indoors. The cooling of the outer surface of the glass would also reduce the urban heat island by the water film which cools down the glazed-building facades, which in turn reduces the heat emission to the surrounding of the building.

5.3 Rainwater harvesting in Malaysia and the tropics

Water is one of the continuously renewable natural resources of the world (Gleick, 2000). This fact is true more in the tropics. For example, Malaysia receives a high rainfall throughout the year yet its potential has not been fully explored from the rainwater (Darus, 2009). However, the decentralization of the rainwater harvesting and the low cost of its system encourage the applications of rainwater harvesting through “water efficiency” (Amin and Han, 2009). For example, the Green Building Index (GBI) of Malaysia names the “water efficiency” factor as one of the six criteria of the rating tools for the certification of green buildings in Malaysia. This encourages the non-residential buildings to include the rainwater harvesting system in their design (GSB, 2009).

5.4 Impact of water on solar radiation transmittance

As mentioned in Chapter 3, there are two means of indicating the total heat gain through glazing, the primary means would be the heat gain due to the direct solar radiation. Whereas the second means is the heat transfer due to the difference in temperature between ambient and indoor spaces and the difference in temperature between glass surfaces. However, reducing the penetration of solar radiation to building workspace, while allowing daylighting, is the proposed strategy of this research.

Water is the main absorber (70%) of the solar radiation in the atmosphere, mainly in the infrared region where water shows strong absorption. Water absorbs almost totally long-wave infrared radiation, whereas the upper surface of water has the ability to reflect this radiation depending on the angle of the incidence (Chaplin, M 2009; Langford, McKinley, & Quickenden, 2001). Therefore, the absorption and the radiation of infrared occur in the water surface, which might be cooled fast at this surface, mainly by evaporation and heat convection.

5.4.1 Optical properties of water

In glazed buildings, blocking the visible light and passing the infrared would be easier than the other way around. The challenge is how to reduce heat gain while increasing the light transmittance. One of the solutions is to apply anti reflective coat on the glazing surface to reduce the light wastage due to the reflection it receives from the outer glazing surface (Kumano & Hanamura, 2004)

With respect to Fresnel's law for optical reflection and transmission, the study of Krauter (2004) showed that "*the solar radiation hitting a glass surfaces at perpendicular incidence angle yield a reflection loss in the range of 4 – 5 %*". However, by using the optical anti reflective coating, it improves the optical transmittance of 3.2% for material refractive index n_1=1.33 and n_2=1.73. If we know that the refractive index of the water is 1.33 and the glass is 1.54, therefore, the water performs as an anti-reflective coat to visible light on the glass that decreases the light reflection and eventually increases its transmittance inwards.

To understand to what extent the above optical theory is true with the application of water of refractive index n_1=1.33, the research makes a concise review to previous studies. The studies reported by Pieters, J. (1997), Pollet, I. (1999), Pollet, I. (2000) and Pollet et. al. (2003) deal with the solar radiation transmittance through the water condensation and water run-off on the glazing. These studies found that as soon as the condensation occurred on the glass, the transmittance decreased varies from 8 – 13% under an overcast sky. Meanwhile, under a clear sky, the transmittance of glazing with the presence of condensation was reduced by between 6 and 15%. This decrease in solar transmittance gradually disappeared with the condensation's run-off and it started to show an increase in the solar transmittance up to 2%. This increase of the water run-off verifies that the condensation on the glass is not as that the flowing water film over the glass.

However, another study was based on the flowing water film over the front of photovoltaic panels. The results showed an increase in the solar transmittance as soon as the water film starts flowing down over the panels, where the water reduces reflection by 2-3.6% resulting in the increase of the light transmittance inwards. Moreover, a smooth flow of the water film on glazing makes a slight increase of the optical transmittance (Pollet,I. 1999).

5.4.2 Estimating the solar radiation on the water surface

The estimation of the solar radiation on the water surface was found in several studies as an important factor to disinfect the natural water from "allochthonous microorganisms", considering UV (315nm – 400nm) is the most effective wavelength of sunlight with regards to the water's disinfect (Davies *et al.*, 2009).

However, solar radiation at the water surface can be calculated as the difference between the incoming and the reflected radiation. The reflected radiation is usually estimated at 3% of the incoming radiation and therefore the equation is (Caissie *et al.*, 2007):

$$Hs = 0.97Hsi\ (1 - SC) \qquad (5.1)$$

Where Hsi is the incoming solar radiation as measured by a pyranometer (W/m^2) and SC is a shading factor specific to the water film (e.g. 0–1, depending on the forest cover and the topography).

5.4.3 Water temperature

Specific heat of the water "*is the measure of the heat energy required to increase the temperature of a unit quantity of water by a certain temperature interval"* (Lechner, 2009). It is significant in this context to know that water has a much higher density and much more specific heat than air. A volume of air about 3000 times greater than water is required to transfer an equal amount of heat (Lechner, 2009). The heat transfer of water depends mainly on the difference of the temperature between the water and its surrounding (Caissie *et al.*, 2007).

5.5 Applications of the water for Cooling and solar controlling in the buildings

The flowing of the water film over the glazing vertical facades is available almost everywhere in the world. They are probably more for visual effects, but also might be an alternative cooling strategy. For instance, the British Pavilion in Seville, Spain (Figure 5.1). The project was a temporary built for the Expo in 1992 with a passive cooling and solar heat controlling. The combination of louvered shades and water flow over the west glazed façade were involved to cool a larger space with the slightest amount of energy consumption. The pumps to recycle the water are powered by PV, (Gissen. D, 2002)

Another example is the ST Diamond building in Putrajaya, Malaysia that also adopt this system. The water becomes an element which provides a visual and physical cooling effect at the space of the building’s main entrance (Figure 5.2).

Figure 5.1:View of the British Pavillion with S-shaped photovoltaic shading panels and water flow film over the west façade (source: Expo, 1992)

Figure 5.2:The water flow film over the glazing of the main entrance of ST Diamond Building Putrajaya, Malaysia, (Author)

5.5.1 Radiant cooling

Radiant cooling is an alternative cooling and indirect solar control option. In the tropical country like Malaysia, which has a hot and humid climate, this strategy is avoided due to condensation reaction of moisture from air on the panel. The temperature of the cooling water must not be lower than dew-point temperature of air (Vangtook, 2005). Radiant cooling systems rely on chilled water in pipes that are embedded on the floor slaps, distributing cooling throughout a workspace. It helps to increase the heat loss from the workspaces to slap that acts as a heat sink.

However, several studies have been carried out in experimental and computer simulation to investigate the performance of this application in the hot and humid climate. These studies generally show the good potential in reducing indoor temperature. And they agreed that the cooling water keeps to 25 °C to avoid condensation of moisture on the slap (Vangtook and Chirarattananon, 2006; Vangtook and Chirarattananon, 2007). However, the radiant cooling strategy in the buildings is generally used for increasing heat loss outdoors. And it is not dealt with in this research scope of work, which mainly focuses on how to control solar heat gain in the glazed buildings.

5.5.2 Evaporation cooling

Evaporation is a process that can substantially result in the lowering of the dry bulb air temperature. It can also result in the lowering of the surface temperature of the building elements which are exposed to the solar radiation. The evaporation process occurs when water changes its state to a vapour (Abu-Hijleh & Mousa, 1997; Bansal, 1994b; Vorster, Schwindt, Schupp, & Korsunsky, 2009). The evaporation cooling can be very effective in the hot and dry and also in warm and humid climate zones, because of the incident solar radiation (Bansal, 1994a). There are three types of evaporative cooling processes in buildings: direct, indirect and indirect/direct (Taufiq, 2007; Qiu & Riffat, 2006).

5.5.2.1 Direct evaporation cooling

The study of Taufiq (2007) entitled "*Exergy analysis of evaporative cooling for reducing energy use in a Malaysian building",* defined the evaporation cooling as a process that can reduce the energy demand for the cooling in building. The study was performed through an exergy modelling and optimisation analysis of a direct evaporative cooling applied in the Malaysian buildings. The evaporation process occurs when the air is brought into direct contact with the water. The study concluded that the evaporative cooling leads to significant reduction of the air temperature in the hot and humid climate. The reduction in the air temperatures results in the reduction of the energy consumption of the mechanical cooling. However, the direct evaporation which is introduced directly in the space might be appropriate in dry climates. But indirect methods, such as roof pond and vertical surface evaporative, allow evaporative cooling to be used in more climates, such as the Malaysian climate.

5.5.2.2 Indirect evaporative cooling

Indirect evaporation occurs when the heat transfers through a heat exchanger that might be a cooled surface, which eventually discards heat to the outside by evaporation effect (Taufiq, 2007). The application of this concept is presented in several past studies. For example a study was conducted by Rincon *et al.* (2001) entitled: *"Experimental and numerical evaluation of a solar passive cooling system under hot and humid climatic conditions".* The study investigates the effect of "*solar passive cooling system"* (the roof water pond), on indoor air temperature in hot and humid climate. It concluded that it is possible to maintain the indoor air temperature below the outdoor air temperature due to the water evaporation. The water reduces the thermal energy through the external surfaces up to 66%.

5.5.3 Water-flow window

The concept of this passive system is based on a clean water circuit flow upward within the entire space of the double glazing with a cavity space of 10mm between the two glass panes (Figure 5.3). Chow *et al.* (2010) designed and tested the potential areas of "water-flow window" in reducing the room heat gain and achieving the energy saving. Through the numerical computation of the application, the study concluded that the system with outer tinted glass is the best configuration. It is able to enhance the thermal and visual comfort, as well as to support the hot water supply system. However, this application might be appropriate for a small window size but not for glazed-buildings with entire glazing. This is due to the relatively high stream water amount within the entire space of the double glass which increases the dead loads of the buildings.

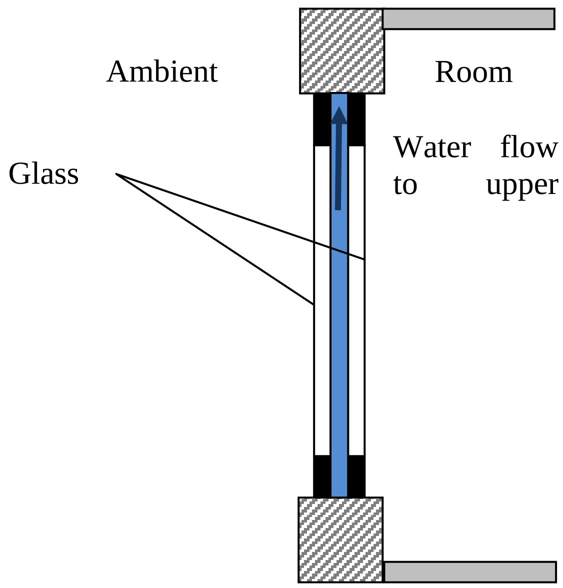


Figure 5.3: Water-flow double-glass window (source: Chow *et al.*, 2010)

5.5.4 Building surface cooling

The concept of surface cooling is to run or spray a thin clear water film over the outer surface of the building in the presence of solar radiation (in this research the west facade) so that the flow of water film takes away heat and lowers the surface temperature. This makes the building surfaces to act as a heat transmission (heat sink) from the inside of the building to the ambient air without increasing the humidity of the indoor spaces (Russell and Surendran, 2001). In addition, the water is able to absorb some solar energy, further limiting the passage of thermal energy. According to Zhou *et al.* (2009) there are three factors that influence the characteristics of water film falling down a flat surface: the water feed mode, the Reynolds number and the surface inclination angle. The film thickness increases with the increased Reynolds number and the decreased surface inclination angle. Apart from that, the temperature also influences the characteristic of water film falling (Ambrosini W, 2002).

Nevertheless, the application of a water- film as a means of thermal transfer in applied science has been extensively reported in many studies for example Belarbi *et al.* (2006), Wu and Lin (2007), He and Hoyano (2010) and Wendelstorf *et al.* (2008). In contrast to the solar control in buildings, it has been reported only in a few studies as follows:

5.5.4.1 Water spray on an atrium roof in the tropics

A study was carried out by Abdullah *et al.* (2009) which reported on the application of two low cost solar controls in the tropics. They are the internal solar blinds compounded with water spry film. The blinds reduce direct solar radiation while the water film cools down the glazing surface. The study was carried out inside the atrium to examine its indoor thermal performance under the proposed solutions. The conclusion drawn is that water spry helped to significantly reduce the thermal loads inside.

5.5.4.2 Water film on a Superhydrophilic of the TiO2-coated surface

The strategy of this alternative solar control is based on the application of the new technology which was recently developed, the Superhydrophilicty of the TiO2-coat. This coat under the irradiation of the UV light from the sunlight causes the contact angle of water with the building surface to become almost 0° (Tusuge *et al.*, 2008, Machida *et al.*, 1999) (Figure 5.4). Therefore the wet-ability of the surface is increased and the water film covers the entire TiO2-coated glass surface. This increases the ability of the water film to control the solar heat gain. Additional advantages of the application of TiO2-coat on the building surfaces are: (a) the resistance of the UV radiation, which fades fabric and degrades other indoor finishing materials, and (b) the self-cleaning function of the building's surfaces, which reduced the cost of the building surface maintenance.

However, He and Hoyano (2008) conducted a numerical simulation that the buildings are cooled by sprinkling water on their external surfaces which are coated with TiO2. The aim of the study was to develop a numerical model to predict the temperature of a TiO2 coated surface (roofs and walls) of buildings with a water film. The result shows that during sunny summer days, the water film lowers the temperature of the building's vertical surface by 2-7 °C.

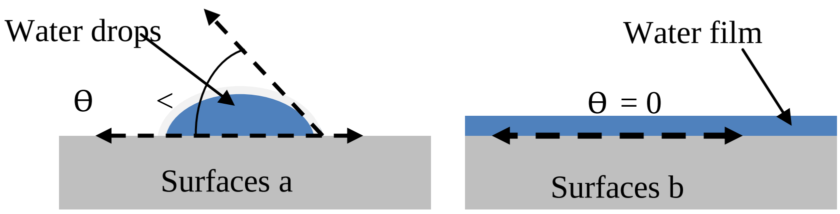


Figure 5.4:Forming water film: (a) surface with contact angle <90. (b) Surface with the Superhydrophilicty of the TiO2-coat that increase the wetting of the glass surface (source: modified from Takata *et al.*, 2004).

5.5.5 Water Film flows down over the glazing surfaces

Although many experimental and theoretical studies were conducted to investigate the water flows and the heat transfer of falling water film, most of them are adopted for industrial applications (Zhou *et al.*, 2009). For a water film falling down a glazed building facade, there is a lack of either experimental or numerical studies, particularly in the tropics. The research, therefore, is attempting to fill this gap. The system of controlling the solar gain to the glazed building in the tropics is based on the evaporative cooling process and the convective cooling by the continuously flowing water film. This carries away heat from the glass surface, thereby preventing the glazed surface and the interior of the building from overheating. It integrates the evaporation and convection cooling in addition to perform as a “heat sink” particularly when the cooled-water is used in the system.

5.6 Summary and research hypothesis

- Evaporative cooling lowers the indoor air temperature by evaporating water. In dry climates, this is commonly done directly in the space. But indirect methods, such as flowing water film over glazing, allow evaporative cooling to be used in the hot and humid climates too. The review of literatures in this Chapter suggests the need for experimental work on the water falling down the glazed facades in the tropics (Table 5.1).

Table 5.1: Summarises the applications of water cooling for glazing in the buildings

Author	System	Building element	Material used	Remarks
Chow *et al.* (2010)	Water-flow window	Double glazing with 10mm cavity	Glass	Water
Abdullah *et al.* (2009)	Water film	Atrium Roof	Glass	System compound with internal blinds.
He and Hoyano (2008)	Water film	External building surfaces	Alumina and glass	The building surface coats with TiO2

- With respect to Fresnel’s laws with refractive index, the solar light transmittance is significantly increased by applying anti reflective coat (low refractive index) on the glazing. Thus, water with a refractive index of 1.33 compared to glass 1.54, causes an increase behind the glazing of 3% for optical transmittance. The water act as a natural anti reflective coat on the glass.

These reviews have promoted the research **hypotheses** that attempt to answer the research questions: The SGWF compounded with the low cost single tinted glazing absorbs a high portion of the long-wave infrared radiation. The SGWF is a sustainable spectrally selective film, which contributes in reducing the transmittance of short-wave infrared (radiation), and increasing the transmittance of visible light.

CHAPTER 6

METHODOLOGY

6.1 Introduction

Following the issues raised in Chapters 2 to 5, there is a significant importance of implementing the sustainable and the passive solar control in midrise glazed-buildings in the tropics. This research of the sustainable-glazed-water-film (SGWF) focuses on the relationship between three issues: the solar heat gain, the glass types, and the flowing water film. This chapter provides the research method for an experimental study on application of the SGWF on west façade as a contribution to bridging the knowledge gap in glazed building design. The research questions are restated and then the tools of the study are discussed.

6.2 Architectural research methods

Because of the ever-increasing part of the architectural practice, the architectural research is significant to renew the building science and then the practice. However, all over the history of architecture developing particular building elements and envelops is the result of trial and error experimentation and observation. Architectural research appears to cover a wide range of areas, including socio-behavioural issues, design methods, and energy conservation. Recently, researches which hold interest in sustainability have gradually increased with a new conceptual model to many earlier issues (Groat and Wang, 2002).

Architectural research is defined as an analytical process, it is a *"systematic inquiry directed towards the creation of knowledge"* (Snyder, 1984). The definition proposes, on the one hand, that the inquiry is systematic and that there is an awareness of the particular information on how it is categorised, analysed and presented. On the other hand, knowledge creation refers to building sciences in the architectural research, such as testing materials and evaluating glazing and building envelop for better thermal performance.

However, several types of methods are engaged in the architectural research. They are, in general, under the umbrella of quantitative and qualitative research methods. Groat and Wang (2002) in their book entitled *Architectural Research Methods* have named seven methods of research. The methods are interpretive-historical research, qualitative research, correlation research, experimental and quasi-experimental research, simulation and modelling research, logical argumentation research and case studies and combined research methods.

6.2.1 Experimental research in architecture

Of all the architectural research methods, the experimental method is unique in its characteristics. It includes (Fraenkel and Wallen, 2006; Groat and Wang, 2002): (a) the use of a treatment (or independent) variable, it is the type of research that looks at the effect of at least one independent variable on one or more dependent variables; (b) the measurement of outcome (or dependent) variable; (c) a clear unit of assignment; (d) an experiment which usually involves two groups, being the treatment and the use of a comparison (or control) group; and (e) it is the best type for testing hypotheses about cause-and-effect relationships.

The above fundamentals define two types of the experimental research in architecture, which are: the laboratory setting research that considers only the physical variables, and the field setting research that focuses on behavioural aspect. The significant distinction is that the experimental laboratory setting in the built environment considers the causality for granted. This because the technology of the built environment, like natural sciences research, tends to incorporate the following characteristics : (a) the use of laboratory settings where appropriate variables can be simply controlled; (b) dependent variables, which are in many cases inert, and therefore change as a consequence of the treatment; (c) explicate theories that enable researchers to identify the expected effects of a particular treatment; and (d) instruments that are calibrated to measure such effects (Groat and Wang, 2002).

6.2.2 Knowledge gap and the research questions

The purpose of this study is to examine the viability of SGWF for controlling the total solar heat gain and to determine whether it is appropriate to be used for glazed buildings in hot-humid tropics. The research is carried out using an experimental method, which is the best type of research method for testing hypotheses.

The research attempts to maximize the benefits of the alternative solar control in glazed-buildings through a sustainable design. The combination of recycled elements (rainwater) with a low cost glazing (tinted glass) that is commercially available in the tropical market was challenged to bridge the current research gap. It is to explore the possibilities of applying SGWF as an alternative solar control on the east and the west glazed-facades of office buildings in the tropics. The group of research questions which have been developed to address the knowledge gap are listed below:

Table 6.1: Restatement of research objectives and research questions

Research objectives	Research questions	Instrumentation
• To review the alternative and passive solar control options for glazing, particularly for the east and the west orientations, that have been practiced in the glazed-green-office buildings in Malaysia	• What are the appropriate passive solar controls for east and west glazed-facades of mid-rise office buildings in the tropics, Malaysia?	Building walkthrough and survey. Measuring Indoor and outdoor data using data logger instruments.
• To investigate the effectiveness of SGWF in reducing solar heat (long-wave) transmittance through glazed facades;	• How could SGWF limit solar heat (long-wave) transmittance through glazed facades?	Experimental study on Surface temperature, Heat transfer & Solar Gain SHGC.
• To investigate the effectiveness of SGWF in absorbing short-wave infrared (radiation), and maximizing the transmittance of visible light.	• How SGWF could contribute in reducing the transmittance of short-wave infrared (radiation), and increasing the transmittance of visible light?	Data logger instruments, and “Alpha, UV/VIS/NIR spectrophotometer”
• To calculate the solar transmittance of SGWF. The transmittance of the entire range of solar radiation; the visible light range and short infrared range.	How far the SGWF is sustainable spectrally selective film?	Calculation analysis in addition to the “Alpha, UV/VIS/NIR spectrophotometer instrument

6.3 Research methods for the SGWF

Based on the review of the architectural research methods and the research questions outlined above, it was suggested that the experimental approach is the appropriate way to carry out an investigation on the solar radiation and the thermal performance of the proposed approach; the SGWF. The justification for involving the experimental method rather than the simulation methods in this research are summarized as follows:

- In referring to Chapter 2, the Malaysian sky condition is volatile during the day, where the vast majority of the time of 85.6% is predominantly intermediate sky, so the simplified design tools and computer software might not be appropriate for the Malaysian sky and climate.
- With respect to the above reason, it is extremely complex to hand a simulation of thermal and light energy performance of the SGWF with the presence of direct solar radiation in the tropics, Malaysia.
- Experimental research is one of the most powerful research methodologies. It is the best way to establish cause-and-effect relationships among the variables. It is also the best type of research method for testing the hypotheses (Fraenkel and Wallen, 2006).
- Physical modelling, a prototype with a scale of 1/1 is recommended for the following reasons: (a) due to the difficulty in scaling-down the climate variables, so the small-scale model may respond differently than a full size model; (b) collecting data from real buildings are difficult; and (c) the flexibility to localize the sensors.

6.3.1 Experimental design and set up

The design of an experiment addresses the questions outlined above by specifying the following (Fig. 6.1):

- The use of a treatment, or independent variable; the water film flow rate, solar intensity and glass type.
- The current thesis seeks to evaluate the outcome of the treatments (dependent variable); the total heat gain (heat transfer and solar gain SHGC), the glazing

surface temperature, thermal conductivity, indoor temperature and visible light transmittance.

