The effectiveness of the sustainable flowing water film in improving the solar-optical properties of glazing in the tropics

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A B S T R A C T
In the tropics, glazed façade is the cause of large solar heat gains into the buildings, thus the aim of this study is to achieve a low cost alternative solar control glazing. The study has experimentally and numerically investigated the potential of a Sustainable Glazed Water Film as a low cost alternative to the use of expensive spectrally selective glazing for buildings in the tropics. The analysis is done for Malaysia and the results have showed the effectiveness of Sustainable Glazed Water Film in reducing the solar heat (infrared) transmittance and maximizing the daylight (visible light) transmittance. About 70% of the short-wave infrared radiation ranging between 1300 nm and 2500 nm is absorbed by the thin water film. The water film in question does not obstruct the visible light, but in fact it increases its transmittance. The study concluded that the "Sustainable Glazed Water Film" is appropriate in improving thermal and visual comfort and reducing the cooling loads for glazed buildings in the tropics. Malaysia has plenty of water resources and hence it will cause no problem to use a small fraction of it to enhance the solar-optical and thermal properties of glazed buildings.

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1. Introduction

In the tropics, solar radiation transmission through glazing in building poses a serious problem for heat gain that increases the energy demands for cooling, particularly on the east and west glazed facades where direct sunlight passes through glazing as short-wave infrared. This short wave IR is absorbed by the internal surfaces of buildings and consequently re-emitted as long-wave infrared (heat), which trapped indoors accounts for 15–30% of overheating in indoor spaces [1]. Shading devices may protect building interiors from solar radiation but do not distinguish between daylight and infrared, particularly on the east and west facades that need a long horizontal shading devices and such shading is impractical and uneconomical. The solution to this problem lies in glazing that has a high visible transmittance but rejects a great proportion of the short-wave infrared radiation from 780 nm to 2500 nm. Solar control glazings, such as a spectrally selective low-e glazing, have been introduced to the market, the main drawback of a spectrally selective glazing is its high cost.

The aim of the present study is to investigate the effectiveness of a Sustainable-Glazed-Water-Film (SGWF) as a low cost alternative to spectrally selective glazing systems, leading to improving the indoor visual and thermal quality and reducing the cooling energy demands. To attain the aforesaid objective, it is essential to understand the solar energy flows through the glazing.

1.1. Solar radiation in glazing

There are two means of indicating the total solar heat gain through glazing. First, the heat gain due to the direct solar beam enters the glazed façade as a short-wave infrared $\tau$. Whereas the second means is the internal heat transfer $Q$, which occurs because of the difference in the temperatures between the outdoor and indoor spaces and the difference in the temperature between the glass surfaces [2,3]. In other words, solar radiation intensity 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 8–9% of the solar beam that reaches to the earth’s surface [4]. The visible radiation is at 0.38–0.78 μm, which forms 46%. The remaining 46% goes to the short wave infrared ranging from 0.78 to 2.5 μm [5,6]. The significant part with respect to solar control of glazed buildings is the short-wave infrared radiation, control of which is highly recommended for tropical glazed buildings to protect indoor spaces from infrared radiation [6]. The fourth part, that of long-wave infrared radiation represents the reradiated energy from ground surfaces spanning from 3 μm to 50 μm (3000–5000 nm) [7], (Fig. 1). The current study focuses on the solar short-wave infrared transmittance that penetrates through the glass as light hitting the indoor objects, and re-emitting as long-wave IR radiation (heat) that cannot pass through the glass.

1.2. Direct solar radiation on glazing (or “short-wave infrared”)

Depending on the solar-optical properties of the glass, the different types of glass have unique responses to solar energy [9]. For example, most of the solar energy is transmitted through the surface of clear glass; its transmittance in part of short-wave IR is about 75% and 89% of visible light [10]. Therefore, an ideal glass for tropical regions should be the one with a high transmission to visible light, which is at 0.38–0.78 μm, and low transmission to infrared (heat radiation), which is at 0.78–3 μm [6,11].

1.2.1. Light to solar gain ratio LSG

The amount of the total solar heat gain (UV, visible and infrared radiation) that passes through a glazing is usually evaluated in terms of the Solar Heat Gain Coefficient (SHGC) [12]. For calculating the SHGC, Pedrini [13] defined the following equation:

\[
SHGC = \tau + q \cdot \alpha
\]  

(1)

where \( \tau \) = solar transmittance of a fenestration system, \( q \) = inward-flowing fraction of absorbed radiation and \( \alpha \) = solar absorption of a single-element.

