AN EMPIRICAL STUDY ON THE USE OF WATER FILM IN GLAZED BUILDINGS TO REDUCE SOLAR RADIATION TRANSMITTANCE IN THE TROPICS

Abdultawab M. Qahtan[1]

ABSTRACT

Solar radiation is the cause of large heat gain in glazed buildings particularly in the tropics, thus the aim of this study is to investigate the impact of a sustainable water film on glazing transmittance to solar radiation. The experimental investigation measured two parameters, namely, type of glazing and solar radiation intensity, utilizing glazed façades oriented west in two full-scale rooms. It was found that the water film on the glazed façade increases the transmittance of solar radiation behind the glazing by 2% - 6.8% depending on the solar intensity and glass type, while the indoor temperature was reduced. The study concluded that the increment of the solar radiation (300-2500nm) transmittance is an increment in the range of the visible light (daylighting).

KEYWORDS

solar radiation, transmittance, light, water film, glazed building, tropics,

1. INTRODUCTION

As a building material, the transparency of glass gives its unique character to the glazing of transmitting light and connecting the outside with the inside [1]. Glazed buildings allow most of the solar radiation to transmit indoors. For instance, the transmission through the façades of clear glass (3mm) in part of visible light (380-780nm) is about 89% and 75% of short-wave infrared (780-2500nm) [2]. This short wave (radiation) passing through glazed façades is absorbed by the internal surfaces of buildings and subsequently emitted as long-wave radiation (heat) which cannot easily pass through the glass to the outside [3]. This causes the indoor environment to heat up, which typically accounts for 15-30% of overheating in indoor spaces [4]. The easiest way to overcome this problem is to prevent the transmitted solar radiation by the use of shading devices. However, shading would be insufficient, particularly on east and west façades that are affected by direct solar radiation, unless light is sacrificed by blocking much of it by the glazing of the facade [5]. Thus, several studies have proposed the use of solar control glazing as an ideal solution to the glazed façades in the tropics [6-8]. Spectrally selective glazing is a new glass technology that can filter or block the short-wave radiation (heat) in the solar beams and allow light to transfer indoors [9]. The drawback is its high

1. Department of Architecture, Faculty of Engineering, Najran University, 1988, Najran, KSA. Tel.: +966535911252; amqahtan@nu.edu.sa / tawab444@gmail.com

production cost compared to tinted glass. Hence, as more glazing is used in buildings, there will be increasing demand for alternative inexpensive solar control glazing, particularly on east and west façades. This study proposes a low-cost solar control glazing system by exploiting the potential of Sustainable Glazed Water Film (SGWF) for reducing solar radiation transmittance. The following is a brief review of the solar radiation fundamentals and the potential of a water film as a low-cost alternative to solar control glazing in the tropics.

2. SOLAR RADIATION IN THE TROPICS

Basically, solar radiation provides information on how much solar energy hits a surface at a location on the earth during a particular time [10]. Many climate factors affect the incoming intensity of the solar radiation, such as the thickness and composition of the atmosphere, the location of the Sun in the sky, as well as the actual conditions of the sky [11]. The intensity of a clear sky with direct radiation is more than the intensity of diffuse radiation on cloudy days [12]. Depending on the distance of the Earth from the Sun, the intensity of solar radiation (solar constant) reaching Earth fluctuates between 1350 and 1440 W/m^2 during the year [13]. However, Malaysia receives abundant sunshine all year long, with irradiation of between 800W/m^2 and 1000W/m^2 [14]. Thus, the ideal sustainable design for glazed façades in Malaysia is to protect glazing from the high intensity of solar radiation.

2.1 Diffuse and direct solar radiation

An important aspect of solar radiation with respect to glazed buildings is the ratio of diffuse and direct radiation which is received by the earth's surface. It is important to distinguish the beam of solar light into direct radiation and diffuse radiation in addition to its total solar radiation. This helps to understand the solar energy performance in order to balance between preventing direct sunbeams and allowing sufficient daylight into glazed buildings. When the designer avoids the east and the west Sun's low angle, the direct sunbeams can be simply blocked out by shading devices [15,16]. However, avoiding east and west is not always acceptable due to limitations of the landform and view aspects. On the other hand, diffuse radiation might have a large impact on the glazed buildings that need to be protected from it [17,18], especially in the tropical region which is close to the equator and faces a very high degree of diffuse radiation [19]. The situation in the tropics results in the need to resort to passive solar control elements that can protect the glazed building envelope from both direct and diffuse solar radiation.

2.2 Solar Heat Gain Coefficient SHGC

The amount of total solar radiation transmission through glazing is expressed by two means: first is the heat gain due to the solar radiation transmittance, τe, and second is the internal heat transfer, qi, due to the difference in the temperature between the ambient and the indoor spaces [20, 21]. In terms of solar transmittance, this depends on the spectral properties of the glass, where different types of glass have unique characteristics with regards to solar radiation [22].

The amount of 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" [23]. The SHGC has replaced the Shading Coefficient (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 [24]. In Malaysia, a tropical country with a hot humid climate, the ideal glazing is one with low SHGC. According to ASHRAE [25], the selected SHGC for north and south glazed façades in warm climates should be ideally no more than 0.35, while east and west glazed-façades should be no more than 0.25. For calculating the SHGC, Pedrini [26], defined the following equation:

$$SHGC = \tau s + Ni \, . \, \alpha s \tag{1}$$

Where: τs = solar transmittance of the fenestration system, Ni = inward-flowing fraction of absorbed radiation, and τs = solar absorption of a single-element.

2.3 Solar control buildings-glazing

In the design guide for glass architecture in the tropics, Fong & Chong [27], reviewed the common types of glass used in architectural applications in such regions, covering higher solar performance glass, including body tinted glass, insulating glass, solar reflective glass, low-emissivity (low-e) glass and spectrally selective glass. The spectrally selective glazing is applicable for the tropics from its solar performance; the drawback is its high manufacturing cost. Most common spectrally selective coats need to be compounded with double glazing for protective purposes and are relatively costly to produce [2]. Yet, from a review of the market and through direct contact with manufacturers, it has been found that tinted glazing is still a popular choice for buildings in Malaysia. In contrast, no large market exists for a higher performing glazing that has only a few practical applications and depends on imported units. Hence, as energy costs rise and more glazing is used in buildings, there will be increasing demand for alternative inexpensive solar control systems for coping with these seemingly conflicting requirements. Thus, this study tries to understand in which ways thin water film flowing over the outer surface of a low cost glazing might be better used as an alternative glazing system for controlling solar heat gain in the tropics. The SGWF facade involves a rainwater film that is easily available and of very high durability for use as a solar control in the tropics. Malaysia receives a very high rainfall throughout the year which is not fully utilised [28]. Thus, proposing the SGWF as a solar control film in this study is a water efficiency issue in the tropics, besides it is a solar heat gain control system in the hot and sunny climate of the tropics.

Although many experimental and theoretical studies have been conducted to investigate the water flows and heat transfer of falling water film, most of them have been adopted for industrial applications [29], and a few on glazed buildings focusing on the effect of the water film on the thermal performance of the building envelope. Table 1 summarises the studies that have been done using the water element as an alternative heat control in buildings. However, no study has focused on the solar transmittance through glazing with a water film, particularly in Malaysia. This study explores the potential of SGWF in controlling the solar transmittance falling on glazing in the tropics.

3. METHODOLOGY

The same equipment and methodology were used as in a previous study conducted by the authors [30]. An experimental investigation of the glazed facade facing the west orientation was conducted by utilising the SGWF. The experiments involved the following two

TABLE 1. Applications of water-cooling for glazed buildings.