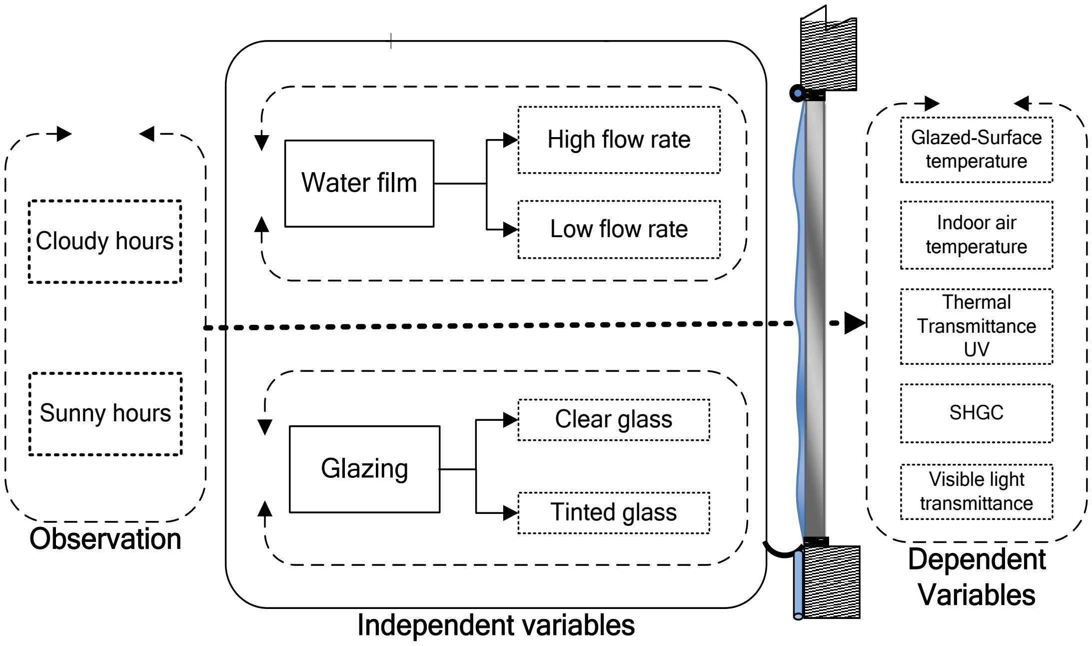


Figure 6.1: Variables examined for SGWF

6.3.2 Design of the test and the control rooms

Before the design of the experimental test and the control rooms, it was deemed essential to fix the site where the laboratory was to be constructed. The fixation was essential as the site would dictate the size and the construction materials. Among the possible sites from which the current site of the experiments was chosen was based on several criteria: to represent the mid-rise building (5 to 20 storeys); its easy accessibility; nearness to the water supply and drainage and the two rooms to be exposed to the direct solar radiation particularly the west facades.

In this study, the configurations of two full-scale rooms, the test room and the reference room (Figures 6.2 to 6.5), are designed with respect to the site selected for conducting the experiment. They correspond to the typical dimensions of the facade modules used in the experiments. They are identical and detached one-storey rooms. In order to be exposed to the solar radiation without any shade, they are located on the roof of a seven-storey building. Both cells are designed so that each of the four walls faces the east, the west, the north and the south, respectively, (Figures 6.6 and 6.7). The internal dimensions are 2.0m x 2.0m with an area of 4.0m² and a ceiling height of 2.60m. They have a steel structure; their walls consist of a steel frame, externally covered with a white sheet metal and internally covered with a white painted plywood board. A layer of 100mm Rockwool insulation for the wall and internal roof (ceiling) is located in the wood frame between the metal sheet and the plywood, (Figure 6.8). Each room has an opening of 1.8m height x 1.4m width forming 63% of WFR[1] and 50% of WWR, oriented to the west, and to be closed with different glazed systems. A plywood door measuring 0.8m x 2.0m was insulated with an aluminium foil is located on the exterior face. The glass types were selected based on their performance against the solar radiation and their relative low production cost. The float bronze tinted glass is selected to represent the lower glass' SHGC (transmitting less solar heat), while the clear glass represents the poor solar heat control. The glass which was installed on the facade was divided into two parts of 10mm float glass. The thickness of the glass was selected to correspond to the thickness applied to the actual glazed buildings to get accurate results in respect of the current research problem. Table 6.2 summarizes the performance of the glasses used in the experiment.

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[1] The requirements of the Malaysian Uniform Building By Law UBBL of WFR is to be not less than 10% for daylighting (UBBL, 2008). In this research, Window Wall Ratio "WWR" of more than 50% is considered as glazed facade.

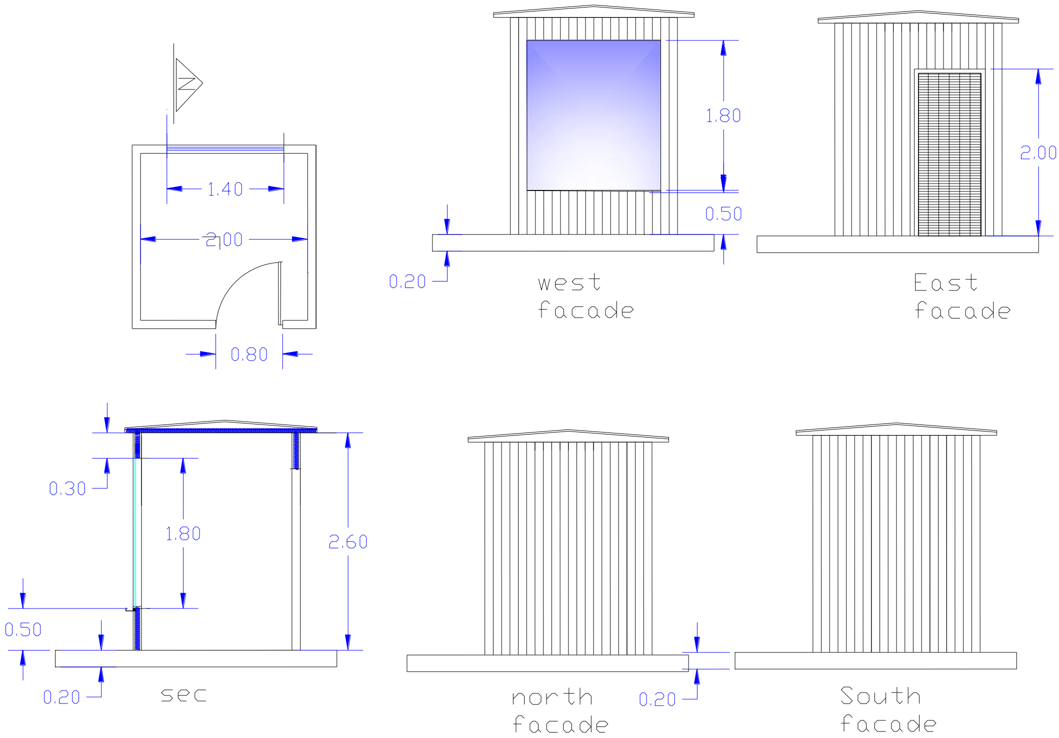

Figure 6.2: The rooms' laboratory drawing

Figure 6.3: View of experiment site: reference room (left) and test room (right).

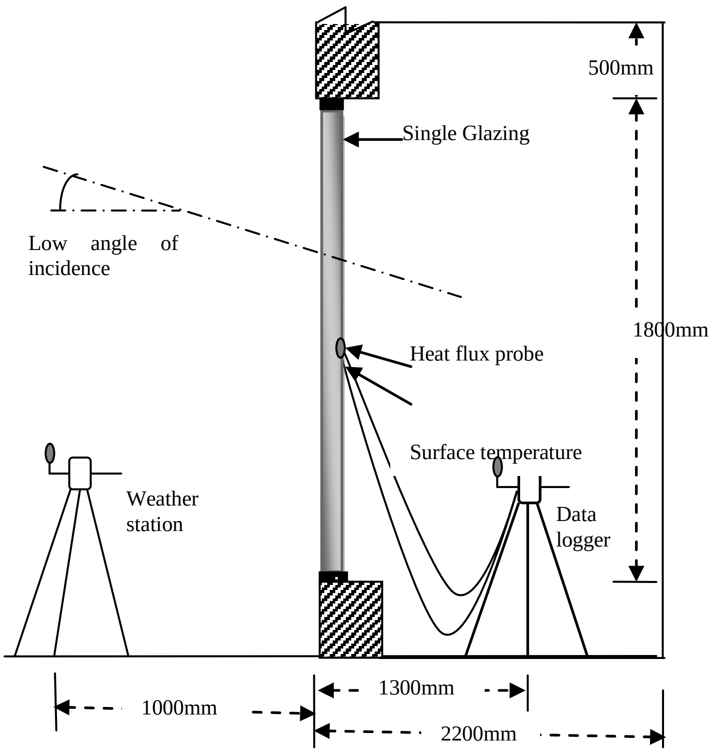

Figure 6.4: Schematic view of the reference room at single glazed façade

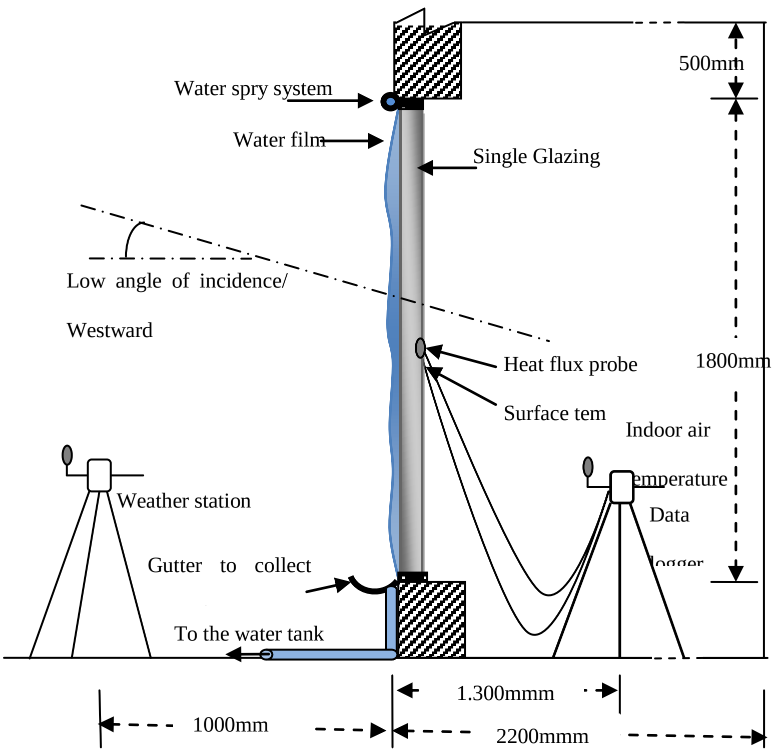

Figure 6.5: Schematic view of the SGWF

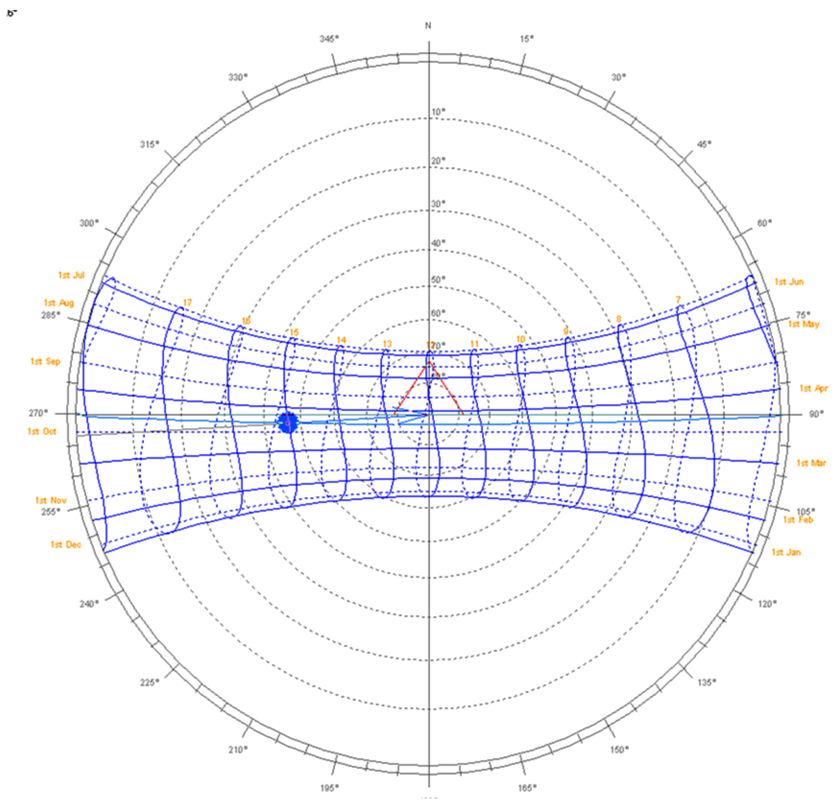

Figure 6.6: The stereographic diagram of 21st March, to the experiment site.

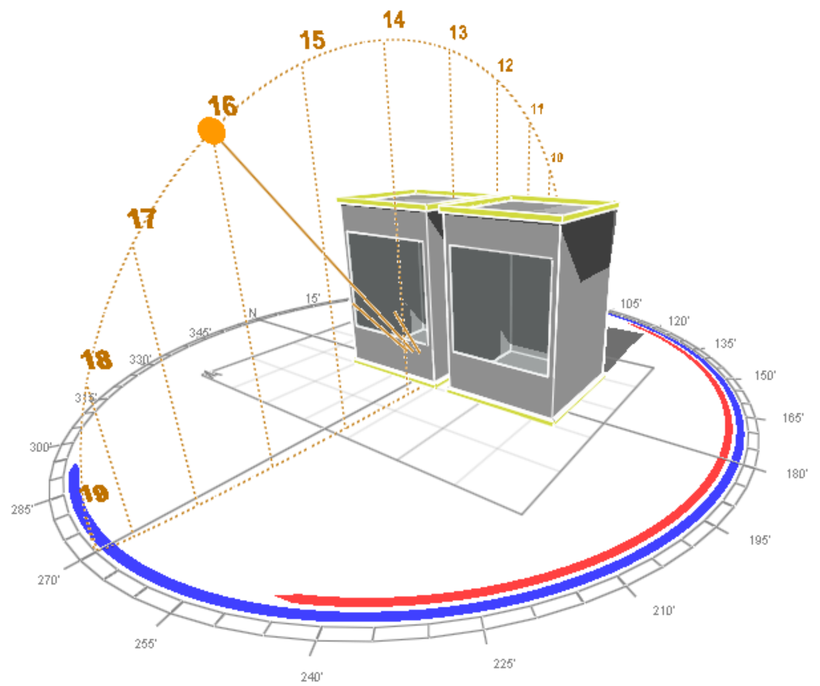

Figure 6.7: Sun path diagram of 21st March, to the experiment site

Figure 6.8: A layer of 100mm Rockwool insulation for the wall and internal roof

Table 6.2: The characteristics of glasses used in experiments (MSG, 2009)

Product	Thickness (mm)	Visible light			Solar radiation				SHGC	SC	U-value W/m^2k
		Transmittance	Reflectance		Transmittance	Reflectance		Absorption			
			Outside	Inside		outside	Inside				
Pilkington Clear	10	86	8	8	72	7	7	21	**0.77**	0.89	5.6
Pilkington Bronze	10	30	5	5	26	5	5	69	**0.44**	0.51	5.6

6.3.3 Forming even flow of water film on the glass surface

As illustrated in Figure 6.9, the application of water as an alternative solar control and glazing insulation might vary according to the glazing systems used: (a) enclosed double glazing system where the water flows through the glazing cavity. This system is suitable for small windows due to the overload of the water filling the cavity; (b) double glazing with ventilation and the water forms a film on the glazing skin, either the inner skin of the outer plate or the outer skin of the inner plate. This case might reduce the green house effect inside the cavity; and (c) flowing water film over the outer skin of a single glazed façade. However, the last system of flowing water film over the single glazing surface has several advantages, for instance, the water film which was exposed to the air movement that increased the ability of the system to carry the heat away by convection and conduction; and the flowing water film over a single glazing will reduce the building cost and increase the rentable workspace if compared with double glazing.

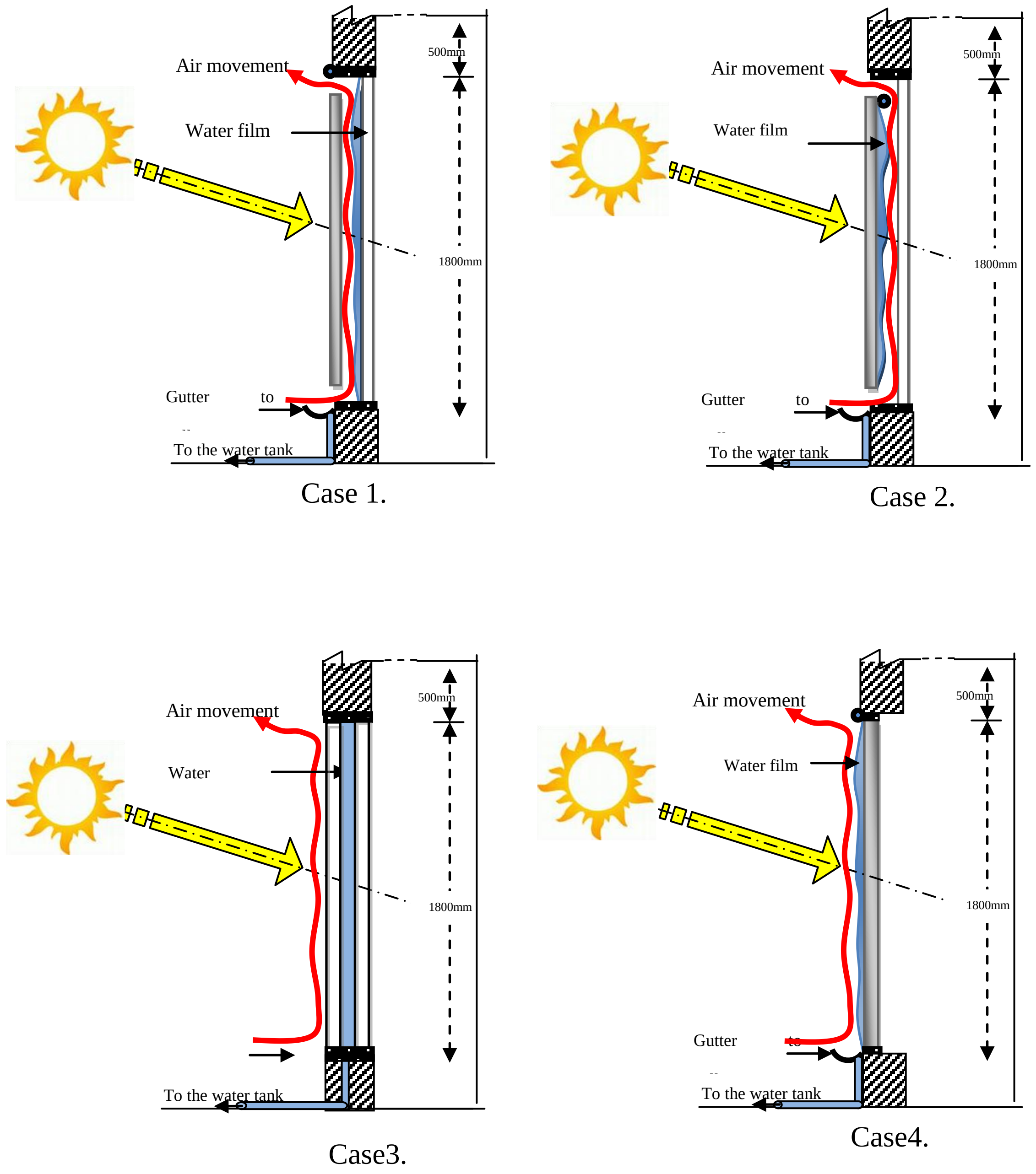

Figure 6.9: The variation of the water film application within glazed facades

The supplying water film to the exterior surfaces of the glazed wall comes from a submersible pump (pump 400W, 230V/50Hz, 7300l/h) which was placed in a reservoir connected to the main water tank. During the experiments, the water reservoir was shaded by an aluminium foil and the PVC pipelines are used to reduce the heat transfer from the sun (Figure 6.10). To collect the water for recirculation from the glass surfaces, a gutter was connected to the bottom of the glazing which in turn re-circulates water back to the reservoir.

Figure 6.10: During experiments, the water reservoir was shaded by an aluminum foil

Drilling 5/32" holes, every 1/2" in the pipe will be sufficient to produce an even flow when the water hits the glazed facade. Feeding the water to the system comes through a t-junction with a pipe going right and left with both ends capped off. Another option of feeding the water to the facade is through a stainless steel gutter to form spill-over flow of the water. The Author found that using the gutter is more difficult than the pipe with holes. The difficulty is the alignment of the gutter for distributing the water equally to the entire facade. This research work adopted the drilling of the holes in the pipes (Figures 6.11 and 6.12). The water flow is generated by means of pumping the water through the valve connected to the water meter, and connected to the room facade by

Figure 6.11: Feeding the water to the system comes through a t-junction with a pipe going right and left with both ends capped off.

Figure 6.12: Feeding the water to the facade comes through a stainless steel gutter to form spill-over flow.

PVC pipes (external diameter 2.0 cm). The desired water film thickness can be adjusted accordingly to the experimental needs, where the thickness of the water film is related to the water supply. To produce a desired film of water on the glazed facade of the test room requires approximately 800 to 1200 litres per hour per meter width according the two flow rates that were tested. The operation of the SGWF system started at 12:00 (the results have been reported, on each run, for the time 13:00-19:00, so that the test system is steady) on the test days and shut down by 19:00 at sunset.

6.3.4 The instrumentation and the sensors

The measurement equipment consisted of 13 sensors connected to data loggers designed to collect the data related to the thermal and solar radiations. The "Babuc/A" data loggers, were utilized for monitoring the indoor thermal performance (Figures 6.13 and 6.14). The "Skye" data logger with three sensors was used to measure the vertical solar radiation indoor/outdoor (Figure 6.15). And a Weather Station was installed to measure the outdoor solar radiation and the climate condition of the experimental site (Figure 6.16). The measurement of the surface temperatures and heat fluxes were conducted with the presence of the incident solar radiation without a shield in the case of both the treated and the reference facade, since the shelter will affect the gentle flow of the water film.

Figure 6.13:Set up of the “Babuc/A” data loggers in one room to check if there are any reading differentiations in order to minimise data errors.

Figure 6.14: Set up of the indoor data logger in the test room

Figure 6.15: The vertical solar radiation monitoring sensors, which are attached to the wooden tripod.

Figure 6.16: Set up of the weather station for measuring the outdoor experiment's variables

The following sensors were adopted for both the test room and the reference room:

- Thermocouples to measure the temperature of the indoor dry-bulb temperature.
- Two Thermocouples to measure the inner surface temperatures of the glass.

- Heat flux meters to measure the thermal flux through the facade on the glass surface facing the indoor environment.
- Two Pyranometers to measure the incident solar energy, W/m^2.
- Two Lux meters to measure the lighting level indoor.
- Probe to measure the global solar radiation W/m^2.
- Outdoor air velocity, m/s.
- Rain gauge, mm.
- Thermocouples to measure the outdoor air temperature, °C.
- Infrared thermometer for monitoring of the water temperature, °C.

The research also involved laboratory equipment for measuring the water performance with respect to the different solar wavelengths. The “Alpha, UV/VIS/NIR spectrophotometer” was used to investigate the solar transmittance and absorptance in the water (Figure 6.17).

Figure 6.17: UV/VIS/NIR spectrophotometer to measure water spectrum

6.3.5 The setting of the treatments and the outcome measures

Because of the total heat gain through the glazing is derived from two sources: the direct solar radiation and the heat transfer due to the difference in temperature between the ambient and the indoor spaces and between the glass surfaces, the thesis work divided the setting of the experiment into two parts: examining the thermal performance of SGWF, and investigating the transmittance of the solar heat gain SHGC of SGWF.

Overall, the experiments were conducted through the "control group design" where the experiments involved two rooms. One room received the experimental treatments while the other did not. Also, both rooms were post-tested on the dependent variables to reduce the errors. A diagram of this design is as in the Table 6.3.

Table 6.3 shows the "control comparison design" of the experiments at all the scenarios. "A" represents the pre-test of both the control and the treatment "SGWF" rooms for reducing errors. "X" symbolizes the experimental treatment while "C" represents the control room, which did not receive any treatments. The two "Os" indicates that the observation of the two rooms occurred at the same time.

Table 6.3: The control comparison design

Treatment room	A	X	*O*	Remarks
Control room	A	C	*O*	
Observation summary				

Another experimental design which was involved in this research work was the comparison of the pre-test against the post-test in one room. This design was engaged in the investigation of the thermal transmittance of both the reference and the treatment rooms because of the limitation of "heat flux" sensor. Also, it was involved during the examination of the indoor air temperature in “STGWF” scenario. This was due to the unexpectedly damage of the sensor monitoring the indoor air temperature of the control room. A diagram of this design is as in the Table 6.4.