However solar transmittance \( \tau \) determined by Eq. (1) shows that SHGC still does not distinguish between visible light and short-wave infrared radiation. The significant fraction related to solar control in the tropics is “Light to Solar Gain” (LSG). It is the ratio of visible light transmittance (VT) to the solar heat gain coefficient (SHGC). It is a measure of the efficiency of glazing admitting visible solar radiation while blocking infrared (or heat) [14]. A high LSG value indicates more daylight in the room with less heat gain, which is shown in the following formula:

\[
LSG = \frac{VT}{SHGC}
\]

(2)

1.3. Solar control glazing in the tropics

Glass usage in buildings in a hot-humid tropical climate, as in Malaysia, causes a higher indoor temperature. The perfect glazing for tropical regions would be one that has the ability to block the infrared radiation and transmit visible light [15].

1.3.1. Low-e glazing

Low emissivity (low-e) glass has special coatings that reflect invisible long-wave radiation passing through glazing. The coatings are an almost invisible metal oxide layer that can reduce the emissivity of the surface of the glass from \( e = 0.87 \) to \( e = 0.04 \), thus reflecting back 65–96% of long-wave radiation. This results in reducing infrared radiation up to 20%, without affecting the transmittance of visible light [16]. Low-e coating is often installed with double glazing for reasons of solar protection and to increase the efficiency of blocking long-wave infrared radiation. There are two types of low-e coatings that have been developed and used in the market. Generally, this glazing shows a high luminous transmissio, and is not so efficient for the infrared protection [15].

In the tropics with the hot humid climate, as in Malaysia where the difference in temperature between the outside and the inside is not high, the heat (long infrared) exchange between outdoors and indoors is not high. The main contributor to interior heat loads is the direct solar radiation that contains short-wave infrared (light) passing through the low-e glazing. It is absorbed by the indoor interior surfaces and then re-emitted from the surfaces as long-wave infrared. The said infrared cannot escape to the outdoors, forming what is called the greenhouse effect, resulting in the increased indoor temperature.

1.3.2. Spectrally selective glazing

Improvements in glazing efficiency might be obtained by applying a low-e coating that reflects long-wave infrared radiation. However in the tropics, priority is given to the control of the short-wave IR radiations, which are still able to penetrate low-e coatings. The success of glazing in the tropics lies in the concept that it transmits the visible light and reflects outwards the short-wave infrared radiation. Low-e coatings have been enhanced to create low-e spectrally selective coatings that combine the best qualities of tinted glazing, reflective glazing and low-e glazing [17–22]. Although the spectrally selective glazing might be the appropriate choice for the tropics, there is an inhibition to use of this glazing in the tropics due to its high production cost.

1.3.3. A low cost alternative to spectrally selective glazing

This paper highlights the benefits of recycling the elements such as rainwater in the tropical countries, combined with low cost glazing that is commercially available in the market. It suggests SGWF as an effective low cost alternative solar control in the tropics. It is to run a thin film of water over the outer surface of the tinted glazed facade in the presence of direct solar radiation. It is assumed that

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1 This range of short-wave infrared (0.78–2.5 μm) will be adopted throughout this research.
the water film acts as a sustainable spectrally selective film to filter the solar spectrum.

This is sustainable in the tropics from several aspects: first, as there is abundant rainfall throughout the year. Malaysia receives a high rainfall throughout the year but has not fully benefited from this [23]. However, Malaysian Green Building Index (GBI) encourages building designers to implement rainwater harvesting [24,25], for reducing the wastage of rainwater. This paper suggests using this rainwater to be collected and used to generate the flowing water film (SGWF) over the glazing. The second is that SGWF combined with the tinted glass that is more than 12 times cheaper in the initial cost than the spectrally selective glass system in the Malaysian market. Moreover, the cost-effectiveness of the SGWF system in the tropics includes use of the rain-water that is available freely and of very high durability for use as an alternative solar control in the tropics. The use of water pumps entail almost zero energy input as it is driven by PV (solar cells). The main cost to implement the system of SGWF is in its construction that includes the rainwater harvesting system (with the benefit of the low-cost rainwater harvesting system [23]) that would also be used for other building purposes, the associated piping and water filters. There are significant savings that should be taken into consideration such as: (a) reducing the building energy operation cost, (b) improving the level of the indoor air temperature and the daylight, (c) reducing the heat-island effect, and (d) self-cleaning ability of the windows.

