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2018

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Ghosh, A. Norton, B. & Mallick, T.K. (2018) Influence of atmospheric clearness on PDLC switchable glazing transmission, *Energy & Buildings*, doi: 10.1016/j.enbuild.2018.05.008

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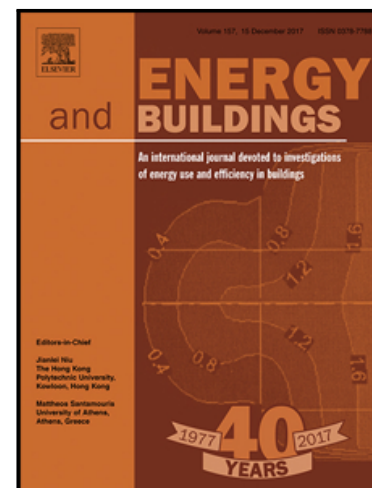


Accepted Manuscript

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PII: S0378-7788(18)30075-6
DOI: [10.1016/j.enbuild.2018.05.008](https://doi.org/10.1016/j.enbuild.2018.05.008)
Reference: ENB 8549



To appear in: *Energy & Buildings*

Received date: 8 January 2018
Revised date: 21 March 2018
Accepted date: 5 May 2018

Please cite this article as: Aritra Ghosh , Brian Norton , Tapas K. Mallick , Influence of atmospheric clearness on PDLC switchable glazing transmission, *Energy & Buildings* (2018), doi: [10.1016/j.enbuild.2018.05.008](https://doi.org/10.1016/j.enbuild.2018.05.008)

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Highlights:

- Correlation between PDLC glazing transmittance and sky clearness index has been calculated.
- Transmitted solar energy and SHGC were evaluated for different clearness index.
- Single glazing transmittance was recommended for different azimuthal orientation of vertical plane PDLC glazing.

ACCEPTED MANUSCRIPT

Influence of atmospheric clearness on PDLC switchable glazing transmission

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Nomenclature

A_i	Anisotropy index
$I_{\text{global,h}}$	Incident global solar radiation on the horizontal surface of glazing (W/m^2)
$I_{\text{global,v}}$	Incident global solar radiation on the vertical 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
SHGC	Solar heat gain coefficient
TSE_{PDLC}	Transmitted solar energy through PDLC glazing
<i>Greek symbols</i>	
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

Abstract:

Electrically activated switchable polymer dispersed liquid crystal (PDLC) is suitable for adaptive windows. A particular type requires 20V to become 71% transparent while in the absence of power it is 27% transparent. Glazing transmission changes with light incident angle. As the clearness of a sky changes the fraction changes alter of direct insolation (that has an azimuthally changing incident) and diffuse insolation (that has a largely constant incident). Thus, the effective overall incident angle determining the glazing transmittance also changes. In this work for the first time, the variation of

PDLC glazing transmission with clearness index has been investigated. For diffuse sky condition, single glazing transmittance value can be used below a particular clearness index for building energy calculation. This threshold clearness index changes with different azimuthal direction. In Dublin for south facing vertical plane PDLC glazing, yearly usable single transmittance (38% for transparent and 25% for translucent state), transmitted solar energy (TSE) (70 W/m^2 for transparent state and 20 W/m^2 for translucent state) and solar heat gain coefficient (SHGC) (0.17 for transparent state and 0.005 for translucent state) for transparent and translucent states were investigated.

Keywords: adaptive, switchable glazing, PDLC, SHGC, transmission, clearness index

1. Introduction

Large glazed façade building elements [1,2] enable commercial and residential buildings to exploit heating energy and daylight [3] from sun [4,5]. Electrically actuated switchable material filled double glazings in such large façade applications offer better control when compared with non-electrically activated switchable glazing. In additions, electrically actuated switchable glazings

- offer more than one transmittance and intermittence transmittance by applying variable power [6–9];
- can control glare[7–10];
- provide daylight where spectrum has a positive influence on occupant comfort[8–10];
- can be powered by connected with PV [11–15];
- addition with vacuum glazing [16–18] electrically activated glazing can form a low heat loss switchable glazing [19–25];

Electrically actuated glazings include electrochromic (EC) [26], suspended particle device (SPD) [27] and polymer dispersed liquid crystal (PDLC)[6] type. Electrically activated EC glazing is powered by direct current power supply. Tungsten trioxide (WO_3) based EC is the well-studied for glazing system [28] in which an ion-conducting polymer or inorganic material based transparent electrolyte is sandwiched between nanoporous W and Ni oxide films. These three layers are placed between two transparent electrical conductors. The functioning of an EC devices is very similar to an electrical battery[29–31]. A voltage applied between these two transparent conductors changes the color of EC material to absorb solar spectrum. In the absence of power, the EC is transparent (bleached). An EC material can control near infrared solar radiation. Modulation of NIR is also possible of EC glazing [26,32]. Colour changes of EC is gradual depending proportionally on the area of the device. An EC changes colour between 1 and 30 min, depends on the device area [33].