Table 6.4 shows the one room for the pre-test against the post-test comparison design of the experiment at the indoor air temperature scenario of STGWF. *“X”* symbolizes the experimental treatment. The two “Cs” in the design symbolise the “control” variables. The control variables might be the “global solar radiation” or the “outdoor temperature” that was measured during the entire periods of the experiments.

Table 6.4: The one group pre-test - post-test design

Treatment room	Pre-test	X	Post-test	Remarks
Control Variables	C		*C*	
Observation summary				

CHAPTER 7

RESULTS AND DISCUSSION

7.1 Introduction

An experimental and calculation investigation of the glazed facade facing the west orientation has been conducted by utilising the (SGWF). The experiments involved the following three parameters namely: the water flow rate, the type of the glazing, and the solar radiation intensity. The aim of this chapter is to present the results of the examined SGWF and the results interpretation as the following, Figure 7.1: (a) the results of improvement in the thermal performance of glazed facade with water flow film; (b) the performance of the SGWF in controlling solar radiation transmittance; (c) the numerically analysis of the “sustainable spectrally selective characteristic” of the SGWF; and (d) the chapter will be closed with highlighting the relevant significance of the SGWF for glazed office buildings in the tropics.

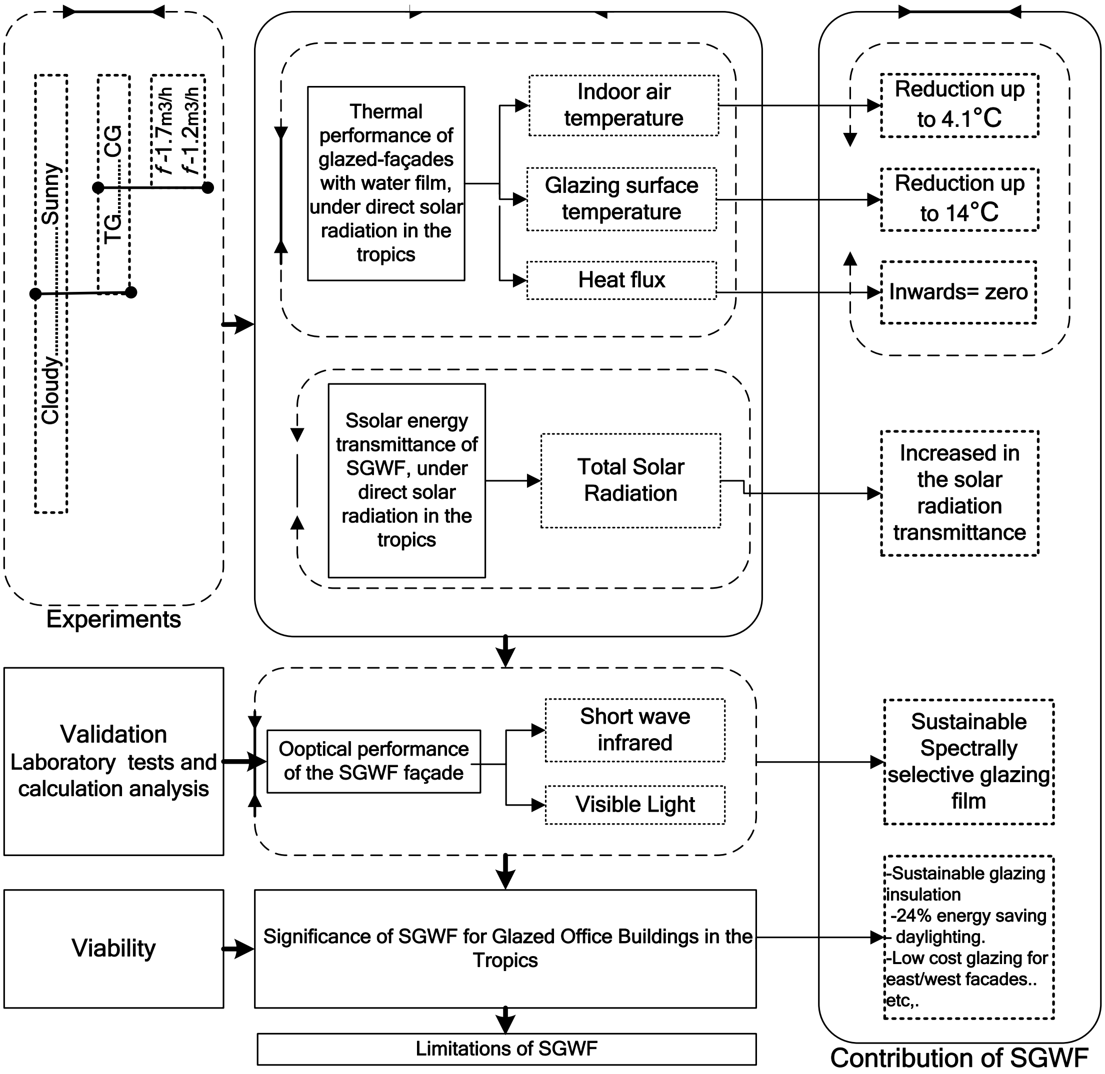

Figure 7.1: Flow chart for Chapter 7

7.2 DETERMINATION OF THERMAL PERFORMANCE OF GLAZED-FAÇADES WITH WATER FILM, UNDER DIRECT SOLAR RADIATION IN THE TROPICS

Two full-scale rooms were used, one as a reference room, with a fixed configuration, and the other as a test room, which could be configured in different ways to assess the thermal performance of SGWF façade under direct solar radiation, Figure 7.2(a & b). The test was started without any treatments in both the test room and reference room to

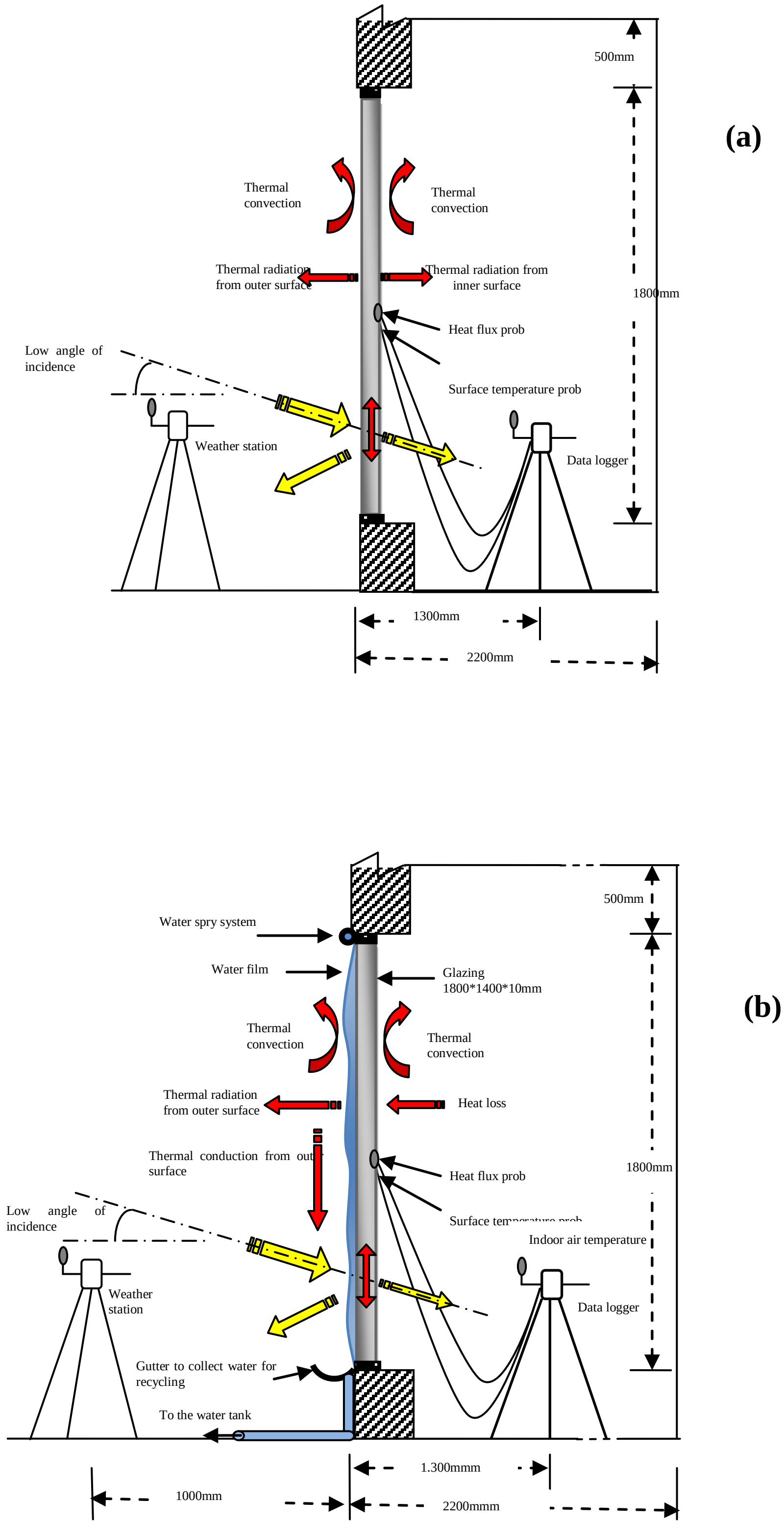

Figure 7.2: (a) The schematic view of the present problem at single glazed façade and (b) the schematic view of the experiment with SGWF facade

reduce data error when comparing the results. The findings of this stage are included in Figures 7.3, 7.6 &7.7 and Tables 7.1 & 7.2; they show that the differences between the two rooms are negligible. All the experimental data have been collected at two different water flow rates to form two different thicknesses of the water film. Case 1 has a flow rate 1.2m^3/h, the lowest flow rate that created a uniform water film on the glazing surface, while the flow rate 1.7m^3/h was the maximum water flow obtained through the water meter in the experiment system. The experiment was conducted on west glazed facades, in the period of the highest solar radiation intensity in Malaysia; February and March, where the sun is overhead the experiment location. So that the high indoor temperature displayed in this study is due to the direct solar beams passing through the large glazing and being trapped inside the insulated test rooms.

7.2.1 Temperature difference inside the rooms

Measuring the SCGWF has been carried out at a flow rate1.2m^3/h and 1.7m3/h. The analysis of the lower flow rate 1.2m^3/h at the SCGWF stage of the experiment was excluded. It did not have a significant effect on indoor temperature because of the lower absorption of the clear glass to the solar radiation and the thinner thickness of the water film. The analysis focuses on the indoor and outdoor air temperature, and the inner glass surface temperature, to get a clear image of the thermal performance of the sustainable glazing system.

The analysis of the SCGWF vs. CG (average five days to each sunny and cloudy hour for the time 13:00 – 19:00) is summarized in Table 7.1. The total reduction in heat load during the sunny hours was 2.2 °C indoor air and 7.2 ºC to the glazing surface. Whereas on cloudy hours the total reduction in heat load was 1.5 °C indoor air and 4.3 °C to the glazing surface. The results indicate the significance of the water film during the sunny time compared to cloudy time.

Table 7.1: Heat transfer performance of 10mm Clear Glass (CG) with a thin film of water under the exposure to direct solar radiation

SCGWF. Judge against control days, verifying with outdoor dry-bulb of each case			Indoor Dry bulb temperature	Surface temperature	Outdoor temperature	The difference dry bulb-temp indoor/outdoor	Remarks
C1. flow-rate (1.7 m^3/h)	Sunny hours	SCGWF	37.7	32.8	32.9	4.8	All variables were measured in both rooms at same time. 1.7m3/h is the maximum rate of the water flow was obtained through the water meter in experiment system
		CG (control)	39.9	40.0		7	
		Difference	2.2	7.2			
		Average heat gain reduction by SCGWF is: (2.2 °C indoor air and, 7.2 °C glass surface)					
	Cloudy hours,	SCGWF	34.9	31.0	30.7	4.2	
		CG (control)	*36.4*	*35.3*		*5.7*	
		Difference	1.5	4.3			
		Average heat gain reduction by SCGWF is :(1.5 °C indoor air and, 4.3°C glass surface)					

Figure 7.3 shows that the peak heat gain through the SCGWF-*f* 1.7m^3/h, and CG at 16:40, created a difference in the indoor air temperature of 5.6 °C, lower with SCGWF-*f* 1.7m^3/h (when the outdoor air temperature was 33.9 °C and total solar radiation was1215W/m^2 at that time). Whereas during a cloudy hours, the peak difference in indoor air temperature between the test room with SCGWF-*f* 1.7m^3/h and reference room with CG was about 3° C at 14:40 (when the outdoor temperature was 33.6 °C and total solar radiation was 802W/m2 at that time).

Figure 7.3 also shows that the thermal performance of the SCGWF-*f* 1.7m^3/h is always better than the reference one with CG and that on the control days without the water film the temperature variation of the two rooms were approximately the same. With SCGWF-*f* 1.7m^3/h, more drop of the heat gain occurs during the sunny hours compared to cloudy hours. It was noted the peak difference in the indoor air temperature in these cases increases during the peak of the solar radiation intensity. This indicates an optimal time for the water film to be applied. However, with increased solar radiation intensity, the SGWF is more efficient in reducing the heat transfer indoors. It was found the

SCGWF-*f* 1.7m^3/h efficiently transfers the thermal energy from inside to outside (increased heat sink) and thus resulting in the temperature drop. It also provides an indication that a portion of a direct solar radiation (short-wave infrared) is absorbed by the water film.

Unfortunately, the instrument used for monitoring the indoor temperature of the reference room was damaged during the final study stage of SCGWF. This led to a change to the method of monitoring the indoor air temperature during the course of examining the STGWF. It was carried out in one test-room as a pre-test with TG (reference days) and then post-test with STGWF (treated days), in judging all against the outdoor air temperature that was recorded in the entire period.

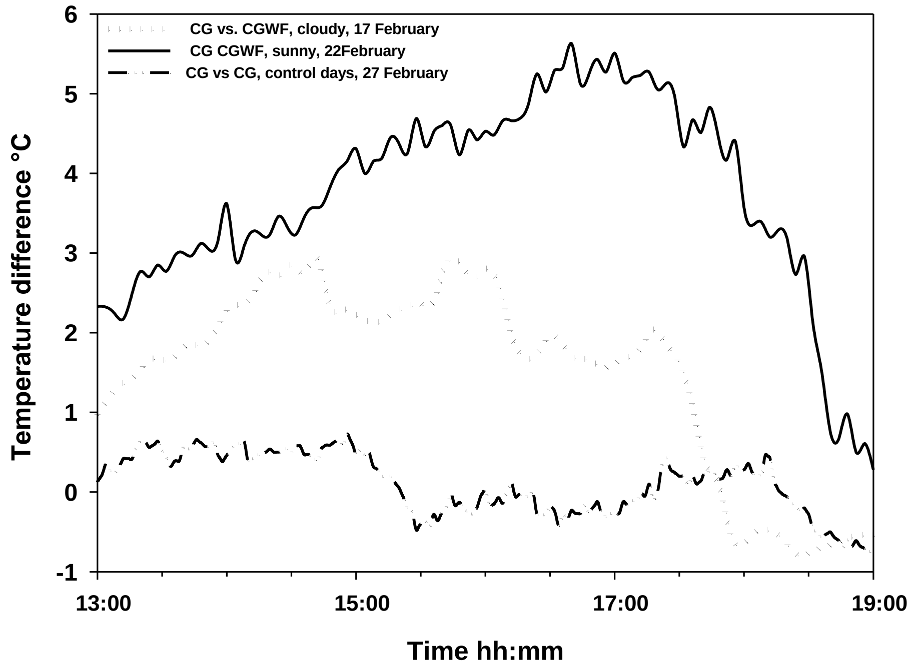

Figure 7.3: Indoor air temperature difference with CG vs. CGWF 1.7m3/h

Table 7.2 contains the detailed information with average 5 days each. The pre-test five days started with TG with no treatments so as to act as a control case in this experimental stage. Table 7.2 also summarizes the results of STGWF with different configurations. The results were monitored on an average of five days for each case for the operation hours 13:00 -19:00. With STGWF-*f* 1.2m^3/h, the total reduction in the heat load during the sunny hours was 4.1 °C in indoor air temperature, and 12.9 °C on the glazing surface, while, with STGWF-*f* 1.7m^3/h, where the reduction in indoor air temperature was 4.0 °C and 14.0 °C on the glazing surface. The unexpected likeness of the indoor air temperature of both flow rates that appeared in Table 7.2 was due to the low difference between both flow rates of the water-film, and the irregular sunshine during the test hours. In this context, it is recommended that an experiment be conducted with much higher flow rate that forms a greater thickness of water film.

Table 7.2: Heat transfer performance of 10mm Tinted Glass (TG) with a thin film of water under the exposure to direct solar radiation

STGWF. Judge against control hours, verifying with outdoor dry-bulb in both cases.			Indoor Dry-bulb temperature	Surface-temperature	Outdoor dry-bulb temp.	The difference dry bulb indoor/outdoor	Remarks
C2; a&b: flow-rate (1.2m^3/h.)	Sunny hours	STGWF	36.1	34.5	34.3	1.8	The glass surface temperature was measured at the same time in both treated room and reference room. Whereas the indoor temperature dry-b has been measured as (pre-test) STGWF vs. (post-test) TG. So the average reduction of the indoor temperatures that demonstrate in the table is the value after deducting the errors due to the differences of the weather at the stages of the pre-test and post-test.
		TG (control)	41.0	47.4	35.1	5.9	
		Difference	4.9	12.9	0.8	4.1	
		Average heat gain reduction is: 4.1 °C					
	Cloudy hours	STGWF	31.8	30.0	30.0	1.8	
		TG (control)	37.5	36.0	32.9	4.6	
		Difference	5.7	6.0	2.9	2.8	
		Average heat gain reduction is :2.8 °C					
C3; a&b: flow-rate (1.7m^3/h.)	Sunny hours	STGWF	35.0	33.4	33.0	2.0	
		TG (control)	41.0	47.4	35.1	5.9	
		Difference	6.0	14.0	2.1	3.9	
		Average heat gain reduction is: 4.1 °C					
	Cloudy hours	STGWF	32.8	30.6	30.6	2.2	
		TG (control)	37.5	37.8	32.9	4.6	
		Difference	4.7	7.2	2.3	2.4	
		Average heat gain reduction is :2.8 °C					

Figure 7.4 shows a temperature profile of sunny hours for the two configurations of STGWF, also the reference case TG. An indoor temperature with TG ranges between 38.4 °C at 13.00 and 37.9 °C at 19:00, with a peak value of 45 °C at 17:33. On the other sunny hours when using the STGWF-*f* 1.2 m^3/h the indoor temperature variation was ranged of between 36.1 °C and 32.9 °C, with a peak value of 38.8 °C at 17:20. For the

STGWF-*f* 1.7 m^3/h the variation ranges from 35.6 °C to 30.5 °C, with a peak value of 39.3 °C at 17:35.

The result peak shows a difference as illustrated in Figure 7.4, where the reduction in indoor temperature was 2.0 °C more with STGWF-*f* 1.7m^3/h than the STGWF-*f* 1.2m^3/h. This indicates that STGWF-*f* 1.7m3/h is more efficient in reducing heat transfer to the interior and increasing heat sink to the outside.

On cloudy hours with STGWF-*f* 1.2 m^3/h and *f*1.7m^3/h, Table 7.2 also shows that the total reduction in solar heat gain was 2.8 °C indoor air temperature, at both flow rates. Also, on the glazing surface with *f*1.2m^3/h, the reduction was 6.0 °C, while at *f*1.7m^3/h it was 7.2 °C. The results verify the significance of the use of the water film during the sunny time compared to cloudy time, and provide an index to the capacity of the water film in absorbing some solar radiation spectrum of direct light.

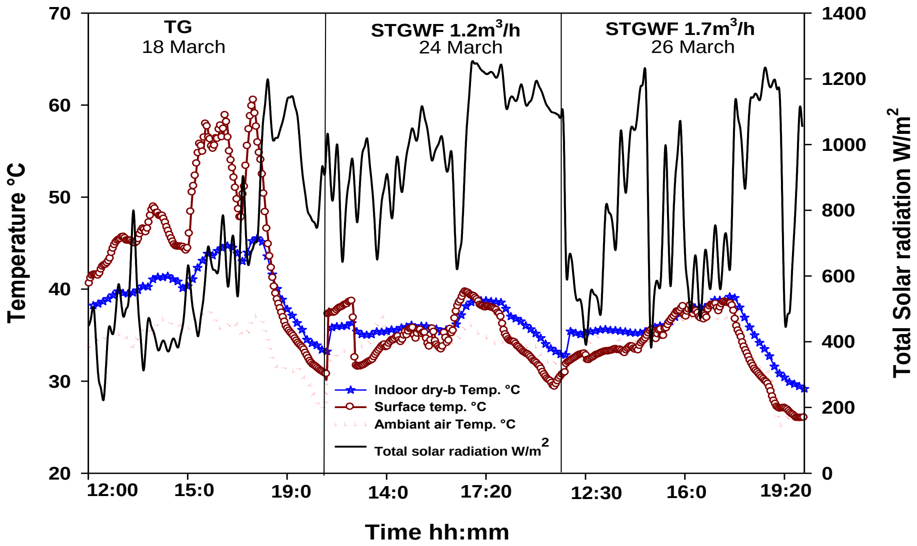

Figure 7.4: Air temperature variation outdoor – indoor, TG reference room vs. STGWF test room, (sunny hours).

Because the examining days of the indoor air temperature at STGWF configurations were not the same days of monitoring the reference TG, there is a need to verify the results of the heat reduction in this stage. The difference between outdoor/indoor air temperatures of STGWF might be the ideal way to confirm these results. Taking into account that, in this experiment stage, the higher the variation between indoor and outdoor air temperatures, the more heat gain there is. And the less the variation, the more optimal it is.

The daily average temperature of all experiment configurations (taken between 13.00 and 19.00) might not give an accurate impression of the performance of the glazed facade with a flowing water film. This is because of the changeability of the tropical sky during the day where the overwhelming proportion of the time (85.6%) is represented by an intermediate sky , as mentioned in the Chapter Two. Given this, the peak value might provide a more appropriate picture of the performance of the different configurations.

As demonstrated in Figure 7.5 with TG on sunny hours, the difference in air temperature between outside and inside is 12.2 °C at 17:58, higher inside the room, when the air-temperature outdoor, indoor and inner surface temperature were 33.2°C, 45.0 °C and 56.1 °C respectively, and the total solar radiation was 1167W/m2, at that time. Whereas, the STGWF-*f* 1.2m^3/h on sunny hours reduced the peak difference to 4.6 °C at 17:40, when the air-temperature outdoor, indoor and inner surface temperature were 34.0 °C, 38.6 °C and 37.7°C respectively, and the total solar radiation was 1203W/m2, at that time. With increasing the water film flow rate, the STGWF-*f* 1.7m^3/h shows more effectiveness during the peak of sunny hours. It was found at 17:40 that the difference was reduced to 3.7 °C from an outdoor 34.0 °C to an indoor 38.0°C and an inner glazing surface temperature of 35.0 °C when the total solar radiation was 1110 W/m2.