Applying a water film over windows and glazed facades as means of temperature control in buildings has been reported in several studies [26–29], in contrast with control of solar-optical transmittance in glazed buildings which has been reported only briefly. The research makes a concise review of previous studies that deal with the effectiveness of water films in improving the solar-optical properties of glazing. The studies reported by [30–33] deal with solar radiation transmittance through water condensation and water run-off on the glazing. These studies found that as soon as water run-off occurred on the glass, the transmittance showed up to 2% increase. Another study [34] 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 increase of the light transmittance inwards.

A further study [10] tested the potential of “water-flow window” in reducing indoor heat gain and achieving energy saving. Through the numerical computation of the application, the study concluded that the system is able to enhance thermal and visual comfort. However, these applications do not cover the transmittance of the whole solar energy spectrum, including the visible light and both short and long-wave IR radiation. Hence, the current study will focus on the SGWF combined with the tinted glass that offers an effective low cost alternative solution for glazing in the tropics that might be one that enhances the efficiency of the glazing through its LSG factor, which is characterized by the performance of glazing vis-à-vis solar heat gain in glazed buildings [35]. The study measures the total transmittance of the solar spectrum through the glazed window in the presence of a thin downward-flowing water film.

2. Methodology

This is an experimental study of a flowing water film in the tropics to enhance the sustainability and the solar-optical properties of glazed buildings. As a result, there will be a change in the two portions of the solar heat gain; the heat conduction and the solar transmission of the glazed facades. The first, which is the thermal performance of the glazing with the presence of the sustainable water film, has been measured by the authors in another study [24]. The second is the solar transmittance, which is the essential portion of the solar heat gain to be controlled, particularly, in the

Fig. 2. View of the experiment site: test room (right) and reference room (left).
tropics. The following are field and laboratory experiments and a numerical attempt to explore the potentials of the glazed water film as a low cost alternative to spectrally selective low-e glazing for the tropics.

Overall, the experiments were conducted through the "control group design". The experiments were done in two phases. The first, the field experiment, uses the same equipment and methodology that were used in a previous study conducted by the authors [24]. It involves a full-scale two identical rooms (Fig. 2). A layer of 100 mm Rockwool insulation was used for the wall and internal roof (ceiling). Both rooms are designed so that each of the four walls faces the east, the west, the north and the south. Each room has an opening of 1.8 m height × 1.4 m width (WWR more than 50%) to be closed with 10 mm float tinted glass oriented to the west. In order to be exposed to the solar radiation without any shade, they are located on the rooftop of a seven-storey building and the experiments were conducted during the month of March, the period of the highest solar radiation intensity in Malaysia, where the Sun is overhead the experiment location (Malaysia 3°08' N the equator) so that to avoid applying shades from one room on the other room.

One room received the experimental treatments while the other did not and was used as the control room. Also, both rooms were post-tested on the dependent variables to reduce the errors. This stage of experiments was measured by a Babuc/A data logger that measured the indoor air temperature while the outdoor/indoor solar radiation was measured by a "Skye" data logger (refer to Fig. 3). The second phase concerns the solar-optical characteristic, measured by a "spectrophotometer". This instrument covers wavelengths of the radiation transmittance from 190 to 2500 nm, which effectively covered the solar radiation wavelengths. Distilled water and tap water were measured in a solar-optical glass of a standard "Quartz Cuvette" with a path length of 10 mm. The experiments were repeated many times to minimize the errors. The transmittance of the solar spectrum 190–2500 nm was measured in three steps.

- the base case (reference) without any water in both of the Quartz Cuvette
- measure the transmittance of distilled water and
- measure the transmittance of tap water.

3. Results and discussion

The results of the experiments will be discussed in two sections: the first is the site experiments. The second is the laboratory examination of the solar-optical performance of the water film.

3.1. Field experiments

Figs. 4 and 5 illustrate an example of the seemingly conflicting measurement results between the solar radiation and the indoor thermal values for two different sunny days. Fig. 4, the results on
the 27th of March, showed the peak data values on the tested west facade during the operation of the sustainable water film. The solar radiation energy was found higher behind the STG-WF than TG, while on the reference day of the 28th of March as shown in Fig. 5, without a 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 attributed to an increase in the visible light energy at the expense of the infrared energy.