Author	System	Building element	Material used	Remarks
Qahtan et al., (2014).	SGWF	West glazed façades	Glass	Water- Solar-Optical
Qahtan et al., (2011).	SGWF	West glazed façades	Glass	Water-Thermal
Chow et al., (2010)	Water-flow window	Double glazing with 10mm cavity	Glass	Water-Thermal
Abdullah et al., (2009)	Water film	Atrium Roof	Glass	System compound with internal blinds.
He &Hoyano, (2008)	Water film	External building surfaces	Alumina and glass	The building surface coats with TiO2

parameters, namely, type of glazing and solar radiation intensity. The water flow rate was set to 1.7m3/h, the maximum flow rate through a pipe which creates an even water film over the outer surface of the glazing (Table 2). The configurations of two full-scale rooms, the test room and the reference room (Figures 1&2), were designed with the typical dimensions of facade modules used in the experiments. They comprised identical and detached one-storey rooms with exposure to solar radiation without any shade (Figure 2). The internal dimensions were 2.0m x 2.0m with a ceiling height of 2.60m and an area of 4.0m².

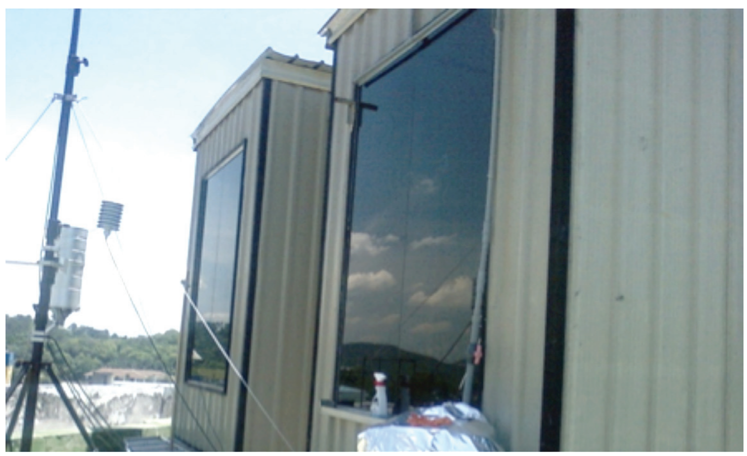


Figure 1: View of experiment site: reference room (left) and test room (right).

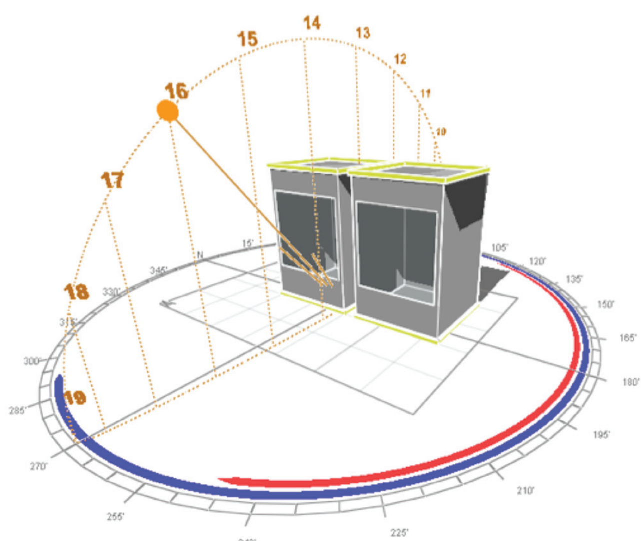


Figure 2: Sun path diagram of 21st March, to the experiment site.

TABLE 2. The characteristics of glasses used in experiments [31].

Product	Thickness (mm)	Visible light			Solar radiation				SHGC	SC	U-value W/m²k
		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

3.1 The instrumentation and the sensors

Flowing water film over the outer skin of a single glazed facade was achieved by drilling 5/32” holes every 1/2” in the pipe to produce an even flow when the water hits the glazed façade. Feeding the water to the system comes through a t-junction with a pipe going right and left with both ends capped off. 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 PVC pipes (external diameter 3/4”). The desired thickness of the water film can be adjusted according to experimental needs, whereby the thickness of the water film is related to water supply. The operation of the SGWF system was started at 12:00 (and the results 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.

The measurement equipment consisted of six sensors connected to data loggers designed to collect the data related to the solar radiations. The “Babuc/A” data loggers were utilized for monitoring the indoor air temperature and the heat flux through the glass. The measurement of the heat fluxes was conducted in the presence of the incident solar radiation without a shield in the case of both the treated and the reference façade, since the shelter will affect the gentle flow of the water film. The “Skye” data logger with two sensors was used to measure the vertical solar radiation indoors and outdoors. In addition, a Weather Station was installed to measure the outdoor global solar radiation and the climate conditions of the experimental site.

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

- Two Pyranometers to measure the incident solar energy, W/m^2.
- Pyranometers to measure the global solar radiation, W/m^2.
- Thermocouples to measure the outdoor air temperature, °C.
- Thermocouples to measure the indoor air temperature, °C.
- Heat flux meter, W/m^2.
- Anemometer for wind speed measurement.

4. RESULTS AND DISCUSSION

4.1 Theory of solar radiation transmittance within the SGWF façade

As mentioned earlier, 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 can be understood as follows (Figures 3 and 4): The incident solar radiation (I0) is either reflected towards the outdoor ambient (I1), transmitted into the inside (I2) or absorbed by the water film and glass pane (I3). Theoretically, when the water film flushes over the glazing, the heat flows via conduction and convection from the surface of the glass to the water film body and is expressed as (I4), while a portion of the heat flows inwards and is expressed as (I5). Therefore, the total solar energy transmittance defined in Equation 1 could be modified and defined as:

$$SHGC = I_2 + (I5 * as) \tag{2}$$

Referring to the measurements of thermal energy transmittance with SGWF discussed by the authors in the previous study [30], the fraction (I5) which forms the inward-flow of the thermal energy absorbed by the glazing was found to vary from zero to (-)50 W/m^2; outwards). Therefore, Equation 2 will be as follows:

$$SHGC = I_2 \tag{3}$$

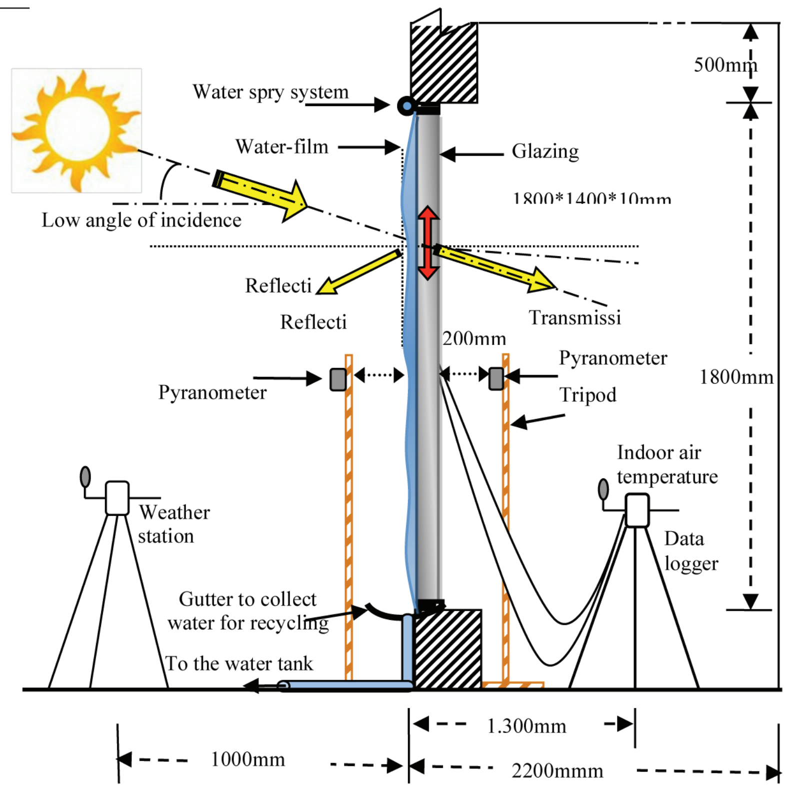


Figure 3: The schematics of the experimental set-up of the solar transmittance within the SGWF.