On the cloudy hours with TG the peak difference in temperature between outdoor and indoor as also plotted in Figure 7.5 was 7.1 °C at 18:10 when the air temperature indoor, outdoor and inner surface temperature were 38.5 °C, 31.4 °C and 46.2 °C respectively, and the total solar radiation was 799W/m^2 at that time. With the application of STGWF-*f* 1.2m3/h, the peak difference varies between 3.0 °C at 14:11 to 2.4 °C at 17:40, where the air temperature indoor, outdoor and inner surface temperature were 30.6 °C; 28.2 °C and 29.7°C respectively, and the total solar radiation was 561-672W/m^2 at that time. With increasing the flow rate of the water film, the STGWF-*f* 1.7 increased the ability to reduce the heat gain through the glazing on cloudy hours. The difference between the temperature inside and outside was 1.0 °C at 17:40, when the outdoor, indoor air-temperature and inner surface temperature were 31.1 °C, 30.4 °C and 28.4 °C respectively, and the total solar radiation was 646 W/m^2, at that time. Compared to the other cases of cloudy hours, the irregular high variation between outdoor and indoor air temperature of 4.1 °C that appeared in Figure 7.5 on the STGWF-*f* 1.7 at 15:10, occurred due to the high solar radiation intensity hitting the glazed-facade at that particular time where it was found of 1129 W/m^2.

7.2.2 Temperature variation on glazing surfaces

The glazing surface temperature is the most important parameter in examining the heat transfer of the SGWF. Tables 7.1 & 7.2 include the average glazing surface temperature for two different glazing types and two flow rates of the water film during 5 hours, both sunny and cloudy hours. It was found that the SGWF, in all cases, has lower temperature values, compared to the reference C/TG, during the operation hours of the water film for the time (13:00–19:00).

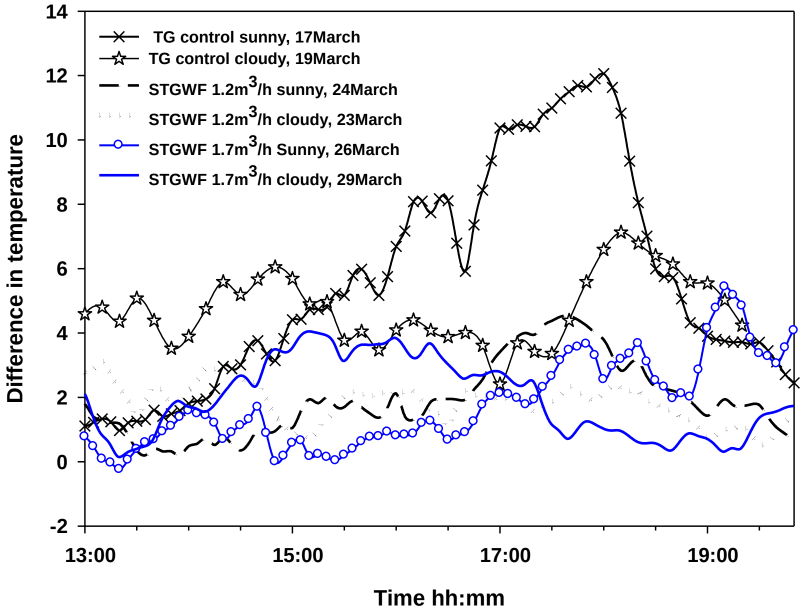

Figure 7.5: Air temperature variation, outdoor – indoor, TG reference room vs. STGWF test room.

The differences between glazing surface temperatures are also plotted in Figures 7.6 & 7.7. In Figure 7.6 the difference from CG to SCGWF-*f* 1.7m^3/h during a cloudy hours was found to be 8°C at 15:56, when the peak value was 41.6 °C on CG and this reduced to 34.1 °C with the application of the SCGWF-*f* 1.7m^3/h. On a sunny hours, the difference in surface temperatures of glazing reached 11.6 °C at 16:55, when the peak values ranged from 48.1 °C on CG to 37.3 °C on SCGWF-*f* 1.7m^3/h.

Figure 7.7 presents the differences of the glazing surface temperature of the optimal configurations of STGWF during sunny and cloudy hours, judged against the tinted glass TG as a reference facade. On sunny hours it was found that the peak surface temperature of TG reached 60.2 °C at 16:36, whereas on the treated room with STGWF-*f* 1.2m^3/h the peak surface temperature remained at 39.7 °C with a 20.5 °C difference from TG. On STGWF-*f* 1.7m3/h, the peak surface temperature was 38.6 °C at 16:20 when the TG surface temperature rose to 60.8 °C at the same time, with a 22.2 °C difference.

The peak value of the reduction on the glazing surface with STGWF-*f* 1.7m3/h was higher of about 2 ° C than STGWF-f 1.2m3/h.

Fig. 7.7 further shows the temperature differences of the glazing surface of STGWF during cloudy hours. With STGWF-*f* 1.2m3/h the glazing surface temperatures were reduced from 40.9 °C to 32.4 °C with a reduction of about 8.5 °C on the glazing surface. Likewise, on the cloudy hours with a higher flow rate of the water film, STGWF-*f* 1.7m3/h, the peak variation of the glazing surface temperature between both facades was recorded at 15:24, with a variation from 49.3 °C on the reference façade (TG) to 34.8 °C on treated façade (STGWF-*f* 1.7m3/h): a reduction of about 14.5 °C.

However, as the water flows over the glazing facade, it carries the thermal energy from the heat sink and then transfers the heat to the ambient air, cooling itself down in the process. In this study, the water temperature was the same as or slightly higher than the outdoor air temperature due to the exposure of the main tank to the sunshine during all periods. However, where the surface temperature is concerned, the increase in water flow rate leads to a greater improvement in the results during cloudy hours than those during sunny hours. This is due to the heat removal capability of the water film in removing the long-wave infrared (heat) which is main portion in the diffused radiation. The water film has higher ability to removing heat than blocking the short wave infrared radiation within the direct solar radiation.

This behaviour of the water film can be understood as follows: the water film flowing down over the glazed façade cooling down the glass surface by convective and conductive methods raises the water temperature, after then the warm water cools itself down by means of evaporative cooling. When the outer surface of the glass is cooler than the indoor air temperature it enhances the outward heat flow, preventing the occurrence of the "thermal bridge" of the glazed building skin indoors, and maximizing the "heat sink" outdoors as well.

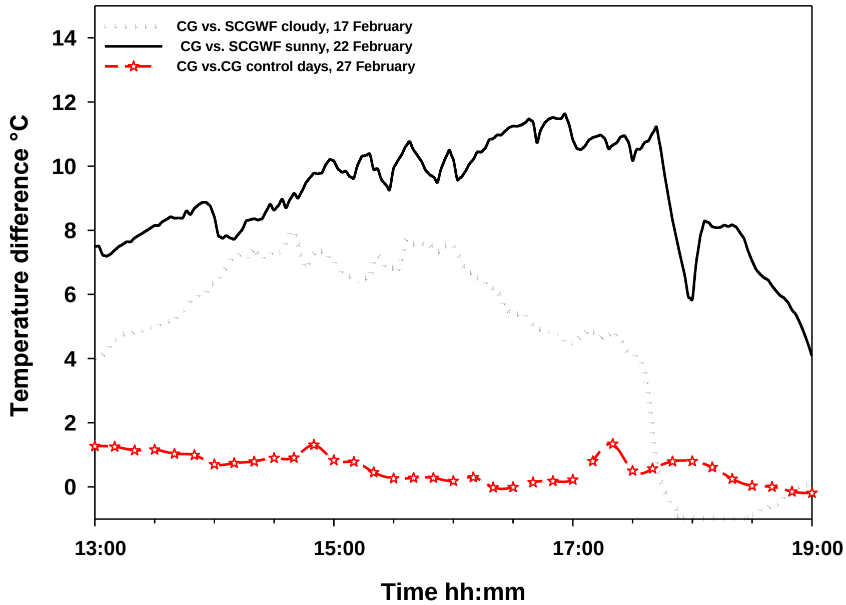

Figure 7.6: Surface Temperature difference, CG vs. SCGWF-f 1.7m3/h.

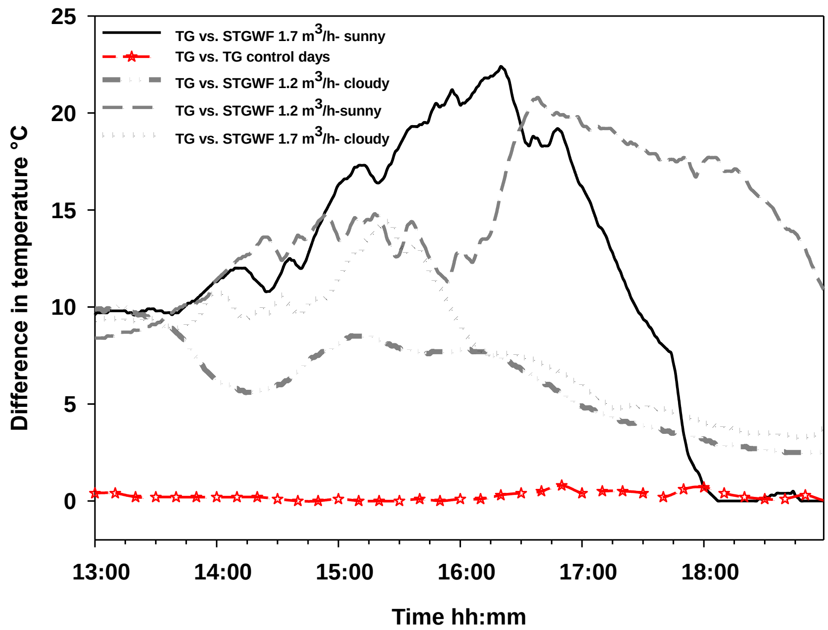

Figure 7.7: The temperature variation of glass surface, TG reference room vs. STGWF test room with two flow-rates during sunny and cloudy hours.

The variation of the water-flow-rate that was tested in this study played a less important role in the direct solar radiation beam than those with the defuse radiation. This happened because the water film is more effective in reducing the glazing surface temperature (long-wave infrared), eliminating the heat conductivity through glazing indoors, separating the inside from the outside. Whereas, the direct solar radiation beam needs a great thickness of the water film to block a portion of the short-wave-infrared (heat) in the solar beam.

7.2.3 Heat flux through SGWF

The heat fluxes through the glazing are presented in Figures 7.8 & 7.9. In all cases of CG, SCGWF, TG and STGWF a negative heat flux means a flux entering the indoor environment, whereas the positive value means that the heat transfers outdoors. Also, note that the heat flux probe cannot measure an energy higher than 50 W/m^2 in both directions and this is why the figures show a straight line when the readings exceed that value; in reality the heat flux is higher than $\pm 50 W/m^2$ at such a time.

The heat fluxes through the CG and SCGWF during sunny hours are plotted in Figure7.8. It can be seen that the heat flux with CG keeps entering the indoor environment, although the indoor temperature is higher than the outdoor (inner-surface 49 °C, indoor air 45 °C and outdoor air 34 °C), because of the direct solar radiation causing a high temperature variation between the inner-surfaces of the glass and outdoor temperature, thus playing the role of “heat bridge” indoors. In contrast, with the application of water film, the outer glazing surface temperatures (water temperature) remain lower than the inner surface temperature almost 1 °C, and nearer to the outside environment temperature, enhancing the outward heat flow. In contrast, increasing the water flow over the glazing leads to a reduction in the entering heat flux. With SCGWF-*f* 1.7m^3/h on average sunny hours the entering heat flux was reduced and reversed in value from (-15)W/m^2 to 40W/m^2, while the peak value of the thermal flow at the same configuration was changed from (-50)W/m^2 to 50W/m^2.

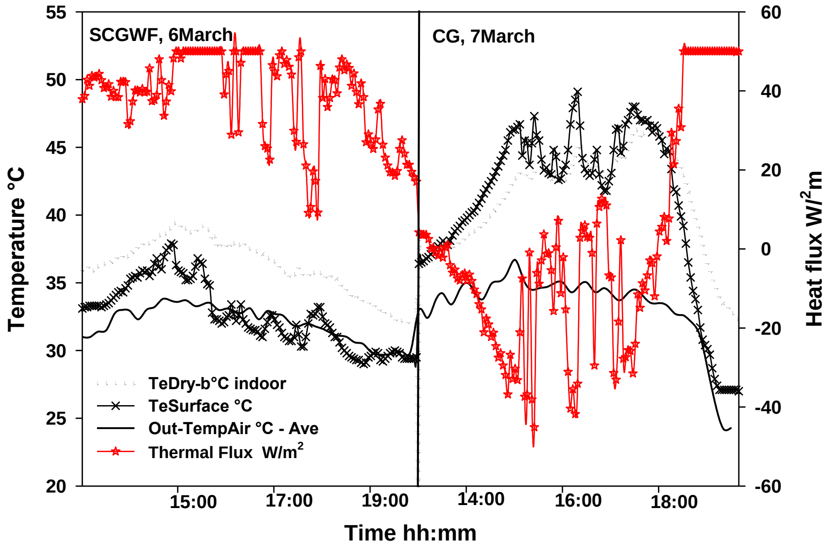

Figure 7.8: The temperature distribution on SCGWF and heat flux through, sunny hours.

For STGWF when the water film is adopted, in the presence of solar radiation as shown in Figure 7.9, the heat flux outwards is larger than the value of the TG. The average heat flux during the sunny hours was found to be (-) 49.1 W/m^2 with TG, and 6.1 W/m^2 at STGWF-*f* 1.2 m^3/h. The increase in the water flow rate STGWF-*f* 1.7 m^3/h makes a progressive reduction in the heat fluxes of 10 W/m^2. However, the heat flux through the glazed facade is mainly related to the temperature of the glass pane, which in turn depends on the temperature of the water film. The water film cools down the outer surface of the glazing, resulting in maximizing the heat loss to the outside, and limiting the heat flux indoors.

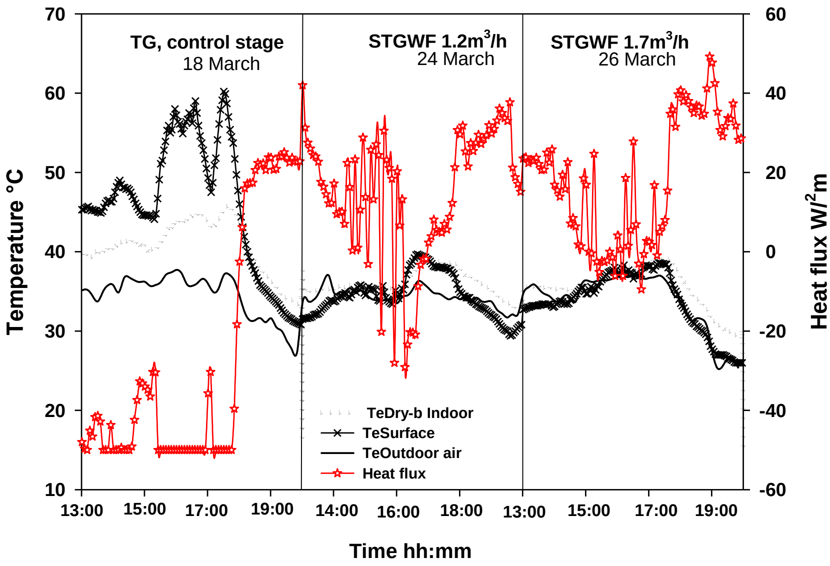

Figure 7.9:The temperature distributions on different configurations of STGWF and heat flux through, sunny hours.

7.3 DETERMINATION OF THE SOLAR ENERGY TRANSMITTANCE OF SGWF UNDER THE DIRECT SOLAR RADIATION IN THE TROPICS

It is useful to start the measurements by recording the data values of the global solar radiation on the east and the west orientations to stand on the differences between both orientations during the entire hours. However, Figure 7.10 and 7.11 show representative samples of the vertical solar radiation on the east and the west facades at the latitude of 3°.9´ N of Kuala Lumpur. The measurements were conducted during the extreme sunny periods of the tropics, where the solar radiation is overhead the equator. The Figures show that the east and the west facades receive almost the same solar radiation. However, there was an increase in the solar heat gain through the west facade because the solar radiation hits the west facade on the hottest time of the day. This is rightly so in the tropics in the non-rainy day-afternoon.

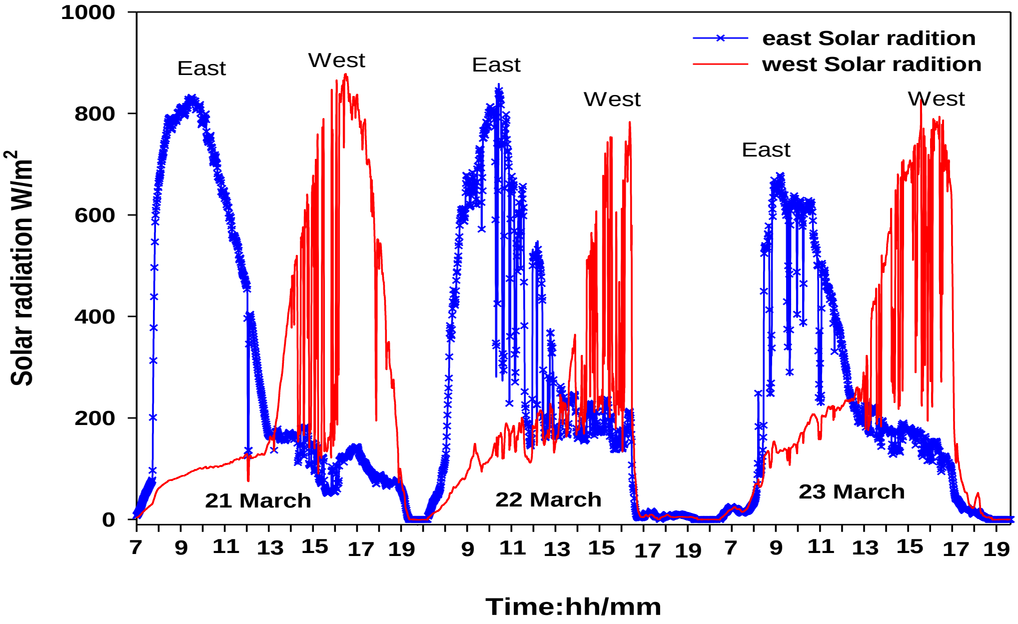

Figure 7.10: Comparison of the east and the west outdoor vertical solar radiation at the experiment site

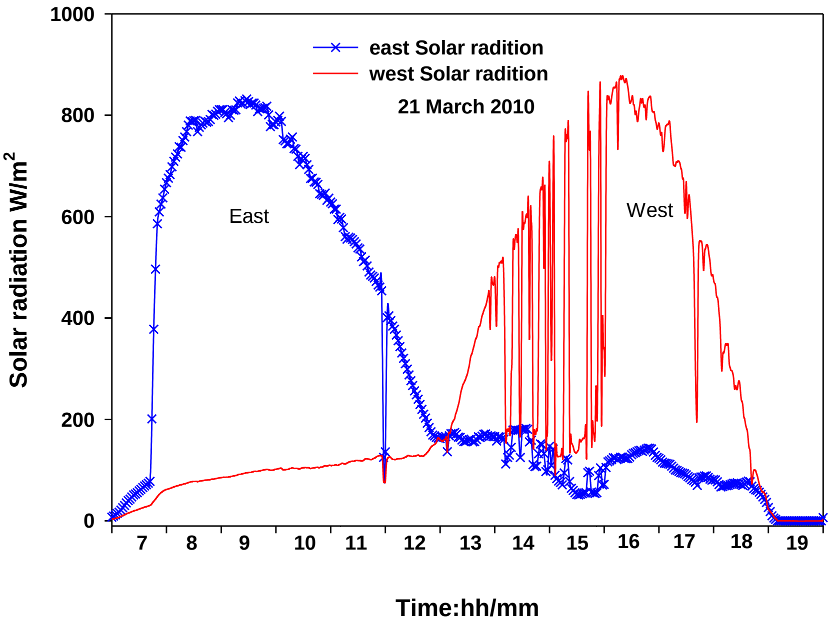

Figure 7.11: The solar radiation at the experiment site on the 21st of March where the equator receives the largest amount of the solar radiation.

7.3.1 Theory of the total solar energy transmittance within the SGWF facade

As mentioned in Chapter Three, the amount of the total solar radiation transmittance (UV, VL and IR) which passes through a glazing is usually evaluated in terms of solar heat gain coefficient “SHGC”. The lower the glazing's SHGC, the less solar heat it transmits. However, in terms of the SGWF facade which consists of the glazing with the outside flowing water film, the solar performance could be understood as follows, Figures 7.12 and 7.13: The incident solar radiation (I_0) is either reflected towards the outdoor ambient (I_1), transmitted into the inside (I_2) or absorbed by the water film and glass pane (I_3). The flowing of the heat in the SGWF facade has been discussed in the above section of the thermal transmittance. It has been found that in the SGWF facade, the heat flows via the conduction and the convection from the surface of the glass to the water film body (I_4) whereas, the heat flux flows inwards which is expressed as (I_5). Therefore, the total solar energy transmittance could be defined as:

$$SHGC = I_2 + I_5 \qquad (7.1)$$

By referring to the measurements of the thermal energy transmittance with SGWF which have been discussed earlier in this Chapter, the fraction (I_5) which forms the inward-flowing of the thermal energy absorbed by the glazed facade as illustrated in Figure 7.13 is found to be zero to (-50; outwards), and therefore, the Equation 7.1 will be as follows:

$$SHGC_{total} = I_2 \qquad (7.2)$$

However, there is a limitation in the measuring values of the fraction I_2 in this study due to the use of pyranometer that measures the total values of the solar energy, it also includes that portion occurred due to the green house effect inside the test rooms.

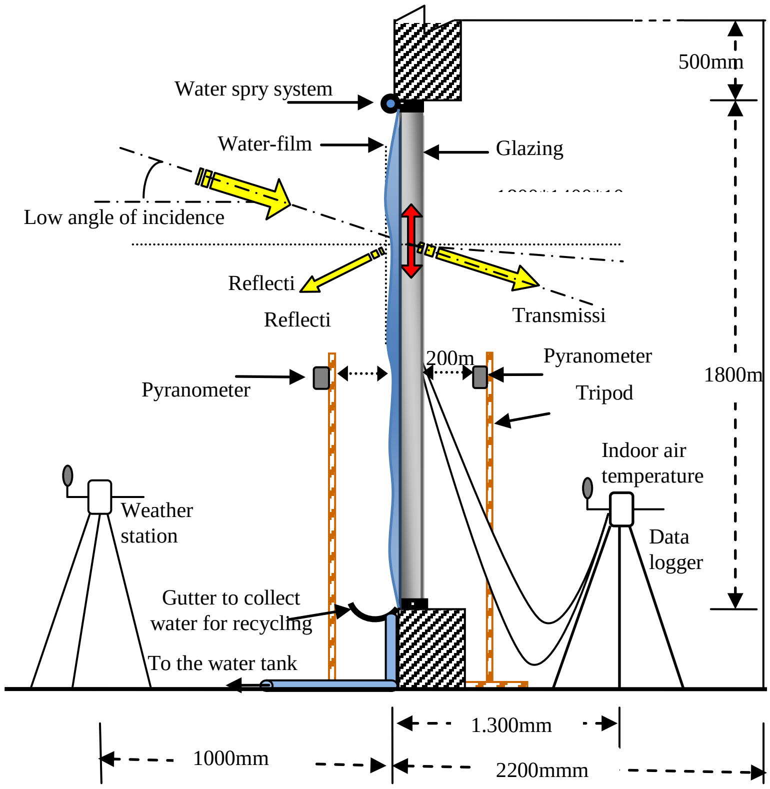

Figure 7.12: The schematics of the experimental set-up of the solar transmittance within the SGWF.