An SPD glazing consist of an SPD film, sandwiched between two glass panes, adhesive films, retaining films and a transparent conductor [34] . An SPD film is made of needle-shaped, rod-shaped, or lath-shaped dihydrocinchonidine bisulfite polyiodide or herapathite particles less than $1 \mu\text{m}$ in linear size [35,36]. These particles exhibit large optical anisotropy. In the presence of alternating current power supply, these particles become aligned to pass light through the film. In the absence of power, the particles exhibit Brownian movement. Thus, the light passing through the cell can be transmitted, absorbed or rejected, depending upon type and concentration of particles and the energy content of the light. The optical change of SPD glazing from transparent to opaque and from opaque to transparent both needs only few seconds [20,37,38]. However, particular example of this glazing needs high 110V AC to become transparent. Long term durability of this technology is also not fully understood [38].

Alternative current (AC) powered electrically activated switchable liquid crystal (LC) is another switchable glazing technology [39]. Polymer dispersed liquid crystals (PDLC) are the best suited for glazing application as they do not need a polarizer to operate compared to twisted nematic, ferroelectric [40,41]. In a PDLC glazing, liquid crystal particles are dispersed into a matrix. The presence of a power supply, orients the particles to allow light pass through. In the absence of power, these particles are randomly oriented so light is scattered. Droplets with radii smaller than the incident light wavelength allow light to pass through without scattering. For large size droplets mainly forward scattering ensues [42]. Reverse mode PDLC have also been investigated in which the glazing is unpowered when transparent and powered to be opaque[43,44]. Figure 1 shows the working principle of PDLC glazing.

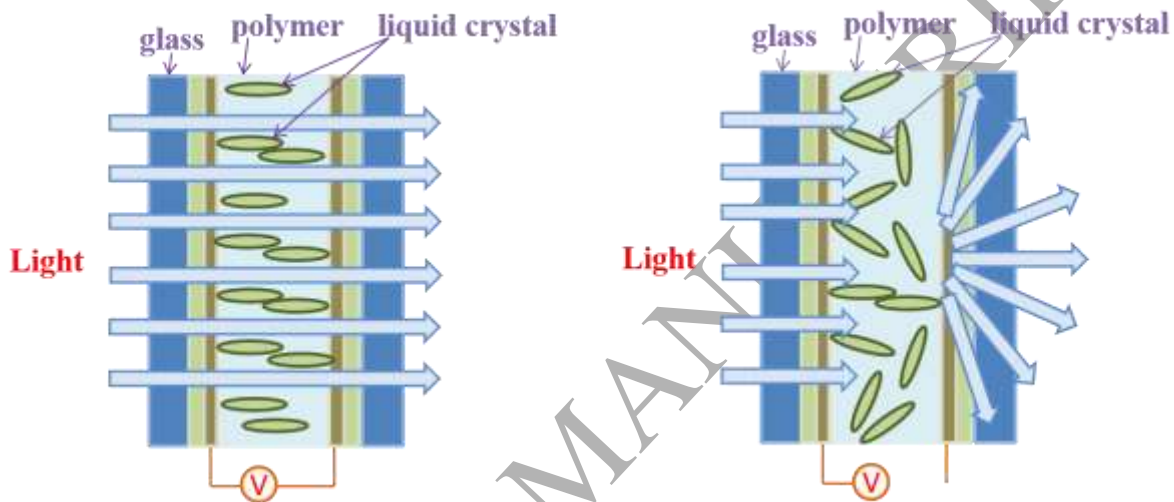


Figure 1: Schematic working principle of PDLC glazing in its transparent and translucent states.

Transmitted incident solar radiation through a glazing system depends on the optical properties of the glazing and incident-angles of the direct, diffuse and ground reflected solar radiation components. Incident angle for a vertical glazing façade also changes with time of a day and season [45–49]. Thus, calculated solar energy for a building based on constant glazing transmittance often leads to an overestimated result. For building energy calculations, incident solar radiation and glazing transmittance are essential parameters. Horizontal global and horizontal diffuse solar radiation data are often available for a particular location. However, glazings are usually installed vertically to receive vertical solar radiation. Clearness index uses global horizontal solar radiation to determine how “clear” a sky is [50–52]. Theoretically, the relation between glazing transmission and clearness index was investigated for selected European locations and surface orientations by Waide and Norton [53]. Experimentally correlations between SPD glazing [54], vacuum glazing [17] and SPD-vacuum glazing [19] with clearness index had also been investigated.

