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Behaviour of a SPD switchable glazing in an outdoor test cell with heat removal under varying weather conditions

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ABSTRACT

Suspended particle device (SPD) switchable glazing has potential to control transmission of solar radiation in the visible range by changing its transparency from 55% to 5%. Outdoor test cell characterisation of a SPD switchable glazing offered the dynamic solar heat gain coefficient (SHGC) which varied between 0.05 (when opaque) and 0.38 (when transparent). Reduction of maximum temperature rise of 11% and 15% was possible using SPD “transparent” and “opaque” state compared to same area double-glazing. Insulated test cell with water flow heat exchanger was employed to measure the cooling load reduction potential of SPD glazing while its transmission changed from “transparent” to “opaque” state. A cooling load reduction up to 6 kW h for a 0.343 m³ volume test cell was possible by changing a 0.21 m × 0.28 m SPD glazing transparency from “transparent” to “opaque”. Average overall heat transfer coefficient of SPD glazing varied between 5.02 W/m² K and 5.2 W/m² K for two different states.

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Nomenclature

A	cross sectional area of heat exchanger tube (m ²)
A_g	aperture area of glazing (m ²)
A_i	anisotropy index
A_{wall}	interior wall surface area (m ²)
C_{tc}	heat capacity of air (kJ/kg K)
C_g	heat capacity of water (kJ/kg K)
h₀	heat transfer coefficient from test cell external surface to ambient (W/m ² K)
h_i	heat transfer coefficient from test cell internal surface to interior of test cell (W/m ² K)
I	incident solar radiation on the vertical surface of glazing (W/m ²)
I_{beam,h}	incident beam solar radiation on the horizontal surface (W/m ²)
I_{dif,h}	incident diffuse solar radiation on the horizontal surface (W/m ²)
I_{extra}	incident extra-terrestrial solar radiation (W/m ²)
I_{sc}	solar constant (W/m ²)
k_d	diffuse factor
k_g	extinction coefficient
k_T	clearness index
K_{pl}	thermal conductivity of polystyrene (W/m K)
K_{wd}	thermal conductivity of wood (W/m K)
L_{pl}	thickness of polystyrene (m)
L_{wd}	thickness of wood (m)
l_h	length of heat exchanger pipe (m)

M_{tc}	mass of the air inside test cell (kg)
m	mass flow rate of water (kg/s)
N_g	number of glass pane
n	refractive index
Q_{in}	total energy incident on the glazing (W)
Q_{tc}	total energy available inside the test cell (W)
Q_g	heat through the glazing Incident solar radiation (W)
Q_{loss}	heat loss through the surfaces of test cell (W)
r_h	radius of heat exchanger pipe (m)
SE_{SPD}	transmitted solar energy through SPD glazing (W/m ²)
T_{tc,in}	interior temperature (°C)
T_a	ambient temperature (°C)
U_g	overall heat transfer coefficient of glazing (W/m ² K)

Greek symbols

α	absorptance
τ	transmittance
τ_v	vertical global transmittance
τ_{dir}	direct transmittance
τ_{dif}	diffuse transmittance
θ	incidence angle

1. Introduction

Building consumes around 30–40% of the world primary energy consumption for heating, ventilation, and cooling systems to enhance indoor thermal comfort [1,2]. To reduce the greenhouse gas emission and energy consumption from fossil fuel, it is necessary to improve the energy efficiency of building cooling systems. Admitted solar radiation through glazed building envelope increases a major portion of

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the total cooling load [3]. To avoid overheating by solar gain due to solar radiation, a building can (i) have small solar aperture [4], (ii) have high thermal mass or other heat sinks [4], (iii) have an appropriately coated glazing [4], (iv) have high natural ventilation rates [4], (v) include blinds at windows, (vi) include switchable glazing to give variable control solar gain through glazing [5–10], (vii) include forced circulation heat removal by air [11–13] or water flow [14–17] on the glazing's outside surface or between the two glass panes.

In a water flow glazing, water acts as an antireflection coating that absorbs short wave radiation but does not reduce the transparency of the glazing [18,19]. Water flow with double-glazing was found to maintain room temperature between 18 and 20 °C [20,21]. Water flow windows can potentially control the heat gain by 32% and 52% compared to double and single glazing respectively [14,16]. Water flow or airflow windows however need maintenance, controls, actuator, and pumps or fans.

