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Thermal and Cost Assessment of Various Polymer-Dispersed Liquid Crystal film Smart Windows for Energy Efficient Buildings

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Buildings consume a considerable amount of energy for air conditioning and artificial daylighting. Buildings use glass as the main enclosing material to provide natural daylighting and for aesthetic reasons, but solar heat gain/loss through the clear glass into the buildings is enormous. This paper aims to explore the solar optical properties and air-conditioning cost-saving potential of various smart PDLC film glasses. This paper presents the solar optical properties of four different smart PDLC film glasses (white, blue, pink, and yellow) with and without applied voltage conditions. A numerical model was developed to compute solar heat gain through smart PDLCs in voltage ON/OFF states. And cost analysis was carried out to estimate the annual air-conditioning cost savings. All the smart PDLC film glasses in voltage ON/OFF conditions had shown a substantial reduction in heat gained/lost compared to generic clear glass in buildings of three climatic conditions. The reduced heat gained/lost in the smart PDLC film glasses accounted for the net annual cost savings (heating cost + cooling cost). The white smart PDLC film glass WSPG (V) was observed to be the most energy-efficient smart glass with the highest annual air-conditioning cost savings ($ 101.76 in the SE of hot and dry climate), lowest payback periods (12.71 yrs in SE of hot and dry climate), and adequate daylight factors as compared to the other studied smart glasses in eight orientations of three climatic conditions. The results help to design and select suitable glazing for sustainable and energy-efficient solar passive buildings.

Keywords: Smart PDLC film window, Heat transfer through smart window, Air-conditioning cost reduction, Thermal and cost assessment, Cost payback period.

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1. INTRODUCTION

Window glazing is the weakest thermal building element that transmits the heat in and out of the building depending upon the external climatic conditions. Higher solar transmittance and U-values of clear glass windows allow more solar radiation through the window glazing [1]. Heat gained/lost through the glazing adversely affects the comfort of occupants and thermal performance of the building [2,3]. The energy efficiency in buildings is an essential issue to achieve a sustainable environment. Optimum design and selection of window glazing is a crucial strategy for energy conservation in the buildings. Numerous experiments and simulations have been conducted to enhance the thermal performance of glazing. Low-emittance coatings [4], PV glazing [5], Vacuum insulated glazing [6], and aerogel insulated glazed windows [7] have a remarkable improvement in thermal insulation. Multi-layer glazing with interspace filled with inert gases had shown an increase in thermal insulation to the heat gain [8,9]. Various colored glasses, stained glasses, and reflective glasses reported a significant reduction in solar transmittance and heat gain compared to clear glass [10]. Silica aerogel glazing in a commercial building was studied for energy savings, visual performance, and thermal comfort in Hong Kong [11]. Titanium oxide (TiO_2) added, tungsten ions (W^{6+}) doped vanadium oxide thermochromic (TC) thin films produced and applied over the smart window systems. The simulation results of produced TC glazing showed a significant reduction in the buildings' energy demands compared to the convention clear glazing [12].

The electrochromic glazing's solar transmittance can be varied with a small applied electric field, and simulations revealed the lighting energy savings, cooling, and heating load reductions [13]. Switchable electrochromic glass is the promising glazing to block the solar energy propagation in near-infrared radiation with modulated transmittance [14]. Oxide-based electrochromic glasses, for the variable solar transmittance and energy savings [15,16] and its feasibility in large window areas of commercial buildings [17]. The frequency of this color-changing electrochromic polymer glasses was estimated with the help of spectrophotometry and electrochemistry. Fast switching high contrast polymers can be made using the plasmonics for glazing applications [18,19].

Polymer-dispersed liquid crystal glass (PDLC) is the switchable glazing used in the low energy building design. It possesses modulated optical properties when an electric field is applied to it [20,21]. Optical properties [22], daylighting characteristics of PDLCs switchable glazing [23], and the effect of atmospheric clearness index on their solar transmittance were explored in detail in the transparent and translucent state [24]. The characterization of the large area PDLCs' optical properties for the building and automotive applications showed a good performance in controlling light and heat [25]. Scattering properties and transmission of the PDLCs can be enhanced with large incident angles [26]. An energy analysis of an electrochromic window over a span of 25 years in Greece climatic conditions had shown about 54 % energy savings compared to clear glass [27]. Electrochromic glasses (EC) with various transition ranges from clear to fully colored state studied for energy savings in heating and cooling requirements of Mediterranean climate as a retrofit to clear and conventional double glazing. The study concluded that EC glasses were the energy-efficient strategies that can be considered for refurbishing the existing glazing in the buildings [28]. A simulation study of thermochromic glazing revealed that thermochromic glazing could reduce the energy consumption of the buildings [29]. Opto-electric properties of the PDLCs depend on the droplet morphology [30]. Studies reported that the transmittance of green-insulated PDLC glass varied from 0.23 to 0.34 depends on the level of applied voltage [31]. Research is in progress to improve the performance and to minimize the power requirements of the PDLCs to maintain transparency. This can be achieved by replacing current nematic LCs in the polymer matrix with the smectic LCs [32]. Kirankumar et al. presented a numerical model to calculate the solar heat gain and net annual cost savings of the double-glazing [33]. The survey on the various smart windows available in the current market concluded that smart PDLC film glasses are the promising choice among all other smart glasses to reduce the external heating and cooling load [34].

The literature discussed reveals the significant gap for the investigation of smart PDLC glazing to mitigate air-conditioning costs with adequate daylighting factors. Smart PDLC film glass is capable of controlling the transmission of solar heat through it. These smart PDLC film glasses can be used for numerous applications ranging from window glazing in hot climatic conditions to buildings with large glazed shells [35]. Air-conditioning and lighting systems of the building can be made much more energy-efficient by neutralizing/reducing thermal load at glazing by providing adequate interior daylight factor. The smart windows can provide thermal comfort, secrecy, and aesthetic looks to the buildings if used appropriately. The inappropriate selection and placing of smart windows lead to higher air-conditioning costs, higher payback periods, and lower daylight factors. In the present study, smart PDLC film gasses in different colors (White, Red, Yellow, and Blue) with applied voltage and without voltage evaluated for the thermal performance and air-conditioning cost savings. Spectral properties of the smart PDLC film glasses were explored experimentally with a spectrophotometer in the entire solar spectrum. These properties were used to evaluate heat gain/loss and air- conditioning cost savings in three climatic zones (hot and dry, warm and humid, and composite). The simulations were also carried out to find average daylight factors. The smart glasses for the highest air-conditioning cost savings, lowest payback periods, and adequate average daylight factors in three climates were reported in this work.