In this work, the first correlation between clearness index and measured PDLC glazing transmittance has been evaluated.

2. Methodology

A schematic of south facing vertical plane PDLC glazing is shown in Figure 2.

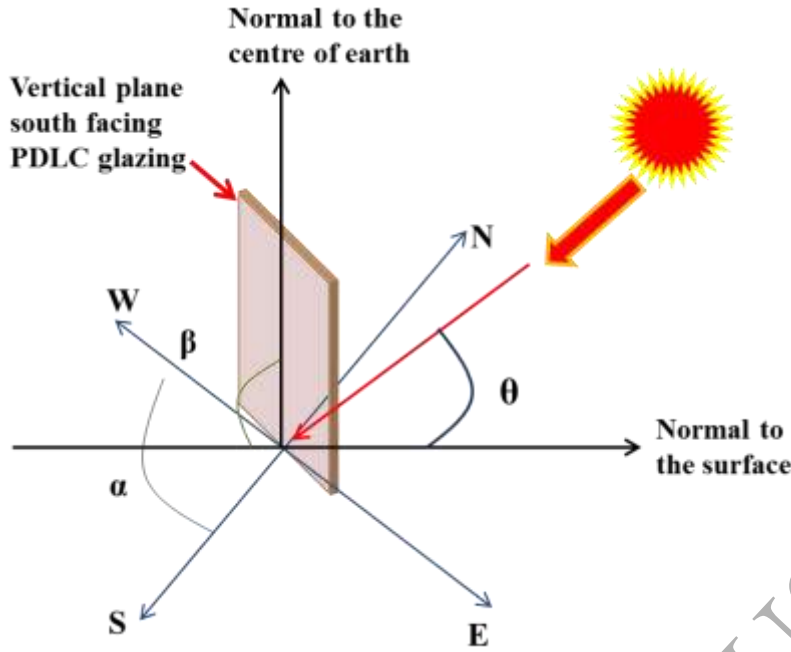


Figure 2: Schematic diagram of a south facing vertical plane glazing with incident angle and solar elevation angle.

The clearness index is given by

$$k_T = \frac{I_{global,h}}{I_{extra}} \quad (1)$$

$$I_{extra} = I_{sc} \left(1 + 0.033 \cos \frac{360n_1}{365} \right) (\cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta)$$

I_{sc} is the solar constant, n_1 is the day of year, ϕ latitude angle, δ declination angle ω hour angle

Most often glazing transmittance value associated with only normal solar incidence. Glazing transmission is not a constant parameter; it changes with incident angle [47–49]. Incident angles also change due to diurnal variation of solar radiation. The transmittance of the vertical glazing is given by [53]

$$\tau_v = \left[k_d \left\{ k_T R_b (1 - k_d) + (1 - \cos \beta) (1 - k_T (1 - k_d)) \right\} + R_b (1 - k_d) + R_s \frac{1 - \cos \beta}{2} \right] \times$$

$$\tau_{dir} R_b (1 - k_d) (1 + k_d k_T) + \frac{\tau_{dif} k_d}{2} (1 + \cos \beta) (1 - k_T (1 - k_d)) + \frac{\tau_s R_s (1 - \cos \beta)}{2} \quad (2)$$

where

$$\tau = \frac{1}{2} \left[\frac{1 - \left\{ \frac{\sin(\theta - n)}{\sin(\theta + n)} \right\}^2}{1 + (2n_g - 1) \left\{ \frac{\sin(\theta - n)}{\sin(\theta + n)} \right\}} + \frac{1 - \left\{ \frac{\tan(\theta - n)}{\tan(\theta + n)} \right\}^2}{1 + (2n_g - 1) \left[\frac{\tan(\theta - n)}{\tan(\theta + n)} \right]^2} \right] \times \exp\left(\frac{-k_g N_g t_g}{\cos \theta}\right) \quad (3)$$

and direct diffuse and reflected transmission can be calculated from [55]

$$\tau = \tau_{dir} \text{ when } \theta = \theta_{dir} \quad (4)$$

$$\tau = \tau_{dif} \text{ when } \theta = \theta_{dif} = 59.68 - 0.1388\beta + 0.001497\beta^2 \quad (5)$$

$$\tau = \tau_g \text{ when } \theta = \theta_g = 90 - 0.5788\beta + 0.002693\beta^2 \quad (6)$$

