World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:6, No:5, 2012

Thermal and Visual Performance of Solar Control Film

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***Abstract*—**The use of solar control film on windows as one of solar passive strategies for building have becoming important and is gaining recognition. Malaysia located close to equator is having warm humid climate with long sunshine hours and abundant solar radiation throughout the year. Hence, befitting solar control on windows is absolutely necessary to capture the daylight whilst moderating thermal impact and eliminating glare problems. This is one of the energy efficient strategies to achieve thermal and visual comfort in buildings. Therefore, this study was carried out to investigate the effect of window solar controls on thermal and visual performance of naturally ventilated buildings. This was conducted via field data monitoring using a test building facility. Four types of window glazing systems were used with three types of solar control films. Data were analysed for thermal and visual impact with reference to thermal and optical characteristics of the films. Results show that for each glazing system, the surface temperature of windows are influenced by the Solar Energy Absorption property, the indoor air temperature are influenced by the Solar Energy Transmittance and Solar Energy Reflectance, and the daylighting by Visible Light Transmission and Shading Coefficient. Further investigations are underway to determine the mathematical relation between thermal energy and visual performance with the thermal and optical characteristics of solar control films.

***Keywords*—**window, solar control film, natural ventilation, thermal performance, visual performance

I. Introduction

WINDOWS, the eyes of our building can provide daylighting as well as supplying fresh air. Many studies have shown that the health of human beings has improved through better hygiene in homes by increasing access to natural light and well ventilated indoor [1]-[2]. Heat gain, indoor thermal comfort and energy conservation depends on building design parameters such as size, shape, orientation, building form, optical and thermophysical properties of building envelope [3]. Among the pertinent window properties to be considered are Visible Light Transmittance (VLT), Solar Energy Absorption (SEA), Solar Energy Transmittance (SET), Solar Energy Reflection (SER), Solar Heat Gain Coefficient (SHGC) or Shading Coefficient (SC) and U-value [4]. VLT is the amount of visible light that pass through glazing system. Higher VLT implies more visible light enters the space [5]. SET is the solar energy transmittance through the window by infrared waves.

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Lower SET value means less solar radiation is transmitted. Meanwhile, SER is the ability for the solar energy to be reflected back to the source. Thus, lower SER value implies less solar radiation is reflected from the surface. SEA indicates the percentage of incident solar radiation that is absorbed by the window film or glass system. The higher the value, the more is the solar radiation absorbed. SC represents the ratio of solar heat gain through a glazing system under specific set of conditions as compared to solar heat gain through a reference glass (1/8” or 3 mm clear glass) under identical condition [6]. Thus, lower SC will give better solar shading. Previous studies recommended that for energy conservation, the SC value must be less than 0.5 for unconditioned buildings and 0.3 for air-conditioned buildings [7].

II. Literature Review

Buildings are built with large glazed surface area for visual appearance and better indoor lighting. However, this construction creates a high risk of thermal discomfort by allowing a large amount of solar radiation passing through glazed windows.

Malaysia lies in equatorial zone at longitude 100^o to 120^o E and latitude 1^o to 7^o N with warm humid climate throughout the year. The monthly average daily solar irradiation is 4000 - 5000 Whr/m^2 [8], and the mean yearly daytime temperature is between 26 ^{o}C to 31 ^{o}C and night-time is about 21 ^{o}C to 24 ^{o}C with mean daily average relative humidity between 67 % - 95 % [9]. The high temperature coupled with high humidity necessitates the use of air-conditioning systems especially in non-residential buildings.

Statistics show that the electrical load apportioning for air-conditioning and lighting in commercial buildings was 55 % - 65 % and 25 % - 35 % respectively [10]. Figures from energy audit and surveys conducted for offices in the country indicate electricity use in commercial buildings for air-conditioning was 52 % - 60 % and artificial lighting was 18 % - 42 % of the total consumption [11]. A recent energy audits and surveys of fully air-conditioning commercial buildings in Hong Kong revealed that lighting and air-conditioning account for 20 % - 30 % and 40 % - 60 % of the energy consumption respectively [12].