2. MATERIALS

Smart PDLC film consists of micro-sized liquid crystal (LCs) molecules incorporated into a polymer matrix. These PDLC films are either laminated between the two glasses or applied on either side of the glass. PDLC films are opaque white or opaque tinted in the normal state due to the random alignment of LCs. LCs will scatter the incident solar radiation in different directions. On the other hand, when an external field (such as electromagnetic, thermal, and mechanical fields) is applied, the liquid crystal molecules are arranged in the preferred direction such that the film becomes transparent. The transparency of the PDLCs film depends on the applied voltage range. The polymer matrix and liquid crystal molecules (LCs) should have a similar refractive index for the proper alignment of the molecules [36]. The polymerization-induced phase separation (PIPS) method is used to prepare the most of PDLC films for the stability and durability with good electro-optical properties. Initially, Liquid crystals are mixed with a pre-polymer solution; polymerization initiated after forming a homogenous solution to form the PDLC films. During polymerization, the liquid crystals (LCs) grow up in the polymer matrix. Liquid crystals droplets sizes depend on the curing temperature and type of the LCs components. Thermal-induced phase separation and Solvent-induced phase separation (SIPS) can also be used to produce the PDLC films based on the applications and the operating parameters.

The PDLC films aid in simplifying design, curbing down the cost, and bringing a surge in the lifetime in the atmospheres of high temperature and humidity in contrast to other polarizers which tend off, peel off, and degrade more readily under such weather conditions. The ability to control solar transmission in the infrared region helps to attain energy efficiency by mitigating the energy requirements for cooling and heating. A commercial PDLC film of 0.4 mm thickness of four different colors (Blue, Yellow, White, and Pink) is applied over the 6 mm clear glass on the outer side for experimentation. Fig. 1(a) represents the schematic of the smart PDLC film glass and Fig. 1(b) depicts the working principle of the smart PDLC film glasses with voltage ON and OFF conditions. In this study, smart PDLC film glasses with and without applied voltage and clear glass were experimentally evaluated for optical properties, and air-conditioning cost-saving analysis was carried out. Fig. 2 presents the four different smart PDLC film glasses studied in this work with and without applied voltage. The power rating of PDLC glazing is 2W per unit area of the smart window.

Fig. 1 a) Schematic of smart PDLC film glasses (b) Schematic of the working principle of smart PDLC film glasses with and without applied voltage.

Fig. 2 Smart PDLC film glasses a) WSPG (NV) b) WSPG (V) c) BSPG (NV) d) BSPG (V) e) PSPG (NV) f) PSPG (V) g) YSPG (NV) h) YSPG (V)

3. EXPERIMENTAL METHODOLOGY

Spectral properties of glazing are required to calculate heating and cooling loads through the glazing numerically. The solar optical properties of smart PDLC film glasses can be evaluated with a weighted average of the experimentally measured solar spectral distribution. The spectral distribution of the solar spectrum (300-2500 nm) through the smart PDLC film glasses was obtained using a double beam double monochromatic integrating sphere spectrophotometer (Perkin Elmer 950), as presented in Fig. 3. The spectrophotometer is integrated with UV WinLab software to record distribution at an interval of 2 nm. This spectrophotometer uses Deuterium and Tungsten-Halogen lamps as the sources in the UV-Vis and Near-infrared (NIR) regions, respectively. The spectrophotometer's wavelength accuracy is of +/- 0.08 nm in the UV-VIS region and +/- 0.30 nm in the Near-Infrared (NIR) region. The spectral data obtained from the spectrophotometer deduced to get total solar optical properties (300-2500 nm) by a weighted average method. Spectral transmission and spectral reflection were measured in diffuse mode with a 10 mm integrated sphere at a zero-angle incidence [37].

MATLAB codes were developed to evaluate transmittance, reflectance, and absorptance using the following Eqs. (1) to (3) as per British standards [38,39].

Solar transmittance, reflectance, and absorptance are the fractions of solar radiation transmitted, reflected, and absorbed by the glazing of the incident solar radiation on the glazing. They were obtained from Eqs. (1), (2) and (3), respectively.

$$T_{SLR} = \frac{\sum_{\lambda=300}^{\lambda=2500} S_{\lambda}\tau(\lambda)\Delta\lambda}{\sum_{\lambda=300}^{\lambda=2500} S_{\lambda}\,\Delta\lambda} \quad (1)$$

$$R_{SLR} = \frac{\sum_{\lambda=300}^{\lambda=2500} S_{\lambda}\rho(\lambda)\Delta\lambda}{\sum_{\lambda=300}^{\lambda=2500} S_{\lambda}\,\Delta\lambda} \quad (2)$$

$$A_{SLR} = (100 - T_{SOL} - R_{SOL}) \quad (3)$$

Figs. 4-7 demonstrate spectral transmission and reflection of the blue, pink, yellow, and white smart PDLC film glasses in voltage ON and OFF conditions and clear glass. The solar transmittance, reflectance, and absorptance of different transparent (Voltage ON) and translucent (voltage OFF) smart PDLC film glasses and clear glass were computed and tabulated in Table 1. From Figs. 4 (a), 5 (a), 6 (a), and 7 (a), it is observed that the spectral transmission of smart PDLC film glasses is deficient compared to the clear glass. Spectral transmission curves of all smart PDLC film glasses in voltage ON condition for visible range (380-780 nm) is almost overlapping with the spectral transmission curves of PDLC glasses in voltage OFF state. It is evident that the applied voltage to PDLC film glasses does not has a noticeable effect on visible spectral transmission. The significant variation in the spectral transmission of PDLC film glasses with and without applied voltage has been noticed in the near-infrared region (780-2500 nm). It is also observed that the spectral transmission of all smart PDLC glasses in the visible range is less compared to spectral transmission in the NIR range. Solar transmittance of the blue, pink, and yellow smart PDLC glasses was computed as 12 %, whereas white smart PDLC was 11 %. These solar transmittances of PDLC glasses were 84.40 to 85.70 % less as compared to the clear glass. Solar transmittances of blue, yellow, white, and pink smart PDLCs without voltage were computed as 8, 7, 7, and 5 % respectively, which is 89.5 to 93.5 % less compared to the transmittance of clear glass.

