2017-02-17

Effect of Sky Conditions on Light Transmission Through a Suspended Particle Device Switchable Glazing

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Recommended Citation

Ghosh, A., Norton, B. and Duffy, A. (2017) Effect of sky conditions on light transmission through a suspended particle device switchable glazing. *Solar Energy Materials and Solar Cells*, Volume 160, February 2017, Pages 134–140. doi:10.1016/j.solmat.2016.09.049

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Effect of sky conditions on light transmission through a suspended particle device switchable glazing

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ARTICLE INFO

Article history:

Received 31 July 2016

Received in revised form 5 September 2016

Accepted 29 September 2016

Available online xxx

Keywords:

SPD glazing

Clearness index

Transmission

Solar energy (SE)

Incident angle; glazing

ABSTRACT

A suspended particle device (SPD) switchable glazing changes its state from opaque to transparent in the presence of a power supply. SPD glazing's near normal transmission varies with incident angle and clearness index. Due to a lower diffuse component, higher glazing transmission ensues at higher clearness indices. Transmittance values for different azimuthal incident angle for a SPD glazing for its "transparent" and "opaque" states have been determined. In Dublin, below 0.5 clearness index, isotropic diffuse transmittance was prevailed while transmission of direct insolation was dominant above 0.5 clearness index. For south facing vertical plane SPD glazing transmittance in its transparent and opaque states are 0.25 and 0.025 respectively while clearness index is below 0.5.

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Nomenclature

I	incident solar radiation on the vertical surface of glazing (W/m^2)
I_{global}	incident solar radiation on the horizontal surface of glazing (W/m^2)
$I_{\text{beam,h}}$	Incident beam solar radiation on the horizontal surface (W/m^2)
$I_{\text{dif,h}}$	incident diffuse solar radiation on the horizontal surface (W/m^2)
I_{extra}	extra-terrestrial solar radiation (W/m^2)
I_{sc}	solar constant (W/m^2)
k_d	diffuse fraction
k_g	extinction coefficient
k_T	clearness index
N_g	number of glass pane
n	refractive index
SE_{SPD}	transmitted solar energy through SPD glazing

Greek symbols

α	absorptance
τ	transmittance
τ_v	vertical global transmittance
τ_{dir}	direct transmittance
τ_{diff}	diffuse transmittance
τ_g	ground reflected transmittance
θ	incidence angle

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1. Introduction

Solar energy transmitted through a glazing system is the consequence of the optical properties of the glazing producing distinct incident-angle dependencies applicable to the differing relative intensities of direct, diffuse and ground reflected solar radiation components. As sunlight is incident at a range of different incident angles changing with time of a day and season, glazing transmittances are therefore significantly different from their values at normal incidence. Thus, design calculations for glazing systems in buildings based on near-normal transmittance and reflectance values alone offer overestimated results [1–5].

For the diffuse transmittance, an equivalent value of the direct transmittance for an average incidence angle of about 60° has been recommended for use in design calculations [6]. Hemispherical normal reflectance and transmittance properties of a variety of coated and uncoated plastics (teflon, tedlar, acrylic) and fiberglass composites (e.g., greenhouse coverings) are available as a function of wavelength, polarization and incident angle [7]. The composition, thickness, density, column shape, size, direction, and the spatial arrangement of column and voids all have an effect on the angular dependent optical properties of glazing [8]. The variation of glazing transmission with clearness index for selected European locations and surface orientations has been studied theoretically [9] as it has the effect on transmission due to presence of coatings [10,11].

1.1. Solar energy material for glazing technology

A wide variety of different advanced glazing technologies are available that (i) control heat and/or light gain, (ii) provide low heat

loss (iii) control air-flow, (iv) deflect daylight deep into a room and/or (v) provide reduced noise transmission [12–14]. A switchable transparency glazing can be actuated electrically or non-electrically [15–20]. Electrically-actuated glazings include AC-powered suspended particle devices (SPD) and DC powered electrochromic (EC) devices [18]. Electrically-actuated SPD glazing can provide control of solar heat gain and glare in building fenestration applications [21–23]. SPD glazing is almost opaque without the application of power supply and transparent when, AC power supply is applied (in this example, an 100 V) as shown in Fig. 1. An SPD glazing will have intermediate transparency, for the particular example chosen, between 5–55% when the applied AC voltage is set between 0 and 100 V [24,25]. The daylighting and thermal performance of an SPD glazing showed that SPD glazing is superior over other glazing applications in building [23,24].

When a SPD glazing is to be considered for inclusion in either new or refurbished buildings, knowledge of solar energy transmission behaviour with clearness index provides a ready means of assessing annual glazing performance [9]. The clearness index has been shown to be useful for parameterising insolation conditions [26].