In recent years, windows have undergone a technological revolution. Development of new materials and advanced window technologies has led to new window products which are more efficient. Many studies have indicated that, daylighting has strong potential for energy savings [13]-[16]. Daylighting scheme shows that it was possible to achieve 10 % - 40 % of energy saving [17], while in another research work; daylighting can lead to 30 % - 50 % saving and in some cases up to 70 % [18].

The conventional clear float glass windows are inefficient in reducing the heat and thermal radiation transfer across the window system [19].

A simple passive strategy is an efficient way to reduce energy transmission through window glazing [20]. By adding solar control coatings it can avoid direct solar radiation entering the space without reducing the natural illumination [21]. Previous research work on glazing surface to reduce solar heat gain using copper based thin coatings has resulted a total of 18 % annual energy saving [22]. A study performed by another researcher showed that using double glazed tinted window can reduce solar heat gain [23]. A field study was performed to investigate the effect of selected shading devices on the room temperature of an office space [24]. Results showed the temperature difference between inside and outside of the office were 4.4 ^{o}C, 3.8 ^{o}C, 3.5 ^{o}C and 2.9 ^{o}C for silver film, blinds, tinted film and clear glass (5 mm) respectively.

An experimental investigation of glazing system was designed to solve the problems of glare and damage to interior furnishing [25]. The result shows that it may improve the visual comfort even in large glazed space area for facing East or West and reduce the heat gain to a minimum. A study of thermal performance at the cities in Turkey had established optimum building aspect ratios and South windows sizes of residential buildings [26].

Many researchers have concluded daylighting is one of the effective ways of reducing energy consumption especially on commercial buildings. But indirectly, this practice also allows unwanted solar radiation to enter the building and cause thermal discomfort to occupants. To solve this, a passive method such as solar control film can be used to reduce solar radiation while allowing the natural illumination from daylight. However, most of the studies have focussed on the building performance for energy efficiency. There are limited studies on mathematical model on the effect of thermal and optical characteristic of solar control film.

Therefore, the ultimate aim of this study is to develop a mathematical model to relate thermal energy and visual performance with thermal and optical characteristic for solar control films. This paper presents the preliminary findings from four types of window glazing systems.

III. METHODOLOGY

A. Objective

The aim of this study is to evaluate the thermal impact and visual impact of solar control films on windows for naturally ventilated test building under Malaysian climate.

Accordingly, the objectives are:

i. to evaluate the effect of window solar control films on thermal condition and daylighting of a test building facility.
ii. to analyze the profiles of thermal and visual impact based on thermal and optical characteristic on solar control films.

B. Description of Test Building

A test building facility located in Universiti Teknologi MARA Shah Alam was chosen for the experimental work. The dimension of building is 4m x 4m x 3m with two identical windows on adjacent walls of size equivalent to 10% of floor area as required by Malaysia Uniform By-Law [27].

The windows with dimension 1.22 m x 1.18 m are made of 6 mm single glazing clear glass facing North and West orientation. Fig. 1 shows the picture of the test cell and Fig. 2 show the schematic diagram for all side view of the building. The building construction is listed in Table 1.