4.2 Case A: Clear Glass CG

Experiments were performed with clear glass at the same time in the two rooms - the treated room and the reference room - to determine the solar radiation transmittance of the SCGWF façade. Table 3 summarizes the average percentage differences in the solar transmittance between the SCGWF facade and the CG as the reference façade. The results were demonstrated under two different sky conditions – sunny hours and cloudy hours - over two weeks each. Overall, as summarized in Table 3, the results of SCGWF showed an increase in the solar energy transmittance with a water film of about 6.2% in the sunny hours, while in the cloudy hours, the increment was found to be about 2.9% with the SCGWF facade compared to the CG façade.

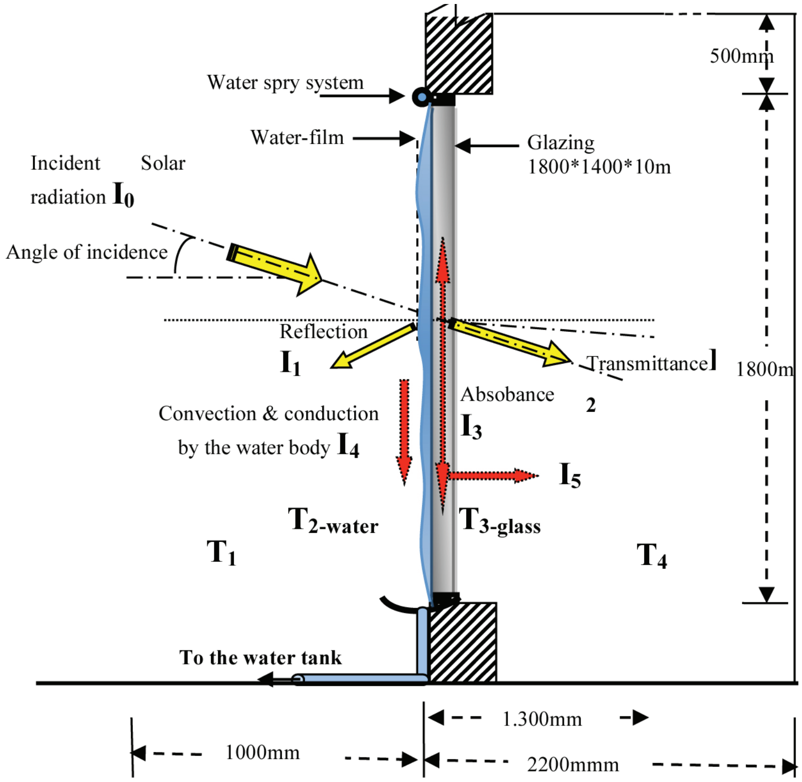


Figure 3: The schematics of the experimental set-up of the solar transmittance within the SGWF.

TABLE 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 (reference)	*173.1*		
		Difference	*1.5W/m²*		
		***0.87%**(error) to be detected from the data values of CG (reference room)*			
Sunny hours	**Peak hour** 11&18Feb at ***4pm***	SCGWF	*485.4*	*1100.1*	
		CG (reference)	*460.4-0.86% (error)*460.4 =456.5*		
		Difference	*28.9W/m²(6.2% out of CG)*		
		Solar radiation increases about 6.2%			
Cloudy hours	***1-5pm***	SCGWF	*116.5*	*8037*	
		CG (reference)	*114.2-0.86% (error)*114.2 =113.2*		
		Difference	*3.3W/m²(2.9% out of CG)*		
		Solar radiation increases about 2.9%			

4.2.1 SCGWF and Solar radiation intensity

Figure 5 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 solar radiation intensity. As further illustration of the SCGWF results, Figure 6 shows the values of the solar radiation transmittance during the sunny hours. The peak value occurred at 15:10 when the water film increases the transmittance of the solar radiation by about 20%. However, the accurate result of the peak may be taken for an hour's peak instead of a particular duration of minutes to avoid any irregularly measured data. Therefore, the average hour peak was found at 15:30 to 16:30 with an increase from 448W/m^2 behind CG to 476 W/m^2 behind SCGWF, which represents an increase of about 6%.

In contrast, Figure 7 shows that the SCGWF facade in the cloudy hours did not increase much of the solar radiation transmittance indoors and there was no fluctuation of the radiation data values either. This is because the radiation in the cloudy hours is generally a diffuse

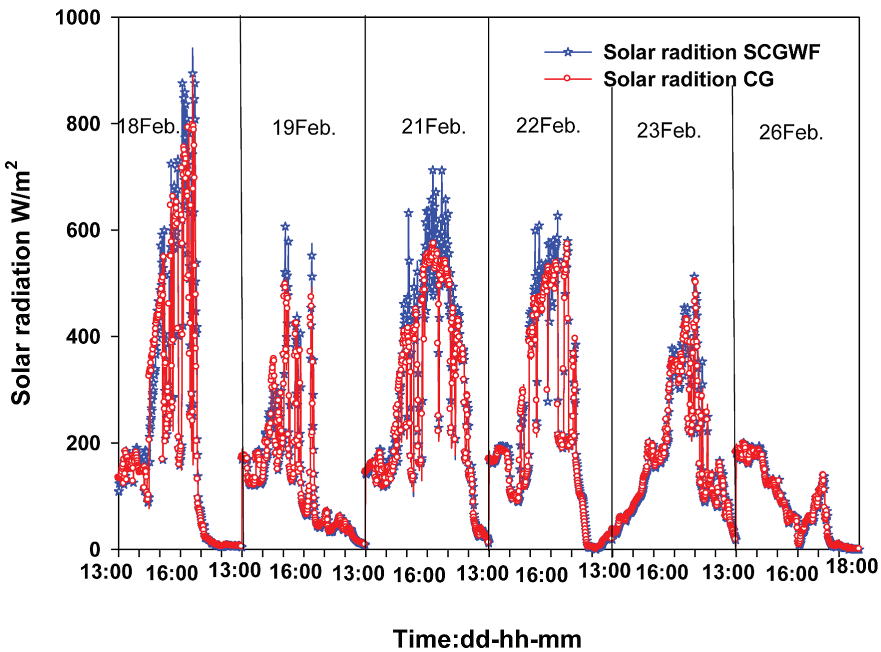


Figure 5: The solar radiation transmittance through SCGWF and CG for the different sunny and cloudy hours of February.

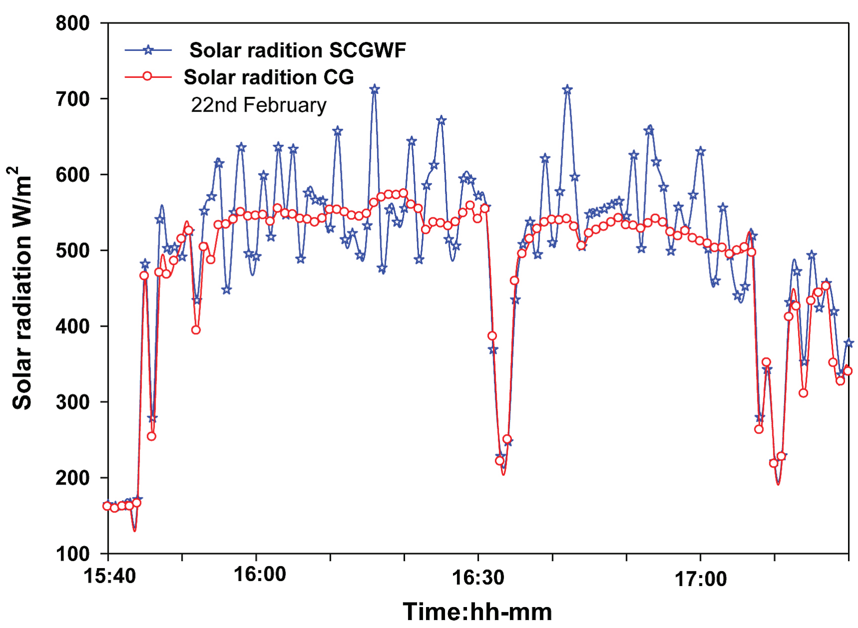


Figure 6: The effect of SCGWF on the solar radiation transmittance at the peak of the sunny hours 22nd February.