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Figs. 4 (b), 5 (b), 6 (b), and 7 (b) depict the spectral reflection of the smart PDLC film glasses in both voltage ON and OFF conditions. Spectral reflection of smart PDLC film glasses in voltage ON condition was found to be higher than the spectral transmission of PDLCs in voltage OFF condition in the entire solar spectrum. Blue smart PDLC has the highest solar reflectance in both voltage ON and OFF conditions among the smart PDLCs studied. The solar reflectance of smart PDLC film glasses was 3 to 4 times higher than the solar reflectance of clear glass. From the solar absorptance results (Table 1) of the smart PDLCs, it is evident that smart PDLC glasses absorb a considerable amount of solar radiation. The absorptances of all smart PDLC film glasses studied were 3 to 4 times higher than the absorptance of clear glass.

Fig. 3 Integrating sphere spectrophotometer (Perkin Elmer 950) with UV-WinLab software
Fig. 4 Spectral characteristics of White smart PDLC film glass a) Transmission b) Reflection
Fig. 5 Spectral characteristics of Blue smart PDLC film glass a) Transmission b) Reflection
Fig. 6 Spectral characteristics of Pink smart PDLC film glass a) Transmission b) Reflection
Fig. 7 Spectral characteristics of Yellow smart PDLC film glass a) Transmission b) Reflection
Table 1 Measured solar optical properties of various smart PDLC film glasses (300-2500 nm)

4. MATHEMATICAL MODEL

Solar radiation reaches the earth as electromagnetic waves with wavelength ranging approximately 300 nm to over 3000 nm. Most of the radiation is concentrated in the visible (0.38 µm-0.78 µm) and near-infrared regions (0.78µm-2.5µm). The total solar irradiance that enters the building through the glazing is the sum of direct normal radiation (I_{dir}), sky-diffuse radiation (I_{dif}), and ground reflected radiation (I_{grr}). Solar radiation in the wavelength range of 300 nm to 2500 nm was considered to calculate the heat gain through the glazing since most of the solar energy lies in this range. Total solar irradiance (Wm^{-2}) that reaches the earth is related to solar geometry, which comprises several angles. Solar azimuth and altitude angles depend on the fundamental angles such as solar declination, latitude, and hour angle. Three climatic conditions were considered, such as hot and dry (Jodhpur), warm and humid (Mumbai), and composite (New Delhi) as per Indian standards and analyzed for heating and cooling loads. The analysis was carried out during day time, between 6:00 am to 6:00 pm (LAT), and 7:00 am to 5:00 pm (LAT) for peak summer and winter days, respectively [40,41]. The room set point temperatures

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are 24°C and 21°C, respectively for summer and winter as per ASHRAE (2001). Building models of dimensions 4 m ×4 m × 3.5 m were considered, and an optimum 40% window to wall ratio (2.8 m × 2 m) was maintained as per standards [42]. The building models are considered as commercial/office buildings that use the air-conditioning system (cooling and heating systems) during diurnal hours. Thermal and cost assessment was carried out for three climatic regions, such as hot and dry (Jodhpur: 26.2389° N, 73.0243° E), warm and humid (Mumbai: 19.0760° N, 72.8777° E), and composite (New Delhi: 28.6139° N, 77.2090° E) in eight cardinal directions to compute the solar heat gain/loss and energy savings. Total solar radiation admitted in building through the glazing is calculated as per the following procedure at a given latitude as per ASHRAE clear-Sky and intermediate sky models [43, 44].

Solar declination is the angle between earth equatorial plane and a line to the sun from the center of the earth, and it can be computed by Eq (4).

$$\boldsymbol{\delta_s = 23.45 \sin\left(\frac{360(n + 284)}{365}\right)} \tag{4}$$

Where n is day number (starting from January 1st as 1)

Solar altitude is the angle made by the line to the sun with a horizontal of the surface, and it is the complement of the zenith angle.

$$\boldsymbol{\sin\alpha_s = \cos L \cos\delta_s \cos h_s + \sin L \sin\delta_s} \tag{5}$$

The solar azimuth angle is the angular distance between the south (zero azimuth) and the projection of beam radiation on the horizontal plane.

$$\boldsymbol{\cos A_s = \frac{\sin\alpha_s \sin L - \sin\delta_s}{\cos\alpha_s \cos L}} \tag{6}$$

Surface solar Azimuth angle is presented in the following Eq. (7)

$$\boldsymbol{\gamma_s = A_s - \Psi} \tag{7}$$

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The surface azimuth angle is measured from the south of the orientation, and its value in the various orientations are listed in Table 2 [45].

Table 2 Surface azimuth angle (Ψ) in various orientations

The angle of incidence ($\boldsymbol{\theta_i}$) is the angle made by the beam radiation on a surface with normal of that surface.

$$\cos\theta_i = \cos\alpha_s \cos\gamma_s \cos\beta - \sin\alpha_s \sin\beta \quad (8)$$

Clear day terrestrial solar irradiance (Wm^{-2}) per unit area is represented by Eq. (9)

$$I_{TNR} = \frac{I_a}{\exp(B/\sin\alpha_s)} \quad (9)$$

I_a Apparent solar irradiance at air mass, m=0

The instantaneous beam radiation (I_{dir}, Wm^{-2}) on glazing is given by Eq. (10)

$$I_{dir} = I_{TNR} \cos\theta_i \quad (10)$$

The diffused solar radiation (I_{dif}, Wm^{-2}) incident on the glazing surface from the sky can be computed by Eq. (11)

$$I_{dif} = C\, I_{TNR} \left(\frac{1 - \sin\beta}{2}\right) \quad (11)$$

The solar radiation reflected from the ground, and that incident on the glazing is given by Eq. (12)

$$I_{grr} = (C + \sin\alpha_s) I_{TNR} \rho_g \left(\frac{1 - \sin\beta}{2}\right) \quad (12)$$

Where I_a, B, and C are the constants used for calculating solar radiation per hour for local conditions in Indian climates [44, 46].