Fig. 1 Test Building

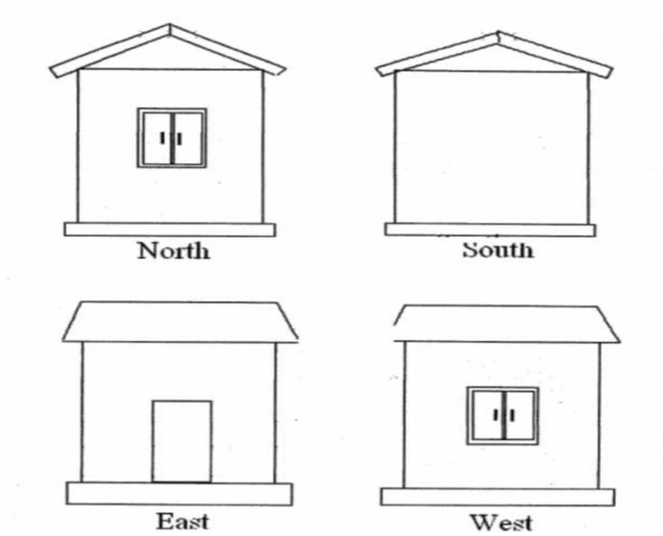

Fig. 2 Test Building's Schematic Diagram

TABLE I
BUILDING CONSTRUCTIONS

Element	Material	Thickness (mm)	k-value (W/mK)	R-value (m^2K/W)	U-value (W/m^2K)
Roof	Cement roof tile	10	0.836	0.21	4.76
Wall	Brickwork with plaster (18mm) on both sides	114	1.154	0.099	3.03
Ceiling	Cement board ceiling	4.5	0.25	3.15	0.32
Floor	Cast concrete	50	1.13	0.04	3.93
Door	Solid timber flush door with frame	38	0.138	0.28	2.17
Window	Clear glass	6	1.053	0.006	5.17

C. Equipments

The materials and equipments for the field measurement are shown in Table II and Fig. 3.

TABLE II
MATERIALS AND EQUIPMENTS USED

Materials/Equipment	Details
Graphtec Datalogger (GL800)	To log up to 20 different sources of input data
Thermocouple wire (t-type)	To measure surface temperature and air temperature
HOBO Data Logger	To measure indoor Illuminance
Solar Control Films	SYS 2, SYS 3 & SYS 4

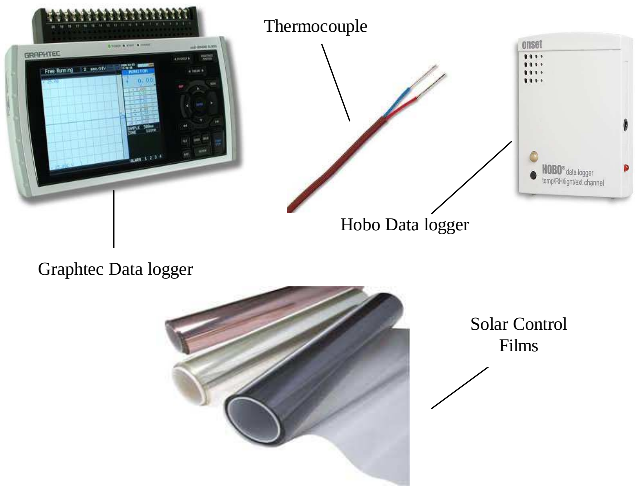

Fig. 3 Equipments Used

D. Experimental Set-up

Field data measurements were consecutively taken for four systems. System 1 (SYS 1), the conventional clear glass was the control system while System 2 (SYS 2), System 3 (SYS 3) and System 4 (SYS 4) were the control system layered with solar control film. Table III shows the window systems and data collection dates and Table IV shows the thermal and optical characteristics. All measurements were taken in natural ventilation with 20 % window opening throughout the duration of field work. Datalogging systems were set in 5-minute interval for duration of 14-days for each system.

TABLE III
FIELD MEASUREMENT

System	Window Material	Date
SYS 1	Clear Glass (control)	6 to 15 DIS 2011
SYS 2	Clear Glass + Solar Control Film Type 1	5 to 18 NOV 2011
SYS 3	Clear Glass + Solar Control Film Type 2	20 NOV to 3 DIS 2011
SYS 4	Clear Glass + Solar Control Film Type 3	17 to 30 DIS 2011

TABLE IV
THERMAL AND OPTICAL CHARACTERISTIC

Description	*SYS 1*	*SYS 2*	*SYS 3*	*SYS 4*
Visible Light Transmission (VLT)	89%	19.5%	3.8%	12.7%
Shading Coefficient (SC)	1.00	0.29	0.25	0.27
Solar Energy Transmission (SET)	80%	13.6%	7.9%	9.2%
Solar Energy Absorption (SEA)	13.6%	45.0%	47.1%	53.1%
Solar Energy Reflectance (SER)	7%	41.4%	45.0%	37.7%

IV. RESULT AND DISCUSSION

The 14-days data were averaged out by the hour to produce a 24-hour profile of temperature performance. All results are presented as graphs. These describe the effect of solar control films on windows under Malaysian climatic condition.