The total solar energy transmitted through a PDLC glazing is given by;

$$TSE_{PDLC, glazing} = (I_{beam,h} + I_{dif,h} A_i) \tau_{dir} r_b + I_{dif,h} (1 + A_i) \tau_{dif,h} \frac{(1 + \cos \beta)}{2} + I_{global,h} \rho_g \tau_g \frac{(1 - \cos \beta)}{2} \quad (7)$$

anisotropy index (A_i) is given by

$$A_i = \frac{I_{beam,h}}{I_{extra}} \quad (8)$$

Solar heat gain coefficient (SHGC) for a glazing indicates the fraction of the incident solar radiation that enters a room after passing through the glazing [56][57]. The dynamic solar heat gain coefficients (SHGC) is calculated from

$$SHGC = \frac{TSE_{PDLC}}{I_{global,v}} \quad (9)$$

3. Measurements & results

In this work, one PDLC glazing from Polytron technology as shown in Figure 3 was investigated. This glazing had dimension of 0.2 m × 0.15 m × 0.01m. It became 71% transparent in the presence of a 20V AC power supply and 27% transparent without a power supply [6]. In the powered state, it had a low diffuse transmittance (7%) and high regular/specular transmittance (64%). In the switch off state it has high diffuse transmittance of 26% and low specular transmittance of 1% [57]. The unpowered state showed 83% haze. Spectral transmittance of this glazing was measured using

AvaSpec-ULS2048L Star Line Versatile Fiber-optic spectrometer for both states results are shown in Figure 4.

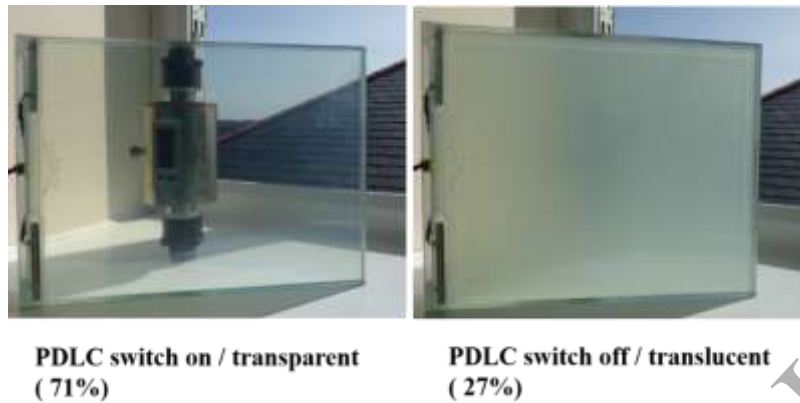


Figure 3: Viewing through the investigated PDLC glazing for its transparent and translucent states.

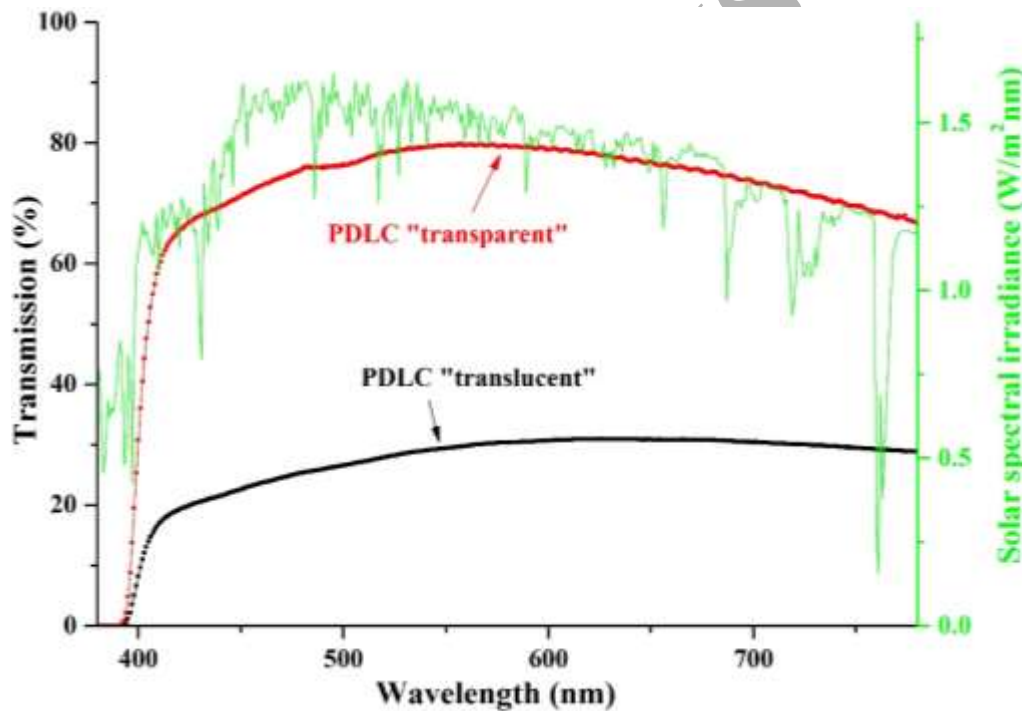


Figure 4: Transmission spectra of the particular PDLC glazing investigated in its “translucent” and “transparent” states.