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Total solar radiation incident on any surface is the sum of direct normal radiation (I_{dir}), sky-diffuse radiation (I_{dif}), and ground-reflected radiation (I_{grr}). It is presented in Eq. (13)

$$\mathbf{I_T} = (\mathbf{I_{dir}} + \mathbf{I_{dif}} + \mathbf{I_{grr}}) \tag{13}$$

The total radiation enters the building through glazing can be obtained from Eq. (14)

$$\mathbf{I_{SRSG}} = (\mathbf{I_{dir}} + \mathbf{I_{dif}} + \mathbf{I_{grr}}).\left(\boldsymbol{\tau}_{\mathbf{SOL}} + \frac{\mathbf{U}}{\mathbf{h_o}}\boldsymbol{\alpha}_{\mathbf{SOL}}\right).\mathbf{A_{GL}} \tag{14}$$

U is the heat transfer coefficient, and it can be computed using Eq. (15).

$$\mathrm{U} = 1/(R_{se} + \mathrm{L}_1/\mathrm{K}_1 + \mathrm{L}_2/\mathrm{K}_2 + R_{si}) \tag{15}$$

The values of R_{se} and R_{si} have been considered as 0.04 m^2K/W and 0.13 m^2K/W, respectively, as per CIBSE standards, and they can be computed using Eqs. (16) and (17) [47].

$$R_{se} = \frac{1}{h_{in} + Eh_r} \tag{16}$$

$$R_{si} = \frac{1}{(1.2Eh_r + h_{out})} \tag{17}$$

The analytical results of this numerical model were compared with the results of Chand et al. (2011) [48] for validation purposes. The MATLAB code was executed for a 3 mm clear glass window of the composite climatic zone of New Delhi (28.58^0N, 77.20^0E) to validate the results. The deviations in the results of the numerical model were within the range of ±1%. So, these numerical model codes were used to study the thermal performance of the other glasses.

4. 1 Cost assessment methodology

To substantiate the glazing's energy efficiency, it is required to calculate the cost savings in energy consumption. So, the annual air-conditioning cost savings of different smart PDLC film glasses with and without applied voltage were calculated. The cost assessments were carried out for three climates of India, such as hot and arid (Jodhpur), warm and humid (Mumbai), and composite (New

Delhi) as per the following procedure [49]. The total radiation incident on the glazing at any location for all the seasons can be calculated using Eq. (13). Solar radiation incident on the earth's horizontal surface varies during summer and winter. Summer prevails from April to August, whereas winter is from September to March. The total solar radiation ($Q_{S,T}$) incident on the glazing during the summer is obtained from Eq. (18).

$$Q_{S,T} = (I_{TS}X30)_{Apr} + (I_{TS}X31)_{May} + (I_{TS}X30)_{Jun} + (I_{TS}X31)_{Jul} + (I_{TS}X31)_{Aug} \quad (18)$$

Where I_{TS} (kWh/m^{2}day) is the diurnal mean solar radiation incident on glazing during summer

The total solar radiation ($Q_{W,T}$) incident on the glazing during the winter is represented in Eq. (19).

$$\mathbf{Q_{W,T} = (I_{TW}X30)_{Sep} + (I_{TW}X31)_{Oct} + (I_{TW}X30)_{Nov} + (I_{TW}X31)_{Dec} + (I_{TW}X31)_{Jan} + (I_{TW}X29)_{Feb} + (Q_{TW}X31)_{Mar}} \quad (19)$$

Where I_{TW} (kWh/m^{2}day) is the diurnal mean solar radiation incident on glazing during winter

The reduced annual cooling load (Q_{Red}, kWh) and increased annual heating load (Q_{Inc}, kWh) can be computed by using Eqs. (20) and (21), respectively.

$$Q_{Red} = Q_{S,T} \times A_{GL} \times (SHGC_{CG} - SHGC_{SPG}) \quad (20)$$

$$Q_{Inc} = Q_{W,T} \times A_{GL} \times (SHGC_{CG} - SHGC_{SPG}) \quad (21)$$

$SHGC_{CG}$ and $SHGC_{SPG}$ are solar heat gain coefficients (SHGC) of clear glass and smart PDLC film glasses.

The unit cost of natural gas and electricity is taken as \$ 0.02/kWh and \$ 0.08/kWh, respectively, as per the Indian scenario (converted to USD at market exchange rate). The least efficiency of the furnace and the least possible COP of the cooling system are taken as 0.8 and 2.5, respectively [2]. Annual cooling costs savings (C_c, \$/year) and an increase in annual heating costs (C_h, \$/year) can be computed using the Eqs. (22) and (23).

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$$C_C = \frac{Q_{Red} \times C_e}{COP} \quad (22)$$

$$C_h = \frac{Q_{Inc} \times C_f}{\eta} \quad (23)$$

Net annual air-conditioning cost savings of the glazing ($/year) can be computed using Eq. (24)

$$C_{Net} = C_c - C_h \quad (24)$$

Payback period (years) and implementation cost (C_i) of the smart PDLC film glazing was computed using the Eqs. (25) and (26).

$$PP = C_i / C_{Net} \quad (25)$$

$$C_i = (C_g + C_{es}) A_{GL} \quad (26)$$

Where C_g is glazing cost, A_{GL} is the area of glazing and C_{es} is the cost of energy supplied to smart glass. The power rating of PDLC glazing is 2W per unit area of the smart window. The annual energy required for a unit area of smart glass to operate is 17.52 kWh. Annual energy cost supplied (C_{es}) to a unit area of smart window glass is $ 1.4.

This numerical model assumes that the air-conditioner runs for all summer and winter days of climatic regions considered. It does not consider the heat gain through a glass frame or window frame. This model does not take into consideration of infiltration loads and internal loads of the buildings. This numerical model considers only heat transfer through the glass's thickness, but it does not take into account the heat transfer in the direction of the window's length and breadth as per CIBSE standards.

5. RESULTS AND DISCUSSIONS

5.1 Heat gain in buildings of various smart windows in different climates

Solar radiation into the building through the various smart PDLC film glasses was computed for peak summer and winter days of three different climatic conditions ((Hot and dry (Jodhpur), Warm, and humid (Mumbai), and Composite (New Delhi)). All smart PDLC film glasses with and without applied voltage and clear glass were studied for the heat gain/loss.