Control of solar heat gain is also possible using a switchable glazing that changes opacity to restrict solar heat gain. Available switchable glazings are either (i) electrically controllable including electrochromic (EC) [22–25], liquid crystal (LC) [26–28], suspended particle device (SPD) [29–36] or (ii) not controllable but rather switch state when specific conditions are present, these include gasochromic [37–41], thermochromic [42–44], thermotropic [45,46] and phase change material [47–53].

Electrochromic glazing uses direct current (DC) to power switching whereas LC and SPD use alternating current (AC). An EC glazing changes from transparent to opaque by redox reaction in the presence of applied DC voltage typically from 0 to 5 V [54] that is reversed by inversion of electrical polarity [55,56]. Switching speed of colouration process for EC material is slow, increasing with the area of device, and affected by environmental conditions [57–59]. Switching time of EC glazing is proportional to the square root of the active

glazing area. EC colouration process (due to switching) does not always ensue evenly over large glazed areas [60,61].

In case of LC glazing, LC particles inside polymer mixtures are sandwiched between two glass panes [27,62]. In the presence of an electric field, liquid crystals align parallel to the field enabling light to pass through, creating a transparent state. The switch between the two states is nearly instantaneous. LC glazings have a hazy appearance as they scatter rather than absorb light [63].

In an SPD glazing, an SPD material is sandwiched between two glass panes. Without applied voltage, particles are suspended randomly and block light. Upon application of AC supply, particles are aligned perpendicularly to the charged plates [32,64] to pass light as shown in Fig. 1. The window changes its transmission from 5% to 55% in the presence of 0–110 V AC supply while switching speed is only few 100–120 ms [35]. SPD glazing also possess variable transparency under variable applied voltage [34]. Overall heat transfer coefficient (U -value) of this SPD glazing has been found to be 5.9 W/m² K using a thermally insulated test cell [32]. Low heat loss switchable SPD glazing offered a low overall heat loss coefficient, which varied between 1.00 and 1.16 W/m² K [33]. It was also found that SPD glazing is a suitable candidate to control the indoor daylight level and glare [34]. SPD glazing was powered from renewable source (photovoltaic device) and found to be a potential combination for future low energy building application where SPD will reduce the building energy demand and PV will generate supply to power the glazing [35]. Thus, SPD glazing can be considered as a potential candidate for zero energy or retrofit building application due to its glare control potential, variable transparency, and ability to switch with PV device. Investigation of SPD glazing is required to find out its solar gain control potential, which enhances the reduction of cooling load demand.

Fig. 1. SPD glazing switching showing (a) “opaque” and (b) “transparent” state.

Buildings experience diurnal solar gain due to diurnal variation of solar radiation. This variable gain can be controlled by varying transparency of switchable SPD glazing. The variable solar heat gain coefficient (SHGC) can enhance the occupant comfort by changing the states of the glazing. Up to date, no characterisation was reported to find the dynamic SHGC and cooling load reduction potential for switchable transmission of SPD glazing.

The aims of this research were to investigate

- the dynamic SHGC for SPD glazing;
- the reduction of cooling load provided by the transition of the SPD from “transparent” to “opaque” states;
- the overall heat transfer coefficient (U -value) of SPD glazing and double-glazing by heat removal (water flow heat exchanger) process from test cell.

Results of this work will be beneficial for building engineers to incorporate in retrofit or design a new low energy building with SPD switchable glazing.

2. Methodology

Outdoor test cell is an appropriate apparatus for the dynamic performance evaluation [65–68] for glazings. In this experiment, a test cell was equipped with a water flow heat exchanger to maintain the test cell temperature at a human comfort level. Heat exchangers were used to extract heat by using fluid flow [69–73] in many applications in the field of solar energy [73–83]. Water was used inside the heat exchanger as it has a high heat capacity [84] that enable to control the inside temperature.