A $0.7 \times 0.7 \times 0.7$ m test cell as shown in Figure 5 was manufactured from wood lined inside with a 0.15 m thick polystyrene insulation material with unobstructed solar illuminance. Internal surfaces were painted with 0.8 reflectance matt white paint. The area of glazing on the test cell was in a ratio of 1:9. Horizontal plane global solar radiation, horizontal plane diffuse solar radiation, vertical plane global solar radiation was measured using Kipp and Zonen pyranometers [13-14,20-23,38,]. AvaSpec-ULS2048L Star Line Versatile Fiber-optic spectrometer measured transmission of this glazing. 5 minutes interval data were recorded using delta T type data logger. Experiment was performed from

1st of January to 1st of December 2016, on the roof of Kevin street building, at Dublin Institute of Technology, Dublin (53.3478°N, 6.2597°W).

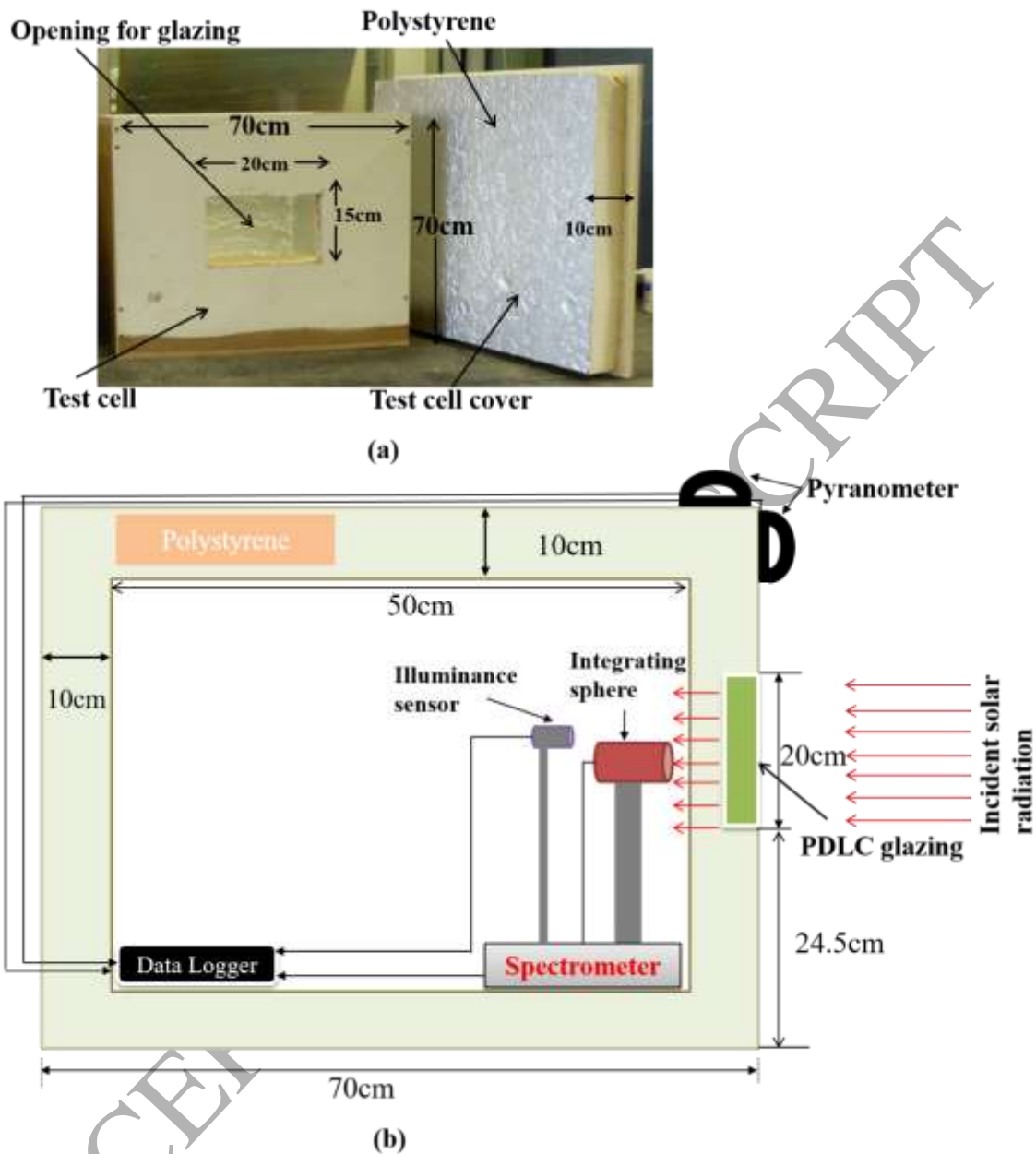


Figure 5: (a) Photograph of test cell, (b) schematic details of experimental set up for optical properties measurement of PDLC glazing using test cell, pyranometer, illuminance sensor and spectrometer.