Fig. 8 depicts heat gain through various smart PDLCs film glazing in different orientations of hot and dry climate (Jodhpur). The peak summer and peak winter days were

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observed for hot and dry climate city (Jodhpur) on 21st June and 21st December, respectively, in line with the Indian standards. Fig. 8 reveals that the smart PDLC film glasses kept in the south direction gain the lowest amount of the heat in summer and the highest in the winter. Smart PDLC film glasses have shown the highest heat gain reductions in the voltage OFF condition compared to voltage ON condition. In voltage OFF condition, pink-colored PDLC film glass PSPG (NV) showed the highest heat gain reduction of 73.30 % compared to the clear glass in the south direction. Both White and Yellow-colored PDLC film glasses have shown 71.95 % reduction, whereas Blue colored PDLC films had shown the 71.21 % reduction compared to the clear glass in the south direction. It is observed that all the studied PDLC films without applied voltage have the approximately same heat gain reductions on the peak summer day in southern orientation. When voltage is applied to the PDLC film glasses, White, Blue, Pink, and Yellow-colored PDLC film glasses have the heat gain reductions of 69.01, 68.28, 68.13, and 67.98 %, respectively as compared to clear glass in the south direction. During summer glazing placed in the west, orientation had experienced the highest heat gain among all other orientations.

During winter, solar heat gain is minimum in the north orientation, and maximum in the south orientation for all the studied glazings. Glazings, which had shown the lowest heat gain in the summer, had experienced the highest heat gain in the winter. Pink-colored PDLC film glass without applied voltage in the north showed the highest heat gain reduction of 73.30 % during winter compared to the clear glazing in the north direction. Whereas White, Yellow, and Blue colored PDLC film glasses have heat gain reductions of 71.90, 71.90, and 71.37 %, respectively. White, Blue, Pink, and Yellow-colored PDLC film glasses without applied voltage have shown the heat gain reductions of 68.93, 68.23, 66.84, and 68.06 %, respectively, compared to clear glass. With applied voltage to the PDLC film glasses, there is an increase in the solar heat gain through the glazing. White, Pink, Blue, and Yellow-colored PDLC film glasses with applied voltage have 10.47, 19.23, 10.20, and 14.13 % of more heat gain, respectively, compared to respective glasses without voltage in the south orientation during the summer. When voltage is applied to smart PDLC film glasses, the glass turns transparent and allows the more heat gain/loss and daylighting through the glasses. All the glasses with applied voltage in all the orientations had experienced more heat gain/loss than the same glasses without applied voltage.

Fig. 8 Heat gain through various smart PDLCs film glazing in different orientations of hot and dry climate (Jodhpur).

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Fig. 9 presents heat gain through various smart PDLCs film glazing in different orientations of warm and humid climate (Mumbai) during peak summer and winter days. The peak summer and peak winter days were observed for a warm and humid city (Mumbai) on 15th May and 21st December. It is observed that all the studied glazings in the south direction had the lowest and highest heat gains during summer and winter, respectively. White-colored PDLC film glazing, WSPG(V) with applied voltage had shown the highest heat gain reduction of 69.01 % in the south direction during the summer among all other studied glazings compared to the clear glazing. BSPG (V), PSPG (V), YSPG (V) were responsible for the heat gain reductions of 68.37, 66.96, and 67.98 %, respectively, compared to the clear glass. During summer, glazing placed in the west orientation had experienced the highest heat gain among all other orientations. During winter, pink-colored film glazing was responsible for the highest heat gain in the south direction, among other glazings.

Fig. 9 Heat gain through various smart PDLCs film glazing in different orientations of warm and humid climate (Mumbai).

Fig. 10 presents heat gain through various smart PDLCs film glazing in different orientations of composite climate (New Delhi). The peak summer and peak winter days were observed for the composite city (New Delhi) on 21st June and 21st December. During summer, White-colored smart PDLC film glazing with applied voltage was responsible for the highest heat gain reductions of 68.98% compared to clear glazing in the south direction. All the glazings placed in the southern direction have shown the lowest heat gains during the peak summer. BSPG (V), YSPG (V), PSPG (V) were reported heat gain reductions of 68.27 %, 67.98%, 66.85%, respectively, compared to clear glazing during the summer. The optimum direction to reduce the solar heat gain during the summer is S < N < SE < SW < NE < NW < E < W. During the winter PSPG (V) received the highest gain among other smart PDLC film glazing. During the winter, the south-oriented window had received the highest heat again, while the north-oriented window received the lowest heat gain.

Fig. 10 Heat gain through various smart PDLCs film glazing in different orientations of composite climate (New Delhi).

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5.2 Yearly air-conditioning cost savings and payback periods of various smart window systems in different climates

Net cost saving is an important parameter to assure the glazing energy efficiency potential of the building since it includes both cooling costs associated with summer and heating costs associated with winter. The cost payback period is the length of time required to return the smart PDLC film glass's initial implementation cost. If the cost payback period of the glazing is less than the life span of the smart PDLC film glasses (25 years), they can contribute to the buildings' net energy savings.

Fig. 11 depicts yearly air-conditioning cost savings and payback periods of smart glasses of hot and dry climate (Jodhpur). From Fig. 11, it can be seen that the smart glass window system with a Pink colored PDLC film is the most energy-efficient among all other studied smart glasses in voltage OFF condition. It accounts for an annual cost saving of $ 108.18 compared to clear glass in the southeast (SE) direction. White, Yellow, and Blue PDLC film glasses without applied voltage in SE direction accounts for the same cost savings of $ 106.18. All the smart PDLC film glasses without applied voltage had shown higher cost savings than the same glasses with applied voltage because of its low transmission values. But the smart PDLC film glasses are used with applied voltage in the buildings for the daylighting and through views. The smart glasses with white, blue, yellow, and pink colored PDLC films with an applied voltage were responsible for the cost savings of $ 101.76, $ 100.75, $ 100.34, and $ 98.64, respectively.

From Fig.11, it is observed that the smart glass window system with White PDLC film glass without voltage accounts for the lowest payback period of 12.11 years compared to the clear glass. But smart PDLC film glasses are used with voltage during the daytime to provide natural daylighting and through views. In voltage ON condition, White PDLC film glass is responsible for the lowest cost payback period of 12.71 years in the southeast (SE) direction. In contrast, smart Blue, Yellow, and Pink PDLC film glasses accounted for the cost payback periods of 15.39, 15.46 and 15.72 years, respectively. The cost payback period is found to be lowest in the South-East (SE) orientation for all the smart PDLC film glasses studied because of the high annual cost savings of respective smart glazing systems in that direction.