2.1. System description

Two identical 0.7 m wide, 0.7 m deep and 0.7 m high test cells were insulated with inside surfaces composed of 0.10 m thick polystyrene material [32–35]. The active area of both SPD glazing and double-glazing was 0.0588 m² as shown in Fig. 2. The ratio of south facing test cell and glazing area was 8:1. 0.45 m long and 0.05 m diameter copper coil heat exchangers pipe was placed for both test cells. Water flow was controlled using ultrasonic flow meter.

Heat gains through the test glazing were balanced by the energy extracted by the heat exchanger of the test cell. The inside temperature was controlled by maintaining the inlet temperature of the circulating water through the heat exchanger at a constant mass flow rate of 0.016 kg/s. The temperature rise and the mass flow rate of the fluid across the heat exchanger were measured and the amount of energy lost by the heat exchanger was calculated.

Vertical plane pyranometer and horizontal plane pyranometer were set up to measure the solar radiation. Ambient, test cell internal ambient, internal, and external surface of glazing, water flow inlet and outlet temperature were measured using T type thermocouples. Delta T type data logger was employed in this experiment to record the continuous data. Fig. 3 illustrates the complete photographic view of experimental set up.

2.2. Glazing transmission

Measured transmission spectra for SPD glazing in “opaque” and “transparent” states and for double-glazing using AvaSpec-UL-S2048L Star Line Versatile Fiber-optic Spectrometer is shown in Fig. 4.

Absorption of SPD glazing was calculated using Eq. (1) where reflection was calculated using Fresnel equation given by Eq. (2) [85].

$$A_{spd} = 1 - (T_{spd} + R_{spd}) \quad (1)$$

$$R_{spd} = \left(\frac{n_g - n_{air}}{n_g + n_{air}} \right)^2 \quad (2)$$

where the refractive indices of SPD glazing (n_g) and air (n_{air}) are 1.6 and 1.0 respectively. The solar absorption for different glazings are described in Table 1.

3. Calculations of glazing properties

3.1. Dynamic solar heat gain coefficients

For vertical surface glazing, direct solar radiation incident to the glazing surface at oblique incidence angles at which the transmittance is different from the near-normal values. This angular behaviour of τ_v (global solar transmittance through glazing) was calculated from as [86] as given in Eq. (3).

$$\begin{aligned} \tau_v = & \left[k_d \{ k_T R_b (1 - k_d) + (1 - \cos \beta) (1 - k_T (1 - k_d)) \} \right. \\ & \left. + R_b (1 - k_d) + R_g \frac{1 - \cos \beta}{2} \right] \times \tau_{dir} R_b (1 - k_d) (1 + k_d k_T) \\ & + \frac{\tau_{dif} k_d}{2} (1 + \cos \beta) (1 - k_T (1 - k_d)) + \frac{\tau_g R_g (1 - \cos \beta)}{2} \end{aligned} \quad (3)$$

$$\begin{aligned} \tau = & \frac{1}{2} \left[\frac{1 - \left\{ \frac{\sin(\theta-n)}{\sin(\theta+n)} \right\}^2}{1 + (2n_g - 1) \left\{ \frac{\sin(\theta-n)}{\sin(\theta+n)} \right\}} \right. \\ & \left. + \frac{1 - \left\{ \frac{\tan(\theta-n)}{\tan(\theta+n)} \right\}^2}{1 + (2n_g - 1) \left[\frac{\tan(\theta-n)}{\tan(\theta+n)} \right]^2} \right] \times \exp \left(\frac{-k_g N_g t_g}{\cos \theta} \right) \end{aligned} \quad (4)$$

and

$$\begin{aligned} \tau &= \tau_{dir} \text{ when } \theta = \theta_{dir} \\ \tau &= \tau_{dif} \text{ when } \theta = \theta_{dif} = 59.68 - 0.1388\beta + 0.001497\beta^2 \text{ [87]} \\ \tau &= \tau_g \text{ when } \theta = \theta_g = 90 - 0.5788\beta + 0.002693\beta^2 \text{ [87]} \end{aligned}$$

Diffuse factor (k_d) and clearness index (k_T) can be calculated by using Eqs. (5) and (6).

$$k_d = \frac{I_{dif,h}}{I_{global}} \quad (5)$$

$$k_T = \frac{I_{global}}{I_{extra}} \quad (6)$$

where

Fig. 2. Experimental set up.

$$I_{extra} = I_{sc} \left(1 + 0.033 \cos \frac{360n}{365} \right) (\cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta) \quad (7)$$

I_{sc} is the solar constant, n is the day of year, ϕ latitude angle, δ declination angle and ω hour angle.