Figures 6 shows correlation between PDLC glazing transmission with incident angle in Dublin, Ireland, for PDLC glazing in “transparent” and “opaque” states. 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. Lower elevation angle offers higher transmission during wintertime.

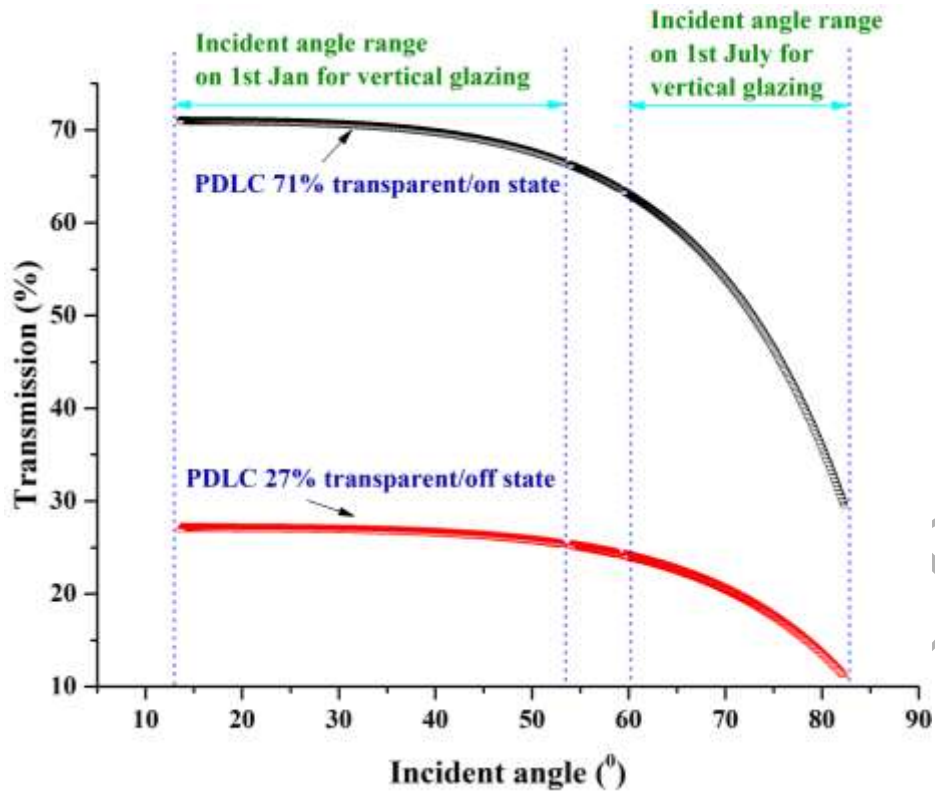


Figure 6: Variation of PDLC glazing 71% and 27% transmission for different incident angle.

Correlation between calculated clearness index and measured PDLC glazing transmission has been represented in Figure 7. Correlation between calculated clearness index and calculated transmitted solar energy (TSE) through PDLC glazing in its transparent and translucent states has been presented in Figure 8. Figure 9 shows the correlation between clearness index and PDLC glazing SHGC in transparent and translucent states.