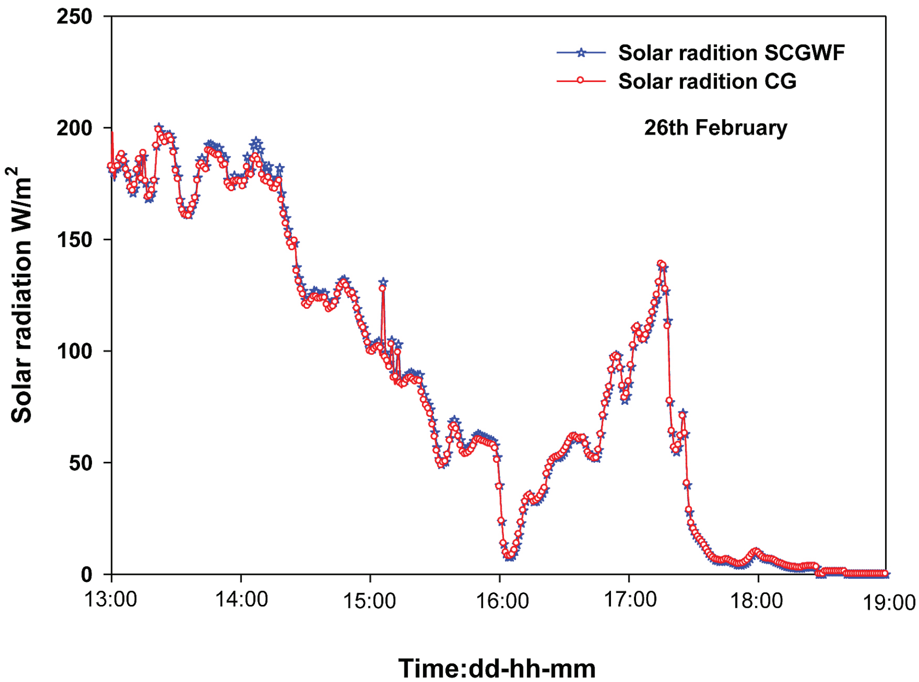


Figure 7: The increase in the solar radiation with the presence of the water film (the cloudy hours of 26th February).

fraction with low intensity compared to the direct solar radiation occurring in the sunny hours. Figure 7 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 1.26 m/s. However, the average increase in solar radiation transmittance due to the water film of the SCGWF facade was, on average, 2% of the total solar radiation transmittance through the SCGWF façade.

Figure 8: The view of the tested west facade showing the pyranometers that measure the internal/external vertical solar radiation of the CG façade.

4.2.2 Validation of SCGWF transmittance against outdoor

This experiment was conducted with respect to the exterior vertical solar radiation (Figure 8) as outdoor/indoor instead of the reference room indoor/indoor. Figure 9 and 10 illustrate the changes in the values of the solar radiation transmittance due to the flowing of the water film over the glazed-façade. Figure 10 shows that the solar radiation value behind the SCGWF during high solar intensity was in some minutes higher than the outdoor value. This resulted in an increase in the solar radiation behind the SCGWF facade due to the use of the water film.

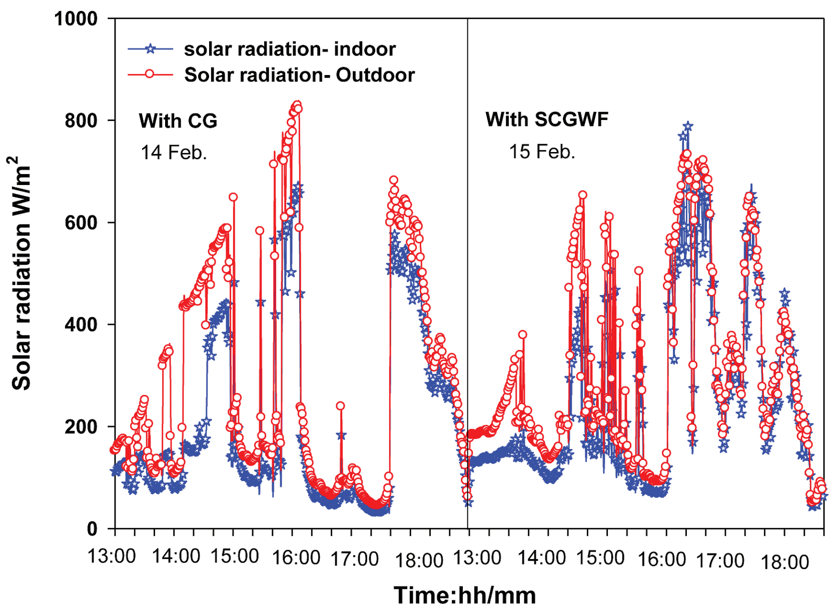


Figure 9: The difference between CG and SCGWF with respect to the exterior solar radiation in both cases (14th and 15th February).

In contrast, Figure 11 demonstrates a reduction of solar radiation that transmits indoors with SCGWF. It was noted that on the 6th of March with the CG façade, the thermal energy flows inwards when the solar radiation value was 647.5W/m^2. While with SCGWF the thermal energy kept flowing outwards when the solar radiation value was 482.8 W/m^2. 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. This indicates that SCGWF results in a reduction of solar radiation indoors, which in turn, enhances the indoor thermal performance.

4.3 Case B: Tinted Glass TG

The study compared the solar transmittance of the clear glass and tinted glass that were used in the experiments described above. Their solar performance, as illustrated in Figure 12, 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 740 W/m^2, 150 W/m^2 respectively, and the outdoor air movement was 1.76m/s at that time.

Figure 10: The peak difference in the solar radiation indoor/outdoor; (a) with water film SCGWF and (b) without water film CG.