Solar energy transmitted through glazing [86] can be written as Eq. (8)

Fig. 3. Photographic view of experimental set up.

Fig. 4. Visible and NIR transmission of SPD glazing opaque and transparent state and low-e coated double-glazing. Transmission was compared with AM 1.5 solar spectrum.

Table 1
Details of glazing.

	Applied voltage (V)	Average solar transparency (%) in visible wavelength	Absorption (%)	Dimensions (m × m)	Supplier
Double glazing	Not applicable	78	17	0.21 × 0.28	Pilkington
SPD “opaque” state	0	5	9	0.21 × 0.28	Smart glass international
SPD “transparent” state	110	55	4	0.21 × 0.28	

$$SE_{spd} = (I_{beam,h} + I_{dif,h}A_i)\tau_{dir}r_b + I_{dif,h}(1 + A_i)\tau_{dif,h}\frac{(1 + \cos \beta)}{2} + I_{global}\rho_g\tau_g\frac{(1 - \cos \beta)}{2} \quad (8)$$

where A_i is anisotropy index that indicates atmospheric transmittance due to beam solar radiation given by

$$A_i = \frac{I_{beam,h}}{I_{extra}} \quad (9)$$

The dynamic solar heat gain coefficient was calculated from Eq. (10)

$$SHGC = \frac{SE_{spd}}{I_{ver,global}} \quad (10)$$

3.2. Overall heat transfer coefficients

To calculate overall heat transfer coefficient, following assumptions were made:

- Measurements were made while the vacuum glazing was in thermal steady state.
- Ground reflected solar radiation was assumed to be zero.
- The test cell was made of homogeneous highly insulating materials.

Energy balance equation using heat exchanger can be written as Eq. (11)

$$Q_{in} = Q_g + Q_{hexchanger} + Q_{loss} \quad (11)$$

where

$$Q_{in} = I(t)A_g\tau_v(\theta)\alpha \quad (12)$$

Heat loss through the glazing is given by

$$Q_g = A_gU_g(T_{tc,in} - T_{tc,out}) \quad (13)$$

Heat removal from the test cell

$$Q_{hexchanger} = \dot{m}_{water}c_{water}(T_{wo} - T_{wi}) \quad (14)$$

$$\dot{m}_{water} = \rho_{water}A_{v_{water}}\Delta T = (T_{outw} - T_{inw})$$

Heat losses through the wall is represented by

$$Q_{loss} = Q_{wall} = (UA)_{wall}(T_{tc,in} - T_{tc,out}) \quad (15)$$

$$(UA)_{wall} = \left[\frac{1}{h_0} + \frac{L_{pl}}{K_{pl}} + \frac{L_{wd}}{K_{wd}} + \frac{1}{h_i} \right]^{-1} \times A_{wall} \quad (16)$$

The convective heat transfer coefficient [88] between ambient air and outer glazing surface is calculated with the local wind speed V_{wind}

$$h_i = 2.0 + 3V_{wind} \quad (17)$$

$$h_0 = 5.7 + 8.8V_{wind} \quad (18)$$

Overall heat transfer coefficient U_g for glazing with heat removal was calculated from

$$U_g = \frac{Q_{in} - Q_{hexchanger} - Q_{loss}}{A_g(T_{tc,in} - T_{tc,out})} \quad (19)$$

4. Results and discussion

4.1. Measurement without heat removal from the test cell

Fig. 5 shows the solar energy transmitted through the SPD in “transparent” and “opaque” states and through double-glazing for a typical sunny day in Dublin. The maximum energy transmitted through the double-glazing, SPD “transparent” and SPD “opaque” nearly at 12:00 noon were 520 W/m², 410 W/m², 50 W/m² respectively. Fig. 6 shows the changing solar heat gain coefficients (SHGC) for incidence angle for double-glazing, SPD “transparent” and “opaque” state. Variation of glazing transmission is shown in the figure, which changed with incidence angle. Direct transmission changed with incidence angle. SHGC changed for SPD “transparent” from 0.38 to 0.08. For SPD “opaque” state SHGC was 0.05 at mid-day period.