Monitoring the result of the indoor air temperature with the same configuration (STG-WF) at the same time (27th and 28th March) would confirm this claim. The STG-WF caused a significant decrease in the indoor air temperature compared to TG as illustrated in Fig. 4 on the 27th of March. On the reference day of 28th March, Fig. 5 shows 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 (daylight) and blocked the infrared (heat), which is appropriate for glazed buildings in the tropics.

However, the reduction in the transmittance of the thermal energy indoors and the increase in the transmittance of the visible light energy resulted in 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 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 as follows:

The probable explanation for the increase in the solar transmittance measurement is that the water plays a role of an anti-reflective coating. Based on Fresnel’s laws the light reflection of the surface becomes low with anti-reflective surface coatings. 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 closer to the index of the air (index of \( n = 1 \)) than glass with an index of \( n = 1.54 \). The fact
that the visible light occupies a large portion within the solar spectrum range confirms the significant increases in the transmittance of the visible light within the total radiation. Moreover, the water film on the outer glass surfaces may cause the inner glass surface to become more reflective. Because of 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 increase of the solar radiation reading behind the SGWF. In summary, it is known that 45% of the total solar energy is in the non-visible infrared region that ranges from 780 to 2500 nm. In addition, the experiment results mentioned earlier concluded a reduction in the thermal flow inwards with SGWF; these factors indicate the increase behind the SGWF in the transmittance of the solar radiation is an increase in the visible light region of the solar radiation (daylight).

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 daylight while preventing heat gain. Laboratory experiments on solar-optical characteristics

Further explanation for this discrepancy that was found in the field experiments could be given by the solar-optical characteristics as measured by the “spectrophotometer”. It is pertinent to understand the solar-optical performance (transmittance, reflectance and absorption) of the solar radiation within the water film. The following results and discussion focus on the solar-optical characteristics (mainly the “transmittance”) of the water film for the entire range of wavelengths of the solar radiation spectrum.

The results of the measurements are illustrated in Fig. 6. The horizontal dashed-line is the transmittance plot of the test baseline of the optical glass “Quartz Cuvette” without water for minimizing the errors. The result shows that the solar spectrum is transmitted with 100% to all solar wavelengths rage. At the plot of “transmittance distilled/tap-water” the figure shows that the transmittance of the VI remain at the maximum of more than 100%. The transmittance started to decrease at the wavelength of NIR ranges from 780 nm to 2500 nm. A lesser transmittance was recorded at the range from 1300 nm to 2500 nm, where the radiation is totally absorbed. Both distilled-water and tap-water show high transmittance to VI that forms the light and less transmittance to IR that forms the heat. IR that transmits through glazing is absorbed by the indoor surfaces and reemitted as heat resulting in increasing indoor spaces temperature. The high VI transmittance values of more than 100% for wavelength from 380 to 780 nm are seemingly not right, but they can be explained as follows: As illustrated in Fig. 7, the reason is that the water refracts the solar beam inwards, causing a slight focussing affect on the detector. So if the beam overfills the detector, a diverging beam can lead to higher transmittance values. This confirms the results of the field experiments on the solar radiation transmittance, which was found to increase at the SGWF facades compared to the glazed facade without the water film.

The following is the attempt to numerically calculate the LSG of the SGWF façade. From the definition of the LSG ratio, the equation will be:

\[ \text{LSG} = \frac{\text{VT}}{\text{SHGC}} \]

(3)

where VT is the overall transmittance of the visible light through the SGWF. The SHGC of the SGWF may be calculated as a multiple glazing with coatings, as shown in the following equation [36]:

\[ \text{SHGC} = T_{\text{total}} + \sum_{k=1}^{n} Q_k \times A_k \]

(4)

where \( T_{\text{total}} \) is the overall solar radiation transmittance of the system; \( Q_k \) 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 \( T_{\text{SGWF}} \) could not be measured by this equipment. One of the problems is that the SGWF requires special equipment to cope with the large sample of the SGWF façade. To design a small sample of SGWF to suit the spectrophotometer 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 site experimental results with the SGWF [24], the inward fraction of the absorbed energy by the SGWF façade, \( Q_a \) in the Eq. (4), was found to be zero. The thermal conduction of the absorbed heat was fluctuating from zero to a negative value of 50 W/m² outwards. Therefore, the Eq. (4) becomes as:

\[ \text{SHGC}_{\text{SGWF}} = T_{\text{SGWF}} + (0 \times A_{\text{SGWF}}) \]