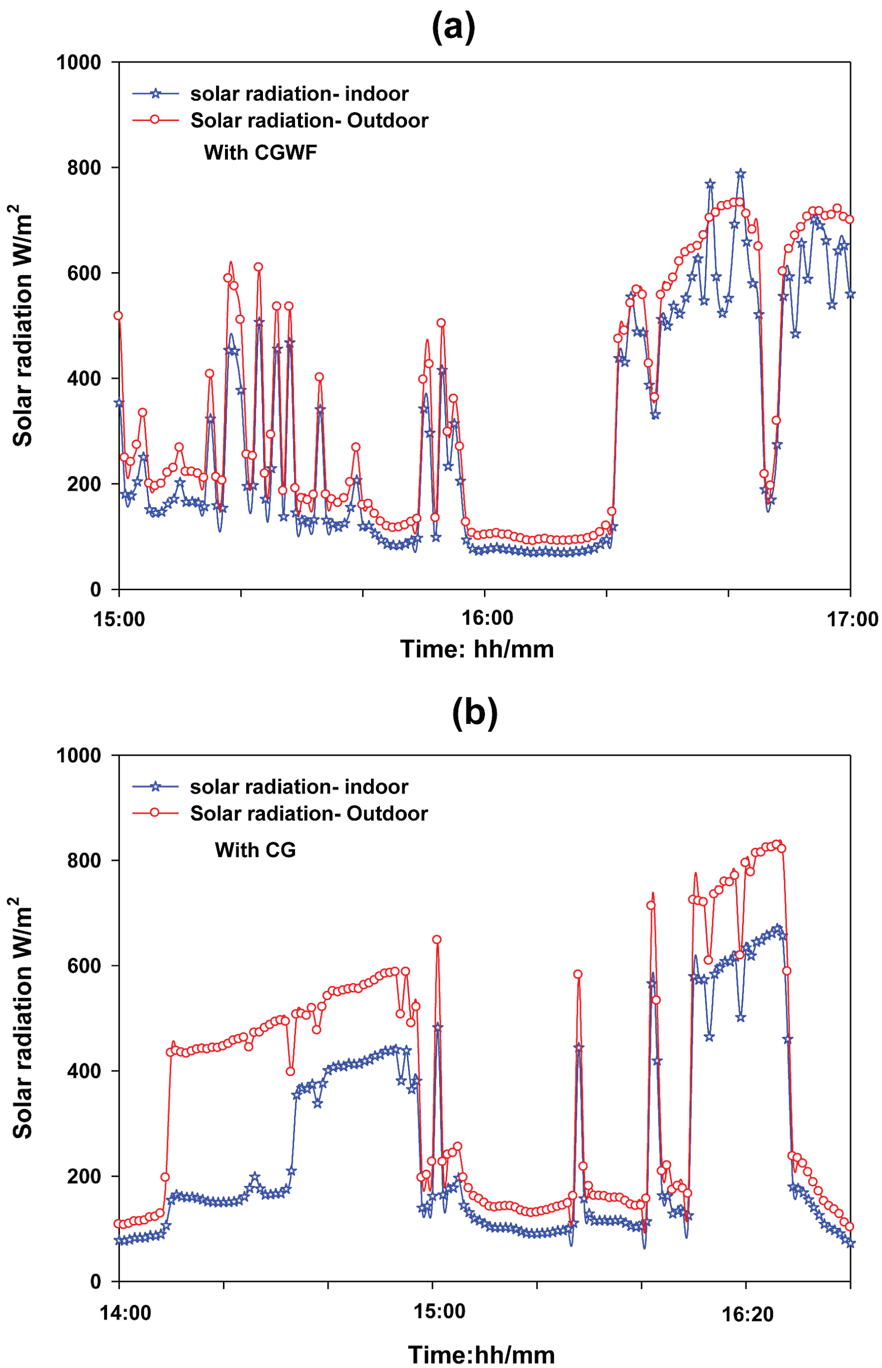


Figure 11: The differences in the solar energy transmittance between the CG facade on 6th March and SCGWF facade on 7th March.

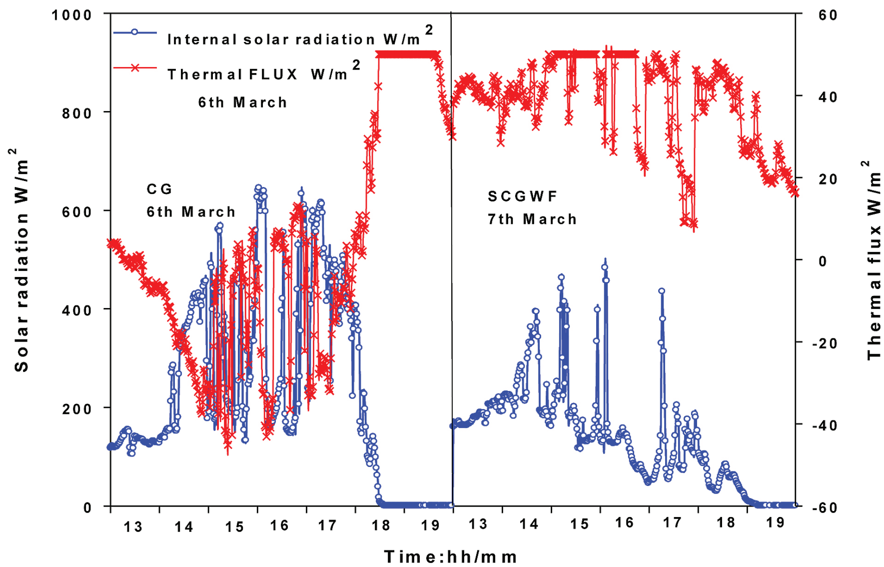
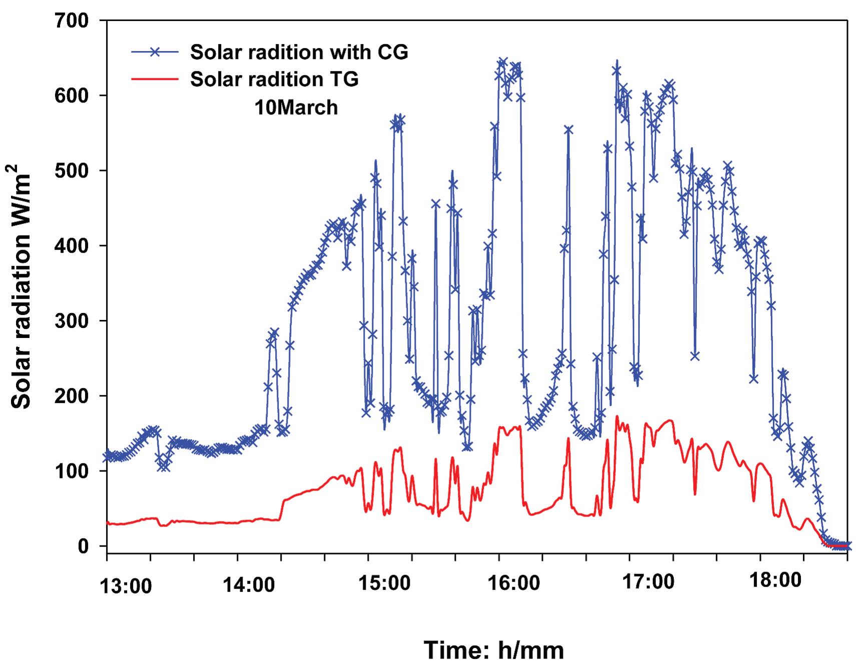


Figure 12: The difference in the solar radiation transmittance between the tinted glass and the clear glass.



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

In general, the fraction of the solar radiation that is admitted through STGWF was larger than that admitted through TG. It can also be seen in Table 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 global solar radiation was 1087.6W/m^2) out of the total admitted value of the solar radiation.

TABLE 4. The amount of the solar radiation transfer towards the interior of STGWF compared to TG facade.