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Implementation cost and cost payback periods for the various smart glazing systems in the South-East (SE) direction of Jodhpur were presented in Table 3.

Fig. 11 Yearly air-conditioning cost savings and payback periods of smart glasses of hot and dry climate (Jodhpur).

Table 3 Cost payback period of various Smart PDLC film glasses in South-East (SE) direction of hot and dry climate (Jodhpur).

Fig. 12 depicts annual air-conditioning cost savings and payback periods of smart glasses of warm and humid climate (Mumbai). It is observed that White-colored PDLC film glazing with applied voltage (WSPG (V)) reported the highest air-conditioning cost savings of $ 96.21 in South-East direction, among other glazings. BSPG (V), YSPG (V), and PSPG (V) were responsible for the cost savings of $ 95.27, $ 94.88, and $ 93.31, respectively. All the smart glasses placed in South-East direction have shown the highest cost savings compared to other directions, and the glazings placed in the North, North-East, and North-West directions had reported the lowest cost savings.

From Fig. 12, it is observed that white smart PDLC film glass with applied voltage (WSPG (V)) has the lowest payback period of 13.45 years in South-East direction. The white smart PDLC film glasses' payback time was short among other studied glasses, because of its low initial implementation cost. All the smart glasses facing the SE direction have the lowest payback periods compared to other directions. Glasses placed in North, North-East, North-West directions have reported the payback periods of about 100 years. So, it is not advisable to place the smart glasses in those directions.

Fig. 12 Yearly air-conditioning cost savings and payback periods of smart glasses of warm and humid climate (Mumbai).

Fig. 13 depicts yearly air-conditioning cost savings and payback periods of smart glasses of composite climate (New Delhi). All the smart glasses have shown air-conditioning cost savings in all directions. White smart PDLC film glazing with applied voltage had reported the highest cost savings of $ 103.1 in SE direction compared to clear glazing. BSPG (V), YSPG (V), and PSPG (V) were responsible for the air-conditioning cost savings of $ 102.08, $ 101.36, and $ 99.99 in SE direction. All the smart glasses placed in SE direction have reported the highest air-conditioning cost savings compared, among other directions. Cost savings of all the smart glasses placed in South, South-East, South-West directions were relatively high compared to other directions. The order of the direction to place the glazing for the high to low cost savings is SE < SW < S < E < W < N < NE < NW. From Fig. 13, it is also observed that WSPG (V) glazing placed in SE reported the lowest payback period of 12.55 years, among other glazings. All the glazings in SE direction have reported the lowest payback periods because of their high air- conditioning cost savings in that direction. Smart glasses placed in N, NE, and NW directions have the highest payback periods over the 100 years because of its fewer cost savings in those directions. The preference order of the directions from low to high payback periods is SE < SW < S < E < W < N < NE < NW.

Fig. 13 Yearly air-conditioning cost savings and payback periods of smart glasses of composite climate (New Delhi).

The PDLC film glasses are used in both ON and OFF conditions based on the requirements of occupant's view, privacy, and thermal comfort. The air-conditioning cost savings are equally good in both ON or OFF conditions. The air-conditioning cost savings of smart glasses (ON/OFF) are significant as compared to conventional 6 mm clear glass windows. The small difference in the air-conditioning cost savings between ON and OFF conditions of smart glasses is due to their smaller difference in solar transmittance values. Though smart glazings' air-conditioning cost savings have less difference, their view is different in transparent and translucent states. In all three climates, glazings in the SE direction had shown the highest cost savings. The northwest (NW) direction is responsible for the lowest cost savings among all other orientations studied. The preferable orientation order from the highest to lowest net annual cost savings point of view is SE < SW < S < E < W < N < NE < NW in all three different climates studied. All the smart glasses with PDLC films in the North-East and North-West directions had shown fewer cost savings with and without applied voltage to them compared to South-East direction. The order of preference of the smart PDLC film glasses from the lowest cost payback period to the highest in all three different climates is WSPG (V) < BSPG (V) < YSPG (V) < PSPG (V). All smart PDLC film glasses kept in the North, North-West (NW) and North-East (NE) directions account for the long payback periods, over the 100 years because of its low annual cost savings in those directions and the high initial cost of glazing. So, it is not recommended to keep the smart PDLC film glasses in those directions. The optimum orientation order to keep smart PDLC film glasses from the lowest to highest payback periods is SE < SW < S < E < W < N < NE < NW.

5.3 Average daylight factor of various smart window systems in different climates

The average daylight factor (ADF) is the parameter describing the level of lighting illuminance inside the building compared to outside. Adequate levels of daylight factors in the buildings shed the need for artificial daylighting. PDLC film glazing turns transparent when the voltage is applied and allows the visible light. The average daylight factor was evaluated for three different climatic zones with the help of the Design builder (V 6.1.5.004) from 6 am to 6 pm during the summer, and 7 am to 5 pm during the winter for four best directions (high-cost savings) to place the glazing (E, SE, S, SW). CIE- standard sky and Clear day conditions were assumed to compute the daylighting factor. The minimum average daylighting factor required is 0.625 for living rooms, bedrooms, office inquiry rooms, library stack rooms, and in other most of the rooms as per the Indian standards [38]. The one percentage of daylight factor is equal to 80 Lux.

From Fig. 14, it is observed that all the smart glasses have the average daylight factors above the recommended levels of daylighting factors for the jodhpur city during both summer and winter. BSPG (V), YSPG (V), PSPG (V) have the same ADF values in all the directions since they possess the same light transmission values in the visible range, and it is 141.6 % higher than the recommended level in east direction. WSPG (V) smart glasses ADF values are relatively low compared to remaining smart glasses in all the directions because of its low light transmission values. Glazings placed in east direction had reported the highest daylight factor values compared to other directions. The optimum direction to place the glass for high daylighting factor values is E < SW < SE < S during the summer and SE < S < SW < E during

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the winter. It is seen that ADF values were higher during the winter compared to summer for all the smart glasses studied in four best orientations.