The variation for a particular SPD, of its glazing transmittance with clearness index is presented in this work.

For a vertical glazing as shown in Fig. 2, direct solar radiation is incident to a glazing surface at oblique incidence angles.

The transmittance of the vertical glazing is given by;

$$\tau_v = \left[k_d \{ k_T R_b (1 - k_d) + (1 - \cos \beta) (1 - k_T (1 - k_d)) \} + R_b (1 - \tau_{dir} R_b (1 - k_d) (1 + k_d k_T) + \frac{\tau_{dif} k_d}{2} (1 + \cos \beta) (1 - k_T (1 - k_d)) + \frac{\tau_i}{2} \right]$$

where

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

and

$$\tau = \tau_{dir} \text{ when } \theta = \theta_{dir}$$

$$\tau = \tau_{dif} \text{ when } \theta = \theta_{dif} = 59.68 - 0.1388\beta + 0.001497\beta^2 \quad [27]$$

$$\tau = \tau_g \text{ when } \theta = \theta_g = 90 - 0.5788\beta + 0.002693\beta^2 \quad [27]$$

Simplified equation for angle dependent glazing transmissions are shown in Table 1.

Transmitted solar energy through the SPD glazing can be calculated from Eq. (3) [9].

$$SE_{spd,glazing} = (I_{beam,h} + I_{dif,h} A_i) \tau_{dir} r_b + I_{dif,h} (1 + A_i) \tau_{dif,h} \frac{(1 + \cos \beta)}{2} + I_{global} \rho_g \tau_g \frac{(1 - \cos \beta)}{2} \quad (3)$$

2. Measurements and results

The variation of spectral transmission with wavelength of an SPD glazing in transparent and opaque states, measured in a laboratory using AvaSpec-ULS2048L Star Line Versatile Fiber-optic spectrometer [22–24] as shown in Fig. 3. Solar spectral irradiance at AM 1.5 is for

Fig. 1. : Operation and appearances a particular example of SPD glazing in its “opaque” and “transparent” states.

Fig. 2. : Schematic diagram of a south facing vertical plane glazing with incident angle and solar elevation angle.

comparison. As can be seen, an opaque SPD glazing would be able to control visible solar radiation, transmitting only a relatively small portion of solar radiation below 820 nm.

Horizontal plane global solar radiation, horizontal plane diffuse solar radiation, vertical plane global solar radiation was measured using Kipp and Zonen pyranometers [21–25]. 5 min interval data were recorded using delta T type data logger.

Fig. 4(a) and (b) show the SPD glazing transmission on 1st January and 1st July in Dublin, Ireland, for SPD glazing in “transparent” and “opaque” states. Fig. 4(c) indicates the sun path and variation of solar elevation for 1st January and 1st July in Dublin. Position of sun is also shown in Fig. 4(d) and (e). Due to change of sun position, incident angle varied. In Dublin for vertical plane south facing glazing, incident angle varied from 53° to 13° on 1st of January from 7 am to 12 pm. In the month of July this incident angle varied from 82° to 59° from 7 am to 12 pm.

3. Comparison and interpretation of results

Fig. 5 illustrate the transmission of SPD glazing in transparent and opaque state using different model described in Table 1. It was found that the model described by Montecchi & Polato [28] gave best fit for $x=3$. Karlsson & Ross [4] gave best fit for $A=8$ $p=2$ $q=2$, $\beta=2$. At higher incident angle, little variation was observed for Karlsson & Ross [4] model from those of Waide & Norton [9] and Montecchi & Polato [28]. Incident angle between 35–60, the measured transmittance deviates from other three models.

Fig. 6 shows the dependency of glazing transmission with clearness index. It is evident that higher transmission occurred at higher

clearness indices and the angular-dependent transmission of direct solar radiation dominates. Fig. 7 shows the transmission with clearness index and incident angle for a south facing SPD glazing in its “transparent” and “opaque” states. Though the transmittance values are different, the trends for the variation of transmittance with clearness indices are similar for transparent and opaque states.

In building design studies, without large computational time and/or resources in western European location it is possible to use only one single transmittance value for vertical plane glazing which is associated with isotropic diffuse solar component [9]. For different azimuthal direction, below a threshold limit of clearness index, this transmittance values gives less than 1% errors [9].

For vertical plane south facing glazing located in Dublin, a single value for the transmittance of an SPD glazing of 25% for the transparent state and 2.5% for the opaque state for clearness indices below 0.5 can be employed in design studies. For a vertical plane SPD glazing, transmittance values for transparent and opaque states for different azimuthal direction and below threshold clearness index with less than 1% errors are shown in Table 2.