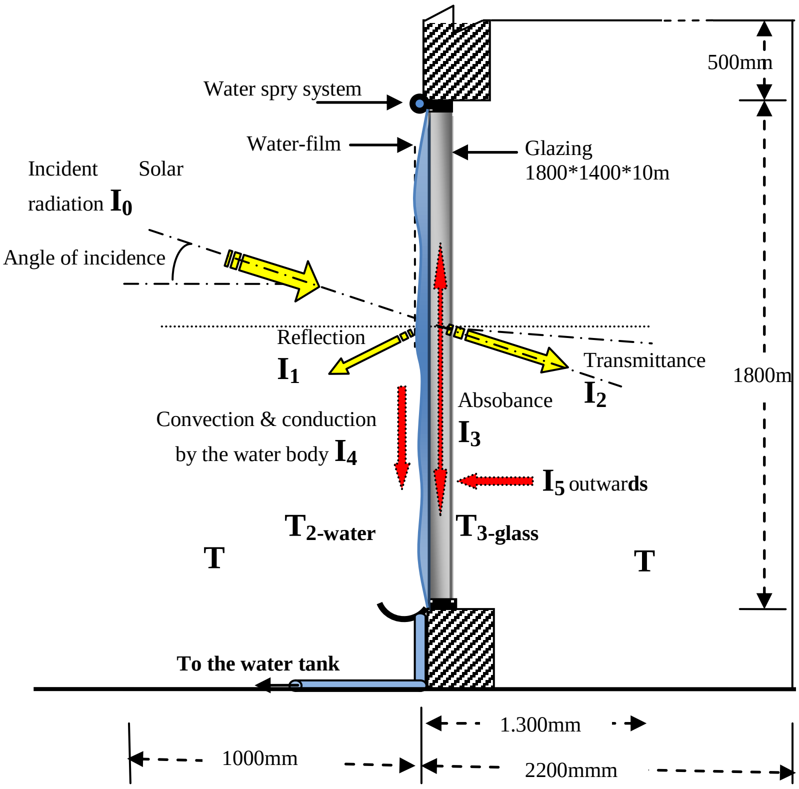

Figure 7.13: The schematics of solar energy performance within components of SGWF facade

Therefore, the fraction I_2 in the experiments of this study is the transmittance of both the shortwave (solar) and the long wave (thermal) that emit by the indoor surfaces.

7.3.2 Test Rooms' calibration

Figures 7.14 and 7.15 show the solar energy performance of the two rooms used at the experimental calibration stage. The measurement was conducted without treatments in both rooms to minimize any data errors. Overall, the measurement data was identical in both rooms. The error was found at 14:36 with an increase in test room of about 30W/m^2 than the reference room. This difference in the solar data may occur because of the difference in the position of the two pyranometers of the two rooms. The pyranometer which showed higher value in the treated room could be exposed at that exact time to additional reflected radiation from the surrounding surface. Nevertheless, the solar radiation throughout the day was recorded to be almost similar in both rooms, even when the solar radiation reached higher than that at the error point.

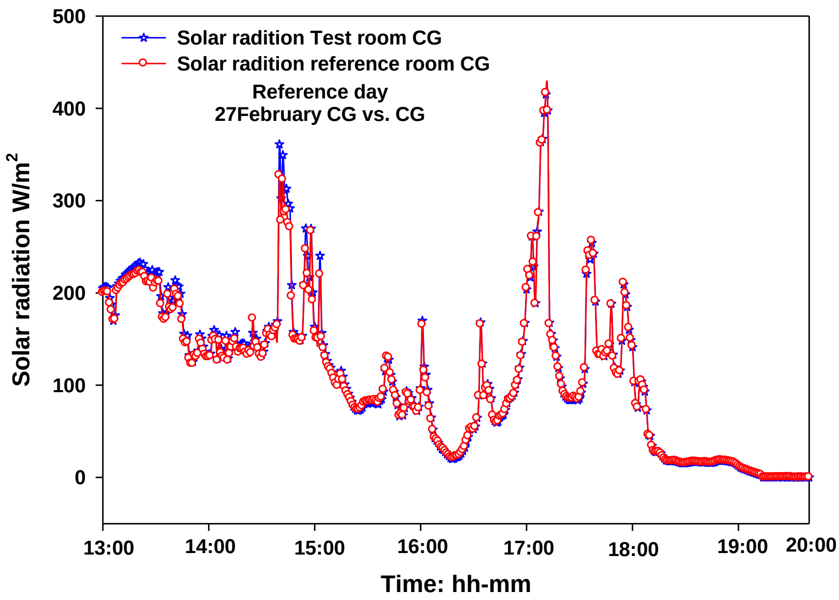

Figure 7.14: The solar radiation data in the two rooms (test room and control room) on the control day without any treatments in both rooms

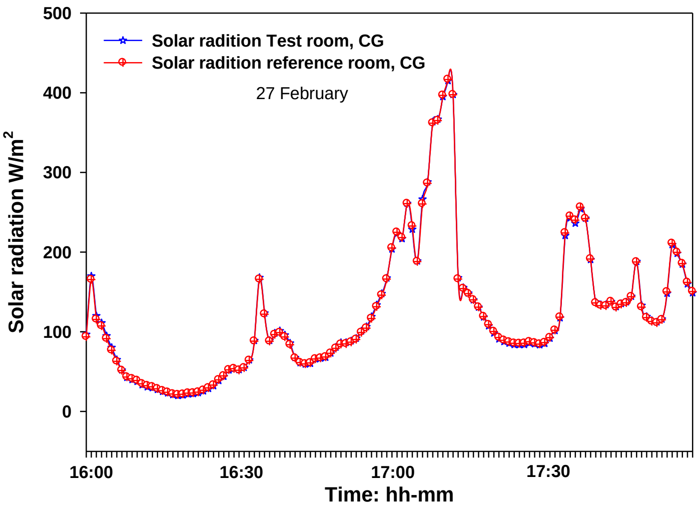

Figure 7.15: The equalization of the solar radiation data in both rooms at a control case

Likewise, the calibration of the rooms within the STGWF before commencing the measurements, as illustrated in Figure 7.16 showed that the solar radiation transmittance into the reference room was higher in the reference room than the treated room with an average of about 6.8%. This increase in the data value should be detected from the data values of TG (the reference room) when comparing and analysing the solar performance of STGWF.

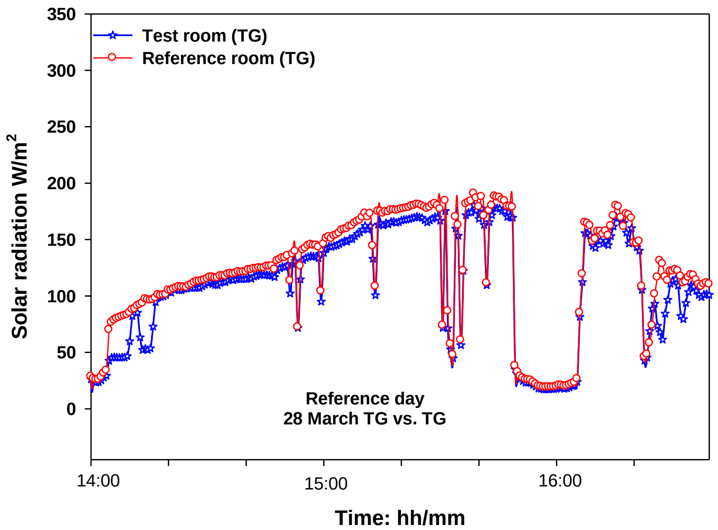

Figure 7.16: The difference between the two rooms without treatments (rooms' calibration)

7.3.3 Solar radiation transmittance through the SCGWF

Experiments were performed at same time in the two rooms; the treated room and the reference room to determine the solar radiation transmittance of the SCGWF facade. Table 7.3 summarizes the average percentage differences in the solar transmittance between the SCGWF facade and the CG as the reference facade. The results were demonstrated in two different sky conditions over two weeks; the sunny hours and the cloudy hours. Overall, as summarized in Table 7.3, the results of SCGWF showed an increase in the solar energy transmittance of about 6.2% on the sunny hours, while on the cloudy hours, the increment was found to be about 2.9% with the SCGWF facade than the CG facade.

Table 7.3: The amount of the solar radiation transfer towards the interior of SCGWF as opposed to the CG facade

SCGWF. Judgement against control room with CG			Indoor-Solar radiation	Ext. global -solar radiation	Remarks
Rooms calibration	27Feb	CG (test room)	*171.6*		On the cloudy hours, the angle of the solar radiation incidence does not apply. So the analysis involved all the operations hours of the water film.
		CG (control)	*173.1*		
		Difference	*1.5W/m^2*		
		More solar radiation in the reference room of about 0.86%			
Sunny hours	Peak hours 11&18Feb at 4pm	SCGWF	*485.4*	*1100.1*	
		CG (control)	*460.4-0.86%=456.5*		
		Difference	*28.9W/m^2*		
		Solar radiation increases about 6.2%			
Cloudy hours	1-5pm	SCGWF	*116.5*	*8037*	
		CG (control)	*114.2-0.86%=113.2*		
		Difference	*3.3W.m^2*		
		Solar radiation increases about 2.9%			

7.3.3.1 Solar radiation intensity

Figure 7.17 shows the hourly solar radiation transmittance, from 13:00 – 19:00, for different selected days within SCGWF. The Figure shows that the solar radiation transmittance of the glazed-facade with the water film increased with the increase in the solar radiation intensity. For more illustration of the SCGWF result values, Figures 7.18 and 7.19 show the values of the solar radiation transmittance on the sunny hours. The peak value occurred at 15:10 where the water film increases the transmittance of the solar radiation by about 20%. However, the accurate result of the peak might be taken for an hour's peak instead of a specific time of minutes to avoid any irregular measured data. Therefore, the average hour peak was found at 15:30 to 16:30 with an increase from 448W/m2 on CG to 476 W/m^2 on SCGWF, which causes an increase of about 6%.

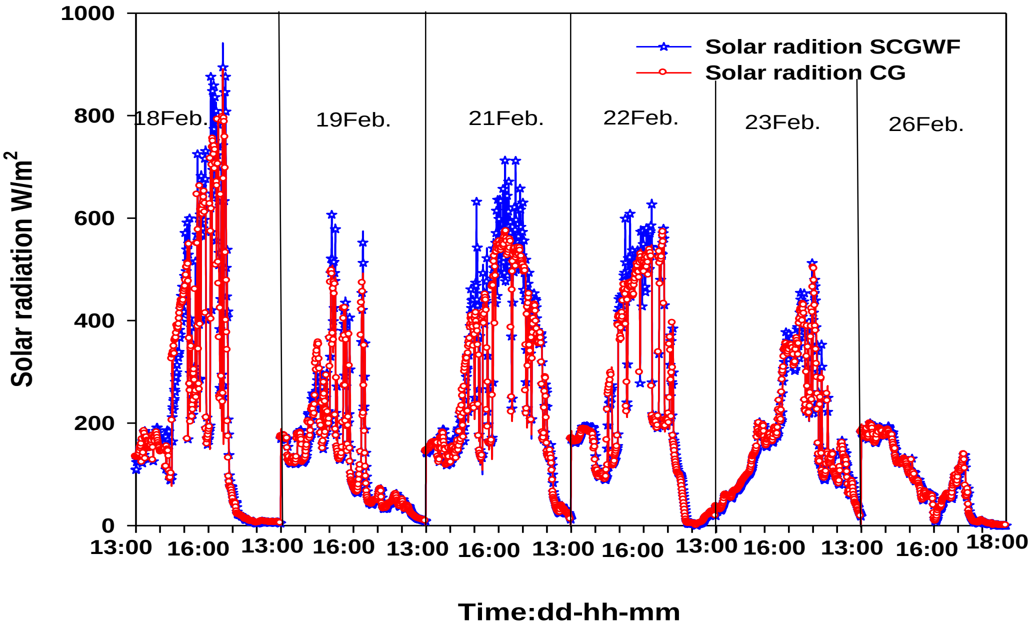

Figure 7.17: The solar radiation transmittance through SCGWF and CG for the different sunny and cloudy hours of February

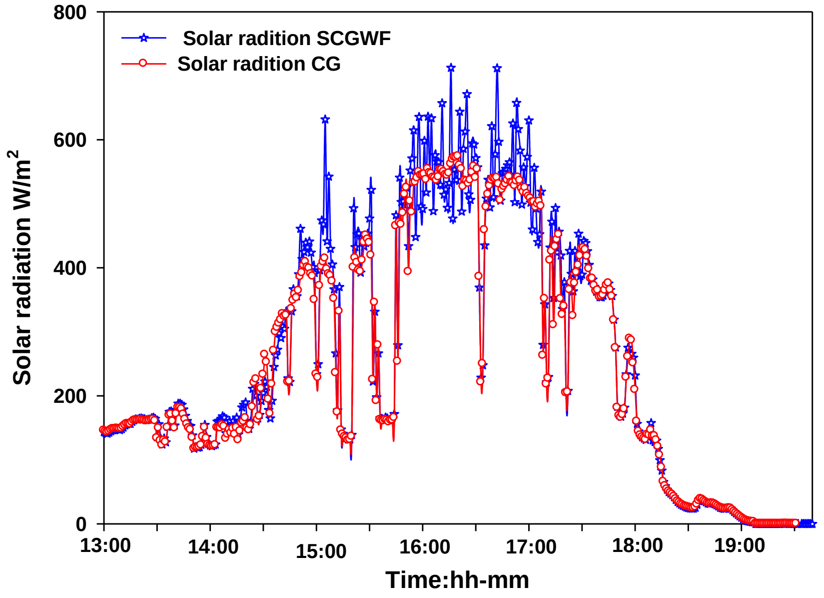

Figure 7.18: The increase in the solar radiation with the water film (the sunny hours of 22nd February)

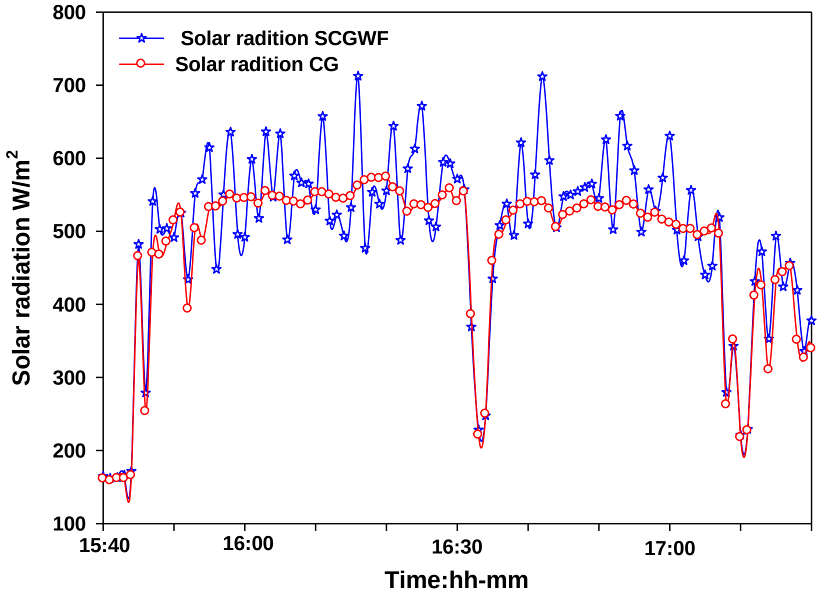

Figure 7.19: The effect of SCGWF on the solar radiation transmittance at the peak of the sunny hours 22nd February

Differently, Figures 7.20 and 7.21 show that the SCGWF facade on the cloudy hours did not increase much of the solar radiation transmittance indoors and there is no fluctuation of the radiation data values as well. As mentioned above in the review chapters, the radiation on the cloudy hours is generally a diffuse fraction with low intensity, which is a small fraction of the global solar radiation if compared to the direct solar radiation occurring on the sunny hours. Figure 7.21 also shows the peak of the solar transmittance on the cloudy day which occurred at 13:00 – 14:10, when the exterior solar radiation was 506.5W/m^2, and the outdoor air movement was 1.26m/s. However, the average increase in the solar radiation due to the water film of the SCGWF facade was on average 2% of the total solar radiation transmittance through the SCGWF facade.

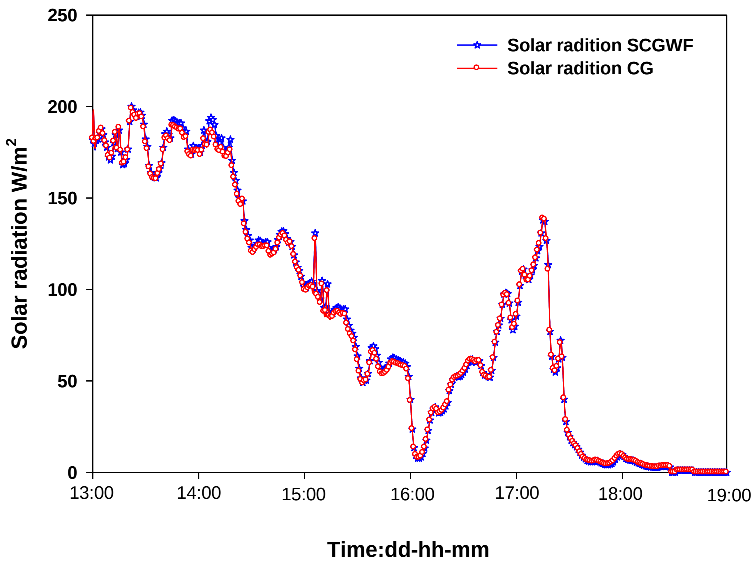

Figure 7.20: The increase in the solar radiation with the water film (the cloudy hours of 26th February)

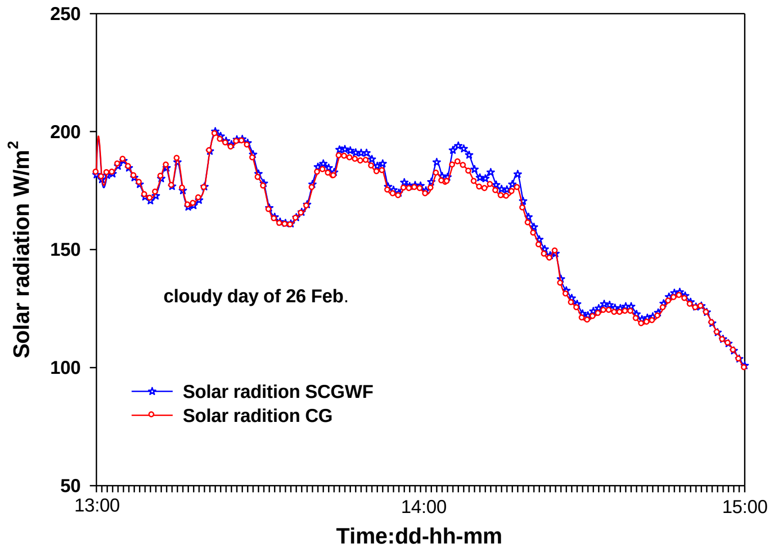

Figure 7.21: Solar transmittance of SCGWF on the cloudy at 13:00 – 15:00, 26th February.

7.3.3.2 Solar heat gain coefficient "SHGC" of SCGWF facade

To monitor the SHGC value of the facades the experiment was conducted with respect to the exterior vertical solar radiation as outdoor/indoor instead of the reference room indoor/indoor, Figure 7.22. With respect to the Equation 7.2, the SHGC is the total solar radiation transmittance measured by the pyranometer probe. However, comparing the measurement of the total solar radiation of the outdoor/indoor with the water film and without water film might be a practical way to investigate the SHGC of the SCGWF façade.

Figure 7.23 and 7.24 illustrate the changes in the values of the total solar radiation transmittance due to the flowing of the water film over the glazed-facade. Figure7.24 shows that the total solar radiation value behind the SCGWF during the high solar intensity was in some minutes higher than the outdoor value. This results to the increase in the SHGC behind the SCGWF façade due to the use of the water film. However, the seemingly negative result of the increase in the SHGC with suggested façade of SGWF will be discussed on the separate section of the solar optical transmittance of glazing with water film in this chapter.

Figure 7.22: The view of the tested west facade showing the pyranometers that measured the internal/external vertical solar radiation of the CG façade.

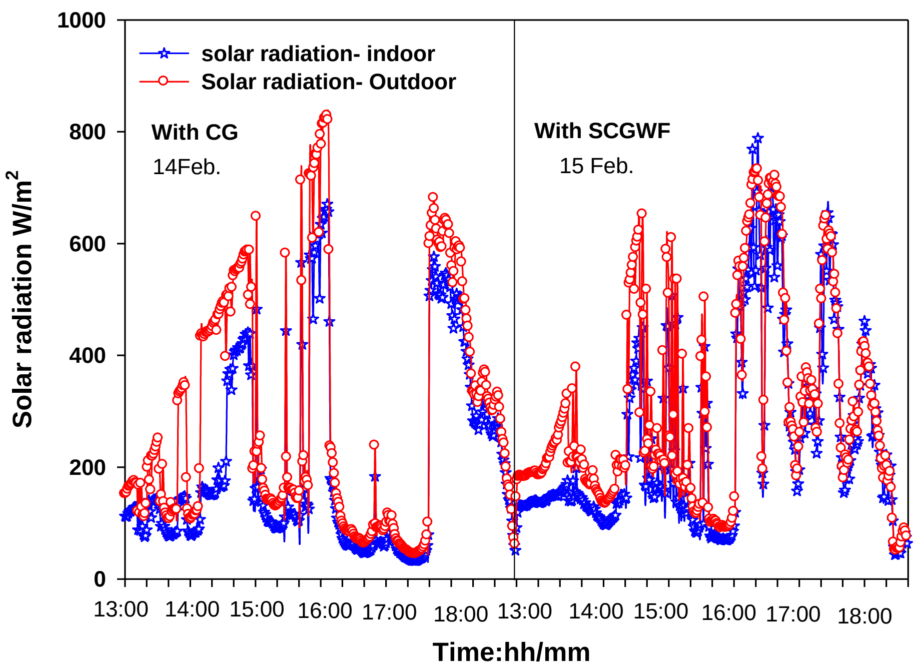

Figure 7.23: The difference between CG and SCGWF with respect to the exterior solar radiation in both cases (14th and 15th February)

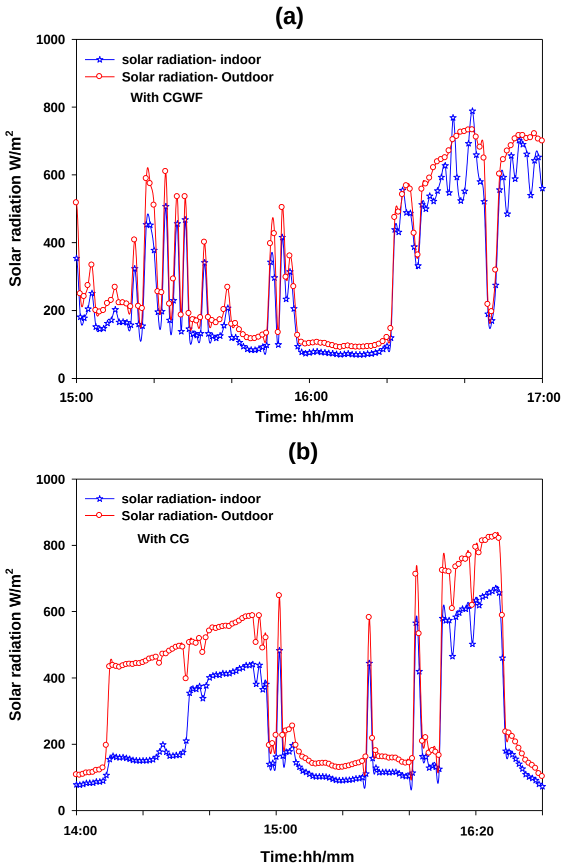

Figure 7.24: The peak difference in the solar radiation indoor/outdoor; (a) with water film SCGWF and (b) without water film CG

Figure 7.25 demonstrates the total solar energy that transmits indoors. It is noted that on the 6th of March with CG facade; although the solar radiation value (peak 647.5W/m^2) was higher than the day with SCGWF facade (peak value 605.4 W/m^2), the thermal energy with SCGWF kept flowing outwards. This is because of the difference in the temperature between the inner and the outer glass surface where the outer-surface temperature with the water film becomes lower with a minimum 1°C than the inner-surface.