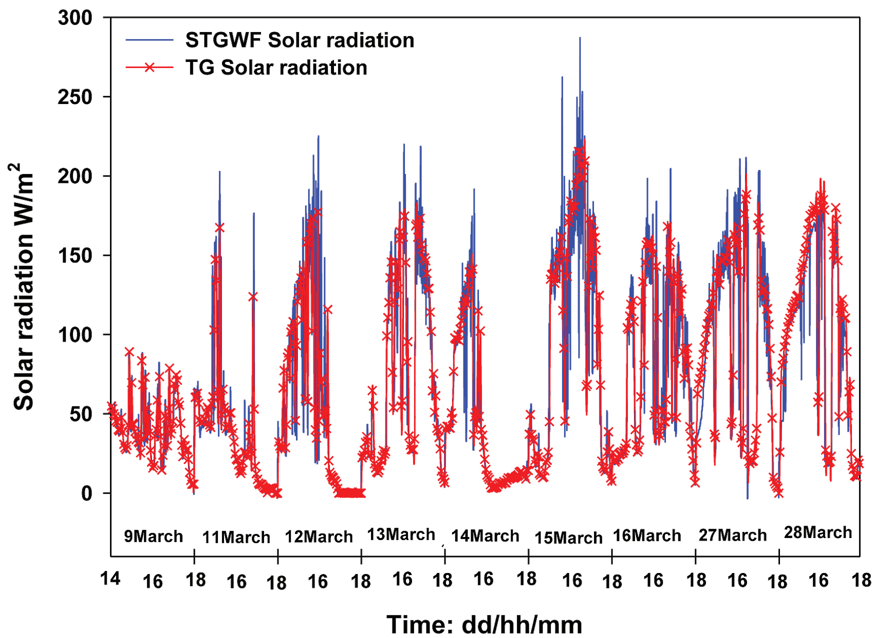
STGWF, Judged against the control room with TG average 5-7 days to each case.			Indoor-Solar radiation	Ext. global -solar radiation	Remarks
Rooms calibration	Average	TG (test-room)	*76.5*	*1087.6*	Rooms Calibration: The two rooms were calibrated before the actual test to reduce data errors when comparing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

4.3.1 STGWF and the solar radiation intensity

Figure 13 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 solar radiation within the reference days on the 9th and 28th of March are approximately identical in their data values to the solar radiation behind the TG. Moreover, by referring to the data value from the 11th to 27th of March, the curves confirm that the solar radiation transmittance increased when applying the water film to the tinted glass, which is the STGWF façade. The variation of the increase in the solar radiation behind the STGWF within that period depended on the solar radiation intensity, specifically, the high solar intensity on 15th of March showed an obvious increase in the solar radiation transmittance indoors.

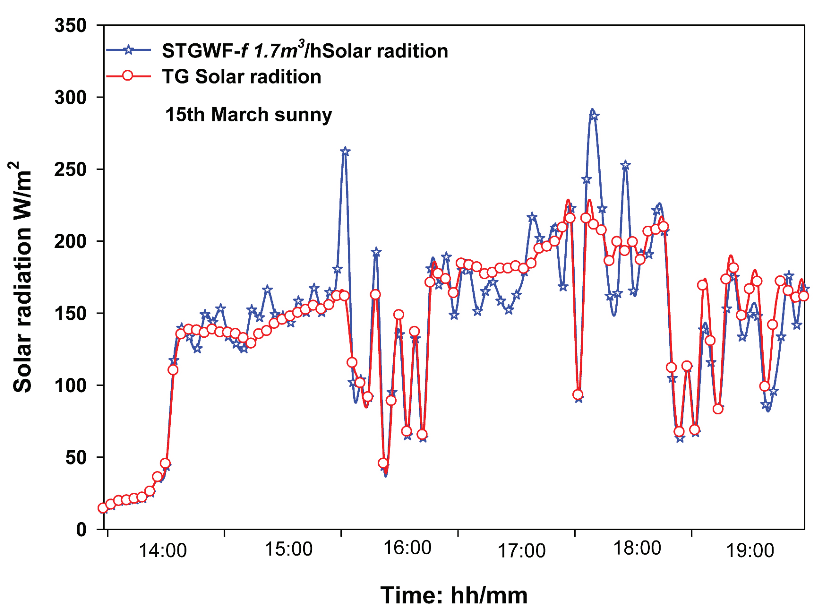
It is essential to note that the results of SCGWF and STGWF are approximately similar with respect to the increase in the solar radiation transmittance and to the fluctuation of the data values behind both façades. The difference in showing the low data values behind STGWF compared to SCGWF is due to the difference in the specifications of the tinted glass and clear glass in both façades. Figure 14 shows the increase of the solar radiation behind STGWF. As illustrated in Figure 14, the peak value of solar radiation transmittance in the sunny hours occurred at 17:05 when 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 may 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 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 a further increase by about 5.6% with STGWF.

Figure 13: The solar radiation transmittance through STGWF and TG for the different sunny and cloudy hours of March.



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

Figure 14: The performance of the solar radiation transmittance with the presence of the water film over the tinted glass on the sunny hours.

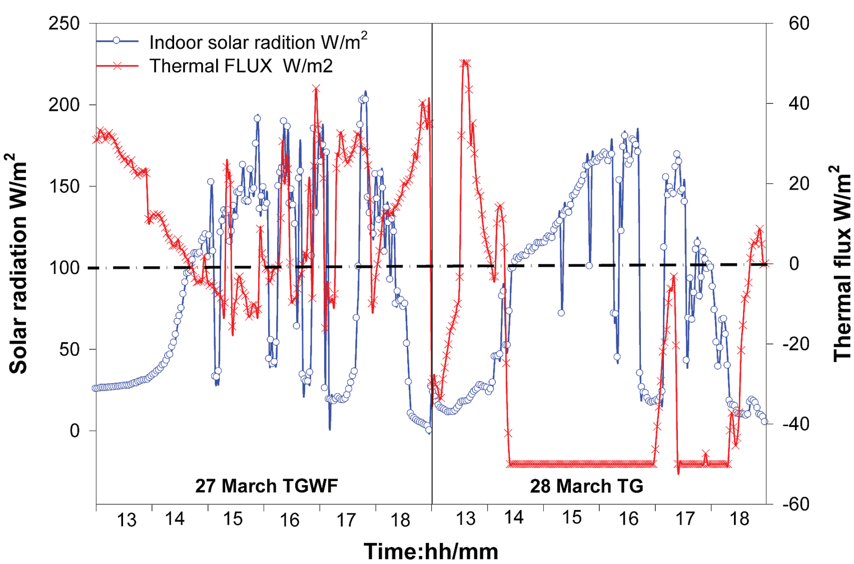


4.3.2 Validation of STGWF transmittance against outdoor

Similarly, the experiment at the STGWF stage was conducted with respect to the exterior vertical solar radiation "outdoor/indoor". However, it is relatively difficult to distinguish the decrease or increase in the solar radiation transmittance behind the STGWF facade when comparing to outdoor solar radiation because of the substantial difference in the solar radiation between the external and internal values due to the use of dark tint, i.e., bronze glass.

Figure 15 shows the solar energy transmittance (conductive) of STGWF compared to TG. The significant reduction in solar energy transmittance was found during the water film operation on the STGWF facade on the 27th of March. It was found that the thermal flow remained approximately zero and the flow outwards reached a peak of (+43.7 W/m^2) when the solar radiation behind the STGWF facade was 179.7 W/m^2. On the other hand, with respect to the TG façade, the solar 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 varied 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 which frequently retains 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 the water film acting as a "heat sink" which enhances the heat flowing outwards.

Figure 15: The difference of the solar energy transmittance between the TG facade on 28th of March and the STGWF facade on 27th of March.



In summation, theoretically as in Equation 3, the value of SHGC was reduced with the SGWF. This happens because the water film eliminates the heat conductivity through glazing indoors. However, the experimental results show that the solar radiation transmittance increased behind the SGWF façade, with the increase varying according to the solar intensity (sky conditions) as well as the glass type. The seemingly negative result of the increase in solar radiation transmittance with suggested facade of SGWF could be understood as follows:

- There is a limitation in the measurement of the fraction I_2 in the field experiment due to the use of the Pyranometers that measure the total values of solar energy (W/m^2), including the portion due to the greenhouse effect inside the sealed test rooms. Therefore, the fraction I2 is the value of both the transmittance of solar radiation (UV, VL and IR) and the long wave (thermal) emitted by indoor surfaces.
- The increase in solar radiation transmittance behind the SGWF is an increment in the Visible Light (VL) transmission due to the water film. This result was supported by the serious reduction of the indoor temperature behind the SGWF that has been reported in another study conducted by the author [30].
- For further discussion in this context, a few studies were found, focussing on the optical properties of glazing with a water film. It can be seen that the results of the current field experiment are in good agreement with the laboratory experimental results reported in another study conducted by the author [32]. Where the study confirms the power of the SGWF in filtration the solar radiation spectrum to allow more VL380nm - 780nm (daylight) into the space while cutting down the IR780nm - 2500nm (heat) transmission. This also confirms that the SGWF is a "Sustainable Spectrally-Selective Film" where the significant fraction instead of SHGC is "Light to Solar Gain" (LSG). It is, in this context, a measure of the efficiency of SGWF admitting visible solar radiation while blocking infrared radiation.