Fig. 8 correlates between transmitted solar energy through the SPD glazing in transparent and opaque states with clearness index. Clearly, the clearness index of the sky is highly influential impact to transmit energy through the SPD glazing for its both states. Table 3 indicates the single usable values for transmitted energy through SPD glazing for its opaque and transmitted states with different azimuthal orientation.

Fig. 9 correlates the clearness index and SHGC for SPD glazing in transparent and opaque states. A strong linear correlation was found between clearness index and SHGC of SPD glazing for its both states. Table 4 shows the yearly usable single SHGC value for SPD glazing transparent and opaque state for different azimuthal direction and the threshold clearness index value for that particular orientation.

4. Conclusions

Correlation between clearness index and glazing transmittance, transmitted solar energy and solar heat gain coefficients has been evaluated for SPD glazing in its “transparent” and “opaque” state. For clearness index below 0.5, isotropic diffuse transmittance was dominant whereas after 0.5 clearness index, transmission of direct insolation was dominant. However, vertical plane glazing transmittance changes with season, day and time, single value glazing transmittance of 0.25 and 0.025 for transparent and opaque south facing SPD glazing can be chosen throughout the year while clearness index is less than 0.5. Present study offers a yearly usable single glazing transmittance, transmitted solar energy, solar heat gain coefficient for SPD glazing in transparent and opaque state, which is advantageous for the building designers in northern latitude areas.

Table 1

Simplified equation for the variation of glazing transmission variation with incident angle for vertical plane.

	Parameters	Reference
Vertical transmission	$\tau_v = \tau(0) \left[1 - \tan^x \left(\frac{\theta}{2} \right) \right]$ $\tau_v = \tau(0) (1 - az^\alpha - bz^\beta - cz^\gamma)$	[28]
	$z = (\theta/90^\circ)$; a =varies with glazing, $b=0.25/q$, $c=(1-a-b)$ $\alpha=5.2+0.7q$, β = varies, $\gamma=(5.26+0.06p)+(0.73+0.04p)q$	[4]

Fig. 3.: Comparison of the transmission spectra of a particular SPD glazing in its "opaque" and "transparent" states with an air-mass 1.5 solar spectrum.

Acknowledgements

The work described in this paper was supported by the Graduate Research Education Programme of the Higher Education Authority, Ireland.

Fig. 4.: (a) Variation of measured transmission for SPD glazing "transparent" (55% transparent) state for different incident angle in 1st of July and 1st of January (b) variation of measured transmission for SPD glazing (5% transparent) for different incident angle in 1st of July and 1st of January (c) the sun path diagram in Dublin for 1st of July and 1st of January (d) the sun ray strike the ground on at an angle 59.78° (e) the sun rays strike the ground at an angle of 13.65°.

Fig. 5. : Fitting parameter for different model for SPD transparent and opaque state.

Fig. 6. Dependency of SPD glazing transmission with clearness index.

Fig. 7. Change of SPD glazing 55% and 5% transmissions due to clearness index and incident angle.

Table 2

Yearly usable single transmittance value of SPD transparent and opaque state for different azimuthal and monthly clearness index.

Azimuthal orientation	Mean monthly clearness index	SPD "transparent" (55% maximum transparent) transmittance	SPD "opaque" (5% maximum transparent) transmittance
North	0.7	25	2.5
South	0.5	25	2.5
East	0.6	25	2.5
West	0.6	25	2.5
North east	0.6	25	2.5
North west	0.6	25	2.5

Fig. 8. Dependency of transmitted solar energy through SPD glazing “transparent” and “opaque” states with clearness index.

Table 3
Yearly usable single transmittance solar energy value for SPD transparent and opaque state.

	Azimuthal orientation	Mean monthly clearness index	SPD “transparent” transmitted solar energy (W/m ²)	SPD “opaque” transmitted solar energy (W/m ²)
Vertical plane SPD glazing	North	0.7	70	20
	South	0.5	70	20
	East	0.6	70	20
	West	0.6	70	20
	North east	0.6	70	20
	North west	0.6	70	20
	west

Fig. 9. Dependency of SHGC of SPD glazing “transparent” and “opaque” states with clearness index.

Table 4
Yearly usable single SHGC value for SPD transparent and opaque state.

	Azimuthal direction	Mean monthly clearness index	SPD “transparent” SHGC	SPD “opaque” SHGC
Vertical plane SPD glazing	North	0.7	0.17	0.05
	South	0.5	0.17	0.05
	East	0.6	0.17	0.05
	West	0.6	0.17	0.05
	North east	0.6	0.17	0.05
	North west	0.6	0.17	0.05

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