A. Surface Temperature and Surface Temperature Difference for North-Facing Window

For all systems, the North-facing window indicates higher daytime surface temperatures but was lower at night-time. Fig. 4 and 5 present the external and internal surface temperature for North-facing window for every window system at the test building. For the North orientation, data was analysed for selected hours of 10:00 hr, 12:00 hr and 14:00 hr.

Table V tabulates the comparison between internal surface temperature and external surface temperature for North-facing window. Further analysis was carried out to determine the relationship between surface temperature difference and solar energy absorption. The values are also tabulated in Table 5.

From Fig. 6, SYS 4 with higher solar energy absorption (SEA) of 53.1 % recorded surface temperature difference of 1.39 ^{o}C at 10:00 hr, 1.77 ^{o}C at 12:00 hr and 1.34 ^{o}C at 14:00 hr. SYS 3 and SYS 2 has a similar value for SEA of about 47.1 % and 45.0% respectively. Accordingly the surface temperature difference of SYS 3 and SYS 2 are quite similar. At 10:00 hr, SYS 3 and SYS 2 noted as 1.31 ^{o}C and 1.03 ^{o}C respectively. Next, at 12:00 hr recorded 1.29 ^{o}C and 1.27 for SYS 3 and SYS 2 respectively. For SYS 3 and SYS 2 at 14:00 hr, the result shows 0.85 ^{o}C and 0.89 ^{o}C respectively. From the SEA value, it shows that SYS 1 is the lowest compared to others and data shows SYS 1 has the lowest surface temperature difference of 0.20 ^{o}C, 0.12 ^{o}C and 0.11 ^{o}C at 10:00 hr, 12:00 hr and 14:00 hr respectively. A summary of surface temperature difference and SEA is tabulated in Table VI.

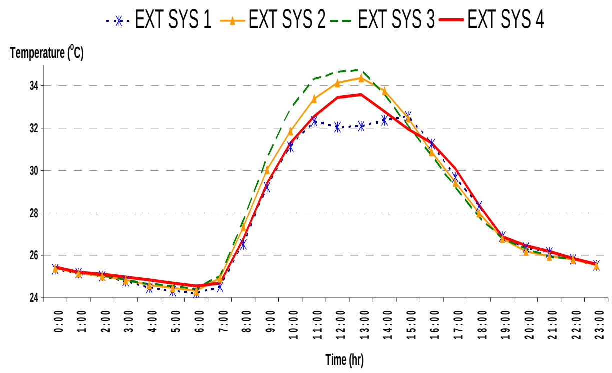

Fig. 4 External surface temperature for North-facing window

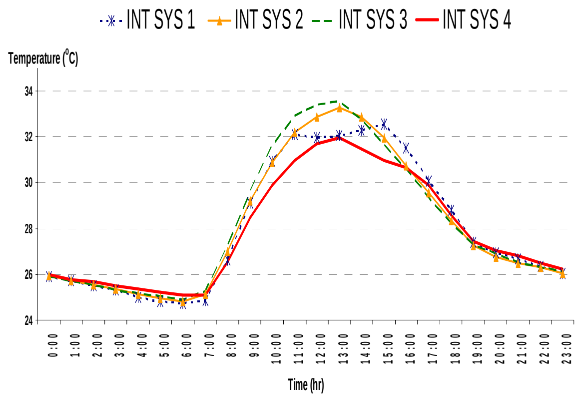

Fig. 5 Internal surface temperature for North-facing window

TABLE V
INTERNAL SURFACE, EXTERNAL SURFACE TEMPERATURE AND TEMPERATURE DIFFERENCE FOR NORTH-FACING WINDOW

SYSTEM	Time (hr)	Internal Surface (°C)	External Surface (°C)	ΔT (°C)
SYS 1	10:00	30.9	31.1	0.20
	12:00	32.1	32.1	0.12
	14:00	32.3	32.4	0.11
SYS 2	10:00	30.9	31.9	1.03
	12:00	32.9	34.2	1.27
	14:00	32.9	33.8	0.89
SYS 3	10:00	31.6	32.9	1.31
	12:00	33.4	34.7	1.29
	14:00	32.8	33.6	0.85
SYS 4	10:00	29.9	31.3	1.39
	12:00	31.7	33.5	1.77
	14:00	31.5	32.8	1.34