(5)

\[ \text{SHGC}_{\text{SGWF}} = T_{\text{SGWF}} \]

(6)

Moreover, based on the “Beer–Lambert law” [37] and referring to Fig. 8, the \( T_{\text{SGWF}} \) could be calculated as follows:

\[ T_{\text{water}} = \frac{I_1}{I_0} \]

(7)
\[ I_i = T_{\text{water}} \times I_0 \]  
\[ T_{\text{glass}} = \frac{I_i}{I_0} \]  
(8)  
(9)  

Replacing the \( I_i \) in the Eq. (9), the \( T_{\text{glass}} \) becomes as follows:

\[ T_{\text{glass}} = \frac{I_i}{T_{\text{water}} \times I_0} \]  
(10)  

Similarly the \( T_{SGWF} \) is the transmittance of the total SGWF facade that is as:

\[ T_{SGWF} = \left( \frac{I_i}{I_0} \right) \]  
(11)  

From Eqs. (10) and (11), the \( T_{SGWF} \) may be determined as follows:

\[ T_{SGWF} = \frac{1}{T_{\text{water}}} \times \left( \frac{I_i}{I_0} \right) \]  
(12)  

\[ T_{SGWF} = \frac{1}{T_{\text{water}}} \times (T_{SGWF}) \]  
(13)  

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

\[ T_{SGWF} = T_{\text{water}} \times T_{\text{glass}} \]  
(14)  

This Eq. (14) holds true with an assumption that the interface between the water film and the glass surface is neglected. However, the \( \varepsilon \) constant might be added to the equation to correct the errors as follows:

\[ T_{SGWF} = T_{\text{water}} \times T_{\text{glass}} \times \varepsilon \]  
(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. Thus, Eq. (15) for the total solar radiation transmittance of the SGWF facade will become as follows:

\[ T_{SGWF} = (T_{\text{water}} \times T_{\text{glass}} \times \varepsilon) + (R_g - R_w) \]  
(16)  

where \( R_g \) is the portion of the visible radiation reflected by glass, which is given by the manufacturer i.e. 10 mm clear glass has a visible light reflectance of 8%; while \( R_w \) is the portion of the visible radiation reflected 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 Eq. (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 manufacturer, as shown in Table 1, and the results of the calculation are summarized in Table 2. The overall solar transmittance value is the same value of \( SHGC \) during the operation of the water film, while without a water film the value of \( SHGC \) is the value of solar transmittance multiplied 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 facade without the water film. The results of the site experiments, as mentioned earlier, showed an increase in the \( SHGC \) with the SGWF facade due to the flowing of the water film over the glass.

| Table 2 | 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 STG-WF. However, the LSG ratio would assist to interpret this seemingly conflicting result. The spectral 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 2, the higher LSG ratio indicates more daylight without adding any extreme amount of the heat in the indoor spaces (low \( SHGC \)). The SGWF façade, therefore, would be the appropriate sustainable glazing system for east and west glazed facades in the tropics. |

### 3.2. Optimization of the water film thickness

The significant variable of the spectral selectivity of the SGWF is the water film thickness. The study determines the relationship between the water film thickness and its transmittance of the solar radiation over the different wavelengths of the solar spectrum. It is significant to note that the transmittance \( T_{\text{water}} \) of the water was measured using a spectrophotometer, ranging from 190 nm to 2500 nm. The light travelled through the Cuvette with a thickness of \( X = 10 \text{ mm} \) (as shown in Fig. 9) and the results varied according to the solar spectrum wavelengths.
Table 1
The characteristics of the glasses used in the experiments [38].

<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Outside</td>
<td>Inside</td>
<td>Outside</td>
<td>Inside</td>
<td>Outside</td>
</tr>
<tr>
<td>Pilkington clear</td>
<td>10</td>
<td>86</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>72</td>
</tr>
<tr>
<td>Pilkington bronze</td>
<td>10</td>
<td>30</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>26</td>
</tr>
</tbody>
</table>

Fig. 9. The water transmittance of a beam of light as it travels through a cuvette of width $X_1 = 10$ mm.