Fig. 14 Average daylight factor of various smart windows in a hot and dry climate (Jodhpur)

Average daylighting factors for a warm and humid climate (Mumbai) were simulated in four cardinal directions and presented in Fig. 15. All the smart glasses during the summer and winter have recorded a high average daylighting factor than the recommended level. The ADF values are high and low in the east and south directions, respectively. WSPG (V) records 117.6%, and remaining smart glasses record 141.6 % more ADF values than recommended values in the east direction. The optimum order of the orientation from high ADF to low ADF during summer is E < SW < SE < S. In winter, WSPG (V) has 212 % higher ADF values and other smart glasses (V) have 229.6 % higher ADF values than the recommended ADF values in the south. During the winter sequence of the directions for high ADF to low ADF is S < SW < SE < E.

Fig. 15 Average daylight factor of various smart windows in a warm and humid climate (Mumbai)

Average daylighting factors for a composite climate (New Delhi) were simulated and presented in four cardinal directions and presented in Fig. 16. All the smart glasses during both peak summer and peak winter have reported adequate ADF values than the recommended levels to provide natural daylighting. At least 50 % higher ADF values were reported among all the directions than the recommended values for all the smart glasses. WSPG (V) has 117.6 % more ADF, whereas remaining smart glasses have 141.6 % more ADF values than the recommended values in the east direction during the summer. During the winter, ADF values are high in the south direction, among other directions. South direction ADF values are 255.2 % more for WSPG (V) and 280.8 % more for the remaining smart glasses than the recommended daylight factor values.

Fig. 16 Average daylight factor of various smart windows in composite climate (New Delhi)

6. CONCLUSIONS

This paper presents a mathematical model to assess the thermal performance and annual cost savings of various smart PDLC film glasses with and without applied voltage in all eight orientations of three different climatic regions. The spectral properties of PDLC film glasses were explored experimentally using a spectrophotometer in the transparent and translucent state. The effect of applied voltage (ON/OFF) on the opacity was presented. This work suggests the optimum orientation to keep the window glazing for the highest annual air-conditioning cost savings. The daylight factor and payback periods of the various smart PDLC film glasses were also presented.

- From Figs. 11, 12 and 13, it is observed that the White smart PDLC film glass (WSPG (V)) in the South-East (SE) orientation accounts for the highest annual air-conditioning cost savings ($ 101.76 in a hot and dry climate) with adequate daylight factor, among other studied smart glasses in all three climatic conditions.
- From an annual air-conditioning cost-savings perspective, the preference order of smart PDLCs from the highest to the lowest cost savings is WSPG (V) > BSPG (V) > YSPG (V) > PSPG (V) in all three different climatic conditions.
- The white smart PDLC film glass (WSPG (V)) was economically more feasible, with the lowest cost payback periods (12.71 years in a hot and dry climate) in all three climatic conditions. The preference order of smart glasses for the lowest payback period in all three climatic zones is WSPG(V) < BSPG(V) < YSPG(V) < PSPG(V).
- However, all the smart glasses had shown approximately the same cost savings in SE orientation, White smart PDLC glass has the lowest payback period because of its low initial costs compared to other glasses.
- It is recommended to place a smart window in SE orientation followed by SW, S, E and W to make use of their air-conditioning cost-saving potential with adequate daylight factors and lower payback periods. It is not advisable to keep the smart glazing in the North (N), North-East (NE) and North-West (NW) orientations, because of its long payback periods of about 100 years, which is much longer than the life span of PDLC film (25 years).
- Modulated solar optical properties of the smart PDLCs, such as solar transmittance and reflectance, significantly affected the thermal performance and air-conditioning cost

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savings. Solar transmittance of white smart PDLC glass (WSPG (V)) was 85.71 % less, and reflectance was observed to be four times higher than the clear glass.

This paper's findings are useful in designing energy-efficient smart window systems for reduced heating and cooling loads. The results are also helpful in retrofitting existing window systems with smart window systems to attain energy efficiency in buildings.

Nomenclature

A_{GL}	Area of the glazing installed[m^2]
A_s	Solar azimuth angle [Deg]
A_{SLR}	Total solar absorptance in the entire solar spectrum [%]
ADF	Average Daylight Factor [%]
B	Atmospheric extinction coefficient [-]
BSPG (NV)	Blue smart PDLC film glass without Voltage
BSPG (V)	Blue smart PDLC film glass with Voltage
b_a	Width of the air space between glasses [m]
C	Sky radiation coefficient [-]
CG	Clear glass
C_c	Annual cooling cost savings [$/year]
C_e	Unit cost of electricity[$/kWh]
C_{es}	Cost of energy supplied to a smart glass per year [$\$m^{-2}$]
C_f	Cost of the fuel [$/kWh]
C_g	Cost of the glazing [$\$m^{-2}$]
C_h	Increase in annual heating costs [$/year]
C_i	Implementation cost of the PDLC film glazing [$\$m^{-2}$]
C_{Net}	Net annual air-conditioning cost savings [$/year]
COP	Coefficient of performance of the cooling system [-]
E	Emissivity factor [-]
h_{in}	Inside heat transfer coefficient [$Wm^{-2}K^{-1}$]
h_{out}	Outside convective heat transfer coefficient [$Wm^{-2} K^{-1}$]
h_r	Radiative convective heat transfer coefficient [$Wm^{-2} K^{-1}$]
h_s	Solar hour angle [Deg]
I_a	Apparent solar irradiance at air mass, m=0[Wm^{-2}]