Fig. 7 indicates the test cell internal temperature of SPD glazing “transparent” and “opaque” states and double-glazing, which was recorded for typical Dublin sunny day. From clearness index and

Fig. 5. Solar energy transmitted through SPD “transparent”, “opaque” and double-glazing.

anisotropic index, it can be seen that influence of direct solar radiation was high until 15:00 h. Maximum temperature for these three cases was 39 °C, 35 °C and 44 °C respectively. Ambient temperature was maximum 22 °C with temperature swing of 11 °C between 04:00 h and 12:00 h. This rise of indoor temperature was higher than the standard 22 °C comfortable room temperature. Test cell temperature for SPD glazing “transparent” and “opaque” state increased at 1.8 °C/h and 1.4 °C/h respectively. For double-glazing, internal temperature increased at 2 °C/h while the ambient temperature increased at 1.0 °C/h. Maximum temperature rise was 11% and 15% less for SPD “transparent” and “opaque” state compared to double-glazing. Maximum temperature and thermal swing from 04:00 h to 14:00 h are listed in Table 2.

4.2. Measurement with heat removal from the test cell

Fig. 8 illustrates the temperature difference of water in and out of the test cell for double-glazing SPD “transparent” and “opaque” states. The water mass flow rate was constant 0.016 kg/s for all three cases. Maximum temperature difference of water inlet and outlet for double-glazing was 3 °C while for SPD “transparent” was 2.4 °C and “opaque” was 0.8 °C.

Total extracted heat from SPD “transparent”, double and SPD “opaque” states were 10.38 kW h, 10.64 kW h, 4.02 kW h for a sunny day while mass flow rate of water was 0.016 kg/s as shown in Fig. 9. It indicates that to keep the room at lower temperature in summer SPD opaque condition is more useful as 62% less heat had to be extracted from test cell and 2% while SPD transparent compared to double-glazing. Thus, SPD “opaque” state reduces the cooling load. The daily energy saving requirement to ensure an indoor temperature close to comfort temperature (21–25 °C) is 6 kW h for SPD “opaque” and 0.26 kW h for SPD “transparent” compared to double glazing.

Fig. 10 shows the test cell internal temperature after constant water mass flow rate 0.016 kg/s inside the heat exchanger. Double-glazing maximum temperature reached 29 °C while SPD “transparent” and “opaque” were 25 °C and 22 °C. Test cell internal temperatures for double, SPD “transparent” and SPD “opaque” state reduced to 32%, 34% and 37% respectively compare to no heat exchanger case (Fig. 7). Table 3 presents the physical parameters, which were used for the calculation of overall heat transfer coefficient.

Diurnal variation of overall heat transfer coefficient was calculated using Eq. (19) are shown for Double-glazing, SPD “opaque” and “transparent” state were 2.3 W/m² K, 5.02 W/m² K and 5.2 W/m² K respectively as shown in Figs. 11–13.

SPD glazing average U -value from our previous investigation was 5.9 W/m² K [32]. In this work, variation of average U -value was due to the heat removal effect from the test cell.

From experimental results, following advantages of SPD switchable glazing are found;

- Variable SHGC – Buildings experience diurnal solar gain due to diurnal variation of solar radiation. Variable transparency of switchable SPD glazing has potential to control this variable solar gain. Two different types of SHGC coefficients are possible from this SPD glazing, which has immense impact on building application. Presence of variable SHGC can enhance the occupant comfort by changing the states of the glazing.

Cooling load reduction potential – Transmission change of SPD glazing from transparent to opaque state has potential to reduce cooling load. Up to 6 kW h reduction of electricity demand reduction was possible from 0.343 m³ test cell by changing the SPD glazing from transparent to opaque state.

High U -value and variable SHGC – High U -value and variable SHGC make this glazing a suitable applicant for summer time where discomfort caused by solar gain will be reduced by changing SPD transparent to opaque and high U -value offers high heat losses from inside room to outside ambient.