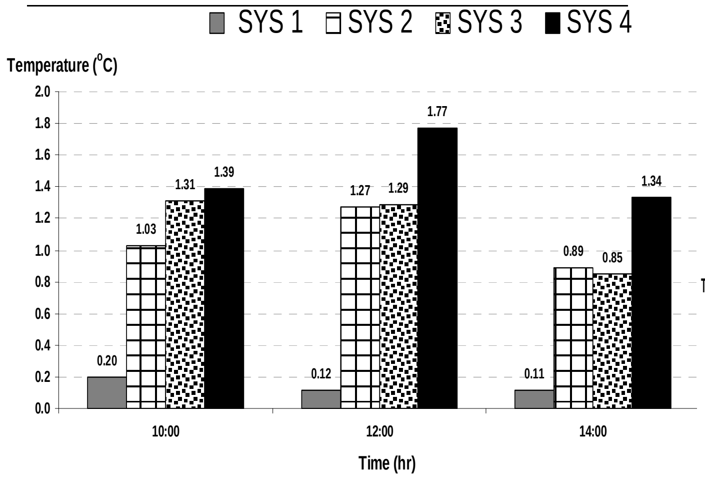

Fig. 6 Surface temperature difference for North-facing window

TABLE VI
SURFACE TEMPERATURE DIFFERENCE FOR NORTH-FACING WINDOW AT 12:00 HR

	ΔT (°C)	SEA
SYS 4	1.77 °C	53.1 %
SYS 3	1.29 °C	47.1 %
SYS 2	1.27 °C	45.0 %
SYS 1	0.12 °C	13.6 %

B. Surface Temperature and Surface Temperature Difference for West-Facing Window

Using similar analyses, the daily profile of surface temperature difference for West-facing window was done. Similar to the North-facing window, the daytime temperature is higher but lower at night-time as depicted in Fig. 7 and Fig. 8. Analysis for the surface temperature was focused at selected hours; 12:00 hr, 14:00 hr and 16:00 hr. Table 7 represents the comparison between internal surface and external surface temperatures and also the temperature difference. Fig. 9 illustrates that SYS 4 with the highest SEA of 53.1 %, has surface temperature difference of 2.03 °C at 12:00 hr, 1.80 °C at 14:00 hr and 2.33 °C at 16:00 hr. This is followed by SYS 3 with SEA of 47.1 %. The result for this system are 1.85 °C, 1.48 °C for 12:00 hr and 14:00 hr respectively. Except at 16:00 hr., SYS 3 showed a slightly lower value of about 1.17 °C as compared to SYS 2, which is recorded as 1.40 °C. This implies that there might be other factors that need to be considered, such as outdoor temperature and external surface temperature. Next, SYS 2 recorded the temperature of 1.57 °C, 1.47 °C at 12:00 hr and 14:00 hr respectively. Because of it lower SEA value, SYS 1 recorded the lowest surface temperature value of 0.87 °C, 0.88 °C and 1.08 °C at 12:00 hr, 14:00 hr and 16:00 hr respectively.