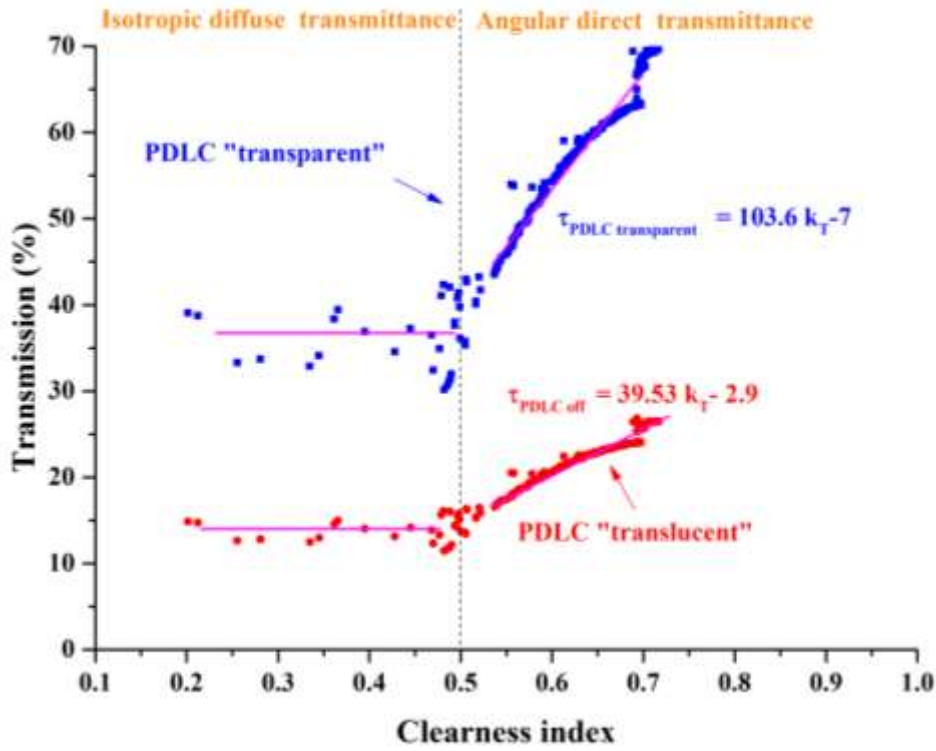


Figure 7: Change of PDLC glazing 71% and 27% transmissions due to clearness index.

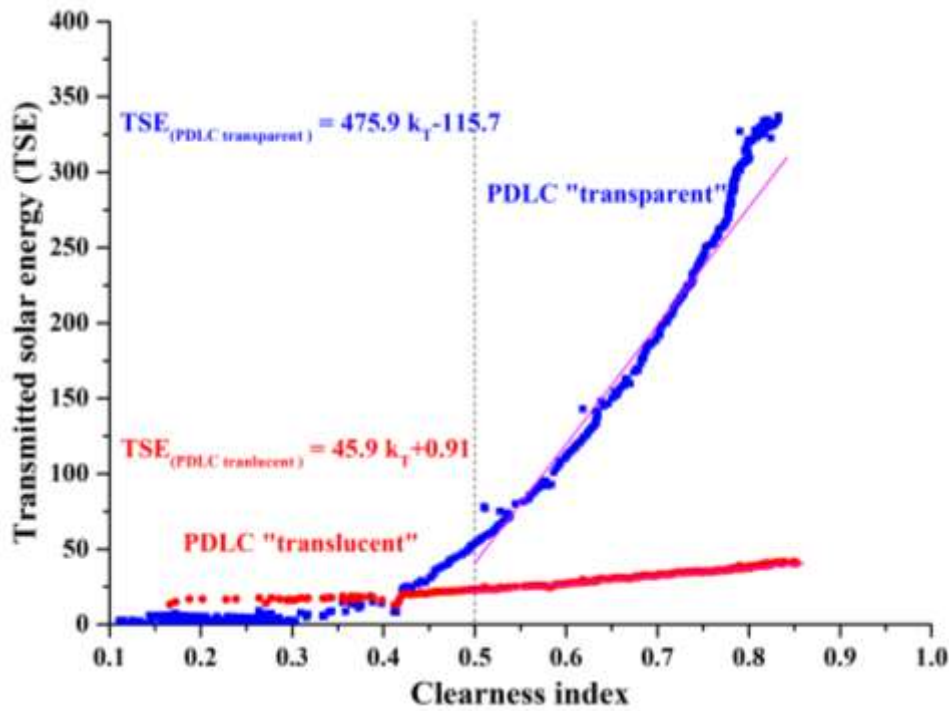


Figure 8: Dependency of transmitted solar energy (TSE) through PDLC glazing "transparent" and "translucent" states with clearness index.