Similarly, the results of the current research supports the conclusions of another study Krauter [33], which showed an increase in the solar optical transmittance of PV panels as soon as the water film starts flowing down over the panels. This increase in the solar optical transmittance with the flowing water film over glass was also confirmed by [34]. However, the studies of [33-36], have concluded that the transmittance of visible light decreases with the water condensation on the glass. This conclusion is not consistent with the results of the current study. The explanation for the discrepancy is that there were differences in the systems principle adopted, i.e., the solar transmittance of condensation on glazing is not the same as that of flowing water film over glass.

4.4 Limitations of the study

Figure 16&17 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. Figure 16, shows the calibration of the rooms within the SCGWF before starting the measurements. An error was found at 14:40 with an increase in test room of about $34W/m^2$ (9.6%) than the reference room. This difference in the solar data may occur because of the difference in the position of the two pyranometers in the two rooms. The pyranometer, which showed higher value in the test room, could have been 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. Overall, the solar radiation transmittance into the rooms was found higher in the reference room than the test room with an average of about 0.87%. This value was detected from the data values of CG when comparing with data values of SCGWF (refer to table 3).

Likewise, as illustrated in Figure 17, the calibration of the rooms within the STGWF before commencing the measurements showed that the solar radiation transmittance into

Figure 16: The solar radiation data in the two rooms (test room and control room) on the control day without any treatments in both rooms.

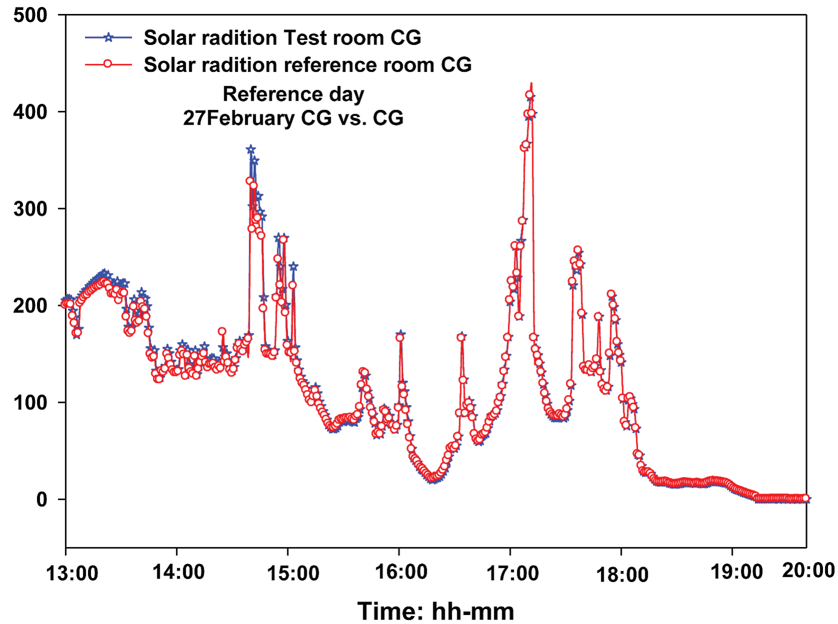
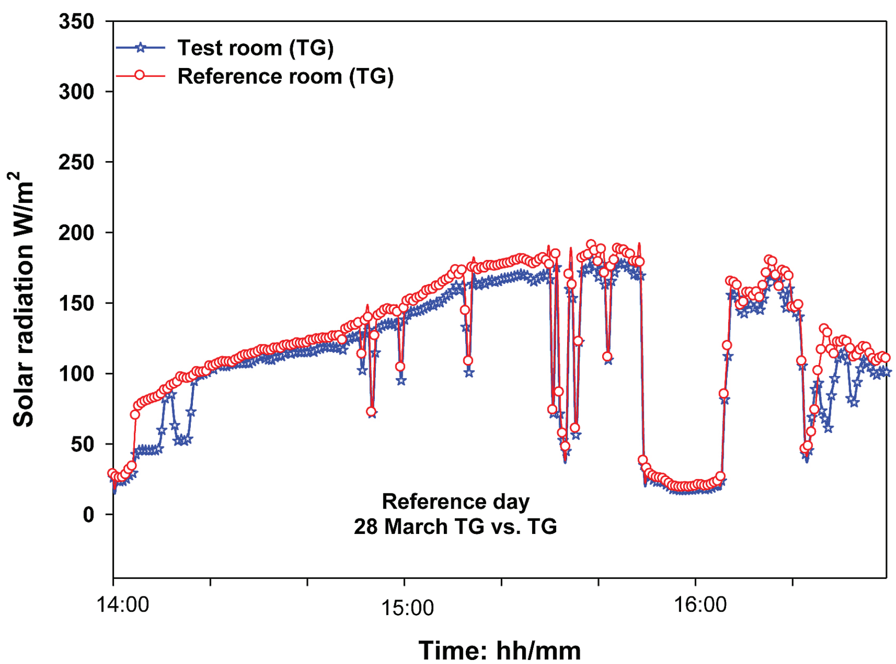


Figure 17: The difference between the two rooms at TG without treatments (rooms' calibration).



the rooms was higher in the reference room than the test 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 (refer to table 4).

5. CONCLUSION

This study provides insights into the use of sustainable water flow film together with low-cost glazing on east and west-facing glazed façades as a potential means of reducing solar radiation transmittance. The results of extensive measurements in two full-scale test rooms during extreme sunny months have been analysed and conclusions have been drawn towards improving the *sustainability* of glazed buildings in the tropics by improving indoor air quality, reducing the energy demands for cooling and reducing the wastage of rainwater.

It is concluded that the solar radiation transmittance increases behind the SGWF facade and that the increment varies according to the solar intensity and type of glass. For SCGWF, the increase varies from 2% (during cloudy hours) to 4% (during sunny hours) compared to CG. Meanwhile, for STGWF, the increment fluctuates from 2.2% (during cloudy hours) to 6.8% (during sunny hours). The study also concludes that the SGWF filtrates the solar radiation spectrum to allow more VL380nm - 780nm (daylighting) into the space, while reduces the heat gain indoors.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support from the Research Grant from the University of Malaya; project no RP009/2012A and RG 130/11SUS. As well as to Najran University; project no NU/ESCI/14/046.

LIST OF ABBREVIATIONS

CG	Clear Glass
TG	Tinted Glass
SGWF	Sustainable-Glazed-Water-Film
SCGWF	Sustainable Clear-Glazed-Water-Film
STGWF	Sustainable Tinted-Glazed-Water-Film
IR	Infrared
UV	Ultra violet
VL	Visible light
I_0	Direct solar radiation intensity on the surface (W/m2),
I1	The reflected solar radiation outwards (W/m2)
I2	The transmitted solar radiation (W/m2)
I3	Solar energy absorbed by glazing (W/m2)
I4	Solar energy absorbed by the water film (W/m2)
I5	Thermal energy flow outwards (W/m2)
T	Temperature °C
τs	solar transmittance of fenestration system

Ni	inward-flowing fraction of absorbed radiation (according to equation (3.4) Ni= 0.4)
αs	solar absorption of a single-element
SHGC	Solar heat gain coefficient
SC	Shading coefficient
PVC	Polyvinyl Chloride
PV	Photo-voltaic (solar cells)

REFERENCES

[1] Watkin, D. (2005). A history of Western architecture: Laurence King Publishers.