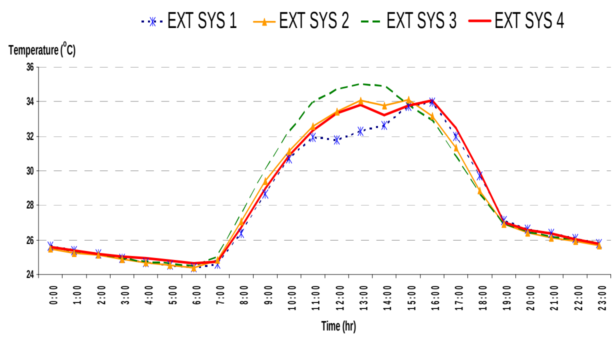

Fig. 7 External surface temperature for West-facing window

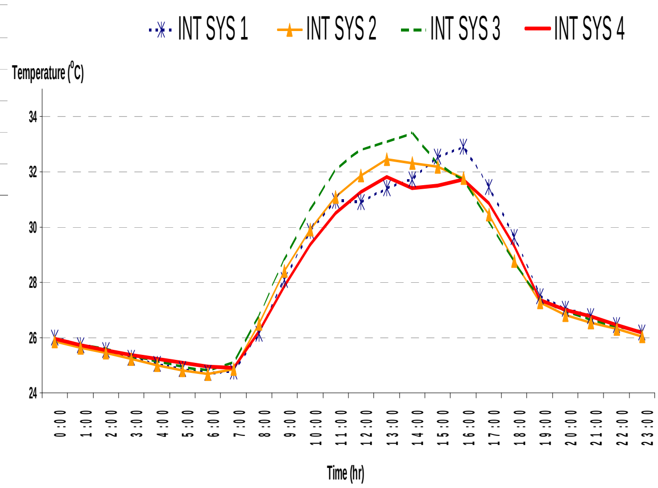

Fig. 8 Internal surface temperature for West-facing window

TABLE VII
INTERNAL SURFACE, EXTERNAL SURFACE TEMPERATURE AND TEMPERATURE DIFFERENCE FOR WEST-FACING WINDOW

SYSTEM	Time (hr)	Internal Surface (°C)	External Surface (°C)	ΔT (°C)
SYS 1	12:00	30.9	31.8	0.87
	14:00	31.7	32.6	0.88
	16:00	32.9	34.0	1.08
SYS 2	12:00	31.8	33.4	1.57
	14:00	32.3	33.8	1.47
	16:00	31.8	33.2	1.40
SYS 3	12:00	32.8	34.7	1.85
	14:00	33.4	34.9	1.48
	16:00	31.7	32.9	1.17
SYS 4	12:00	31.3	33.3	2.03
	14:00	31.4	33.2	1.80
	16:00	31.7	34.1	2.33

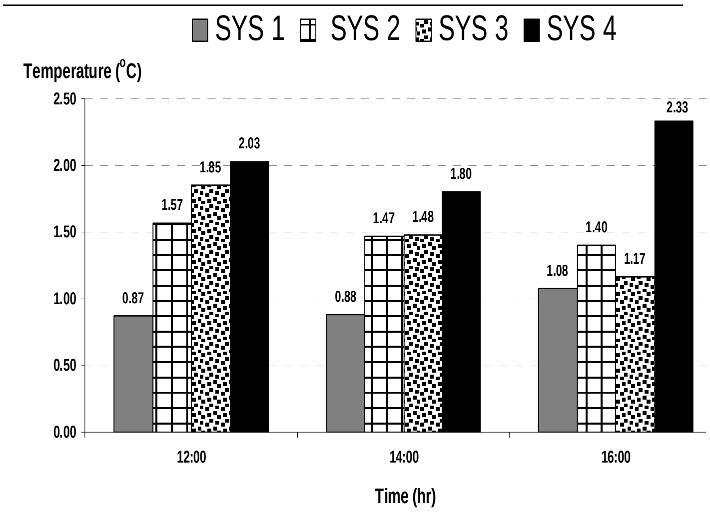

Fig. 9 Surface temperature different for West-facing window

From the comparison for both North and West orientation, it can be concluded that the surface temperature difference was affected by the value of SEA for each system. Higher SEA value has higher surface temperature difference for window and vice-versa as summarized in Table VIII.