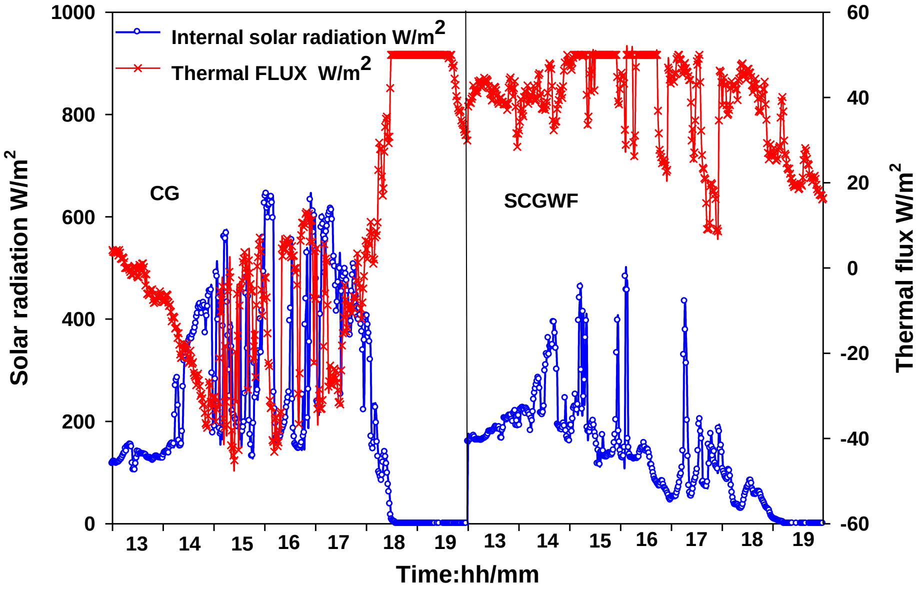

Figure 7.25: The differences in the total solar energy transmittance between the CG facade on 6th March and SCGWF facade on 7th March

This indicates that SCGWF results in the reduction of SHGC indoor, which in turn enhances the indoor thermal performance which has been verified earlier in the results of the thermal performance of the SGWF facades.

7.3.4 Solar radiation transmittance through the STGWF

Although the study does not intend to compare the performance of the different glass types, it is useful at this stage of the research to compare the solar transmittance of the clear glass and tinted glass types that were used in the experiments of this study. The analysis of the thermal parameters of the clear glass and the tinted glass was discussed above in this chapter. However, their solar performance as illustrated in Figure 7.26 showed that the tinted glass produced a significant reduction in the solar radiation transmittance compared to the clear glass. The difference in the reduction reached approximately 600W/m^2 peak value which was recorded at 16:00 of the measured day, when each of the external and the interior vertical solar radiations were 150 W/m^2 and 740 W/m^2 respectively, and the outdoor air movement was 1.76m/s at that time.

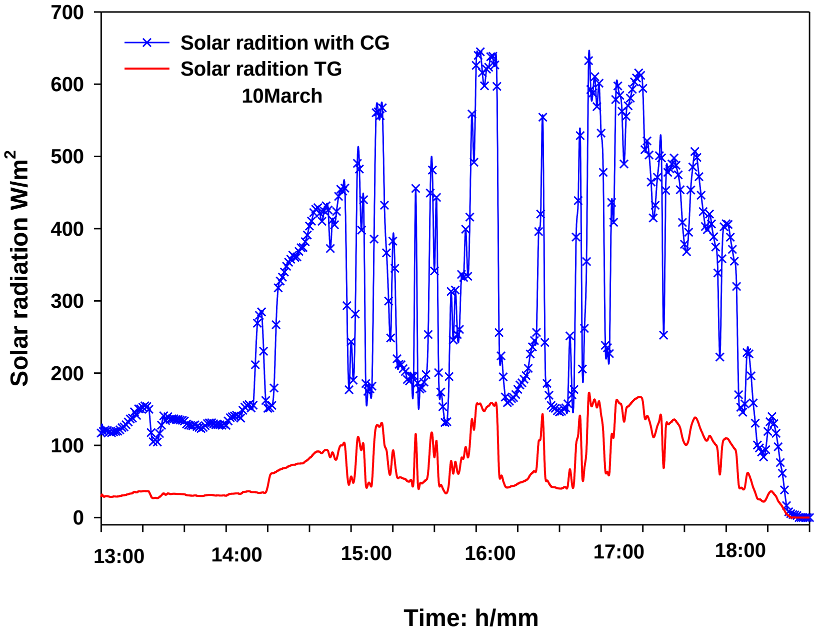

Figure 7.26: The difference in the solar radiation transmittance between the tinted glass and the clear glass

However, it is essential to note that the large value of the reduction in the solar radiation indoors within the tinted glass is due to the "bronze" [1] tint of the examined glass in this research. This reduction corresponds to the entire spectrum of the solar radiation which includes the ultraviolet, the visible light and the infrared.

In general, the fraction of the solar radiation that is admitted through STGWF is larger than that admitted through TG. It could also be seen in the Table 7.4 that the increased value of the solar radiation transmittance towards the interior of the STGWF facade occurred during high solar intensity (sunny hours). The differences vary from 2.2% (when the outdoor global solar radiation was 576.1W/m^2) to 8.5% (when the outdoor

1 This research chose the "bronze" tinted glass to cover the requirements of the selected method in this study, it is advisable for the office glazed-buildings to use bright tint options such as green and blue as reported above in the research review chapter.

global solar radiation was 1087.6W/m^2) out of the total admitted value of the solar radiation.

Table 7.4: The amount of the solar radiation transfer towards the interior of STGWF compared to TG facade

STGWF. Judged against the control room with TG average 5-7 days to each case.			Indoor-Solar radiation	Ext. global -solar radiation	Remarks
Rooms calibration	Average	TG(testroom)	*76.5*	*1087.6*	Rooms Calibration: The two rooms were calibrated before the actual test to reduce data errors when comparing between the two rooms. The difference recorded in this case will be subtracted from TG (reference room) result values.
		TG (control)	*82.1*		
		Difference	*-5.6*		
		6.8% to be detected from the data values of TG (reference room)			
Sunny hours	Peak hours	STGWF	*111.9*	*1164.6*	
		TG (control)	*109.9-6.8%=102.4*		
		Difference	*9.5W/m^2*		
		Solar radiation increases of about 8.5 %			
Cloudy hours	1-5pm	STGWF	*93.4*	*576.1*	
		TG (control)	*98.1-6.8%=91.4*		
		Difference	*2W/m^2*		
		Solar radiation increases of about 2.2%			

7.3.4.1 Solar radiation intensity

Figure 7.27 shows the solar radiation transmittance on different days, during the water film operation hours of 13:00 – 19:00 within STGWF. The Figure also shows that the transmittance of the solar radiation within the reference days, which are the 9th and the 28th of March, are approximately identical in their data values of the solar radiation behind the TG. Moreover, by referring to the data values of the days from the 11th to the 27th of March, the curves confirmed that the solar radiation transmittance increased when applying the water film to the tinted glass which is the STGWF facade. The variation of the increase in the solar radiation behind the STGWF within these days depended on the solar radiation intensity, where the high solar intensity on 15th of March showed an obvious increase in the solar radiation transmittance indoors.

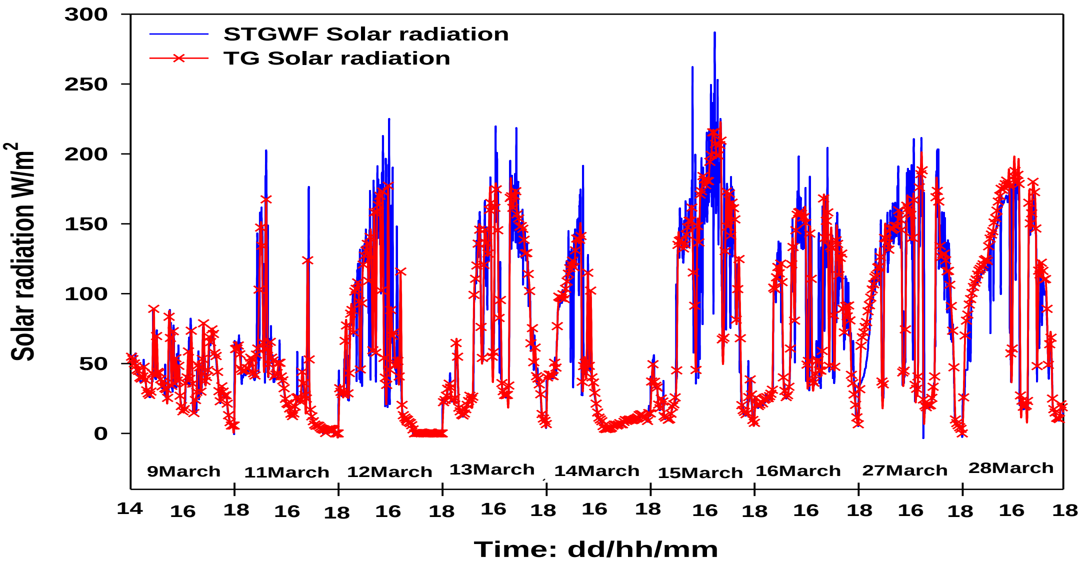

Figure 7.27: The solar radiation comparison on different days

It is essential to note that the results of SCGWF and STGWF are approximately similar in respect to the increase of the solar radiation transmittance and to the fluctuation of the data values behind both facades. The difference in showing the low data values behind STGWF compared to SCGWF is due to the difference in the specifications of the glass in each facade. Figures 7.28 and 7.29 show the increase and the fluctuation of the solar radiation behind STGWF. On the sunny hours as illustrated in Figure 7.28, the peak value of the solar radiation transmittance occurred at 17:05 where the water film increased the transmittance of the solar radiation by about 38.9%. However, as discussed above, with SCGWF, the perfect result of the peak might be taken for an hour peak instead of a specific time of minutes to avoid any irregular measured data. Therefore, the average hour peak increase value was found at 15:00 with an increase from 123.2 W/m^2 on TG to 130.5 W/m^2 on STGWF, causing an increase by about 5.6% more with STGWF.

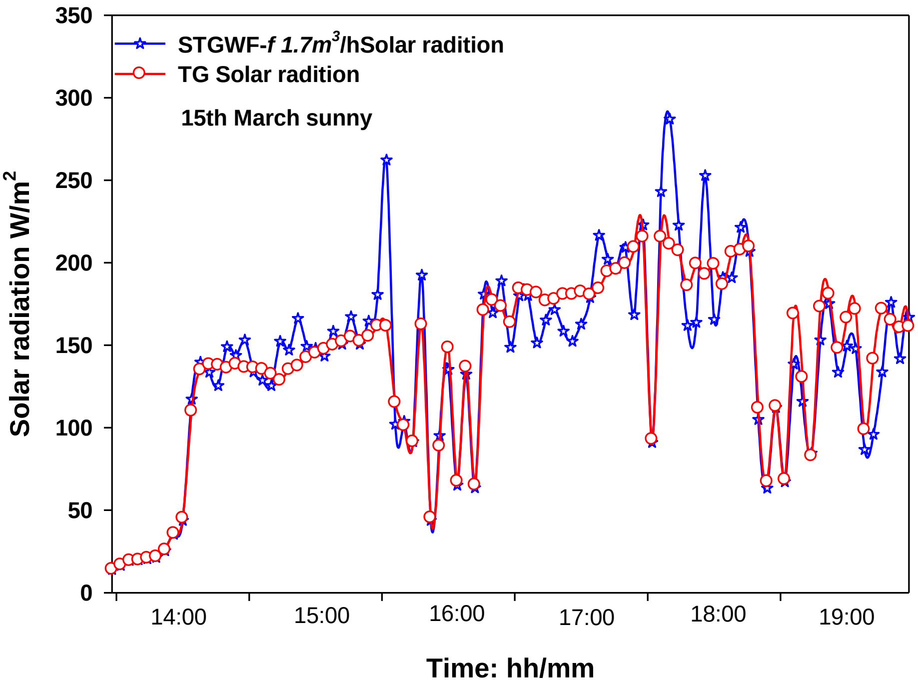

Figure 7.28: The performance of the solar radiation transmittance with the presence of the water film over the tinted glass on the sunny hours

Meanwhile, on the cloudy hours as illustrated in Figure 7.29, the STGWF facade did not increase much of the solar radiation transmittance indoors and there was no high fluctuation of the data values of the solar radiation. The average increase in the solar radiation due to the water film within the STGWF facade on this day was on average 2.4% more with the STGWF facade.

However, the appeared fluctuation in the solar transmittance during the cloudy hours with STGWF occurs due to the sky condition of Malaysia as a tropical country. It is conceded as an intermediate sky and difficult to confirm either sunny or cloudy sky for the entire day as has been discussed earlier in the Chapter 2.

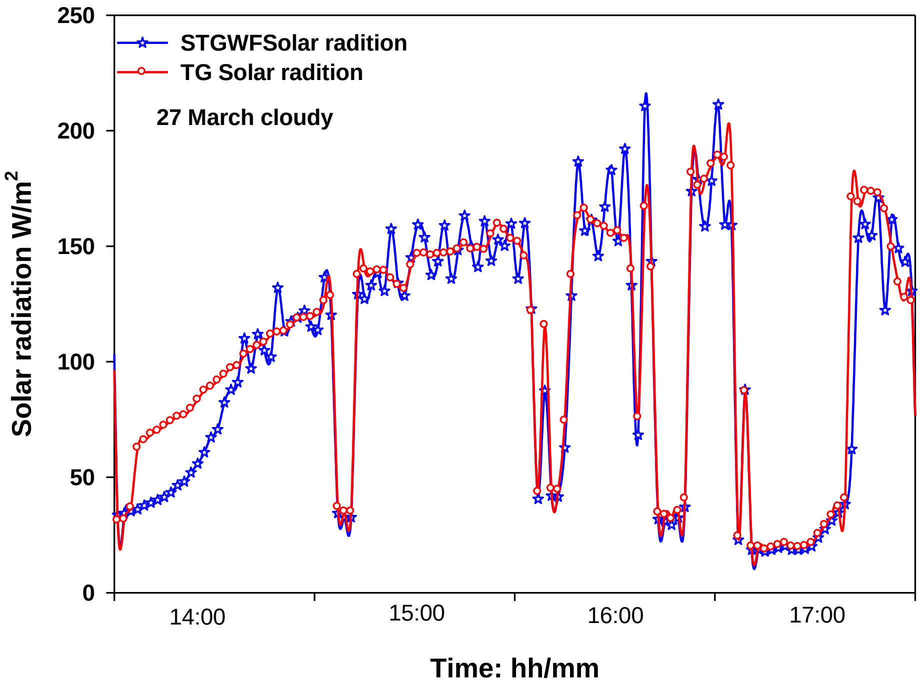

Figure 7.29: The difference of the solar transmittance between TG and STGWF on the cloudy hours.

7.3.4.2 Solar heat gain coefficient "SHGC" of STGWF facade

Figures 7.30 and 7.31 are further illustrations of the changes in the solar radiation transmittance behind the STGWF, but comparing the outside/inside as pre-test and post-test method instead of the reference facades. The increase in the solar radiation transmittance with the STGWF could be seen on Figure 7.31 (a), compare to the TG on Figure 7.31 (b). Predicting the overall solar radiation transmittance is a key to stand on the SHGC of the glazed facades. However, it is relatively difficult to distinguish the decrease or increase in the solar radiation transmittance behind the STGWF facade within these plots because of the high difference in the solar radiation between the external and the internal values due to the use of dark tint; bronze glass.

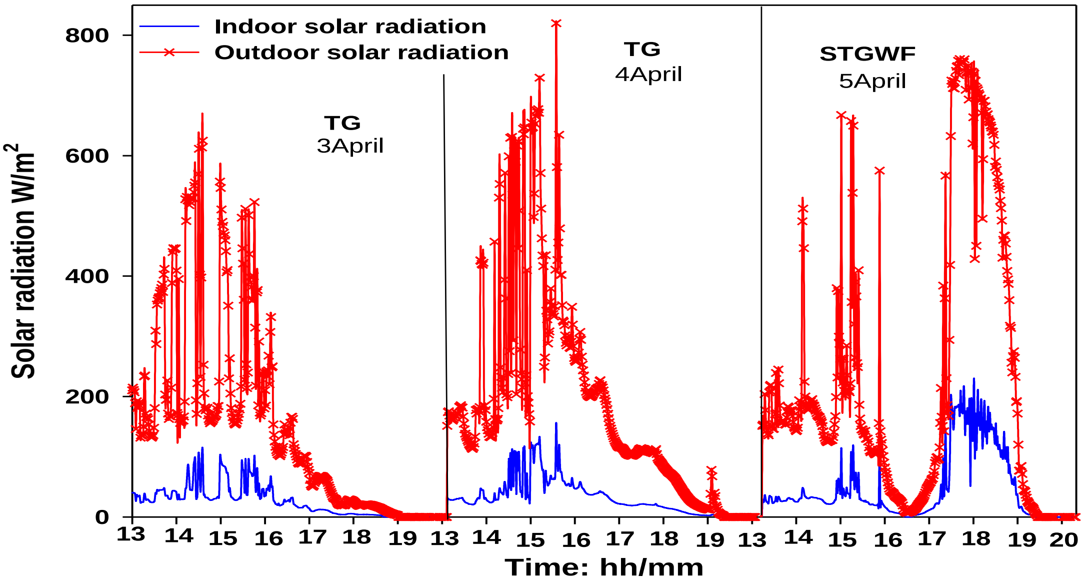

Figure 7.30: The difference of the solar radiation between the outdoor and the indoor within TG and STGWF

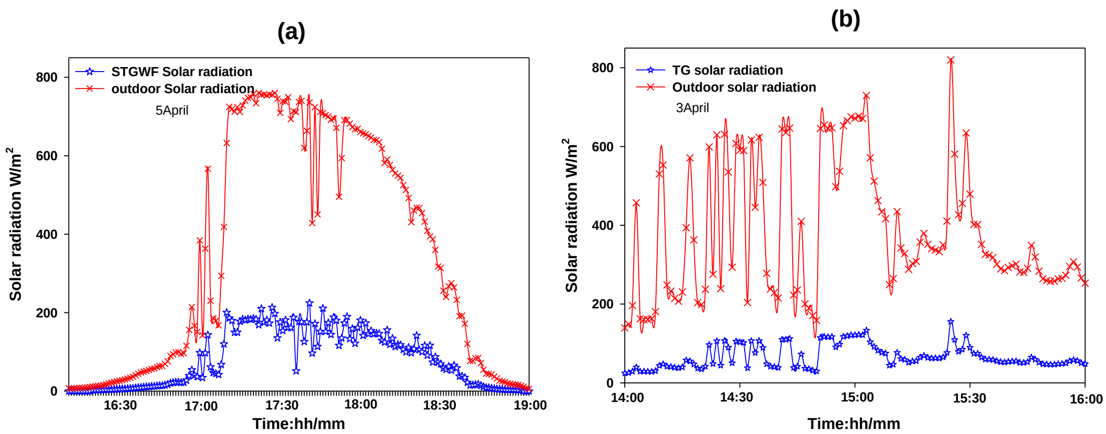

Figure 7.31: Comparisons between outdoor solar radiation and indoor solar radiation within TG and STGWF

Figure 7.32 shows the total solar energy transmittance within STGWF compared to TG. The significant reduction in the solar heat energy was found during the operation of the water film on the STGWF facade on 27th of March. It was found that the thermal flow remained approximately zero and the flow outwards reached a peak of (+43.7 W/m2) when the solar radiation behind the STGWF facade was 179.7 W/m^2. On the other hand, in respect of the TG facade, the solar heat energy kept flowing inwards and reached the maximum of the heat flux prop range of (-50 W/m^2) when the solar radiation behind the TG facade varies from 100 to 160 W/m^2. This significant value of the heat energy flow inwards was due to the high solar absorptive of the TG that frequently retained a portion of the absorptive energy inwards. With STGWF, the water film prevented this portion of the heat energy from admitting inwards, in addition to that water film acting as a "heat sink" which enhanced the heat flowing outwards.

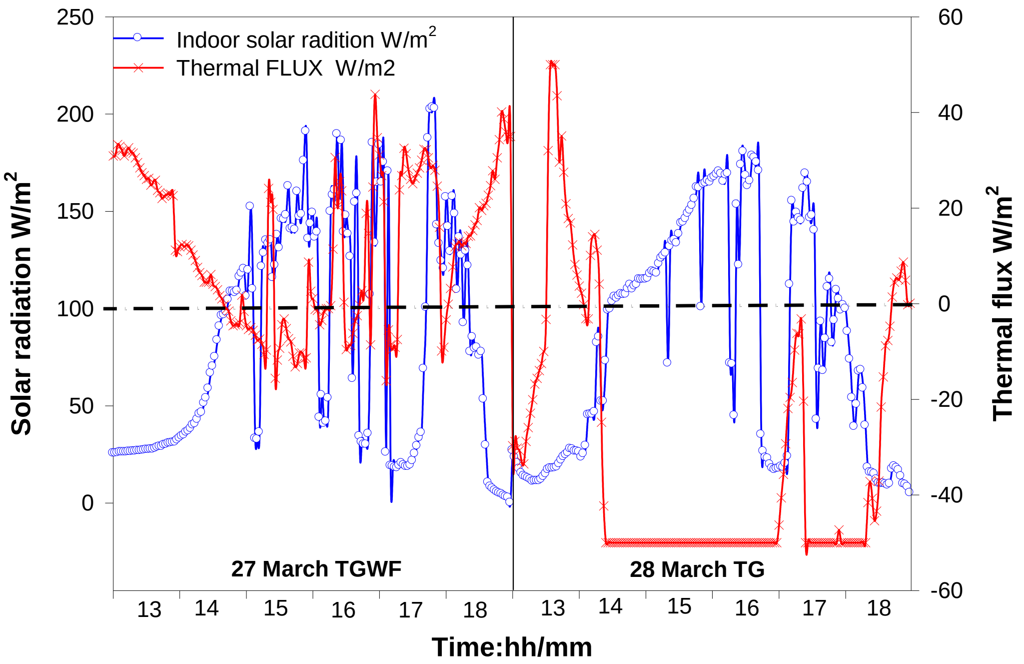

Figure 7.32: The difference of the total solar energy transmittance between the TG facade on 28th of March and the STGWF facade on 27th of March

The solar radiation transmittance increased behind the SGWF facade, and the increase varied according to the solar intensity and the sky condition. For SCGWF as mentioned above, the increase varied from 2% to 4% compared to CG. While within STGWF, the increase fluctuated from 2.2% during the cloudy hours to 6.8% on the sunny hours. However, this increase of the solar radiation transmittance as found in this study showed an agreement and disagreement with some previous studies, which are related to water element.

The studies which have been cited in the literature review of the current research (Pollet and Pieters, 1999; Pieters et al., 1997; Pollet and Pieters, 2000; Pollet et al., 2003) were focusing on the effect of the water condensation on the visibility of the glass. The studies concluded that the transmittance of the visible light decreases with the condensation on the glass. Nevertheless, this finding does not comply with the results of the current study. The explanation for this non-compliance is the differences of the systems principle adopted; where, the solar optical transmittance of the condensation on the glazing is not as that on the flowing water film over the glass. The results of the current research showed an agreement with another study reported by Krauter (2004), which showed an increase in the solar optical transmittance of PV panels as soon as the water film started flowing down over the panels. The increase of the solar transmittance due to the application of the flowing water film over the glass was also confirmed by Pollet (1999) that a smooth flow of a water film produces an increase of the solar optical transmittance.

In summary, because of the large portion of the infrared (or heat) is absorbed by the SGWF facade but then is totally prevented from admitting inwards, SHGC is reduced according to the Equation 7.1. However, theoretically the amount of the total solar energy (the UV, the visible and the infrared radiations) which transmits through the SGWF facade will be reduced. But the measuring values by the pyronometer of the total solar energy transmittance behind the SGWF facade were found to have increased, which accordingly means an increase in SHGC. This seemingly conflicting result of the solar transmittance with the water film would be interpreted and further discussed in the following section of the solar optical transmittance calculation of SGWF facade.