[2] Chow, T., Li, C., & Lin, Z. 2010. Innovative solar windows for cooling-demand climate. Solar Energy Materials and Solar Cells, 94(2), 212-220.

[3] Baker, N. V. 2009. The handbook of sustainable refurbishment: non-domestic buildings: Earthscan.

[4] Woolley, T., & Kimmins, S. 2000. Green Building Handbook: A Guide to Building Products and Their Impact on the Environment, Vol. II: London: E & FN Spon.

[5] Shen, Hui, & Tzempelikos, Athanasios. (2012). Daylighting and energy analysis of private offices with automated interior roller shades. Solar Energy, 86(2), 681-704. doi: http://dx.doi.org/10.1016/j.solener.2011.11.016

[6] Dussault, Jean-Michel, Gosselin, Louis, & Galstian, Tigran. (2012). Integration of smart windows into building design for reduction of yearly overall energy consumption and peak loads. Solar Energy, 86(11), 3405-3416. doi: http://dx.doi.org/10.1016/j.solener.2012.07.016

[7] Manz, Heinrich.(2008). On minimizing heat transport in architectural glazing, Renewable Energy, 33 (1), 119-128, doi:http://dx.doi.org/10.1016/j.renene.2007.01.007.

[8] Ye, H., Meng, X., Long, L., & Xu, B. (2013). The route to a perfect window. Renewable Energy, 55(0), 448-455, http://dx.doi.org/10.1016/j.renene.2013.01.003

[9] Kamalisarvestania M., Saidura R., Mekhilefb S., Javadia F.S. Performance, materials and coating technologies of thermochromic thin films on smart windows. Renewable and Sustainable Energy Reviews 10.1016/j.rser.2013.05.038.

[10] Elminir, H. K., Areed, F. F., & Elsayed, T. S. 2005. Estimation of solar radiation components incident on Helwan site using neural networks. Solar energy, 79(3), 270-279.

[11] Mingfang, T. 2002. Solar control for buildings. Building and Environment, 37(7), 659-664.

[12] Paoli, C., Voyant, C., Muselli, M., & Nivet, M. L. (2010). Forecasting of preprocessed daily solar radiation time series using neural networks. Solar energy, 84(12), 2146-2160.

[13] Bansal, N. K. 1994. Concepts and Elements of Natural Climate Control. In G. H. Narenda K. Bansal, Gernot Minke (Ed.), Passive building design Netherlands: Elsevier Science B.V.

[14] Mekhilef, S., Safari, A., Mustaffa, W. E. S., Saidur, R., Omar, R., & Younis, M. A. A. 2012. Solar energy in Malaysia: Current state and prospects. Renewable and Sustainable Energy Reviews, 16(1), 386-396. doi: http://dx.doi.org/10.1016/j.rser.2011.08.003

[15] Offiong, Anickan & Ukpoho, A.U. 2004. External window shading treatment effects on internal environmental temperature of buildings, Renewable Energy, 29(14), 2153-2165, doi:http://dx.doi.org/10.1016/j.renene.2003.11.015.

[16] Tzempelikos, A. 2008. The impact of venetian blind geometry and tilt angle on view, direct light transmission and interior illuminance. Solar Energy, 82(12), 1172-1191.

[17] Aboulnaga, Mohsen M. 2006. Towards green buildings: Glass as a building element—the use and misuse in the gulf region, Renewable Energy, 31(5), 631-653, http://dx.doi.org/10.1016/j.renene.2005.08.017.

[18] AbdelKhaleq, R. A., & Ahmed, I. A. .(2007). Rainwater harvesting in ancient civilizations in Jordan. Water Science and Technology -Water Supply, 7(1), 85-94.

[19] Lauret, A. J. P., Mara, T. A., Boyer, H., Adelard, L., &Garde, F. (2001). A validation methodology aid for improving a thermal building model: case of diffuse radiation accounting in a tropical climate. Energy and Buildings, 33(7), 711-718. doi: http://dx.doi.org/10.1016/S0378-7788(00)00133-X

[20] Kuehn, T. H. 2005. ASHRAE Handbook of Fundamentals, New York, : American Society of Heating, Refrigerating, and Air Conditioning Engineering.
[21] Manz, H. 2004. Total solar energy transmittance of glass double façades with free convection. [doi: doi: 10.1016/j.enbuild.2003.10.003]. Energy and Buildings, 36(2), 127-136.
[22] Gueymard, Christian A., &duPont, William C. (2009). Spectral effects on the transmittance, solar heat gain, and performance rating of glazing systems. Solar Energy, 83(6), 940-953. doi: http://dx.doi.org/10.1016/j.solener.2008.12.012
[23] Li, D. H. W., & Lam, J. C. 2001. Analysis of solar heat gain factors using sky clearness index and energy implications. Energy Conversion and Management, 42(5), 555-571.
[24] Deal, B. M., Nemeth, R. J., & DeBaille, L. P. 1998. Energy Conservation Strategies for Windows and Glazed Surfaces: US army corps of engineers, Construction Engineering Research Laboratories.
[25] ASHRAE. 2008. Advanced Energy Design Guide for Small Office Buildings: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (www.ashrae.org).
[26] Pedrini, A. 2003. Integration Of Low Energy Strategies To The Early Stages Of Design Process Of Office Buildings In Warm Climate. PhD, The University of Queensland, Australia.
[27] Fong, F. A., & Chong, T. Y. 1999. Designing with Glass, a design guide for glass architecture in tropics. Singapor: National University of Singapore, Fculty of Architecture, Building and Real Estate.
[28] GBI. 2012. Green Building Index (GBI), rating system, avalable from <http://www.greenbuildingindex.org/rating_system.htm>.
[29] Zhou, D. W., Gambaryan-Roisman, T., & Stephan, P. 2009. Measurement of water falling film thickness to flat plate using confocal chromatic sensoring technique. Experimental Thermal and Fluid Science, 33(2), 273-283. doi: 10.1016/j.expthermflusci.2008.09.003
[30] Qahtan, A., Keumala, N., Rao, S., & Abdul-Samad, Z. 2011. Experimental determination of thermal performance of glazed-fa ades with water film, under direct solar radiation in the tropics. Building and Environment, 46(11), 2238-2246.
[31] MSG. 2012. Technical Data, Glass Performance Data, Pilkington Malaysia, avalable from <http://www.msg.com.my/msg>
[32] Qahtan, A., Rao, S. & Keumala, N.,(2014). The effectiveness of the sustainable flowing water film in improving the solar-optical properties of glazing in the tropics. Energy and Buildings, Volume 77, July 2014, Pages 247–255.
[33] Krauter, S. 2004. Increased electrical yield via water flow over the front of photovoltaic panels. [doi: DOI: 10.1016/j.solmat.2004.01.011]. Solar energy materials and solar cells, 82(1-2), 131-137.
[34] Pieters, J., Pollet, I., & De Clercq, S. 1997. Measuring facility for light transmittance and diffusion of condensation or rain covered glazing materials.
[35] Pollet, I. V., & Pieters, J. G. 2000. Condensation and Radiation Transmittance of Greenhouse Cladding Materials, Part 2: Results for a Complete Condensation Cycle. [doi: 10.1006/jaer.1999.0487]. Journal of Agricultural Engineering Research, 75(1), 65-72.
[36] Pollet, I. V., Pieters, J. G., & Verschoore, R. 2003. Impact of water drops on the visible radiation transmittance of glazings under outside radiant conditions.Solar Energy, Elsevier Science Ltd., 73.