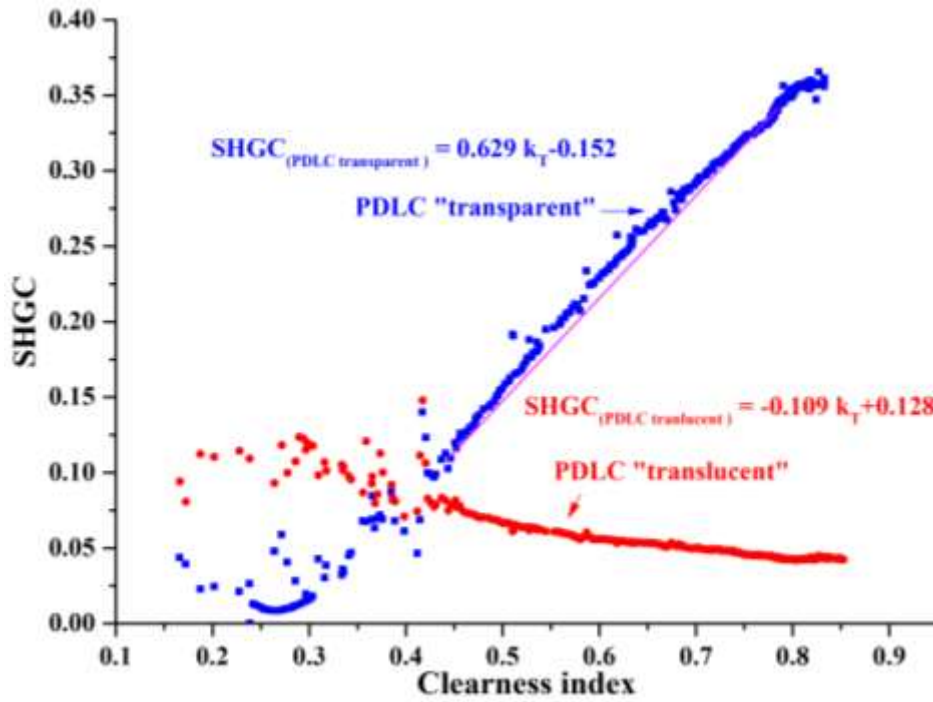


Figure 9: Dependency of SHGC of PDLC glazing “transparent” and “translucent” states with clearness index.

In figure 7, below clearness index of 0.5, isotropic diffuse transmission was dominant. Above 0.5 clearness index, direct solar radiation was dominant and glazing transmittance was linearly correlated with clearness index. 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. This single value will reduce large computational time and/or resources for building design studies. In Dublin, for below 0.5 clearness index, south facing vertical plane PDLC glazing transmission of 38% was found which could be used for building performance using PDLC glazing over the year with negligible error. For different azimuthal direction a threshold clearness index is attainable below that one single glazing transmittance can be used with less than 1% error, which is listed in Table 1.

Table 1: Yearly usable single transmittance value of PDLC transparent and translucent state for different azimuthal and monthly clearness index due to isotropic diffuse solar radiation component.

Inclination	Azimuthal orientation	Single diffuse component dominant		Up to a clearness index
		PDLC “transparent” (71% maximum transparent) transmittance	PDLC “translucent” (27% maximum transparent) transmittance	Mean monthly clearness index
Vertical Plane PDLC glazing	North	38	25	0.7
	South	38	25	0.5
	East	38	25	0.6
	West	38	25	0.6
	North east	38	25	0.6
	North west	38	25	0.6

Glazing transmittance has direct influence on transmitted solar energy and SHGC both as shown in equation 7 and 9. Thus, below 0.5 clearness index, vertical plane south facing PDLC glazing offers single yearly useable transmitted solar energy of 70 W/m^2 and 20 W/m^2 , SHGC of 0.17 and 0.05 for transparent and translucent states respectively. These values can be used for building energy calculation with less than 1% error. Vertical plane PDLC glazing single transmitted solar energy and SHGC for different azimuthal direction and threshold clearness index for that particular azimuthal direction are listed in Table 2.

Table 2: Yearly usable single SHGC and TSE value of PDLC transparent and translucent state for different azimuthal and monthly clearness index due to isotropic diffuse solar radiation component.

Inclination	Azimuthal direction	Single diffuse component dominant				Up to a clearness index
		PDLC "transparent" /ON SHGC	PDLC "translucent" /OFF SHGC	PDLC ON TSE (W/m^2)	PDLC OFF TSE (W/m^2)	Mean monthly clearness index
Vertical plane PDLC glazing	North	0.17	0.05	70	20	0.7
	South	0.17	0.05	70	20	0.5
	East	0.17	0.05	70	20	0.6
	West	0.17	0.05	70	20	0.6
	North east	0.17	0.05	70	20	0.6
	North west	0.17	0.05	70	20	0.6

4. Conclusions

Clearness index is an influential parameter for solar energy application but requires only one measured solar radiation intensity to evaluate. Correlation between clearness index and glazing transmittance, transmitted solar energy (TSE) and solar heat gain coefficients (SHGC) has been evaluated for PDLC glazing in its two switched states. Below a clearness index of 0.5, the majority of transmission is of the diffuse solar radiation. Above a clearness index of 0.5, the glazing transmission is dominated by direct component of solar radiation. However, using a single value of transmission, SHGC, and TSE is possible for PDLC glazing transmission calculation for clearness indices below 0.5. In Dublin, a south facing vertical plane PDLC glazing below 0.5 clearness index offer 38% glazing transmittance, 70 W/m^2 TSE and 0.17 SGHC for transparent state and 28% glazing transmittance, 20 W/m^2 TSE and 0.05 SGHC for translucent states. These can be used for calculation at all terms of year with less than 1% calculation error.

Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors acknowledge Dublin Energy lab at Dublin Institute of Technology and Solar lab at University of Exeter for use of equipment and facilities.

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