High U -value indicates SPD glazing behaviour as a single glazing with controllable switchable transparency, which offers variable SHGC and cooling load reduction. These unique properties make it a potential candidate for retrofit or new building application.

5. Conclusions

Cooling load reduction potential of suspended particle device (SPD) glazing from “transparent” state to “opaque” state was investigated using an outdoor test cell integrated with one copper coil water flow heat exchanger. Without heat removal, maximum test cell temperatures were 35 °C and 39 °C for SPD glazing “opaque” and “transparent” states. Variable solar heat gain coefficient from 0.05 to

Fig. 6. Change of SHGC and transmittance of SPD glazing for its transparent (55%) and opaque (5%) states and double-glazing (78% transparent) with incident angle.

0.38 was achieved using SPD switchable glazing. A 0.016 kg/s constant water mass flow rate through heat exchanger reduced the inter-

nal test cell temperatures to 25 °C and 22 °C for SPD “transparent” and SPD “opaque”. For the particular test cell, reduction of cooling

Fig. 7. Test cell internal temperature of double-glazing, SPD “transparent” and “opaque” states before using the water flow for a typical sunny day in Dublin.

Table 2

Test cell temperature for different glazing.

	Maximum internal temperature (°C)	Internal temperature swing (°C) (between 04:00 h and 14:00 h)
SPD “transparent” test cell	39	18
Glazing SPD “opaque” test cell	35	15
Double glazing test cell	44	20
Ambient	22	10

opaque state was 6 kW h. Overall heat transfer coefficient of SPD glazing when “transparent” and when “opaque” state were 5.2 W/m² K and 5.02 W/m² K respectively. Variable switchability of SPD glazing is advantageous for building application as cooling demand of building also vary throughout the day.

6. Uncited references

[60,61].

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load when comparing the SPD in the transparent with the SPD in the

Fig. 8. Temperature difference of water flowing inside the test cell for double-glazing, SPD “transparent” and “opaque” states at constant water mass flow rate 0.016 kg/s.

Fig. 9. Heat extracted from SPD “transparent”, SPD “opaque” and double-glazing test cell at constant 0.016 kg/s water mass flow rate.

Fig. 10. Test cell internal temperature of double-glazing, SPD “transparent” and “opaque” state at 0.016 kg/s water mass flow rate.

Table 3

Parameters used for the calculations.

Parameter	Dimensions	Value
Dimensions	Aperture area of glazing (A_{vacuum})	0.0588 m ²
	Interior wall surface area (A_{wall})	0.44 m ²
	Internal volume of test cell (V_{air})	0.174 m ³
	Thickness of wood (L_{wd})	0.02 m
	Mass of air inside test cell ($M_{\text{ic}} = V_{\text{air}} \times \rho_{\text{air}}$)	0.2134 kg
	Mass flow rate of water ($\dot{m}_{\text{water}}$)	0.016 kg/s
	Thickness of Polystyrene (L_{pl})	0.15 m
	Length of heat exchanger pipe (l_{h})	0.45 m
	Radius of heat exchanger pipe (r_{h})	0.005 m
	Density of air (ρ_{air})	1.2250 kg/m ³
Properties	Density of water (ρ_{water})	997.8 kg/m ³
	Heat capacity of air (C_{air})	1.006 kJ/kg K
	Heat capacity of water (C_{g})	4.18 kJ/kg K
	Thermal conductivity of polystyrene (K_{pl})	0.022 W/m K
	Thermal conductivity of wood (K_{wd})	0.09 W/m K
Variable	Temperature inside test cell ($T_{\text{in,ic}}$)	Measured by T type thermocouple (K)
	Temperature inside test cell ($T_{\text{out,ic}}$)	
	Incoming cold water temperature ($T_{\text{in,w}}$)	Measured by pyranometer (W/m ²)
	Outgoing hot water temperature ($T_{\text{out,w}}$)	
	Vertical surface incident solar radiation ($I(t)$)

Fig. 11. Diurnal variation of overall heat transfer coefficient (U -value) for SPD glazing "transparent" state.

Fig. 12. Diurnal variation of overall heat transfer coefficient (U -value) for SPD glazing "opaque" state.

Fig. 13. Diurnal variation of overall heat transfer coefficient (U -value) for double-glazing.

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