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

$$T = \frac{I_1}{I_0} = 10^{-\alpha x}$$

(17)

where $\alpha = \log (T/X)$

$$\frac{T_2}{T_1} = \frac{10^{-\alpha x_2}}{10^{-\alpha x_1}}$$

(18)

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

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

$$T_1 = \frac{I_1}{I_0} = \frac{37.68}{100} = 0.38$$

where $I_0$ is the intensity of the incident light (100) and $I_1$ is the total transmitted light through the water (37.68) that was measured using a spectrophotometer.

From Eq. (18), the value of $T_2$ can be calculated as:

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

(19)

This equation may be applied to the entire solar transmittance spectrum: the visible light transmittance and the short-wave infrared transmittance individually. The result is illustrated in Fig. 10. 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 short wave infrared can be divided into two ranges. The first range is from the 780 nm to 1300 nm (representing 30% of the entire short-wave IR in the solar radiation spectrum), its transmittance depends on the thickness of the water film, with weaker absorption at a thin thickness. The second range is from 1300 nm to the maximum range of the short wave infrared of 2500 nm (representing 70% of the entire short-wave IR radiation), which is strongly absorbed by the water film and a very thin water film showed a significant absorption in this range, as the absorption occurs on the upper surface of the water film. This is why the water film in the current experiment reduced the direct heat gain (short-wave infrared) besides preventing the heat conduction (long-wave infrared) from admitting inwards.

However, referring to Fig. 10 the optimum thickness of the water film that transmits more VL and less IR is at the point “p” with a water thickness of 10 mm that still easy to maintain. This thickness of 10 mm provides IR transmittance of less than 20%. Reducing the water thickness will result much more IR transmittance, while increasing the thickness to 20 mm will make a marginal reduction in IR transmittance. The maximum thickness of the water film for absorbing the entire short-wave IR radiation was found to be 20 mm, which is difficult to achieve on the glazed facades unless it is made as a water-filled window (double glazing with a cavity of 20 mm 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

Table 2
The solar control parameters evaluated for the glazing types used in the experiment, following the system suggested by this study i.e. the SCGW and STGW.

<table>
<thead>
<tr>
<th>Glazing type</th>
<th>Inward flowing solar heat, Q</th>
<th>Refractive index, n</th>
<th>Toverall solar</th>
<th>TVT</th>
<th>SHGC</th>
<th>LSG</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG</td>
<td>27% of 21 = 5.67</td>
<td>1.54</td>
<td>0.72</td>
<td>0.86</td>
<td>0.77</td>
<td>1.1</td>
</tr>
<tr>
<td>TG</td>
<td>27% of 69 = 18.63</td>
<td>1.54</td>
<td>0.26</td>
<td>0.3</td>
<td>0.44</td>
<td>0.75</td>
</tr>
<tr>
<td>SCGW</td>
<td>Zero</td>
<td>1.33</td>
<td>0.27</td>
<td>0.94</td>
<td>0.27</td>
<td>3.4</td>
</tr>
<tr>
<td>STGW</td>
<td>Zero</td>
<td>1.33</td>
<td>0.1</td>
<td>0.35</td>
<td>0.1</td>
<td>3.5</td>
</tr>
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controlled if the water film is evenly flowing. It is essential to note that smooth flow of the water film over the entire glass area is difficult to achieve, due to the effect of air movement over the facade, which causes the water to be flowing in a wavy condition. The hydrophilic coating which increases the wettability of the glass has a significant impact on the water flow with a smoother flow. This is in addition to its ability to clean the glass surfaces, which increases the light transmittance inversely.

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 1300 nm and 2500 nm which are totally absorbed by a thin water film.

4. Conclusion

It has been concluded that the use of water film with clear glazing building façade and with tinted glazing façade shows that both types of glazing absorb short wave infrared radiation and thus reduce the building up of internal heat. Also both types increase the transmittance of visible light due to the fact that the water film acts as an anti-reflective coat. The experiments show that tinted glazing performs better than clear glazing. The experiments show that the transmittance of visible light does not depend on the water film thickness. As for the infrared short wave radiation it is found that up to 70% of the radiation absorbed by the thin water film. The experiments also show that the remaining 30% of the infrared does correspond slowly with the increase in the thickness of the water film.

As for future experiments in this area we can suggest that the use of the water film technique with transparent photovoltaic (PV) would increase the efficiency of the PV tremendously as it cools down the temperature of the PV, cleans up the surface of PV and once more the use of water film works as antireflective surface to light.

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