7.4 THE LABORATORY AND CALCULATION VALIDATION OF THE SOLAR OPTICAL PERFORMANCE OF THE SGWF FACADE

The presence of the water film over the glazing will affect the natural convection and the radiant heat transfer from the window. As a result, there will be a change in the two portions of the solar heat gain; the heat conduction and the SHGC of the glazed facades. The first, which is the heat conduction through the glazing with the presence of the water film that has been measured in this current study and confirmed mathematically in many previous studies as were cited in the literature. Meanwhile, the SHGC is the essential portion of the solar heat gain to be controlled in the tropics. The current study has measured and discussed the SHGC. The following are laboratory experiment and numerical attempt to validate the results of the site experiments.

Figures 7.33 and 7.34 illustrate an example of the seemingly conflicting measuring results between the solar radiation and the indoor thermal values for two different sunny days. The results on 27th of March showed the peak data values on the tested west facade during the operation of the sustainable water film. The result of the solar radiation energy was found higher behind the STGWF than TG, while on the reference day of 28th of March, without water film in both rooms, the solar radiation behind the tested glazed facades (TG vs. TG) showed almost identical results in both rooms. Thus, the increase in the solar radiation could be claimed as an increase in the visible light energy at the expense of the infrared energy.

Monitoring the result of the indoor air temperature of the same configurations (STGWF) at the same time of (27th and 28th March) would confirm this claim. The STGWF caused a significant decrease in the indoor air temperature compared to TG as illustrated in Figure 7.34 on the 27th of March, while the reference day, Figure 7.33

showed that the two rooms without the water film were almost similar in respect of the indoor air temperature. Thus, the SGWF facade performed as a sustainable spectrally selective facade which transmitted the visible light (daylighting) and blocked the infrared (heat), which is appropriate for the glazed buildings in the tropics.

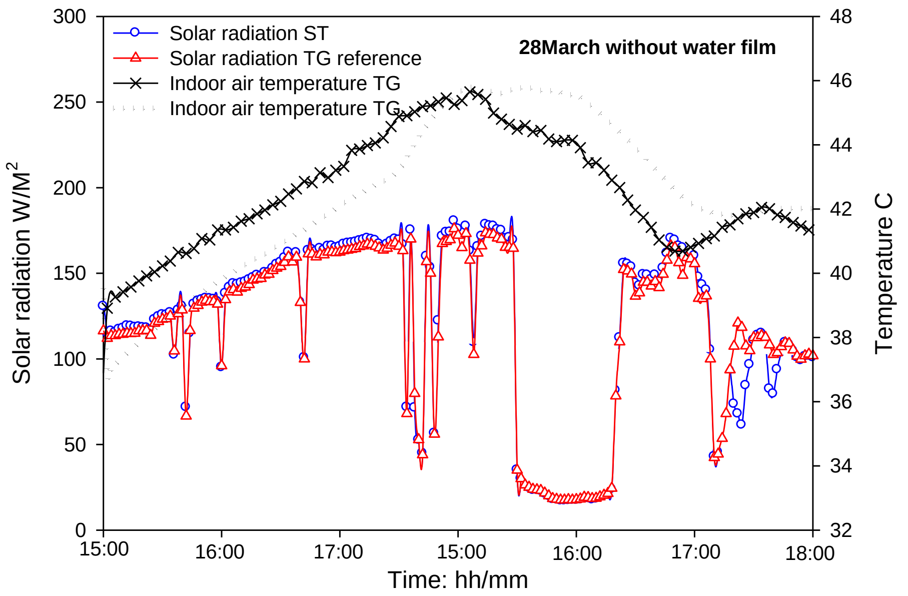

Figure 7.33: The calibrated day without water film in both rooms

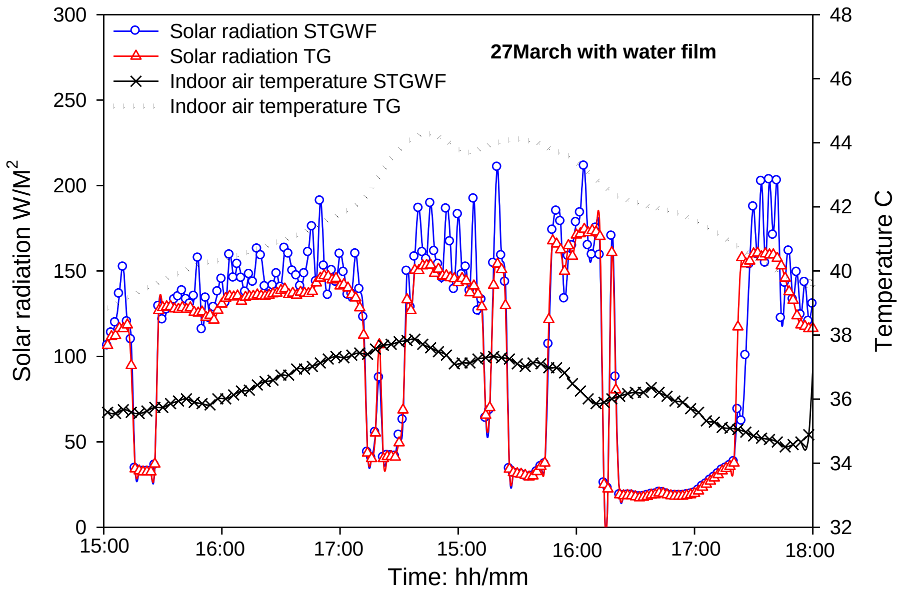

Figure 7.34: The decrease in the indoor air temperature and the increase in the solar radiation behind the STGWF

However, the reduction in the transmittance of the thermal energy indoors and the increase in the transmittance of the visible light energy resulted in the increase of SHGC of the SGWF facade compared to the reference facade without the water film. In this context, there was no clear justification for this an increase of the SHGC behind the SGWF façade, except that the water had caused the increase of the transmittance of the visible light while reducing the transmittance of the thermal energy.

Further, explanation for this discrepancy could be given by the following:

(a) To understand the increase in the solar radiation transmittance with SGWF, it is pertinent to understand the solar optical performance (transmittance, reflectance and absorption) of the solar radiation within the water element. The following results and discussion focus on the solar optical characteristic (mainly the "transmittance") of the water film for the entire wavelengths of the solar radiation spectrum. These solar optical characteristic were measured by the laboratory equipment *"spectrophotometer*" (as shown in Figure 7.35). Distilled water and tap water were measured in a solar optical glass of a standard "*Quartz Cuvette"* with a path length of 10mm (as shown in Figure7.36). The wavelength covered from 190 to 2500 nm, which effectively covered the solar radiation wavelengths. The results of the measurements are illustrated in Figure 7.37. It showed that the absorptive wavelength range of the water started at the NIR range from 780 to 2500nm. A higher absorption was recorded at the range from 1300nm to 2500nm, where the radiation is totally absorbed. Whereas the high transmittance was at the visible light VL region of the solar spectrum from 380 to 780nm. The visible light transmittance values of more than 100%, is seemingly not right, but they can be explained as follows. As illustrated in Figure 7.38, the reason is that the water refracts the solar beam inwards, causing

Figure 7.35: The set up of the “spectrophotometer” for measuring the solar optical properties of water.

Figure 7.36: The optical glass of a standard “Quartz Cuvette” that was used for testing the water transmittance

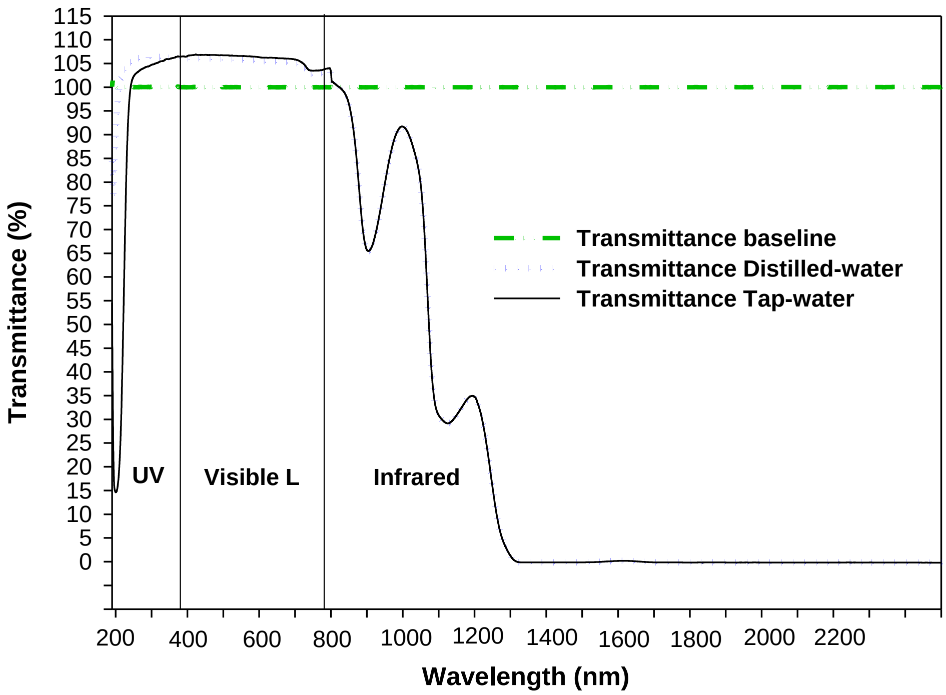

Figure 7.37: The solar optical properties of the water for regular incident solar radiation (Author).

a slight focussing affect on the detector. So if the beam over-fills the detector, a diverging beam can lead to a higher transmittance values. This confirms the site experiments results of the solar radiation transmittance, which were found increase at the SGWF facades compared to the glazed facade without the water film.

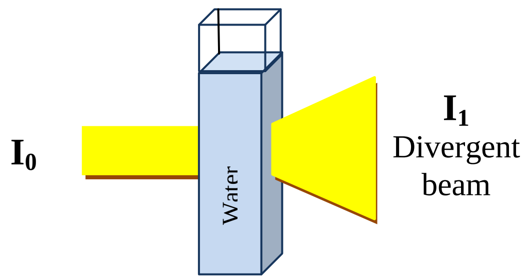

Figure 7.38: The divergent solar beam in water at the regular transmittance

(b) The probable explanation for the increase in the solar transmittance measurement is that the water plays a role of anti-reflective coating to the light. Based on the Fresnel's laws the light reflection of the surface becomes low with anti-reflective surfaces. Hence, by applying the water film on the glazed facade, the water serves as an anti-reflective coating because the water has a solar optical refractive index of n=1.33, which is close to the air with an index of n=1 than glass with an index of n=1.54. However, the fact that the visible light has a large portion within the solar spectrum range, confirms the significant increases in the transmittance of the visible light within the total solar radiation. Moreover, the water film on the outer glass surfaces may cause the inner glass surface to become more reflective. Following this, the visible light that transmits indoors and reflects from the indoor surfaces onto the inner-glass surface could reflect back onto the pyranometer. This leads to the increased of the solar radiation reading behind the SGWF. In summary, if was known that 45% of the total solar energy is in the non-visible infrared region that ranges form 780 – 2500 nm, in addition to the experiment results mentioned earlier that concluded a reduction in the thermal flow inwards with SGWF; verily, the increase behind the SGWF in the transmittance of the solar radiation is an increased in the visible light region of the solar radiation (daylighting).

(c) Based on the above discussion, the study proposes that the SGWF is a "sustainable spectrally selective glazing", which has a high transmittance of visible light and low transmittance of infrared radiation (heat). However the SHGC might be not an appropriate factor to evaluate the solar performance of the SGWF façade. Therefore, the Light-to-Solar Gain ratio (LSG) is the accurate ratio to evaluate the efficiency of the "spectrally selective glazed facade". The LSG ratio measures the efficiency of the glazing in transmitting the daylighting while preventing the heat gains. The following is the attempt to numerically calculate the LSG of the SGWF facade.

From the definition of the LSG ratio, the equation will be:

$$LSG = \frac{VT}{SHGC} \qquad (7.3)$$

Where *VT* is the overall transmittance of the visible light through the SGWF. While the SHGC of the SGWF might be calculated as a multiple glazing with coatings, as shown in the following equation (Klems and Warner, 1997):

$$\boldsymbol{SHGC = T_{total} + \sum_{k=1}^{n} \mathrm{N_k} * \mathrm{A_k}} \qquad (7.4)$$

Where, $\boldsymbol{T_{total}}$ is the overall solar radiation transmittance of the system;

N_k is the inward-flowing fraction of absorbed radiation; and A_k is the solar absorption of a single-element.

However, normally the overall solar transmittance of a glazing system is measured in a laboratory using the spectrophotometer. But in the case of SGWF, the transmittance (T_{SGWF}) could not be measured by this equipment. One of the problems is that the SGWF requires a special equipment to cope with the large sample of the SGWF facade or to design a small sample of SGWF to suit the spectrophotometer, which is also not possible due to the requirement of installing the water spraying system. Therefore, the calculation might be the easiest way to predict the overall solar transmittance of the SGWF.

Referring to the experiments results, the N_k in the Equation 7.4 was found to be zero and the thermal conduction of the absorbed heat fluctuating from zero to -50W/m^2 outwards. Therefore, the Equation 7.4 becomes as:

$$\boldsymbol{SHGC_{SGWF} = T_{SGWF} + (0 \times \mathbf{A_{SGWF}})} \quad (7.5)$$

$$\boldsymbol{SHGC_{SGWF} = T_{SGWF}} \quad (7.6)$$

The value (0) is the inward fraction of the absorbed energy by the SGWF facade. It was found in the site experiments with the SGWF (the water film and the glass) equalizes zero or flows outwards with a negative value.

Moreover, based on the "Beer–Lambert law" and referring to Figure 7.39, the $\boldsymbol{T_{SGWF}}$ could be calculated as follows:

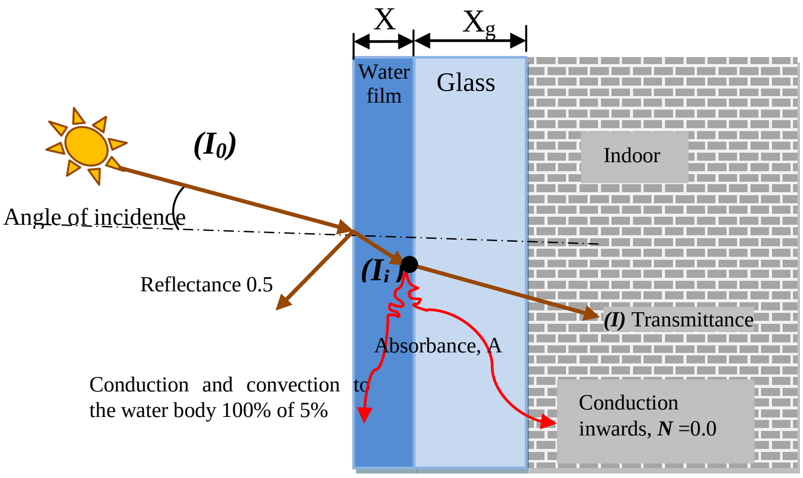

Figure 7.39: The transmittance of the solar radiation through the SGWF facade (Author)

$$\boldsymbol{T_{water}} = \frac{\boldsymbol{I_i}}{\boldsymbol{I_O}} \tag{7.7}$$

$$\boldsymbol{I_i} = \boldsymbol{T_{water}} \times \boldsymbol{I_o} \tag{7.8}$$

$$\boldsymbol{T_{glass}} = \frac{\boldsymbol{I}}{\boldsymbol{I_i}} \tag{7.9}$$

Replacing the I_i in the Equation 7.9, the T_{glass} becomes as follows:

$$\boldsymbol{T_{glass}} = \frac{\boldsymbol{I}}{\boldsymbol{T_{water}} \times \boldsymbol{I_o}} \tag{7.10}$$

Similarly the $\boldsymbol{T_{SGWF}}$ is the transmittance of the total SGWF facade that is as:

$$\boldsymbol{T_{SGWF}} = \left(\frac{\boldsymbol{I}}{\boldsymbol{I_o}}\right) \tag{7.11}$$

From Equations 7.10 and 7.11, the $\boldsymbol{T_{SGWF}}$ might be determined as follows:

$$\boldsymbol{T_{glass}} = \frac{\boldsymbol{1}}{\boldsymbol{T_{water}}} \times \left(\frac{\boldsymbol{I}}{\boldsymbol{I_o}}\right) \tag{7.12}$$

$$\boldsymbol{T_{glass}} = \frac{\boldsymbol{1}}{\boldsymbol{T_{water}}} \times (\boldsymbol{T_{SGWF}}) \tag{7.13}$$

Therefore, the overall transmittance of the SGWF facade is as follows:

$$\boldsymbol{T_{SGWF}} = \boldsymbol{T_{water}} \times \boldsymbol{T_{glass}} \tag{7.14}$$

This Equation 7.14 holds true with assumption that the interface between the water film and the glass surface is neglected. However, the Є constant might be added to the equation to correct the errors as follows:

$$\boldsymbol{T_{SGWF} = T_{water} \times T_{glass} \times \epsilon} \quad (7.15)$$

Nevertheless, for the visible light transmittance with respect to the refraction index of the water, the water film over the glazed facade serves as an anti-reflective coating. Where water has a solar optical refractive index of n=1.33, which is close to air with an index of n=1 than glass with an index of n=1.54, thus, Equation 7.15 for the total solar radiation transmittance of the SGWF facade will become as follows:

$$\boldsymbol{T_{SGWF} = \left(T_{water} \times T_{glass} \times \epsilon\right) + (R_g - R_w)} \quad (7.16)$$

Where R_g is the portion of the reflected visible radiation by glass, which is given by the manufacture i.e. 10mm clear glass has a visible light reflectance of 8%. While R_w is the reflected portion of the visible radiation by the water film that was found to be 0.5%.

However, to calculate the $SHGC_{SGWF}$ it is essential to first determine the total transmittance of the SGWF facade (T_{SGWF}), which hereafter can be calculated by Equation 7.16. The transmittance of the water was measured in the laboratory by the spectrophotometer, while the transmittance of the glazing was given by the glass manufacture, as shown in Table 7.5, and the results of the calculation are summarized in Table 7.6. The overall solar transmittance value is the same value of SHGC during the operation of the water film, while without water film the value of SHGC is the value of solar transmittance multiplies by the inwards conduction value. However, the calculation shows an improvement in the SHGC of the SGWF facade, which has low SHGC compared to the glazed façade without the water film. Differently, the results of the site experiments, as mentioned earlier, showed an increase in the SHGC with the SGWF façade due to the flowing of the water film over the glass.

However, the LSG ratio may interpret this seemingly conflicting result. The spectrally selectivity of the water film has the ability to transfer and increase the visible light while absorbing the short wave infrared. As shown in Table 7.6, the higher LSG number indicates the more daylighting without adding any extreme amount of the heat in the indoor spaces (low SHGC). The SGWF façade, therefore, might be the appropriate sustainable glazing system for east and west glazed facades in the tropics.

Table 7.5: The characteristics of the glasses used in the experiments

Product	*Thickness (mm)*	*Visible light*			*Solar radiation*				*SHGC*	*SC*	*U-value W/m^2k*
		Transmittance	*Reflectance*		*Transmittance*	*Reflectance*		*Absorption*			
			Outside	*Inside*		*Outside*	*Inside*				
Pilkington Clear	*10*	*86*	*8*	*8*	*72*	*7*	*7*	*21*	***0.77***	*0.89*	*5.6*
Pilkington Bronze	*10*	*30*	*5*	*5*	*26*	*5*	*5*	*69*	***0.44***	*0.51*	*5.6*

Table 7.6: The solar control parameters evaluated for the glazing types used in the experiment, following the system suggested by this study i.e. the SCGWF and STGWF

Glazing type	Inward flowing solar heat , *N*	*Refractive index* ***,n***	$T_{Overall\ Solar}$	T_{VT}	**SHGC**	$LSG = \frac{VT}{SHGC}$	Remarks
CG	27% of 21=5.67	1.54	0.72	0.86	0.77	1.1	
TG	27% of 69=18.63	1.54	0.26	0.3	0.44	0.75	
SCGWF	zero	1.33	0.27	0.94	0.27	3.4	
STGWF	zero	1.33	0.1	0.35	0.1	3.5	

7.5 Water film thickness

The significant variable of the spectrally selectivity of the SGWF is the water film thickness. The study determines the relationship between the water film thickness and its transmittance to the solar radiation over the different wavelengths of the solar spectrum. It is significant to note that the transmittance T_{water} of the water was measured using a spectrophotometer, ranging from 190nm to 2500 nm. The light travels through the cuvette with a thickness of X=10mm (as shown in Figure 7.40). And the results varied according to the solar spectrum wavelengths.

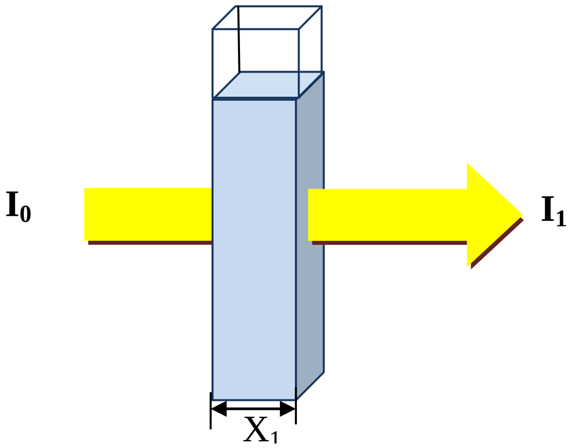

Figure 7.40: The water transmittance of a beam of light as it travels through a cuvette of width X1=10mm

According to the Beer–Lambert law, the transmittance equation is as follows:

$$\boldsymbol{T = \frac{I_1}{I_0} = 10^{-\alpha . x}} \quad (7.18)$$

Where $\boldsymbol{\alpha = \frac{logT}{X}}$

$$\boldsymbol{\frac{T_2}{T_1} = \frac{10^{-\alpha . x_2}}{10^{-\alpha . x_1}}} \quad (7.19)$$

$\boldsymbol{x_1}$ = 10mm standard width of the solar optical cuvette filled by water, while the $\boldsymbol{x_2}$ is the new thickness of the water film.

The result of the water transmittance T_1 was found as follows:

$\boldsymbol{T_1 = \frac{37.68}{100}}$ = 0.38

From Equation 7.19, the T_2 could be calculated as:

$$\boldsymbol{T_2 = T_1 \times 10^{\alpha(x_1 - x_2)}} \quad (7.20)$$

This equation might be applied to the entire solar transmittance: the visible light transmittance and the near infrared transmittance individually.

The result is illustrated in Figure 7.41. The effect of the water film thickness on the solar radiation transmittance varied according to the spectrum wavelength. The visible light does not depend on the water thickness and it is totally transmitted through the water. The transmittance of the near infrared could be divided into two ranges. The first range is from the 780nm to 1300nm (representing 30% of entire short infrared in the solar radiation spectrum), which its transmittance depends on the thickness of the water film, with weaker absorption at a thin thickness. The second range is from 1300nm to the maximum range of the near infrared of 2500nm (representing 70% of the entire short infrared radiation), which is strongly absorbed by the water film and a very thin water film showed a significant absorption to this range as the absorption occurs on the upper surface of the water film. This is why the water film in the current experimental results reduced the direct heat gain (short-wave infrared) besides preventing the heat conduction (long-wave infrared) from admitting inwards.