TABLE VIII
SURFACE TEMPERATURE DIFFERENCE FOR WEST-FACING WINDOW AT 12:00 HR

	ΔT (°C)	SEA
SYS 4	2.03 °C	53.1 %
SYS 3	1.85 °C	47.1 %
SYS 2	1.57 °C	45.0 %
SYS 1	0.87 °C	13.6 %

C. Indoor and Outdoor Temperature Difference

For indoor and outdoor temperature difference are influenced by the solar energy transmittance (SET) and solar energy reflectance (SER). Fig. 10 illustrates the indoor and outdoor temperature difference profile focusing on daytime from 9:00 hr to 17:00 hr. At 12:00 hr, the comparison of temperatures difference was analyzed for all systems.

From Fig. 11, SYS 3 shows higher temperature difference of about 2.00 °C, because it has the lowest SET and the highest SER. The lower value of SET, the less solar radiation is transmitted while the higher value of SER, the more solar radiation is reflected. Then it followed by SYS 4 with temperature difference of 1.81 °C. Next the result shows the temperature difference for SYS 2 is 1.63 °C. For the lowest temperature difference, SYS 1 recorded as 1.19 °C. SYS 1 has a highest value for SET about 80 % and lowest value of SER about 7 % as shown in Table IX.

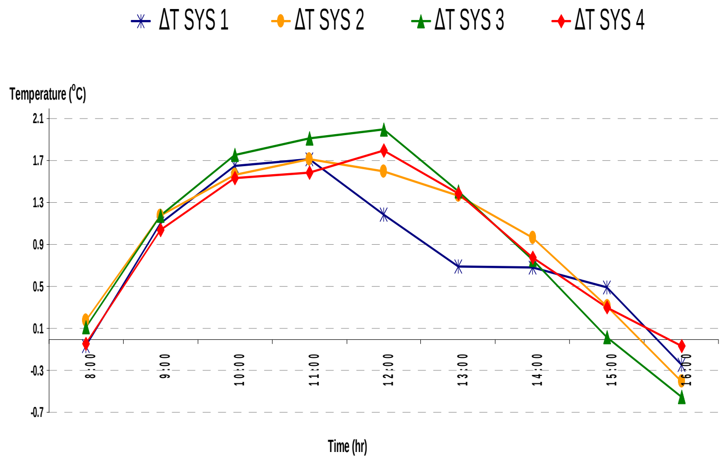

Fig. 10 Indoor and outdoor temperature difference for Test Cell

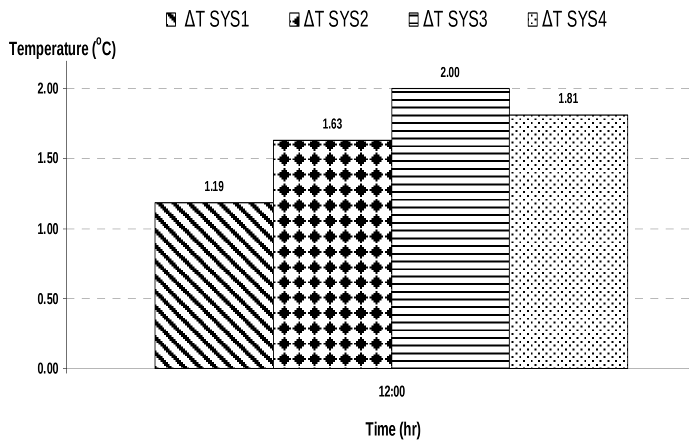

Fig. 11 Indoor and outdoor temperature difference for test building at 12:00 hr

TABLE IX
INDOOR AND OUTDOOR TEMPERATURE DIFFERENCE AT 12:00 HR

	ΔT (°C)	SET	SER
SYS 3	2.00 °C	7.9 %	45 %
SYS 4	1.81 °C	9.2 %	37.7 %
SYS 2	1.63 °C	13.6 %	41.4 %
SYS 1	1.19 °C	80 %	7 %

D. Illuminance Value in the Test Building

Illuminance is the total amount of visible light falling on a point on a surface from all directions above the surface in a time given. Its value is influenced by the amount of visible light transmittance (VLT) and shading coefficient (SC) of glazing system. Fig. 12 and Table 10 show that, the illuminance values increased from SYS 1, SYS 2, SYS 4 and SYS 3. At 12:00 hr, the higher value of illuminance of SYS 1 is 585.9 lux as a result of higher rating for VLT and SC. SYS 3 having the lowest rating for VLT and SC of about 3.8 % and 0.25 respectively has the lowest illuminance with a maximum of only 146.8 lux.

The illuminance value for SYS 1 exceeded the range use in residential and office buildings for common purpose. SYS 2 and SYS 4 which are in the range of two dotted red lines as shown in Fig. 12 have sufficient daylight in test building for about 384.0 lux and 244.7 lux respectively at 12:00 hr. This means both of these systems are verify the illuminance value as recommended in Malaysia Standard [28].

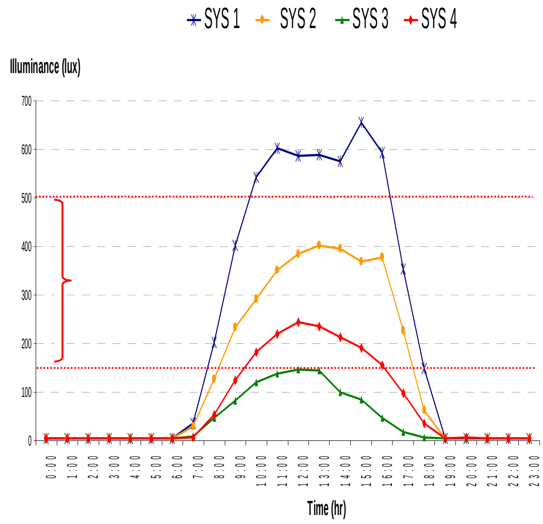

Fig. 12 Illuminance level in Test Cell

TABLE X
ILLUMINANCE VALUE

	10:00 hr	12:00 hr	14:00 hr	16:00 hr	VLT (%)	SC
SYS 1	541.7 lux	585.9 lux	576.3 lux	593.2 lux	89.0	1.00
SYS 2	291.0 lux	384.0 lux	394.5 lux	377.9 lux	19.5	0.29
SYS 4	182.7 lux	244.7 lux	213.7 lux	156.1 lux	12.7	0.27
SYS 3	121.0 lux	146.8 lux	100.9 lux	47.6 lux	3.8	0.25

V. CONCLUSION

This study has presented the thermal and visual impact based on thermal and optical characteristic on solar control films. Based on experimental work, the windows surface temperature difference for both orientations depends on its solar energy absorption (SEA). The higher SEA value will lead to a higher surface temperature difference.

From the experiment, the difference between indoor temperatures and outdoor temperatures at 12:00 hr were respectively 2.00 ^{o}C, 1.81 ^{o}C, 1.63 ^{o}C and 1.19 ^{o}C for SYS 3, SYS 4, SYS 2 and SYS 1. This temperature differences for all systems were affected by the value of solar energy transmittance (SET) and solar energy reflectance (SER). It is concluded that SET between 8 % - 9 % gives better thermal control. Visible light transmittance (VLT) and shading coefficient (SC) are the important factors affecting the amount of daylight through glass windows. The higher values of VLT and SC, the bigger amount of light can pass through the windows. From the graph, SYS 2 and SYS 4 with 12 % - 20 % of VLT provided sufficient daylight in test building and the illuminance levels meet the requirement in Malaysia Standard. This two systems maintained the required work plane illuminance of 240 lux – 380 lux for about six hours from 10:00 hr to 16:00 hr. Meanwhile, illuminance level for SYS 1 with VLT 89.0 % exceeded the recommeded range and SYS 3 with VLT 3.8 % is below the range. Additional data collection using more solar control films are in progress to get their relationship in simple mathematical model.

ACKNOWLEDGMENT

The authors greatly appreciate the support rendered by Faculty of Applied Science and IOS, Universiti Teknologi MARA by providing the necessary infrastructure and equipment for data collection. Special thanks to MIMG for collaboration and linkages.

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