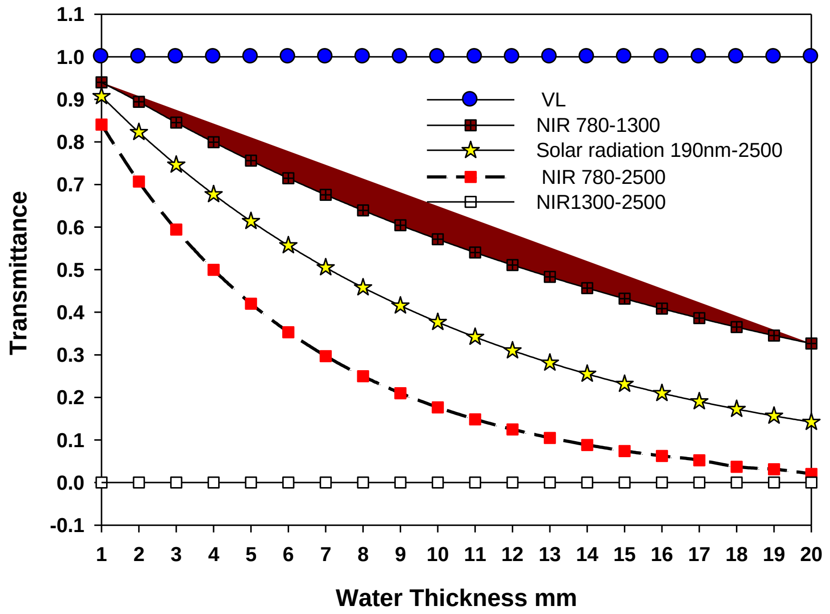

Figure 7.41: Overall transmittance of the wavelength of the solar radiation through the water film (Author).

However, the optimum thickness of the water film for absorbing the entire short wave of the infrared radiation was found to be 20mm, which is difficult to be preserved on the glazed facades unless to be made-up as a water-filled-window (double glazing with a cavity of 20mm and filled with water), but this glazing system might only be suitable for small windows.

Finally, the fluctuation of the indoor illumination which might occur because of the flowing character of the water film could be controlled if the water film is evenly flowing. It is essential to note that the total smooth flow of the water film is difficult to be achieved due to the effect of the air movement over the facade, which causes the water to be flowing in a wavy condition. The hydrophilicity coat which increases the wet-ability of the glass has a significant impact on the water flow with a smooth flow. This is in addition to its ability to clean the glass surfaces which increases the light transmittance inwards.

In summary, the water film strongly absorbs the entire solar spectrum except the visible light that it totally transmits. About 70% of the short infrared absorption takes place in the superficial layers of the water film. This is why the thickness of the water film does not change the absorption of the wavelengths between 1300nm to 2500nm which is totally absorbed by a thin water film.

7.6 Relevant Significance of SGWF for Glazed Office Buildings in the Tropics

It is significant to note that SGWF is suggested mainly for the east/west glazed facades, if necessary to be oriented to the east/west. Nevertheless, under the low altitude angle of the solar radiation, the shading devices are not practical. The appropriate solar control, however, is the sustainable spectrally selective glazing, which is suggested in this study as SGWF.

The cost- effectiveness of the SGWF system in the tropics includes the rain-water that is available freely and the use of water pump that entails zero energy as it is driven by PV. The main cost to the system is in its construction. The cost elements of SGWF include the rainwater harvesting system (ground and rooftop tanks), the associated pipe-work, water filter and the pumping system for recycling the water during the non-rainy period (as shown in Figure 7.42). Although the costs associated with the installation of SGWF could be slightly higher, there are significant savings that should be taken into consideration:

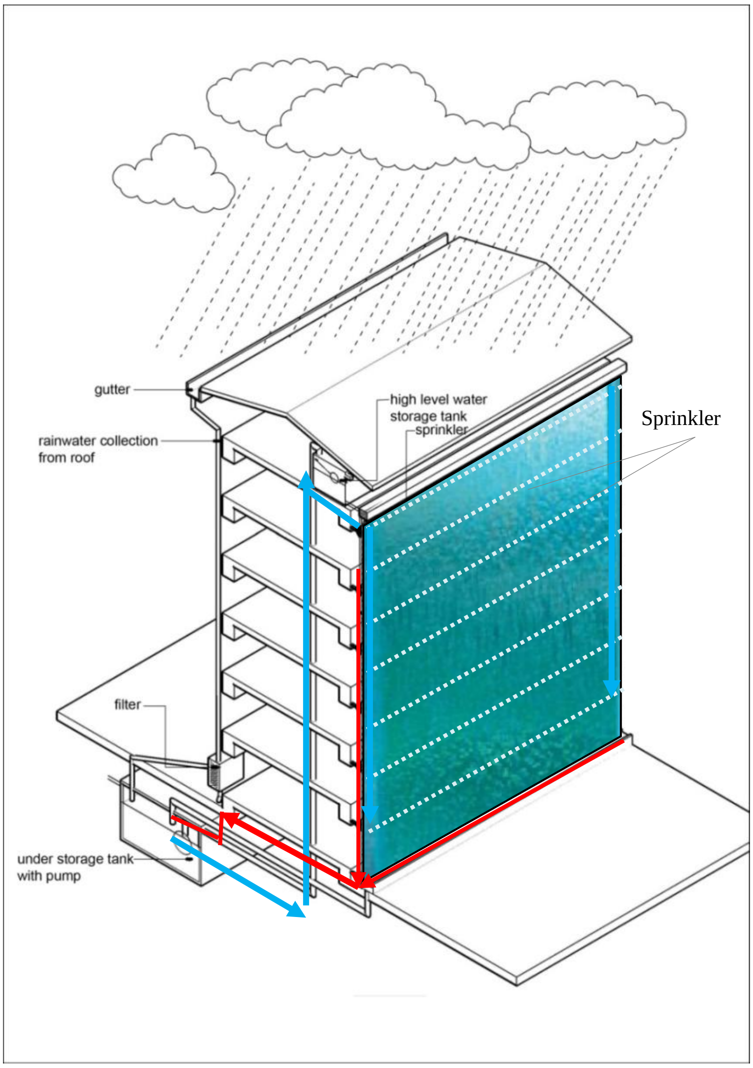

Figure 7.42: Rainwater harvesting for forming the SGWF, not to scale (Author)

7.6.1 Reducing the building energy operation cost

Energy cost is one of the highest operating cost components of office glazed buildings. However, the SGWF facade could reduce the running costs in several ways:

(i) It is shown that the indoor air temperature is lowered by 2–4°C (on average) with the use of SGWF and according to the previous studies, a decrease of 1°C in the indoor air temperature would result in the cooling energy savings from 4-6% (Yamtraipat et al., 2006; Fong et al., 2010). Therefore, the cooling load with the presence of SGWF could be reduced by 24% compared to a building without the water film.

(ii) The water film increases the transmittance of the visible light. This is because the water film performs as an anti-reflective coat to the solar optical radiation on the glazing. This increases the opportunity of reducing the artificial lighting which could lead to significant energy savings of lighting in the offices. However, the extensive use of artificial lighting in the workspaces consumes energy apart from emitting heat could consequentially increase the indoor air temperature.

(iii) It has been found that SGWF reduces the glazed-building surfaces by up to 14°C (on average) and more than 25°C (at its peak). This reduces the heat from being reradiated from the glazed building surfaces to the building surroundings. The previous study reported that the peak urban electric demand is reduced by 2–4% for each 1°C reduction in the daily maximum temperature (Akbari et al., 2001). Therefore, the SGWF can contribute to the reduction of the ambient temperature, which in turn reflected on the reduction of the indoor air temperature of the glazed buildings.

7.6.2 Reducing the heat island effect

The SGWF facade can reduce the heat island effect in two ways:

(i) By reducing the indoor air temperature that results in reducing the air conditioning for the cooling and then reduces the heat rejection from the air conditioning towards the urban environment.

(ii) By reducing the buildings surface temperature that was lowered up to 25°C with the use of the water film during the sunny hours. This reduction in the surface temperature will cut off the irradiative heat from the glazing surfaces to the surrounding buildings, hence resulting in the reduction of the urban heat island effects.

7.6.3 Contributing to the sustainable and green building

Referring to Chapter 4, the Malaysia's Green Building Index (GBI) for non-residential buildings has prescribed the necessary rating system for the certification of green buildings. Where the energy efficiency, the indoor environmental quality, and the water efficiency are significant criteria out of the total six criteria that make up the GBI rating. Therefore, the SGWF which is compounded with the tinted glass complies with these three criteria with significant contribution to the glazed-green buildings in the tropics by way of:

(a) Increasing the efficiency of the cooling system by increasing the heat sink and reducing the heat gain through the glazing. This leads to the improvement of the indoor environmental quality and further increases the energy efficiency of the glazed buildings as has been discussed earlier.

(b) Minimizing the rain-water wastage in the tropics, which receives a very high rainfall throughout the year and has not been fully utilised, is the number one water efficiency issue. The SGWF facade involves a rainwater film that is of very high durability and availability glazing-insulation-film in the tropics. Moreover, there are other sustainable aspects which might be recorded with the SGWF facade such as: the aesthetically pleasing feature that is created on the building glazed facade and the reduction of the air pollution due to the low energy usage.

7.6.4 The low cost and high performance of glazed building insulation

The SGWF could be coupled with the low cost single tinted glass (absorptive glass) that is commercially available in Malaysia. The advanced building glazing that is low-e spectrally selective glazing is not acceptable to the clients for economic reasons. They are imported to the country of Malaysia and most common low-e and spectrally selective coat need to be coupled with a double glazing for protection purposes and is relatively costly to produce. However, SGWF converts the low-cost tinted glazing to a sustainable spectrally selective glazing. The visible light totally admits through the SGWF as the water film acts as an anti-reflective coat to the entire visible light range. The SGWF at the same time absorbs the infrared range (both short-wave and long-wave) which further reduces the penetration of the solar heat inwards, as was discussed earlier in this chapter.

7.6.5 Improving the level of the indoor air temperature and the daylighting

In general, the SGWF facade would preserve the indoor temperature and the lighting level. This leads to the improvement of the comfort level of the building occupants in the glazed buildings by reducing the indoor air temperature and increasing the daylight, which consequently, increases the productivity at the workspace of the glazed buildings (Fisk, 200).

7.6.6 Increased in the rentable spaces

In general, in respect of the east/west facades, shading is not applicable in the tropics, unless it is used to block the whole facades. Moreover, shading devices, double skin and double glazing would result in a decrease in the rentable spaces, while the SGWF is just a thin water film flowing over a single glazed facade. The SGWF plays a role of glazed-insulation to prevent the penetration of the solar heat gain into the workspaces while admitting the light inwards without reducing the rentable spaces.

7.6.7 Self-cleaning ability

The application of SGWF results in the reduction of cost for the cleaning of the glazed-facade hence reducing the maintenance expenditure and the relative running costs. This savings will be enhanced if the SGWF is compounded with the hydrophilicity coat of titanium dioxide (TiO2) which would increase the wet-ability of the glazing hence leads to the increase in the function of self-cleaning of the glaze faced by the water film.

7.7 Water volume flow supply

In the case of a building with a base area of 20m*20m and 20 storeys, and each storey with 3m height, and the east and west facades are designed with 20m width of tinted glazing to each, the following discussion will provide a brief calculation for the rain-water harvesting tank for forming the water flow film over the glazed facades.

If it is determined that the high flow rate of the water film was involved, (according to the experiment the high flow rate of the water film which was shown to be 1.7m3/h and covering the entire tested facade of 1.4m width), the formula would, therefore, be as follow:

$$V = \frac{X * v_0}{x_0} \qquad (7.21)$$

Where: V is volume rate of the designed facade

X is the width of the designed façade

v_0 is the volume flow rate tested in the experiment, its value =1.7m^3/h

x_0 is the width of the tested façade in the experiment, its value =1.4m.

Therefore, the equation 7.21 would be as follows:

$$V = X \times \left(\frac{1.7}{1.4}\right) = X \times (1.2) \qquad (7.22)$$

$$V = X \times \omega \qquad (7.23)$$

Where: ω is constant with value of 1.2.

However, for instance, the water volume needed for the building facade with width of 20m is as follows:

$V = 20 \times 1.2$

V = 24m^3/h

If the operation hours on the west facade are 3-5 hours (maximum), then the volume flow rate is 121.4m^3. However, this volume of the water requires a water tank of approximately 6m*6m*3m, which could easily locate on the rooftop of the building for the natural flow of the water film. It could be refilled again by recycling the water from the bottom rainwater harvesting tank during the night time for the natural cooling down of the water for the next day use. Likewise, the east facade would need the same water volume for the same operation. It is essential to note that the water film will not run over the two facades at the same time due to the different orientations of each facade that is exposed to the direct solar radiation at different times. It is therefore suggested to either build two water tanks on the roof top one for the east supply and the other one for west, or to use one tank for the east facade and then refilling the same for the west facade supply, with concerns the cooling down of the recycling water. Moreover, the calculation will be different if the design of the SGWF facade was made to operate with individual control for each floor and each office.

7.8 Limitations of the study

The study was conducted using the tap water supply from the rooftop tank of the Faculty of Built Environment at the University of Malaya. The water temperature reached 35 °C, and contains added specific chemical compounds as well as chlorine. The research suggests using the rainwater with a temperature lower than the ambient by cooling it during the night-time and shielding the water tank from daytime radiations.

In this experiment, there could be some inaccuracies in the data during the long period of measuring. Although the reference room was built to be geometrically very similar to the test room for comparison purposes, they may show slight difference in data values. However, the two rooms were calibrated before the actual use during the experimentation as discussed earlier and illustrated in Figures 7.3, 7.6, 7.14 and 7.15 at plots CG vs. CG. The differences were reported to be 0.4 °C more inside the reference room and 0.1°C more on the reference glass surface, therefore the error values should be deducted from the result value. Likewise, in respect of TG as illustrated in Figure 7.5, 7.7 and 7.16 at plot TG vs. TG, the error was found to be 0.3°C more on the reference glass surface temperature, while the indoor temperature was measured in one room as pre-test/ post-test with judgement against the outdoor temperature. Moreover, attention should be paid to the data-logger which was calibrated with (±0.3°C) of the outdoor temperature and (±0.1°C) of the surface and the indoor temperature. In relation to the solar radiation data, the pyranometer was calibrated with the uncertainty of approximately +5%.

7.9 Disadvantages of the SGWF facades

However, there could still arise some practical problems in respect of the SGWF facade, including: (a) the reduction of the transparency of the glass that impedes the view outdoors during the operation of SGWF; (b) the fluctuation of the indoor illumination, which could occur because of the flowing character of the water film. This could be controlled if the water film is flowing evenly. It is essential to note that there was no significant change in the outdoor ambient relative humidity with the SGWF façade over the experiments period. The reason is that the flowing water film over the glazing has a convective and conductive heat transfer instead of evaporative cooling.

CHAPTER 8

CONCLUSION AND FUTURE STUDIES

8.1 Introduction

This thesis began by establishing a number of connections. First, there is a connection between the Malaysian climate, the solar radiation aspects and the appropriate passive solar control for glazing in Malaysia. The second identified set of connections revolves around the concept of green architecture in Malaysia and its application in the office-glazed buildings. Whereas the final set of connections frames all the previous sets of relations in the experimental study of the suggested alternative solar control, which is the SGWF, for the east and the west glazed facades in the tropics.

The use of passive solar control elements proved to be successful in maintaining the indoor spaces of the green buildings in the tropics. Nevertheless, there is lack of study of the proper alternative passive concepts for glazed buildings particularly on the east and the west orientations. The current thesis has been prompted to look for further elements, which are efficiently available and appropriate for the east-west facades of the glazed buildings in the tropics, Malaysia. This chapter concludes the thesis by recapping the findings and the discussions from each chapter of this thesis to aid the design process of the passive solar control and the application of the new suggested alternative solar control of SGWF in designing the glazed office buildings. The contribution of SGWF to the knowledge and to the designing of the glazed buildings in the tropics are summarised in this chapter. The chapter concludes with the recommendations for further research that revolves around the idea of SGWF and the related areas.

8.2 Conclusion of the field study

The survey over the glazed buildings in the Klang-Valley of Malaysia and the review of the market in addition to the direct contact with relevant manufacturers reveal that tinted glazing is still the popular choice for the buildings in Malaysia. In contrast, no large market exists for a higher performing glazing that has only a few practical applications depending on the imported units.

The current research drew on the field study of the solar heat and the light performance of the green and glazed buildings in Klang-Valley of Malaysia. It is concluded that for the climate of Malaysia where the heat gain mainly occurs because of the direct solar radiation, the double skin facades are not preferable. The overheating of the glazing cavity during the sun shine forms the “green house effect” which may cause the inner glass panes to be shuttered due to the difference between the glass surfaces temperature; the outer surface exposed to high temperature of the “green house effect” and the inner surface exposed to low temperature of the air-conditioned space. This is in addition to other disadvantages, for instance the high construction cost, the reduction of the rentable office space and the additional maintenance and operational costs.

Therefore, it is concluded that the concept of slanting-in design to glazed building is more appropriate for the tropics, particularly on the two facades facing the north and the south orientations. The slanting-in of the glazed facade on the east and the west orientations requires additional passive elements for controlling the low angle of the solar incidence. However, these conclusions provide the direction for the development of the current SGWF approach.

8.3 Conclusion of the SGWF

Results of the extensive measuring during the extreme sunny months in the tropics in two full-scale test rooms have been analyzed and conclusions have been drawn with the view to improve the sustainability of the glazed buildings. The passive solar control of SGWF gives consideration to the Malaysian climate to avoid the possibility of increased building construction cost without deriving full benefits from it. The SGWF also integrates with the low cost glazing and become flexible to be operated automatically when necessary (during sunny hours) and to be stopped when it is not required (during cloudy hours).

8.3.1 Thermal performance of SGWF

The effect of the water film flow over the glazed facades is to lower the glazing temperature. This results in the rapid transfer of the heat from the inside of the building to the glazing surface (the heat sink), from the heat sink to the water film body and eventually to the outdoor environment. This evidences the effectiveness of SGWF in preventing the solar heat from transferring to the indoors and increases the thermal energy loss with a much greater heat capacity, resulting in the reduction of the indoor temperature without interrupting the light. If the rate of the flow of the water film is increased, the cooling effect of SGWF is increased accordingly. This is due to the increase in the water body to carry away the heat and the enlargement in the water film thickness, which leads to the increase in the heat exchange between the indoor and the heat sink.

The STGWF presents better results than the SCGWF for both water flow rates *f* 1.2m3/h and *f*1.7m3/h, during both the sunny and the cloudy days due to the increase in its solar absorption. Overall, in achieving a higher reduction in the heat transfer, the STGWF-*f* 1.7m3/h during the sunny day is found to be the optimum among the cases examined. It is suggested in this study that the water should be cooler than the outdoor air-temperature in order to maximize the efficiency of the SGWF by preventing the solar load from passing inside the buildings and to maximize the heat loss.

8.3.2 Solar radiation transmittance of SGWF

The transmittances of the ordinary glazed-facade were analysed with water film (flow rate of 1.7m^3/h) flowing over the entire glazing surface on different sky conditions. It is concluded that the solar radiation transmittance increase behind the SGWF facade, and the increment varies according to the solar intensity. For SCGWF, the increase varies from 2% to 4% as opposed to CG. Meanwhile, for STGWF, the increment fluctuates from 2.2% (during the cloudy hours) to 6.8% (during the sunny hours). However, the increment of the solar radiation transmittance is found as an increment in the visible light range (daylighting), whereas, the infrared range (heat) decreases significantly within the same monitoring cases.

8.3.3 Spectrally selective solar control of SGWF

It was concluded from the experimental and calculation analysis that SGWF is a “sustainable spectrally selective film”, which is appropriate for the glazed buildings in the tropics. The spectrally selective of the SGWF shows the ability to transmit and increase the visible light while absorbing the short wave infrared. This generates an indoor environment with more daylighting without adding extra amount of heat. SGWF, therefore, has low SHGC and the optimum in relation to the SHGC was found with STGWF configuration.

The sustainable spectrally selectivity feature of the SGWF improved with the increased thickness of the water film. However, the visible light did not depend on the water thickness and it was totally transmitted through the water, while approximately 70% of the short infrared was strongly absorbed by the thin water film. The absorption took place in the superficial layers of the water film. The remaining 30% of the short-wave infrared depended on the thickness of the water film, with weaker absorption capabilities. Moreover, with respect to the "*refraction index"* of the water film over the glazed facade, the visible light transmittance increased because the water film served as an anti-reflective coating to light. This shows that SGWF offers better light transmission characteristics than the same single glass without water.

8.4 Contributions of the study

The study has bridged the gap of investigating, in substantial detail, the possibility of using the SGWF facade as an economical means to provide for the sustainable solar control for glazed office buildings in the tropics, Malaysia. It is the first time where experimental work was conducted on the subject in the tropical region. This study will help to provide an overall insight to the use of the sustainable water flow film together with the low-cost glazing on the east and the west glazed facades in the possibility of preventing the solar heat gain and increasing the admission of the daylighting to the workspaces in the tropics.

The research work found that the SGWF facade has the advantage over the typical glazed facades in terms of reducing the heat gain and increasing the daylighting by introducing the passive solar control to the glazed building design. The use of water flow film as a sustainable spectrally selective film to glazed facades proves to be a better alternative to the low solar altitude angle of the east and the west orientations on the glazed facades in the tropics. This uncomplicated glazed facade system of SGWF provides better results as opposed to the typical glazed facades without the water film. As much as 24% of energy consumption in terms of energy reduction for the cooling in addition to the reduction of the lighting energy due to the increased visible light transmittance were found with the use of the SGWF facade. The designers could advise the clients to use SGWF facade for that particular project with the east and the west glazed-facades as it could save time and money and contribute to the sustainability of the buildings sector in addition to the beauty feature.

8.5 Recommendations for further research

This study attempts to answer the research questions that were mentioned in the earlier chapters. The areas of the passive solar control to the east/west glazed facades have been surveyed and the sustainable glazing (both thermal and solar) insulation of the flowing water film has been experimentally and numerically investigated. The topic is complex hence some significant parts of the problem deserve further investigations. The following are some of the broad areas for further research, which may contribute to the more understanding of the use of alternative recycled elements in controlling the total solar gain on the east and the west glazed facades:

8.5.1 Integration of SGWF with PV buildings envelope

PV technologies are expanding and this could be incorporated with the SGWF facade to improve the PV performance and enhance the energy efficiency of the glazed facades. There are some positive initial research findings that could support this argument. For instance, Krauter (2004) and Krauter (2006) found that integration of photovoltaic (PV) with water film would be beneficial to the electrical performance of PV which results from the reduction of the cell temperature and increased electricity conversion efficiency. This research could be done for the PV building facades in the tropics.

8.5.2 Glazed-building solar and thermal simulation with SGWF; the effect of SGWF on the urban heat island in Malaysia

Urban cities could be several degrees warmer than the outskirts due to the heat emission by the buildings surfaces, the mechanical cooling devices and other humane activities. This phenomenon is known as “urban heat island”. Reflective glazings have become an important contributor to this effect by reflecting all the infrared wavelengths to the urban area. This suggested study would present a simulation based on the experiment data values provided by this current study aiming at evaluating the effects of the water flow film over glazed facades on the outdoor air temperature which contributed to the increased urban heat islands of the city. The simulation attempts to quantify the thermal performance of the different glass commonly used on the buildings facades in the tropics before and after the water flow film is applied with respect to the glazing outer-surface temperature. The improvement on the outdoor air temperature and the urban heat island will be observed with the presence of SGWF on the outdoor glazing surfaces, taking into account the reduction in the use of the air-conditioning system that leads to the reduction in the heat emission to the urban surrounding.

8.5.3 Thermal and optical simulation of SGWF; the effect of SGWF on the energy consumption of office glazed-buildings in the tropics

A case study of the conventional glazed building will be measured to assess the energy consumption of the building. The application of SGWF on the building may alter this energy consumption with significant reduction for the cooling and the lighting. The study calculates the heat and the light performance of the building and simulates the building with the SGWF system.