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I_{dif}	Sky-diffuse solar radiation [Wm^{-2}]
I_{dir}	Direct solar radiation from the sun [Wm^{-2}]
I_{grr}	Ground reflected solar radiation [Wm^{-2}]
I_T	Total incident solar radiation [Wm^{-2}]
I_{TNR}	Solar radiation at normal incidence [Wm^{-2}]
IST	Indian Standard Time
K_1	Thermal conductivity of inside glass [$Wm^{-1}K^{-1}$]
K_2	Thermal conductivity of PDLC film [$Wm^{-1}K^{-1}$]
L	Latitude [Deg]
L_1	Thickness of the glass [m]
L_2	Thickness of the PDLC film [m]
N	Day number, starting from January 1st as 1
PDLC	Polymer Dispersed Liquid Crystal
PP	Payback period of smart PDLC film glasses [Years]
PSPG (NV)	Pink smart PDLC film glass without Voltage
PSPG (V)	Pink smart PDLC film glass with Voltage
Q_{Inc}	Increased annual heating load [kWh]
Q_{Red}	Reduced annual cooling load [kWh]
R_{si}	Inside surface resistance film coefficient [m^2KW^{-1}]
R_{SLR}	Total solar reflectance in the entire solar spectrum [%]
R_{so}	Outside surface resistance film coefficient [m^2KW^{-1}]
SHGC	Solar heat gain coefficient [-]
S_λ	Relative spectral distribution of the solar radiation [Wm^{-2}]
t_a	Air space between the glass panes [m]
T_{SLR}	Total solar transmittance in the entire solar spectrum [%]
U	Overall heat transfer coefficient [$Wm^{-2}K^{-1}$]
WSPG (NV)	White smart PDLC film glass without Voltage
WSPG (V)	White smart PDLC film glass with Voltage
WWR	Window to wall ratio
YSPG(NV)	Yellow smart PDLC film glass without Voltage
YSPG(V)	Yellow smart PDLC film glass with Voltage

Greek letters

α_s	Solar altitude angle [Deg]
$\alpha(\lambda)$	Spectral absorption of smart PDLC film glass
β	Smart window system inclination with normal of the surface [Deg]
γ_s	Surface solar azimuth angle [Deg]
δ_s	Solar declination [Deg]
η	Efficiency of the furnace [%]
θ_i	Solar incidence angle [Deg]
λ	Wavelength [nm]
$\Delta\lambda$	Wavelength interval [2 nm]
ρ_g	Ground reflectance factor [-]
$\rho(\lambda)$	Spectral reflection of smart PDLC film glass
$\tau(\lambda)$	Spectral transmission of smart PDLC film glass
Ψ	Surface azimuth angle [Deg]

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TABLES:

Table 1

Measured optical **p**roperties of smart PDLC film glasses in the solar spectrum (300-2500 nm)

S.NO	Glass material	Transmittance (%)	Reflectance (%)	Absorptance (%)	SHGC (%)
1	Clear glass (6mm)	77	7	16	81
2	WSPG(NV)	7	24	69	23
3	WSPG(V)	11	27	62	25
4	BSPG(NV)	8	25	67	23
5	BSPG(V)	12	28	60	26
6	PSPG(NV)	5	22	73	22
7	PSPG (V)	12	23	65	27
8	YSPG(NV)	7	24	69	23
9	YSPG(V)	12	27	61	26

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Table 2

Surface azimuth angle (Ψ) in various orientations

Orientation	N	NE	E	SE	S	SW	W	NW
Surface azimuth angle (Ψ)	180	-135	-90	-45	0	45	90	135

Table 3

Implementation cost and cost payback periods of various Smart PDLC film glasses in South-East (SE) direction of hot and climate (Jodhpur)

Glazing	C_g($/m²)	C_{es} ($/m²)	C_i ($)	C_{Net} ($)	PP (Years)
WSPG(NV)	229.6	0	1285.76	106.18	12.10
WSPG(V)	229.6	1.4	1293.6	101.76	12.71
BSPG(NV)	275.6	0	1543.36	105.18	14.67
BSPG(V)	275.6	1.4	1551.2	100.75	15.39
PSPG(NV)	275.6	0	1543.36	108.18	14.26
PSPG(V)	275.6	1.4	1551.2	98.64	15.72
YSPG(NV)	275.6	0	1543.36	106.18	14.53
YSPG(V)	275.6	1.4	1551.2	100.34	15.46

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FIGURES:

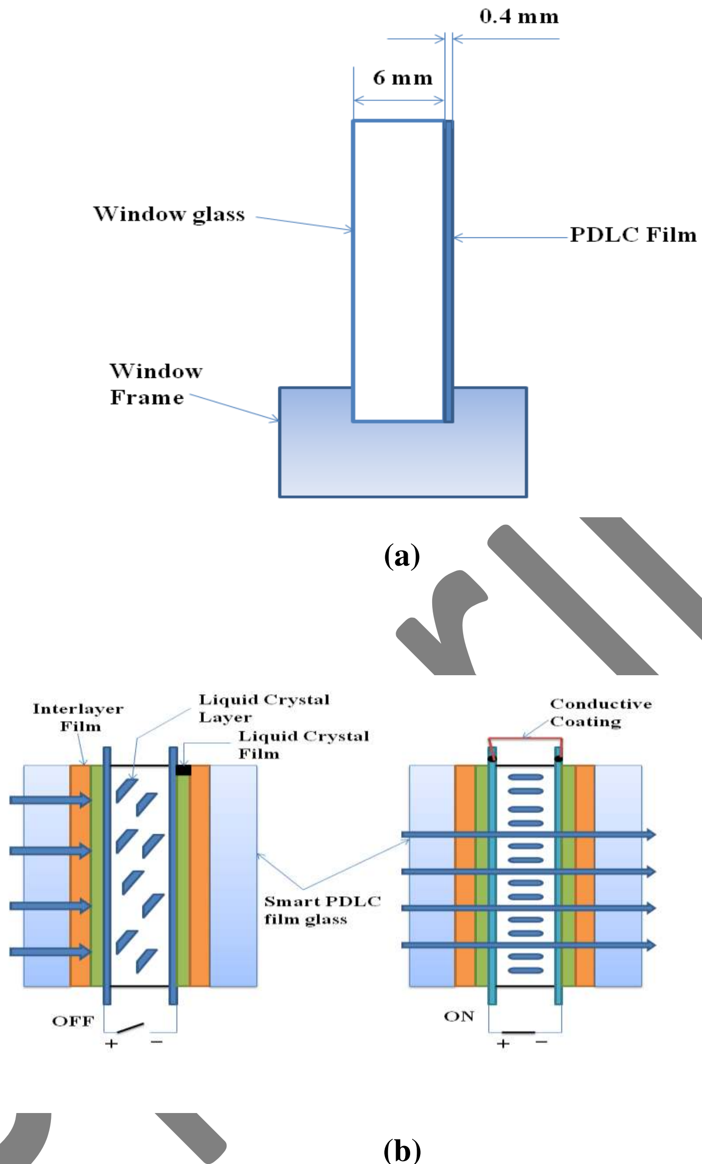

Fig. 1 Schematic of a) smart PDLC film glasses (b) Working principle of smart PDLC film glasses with and without applied voltage

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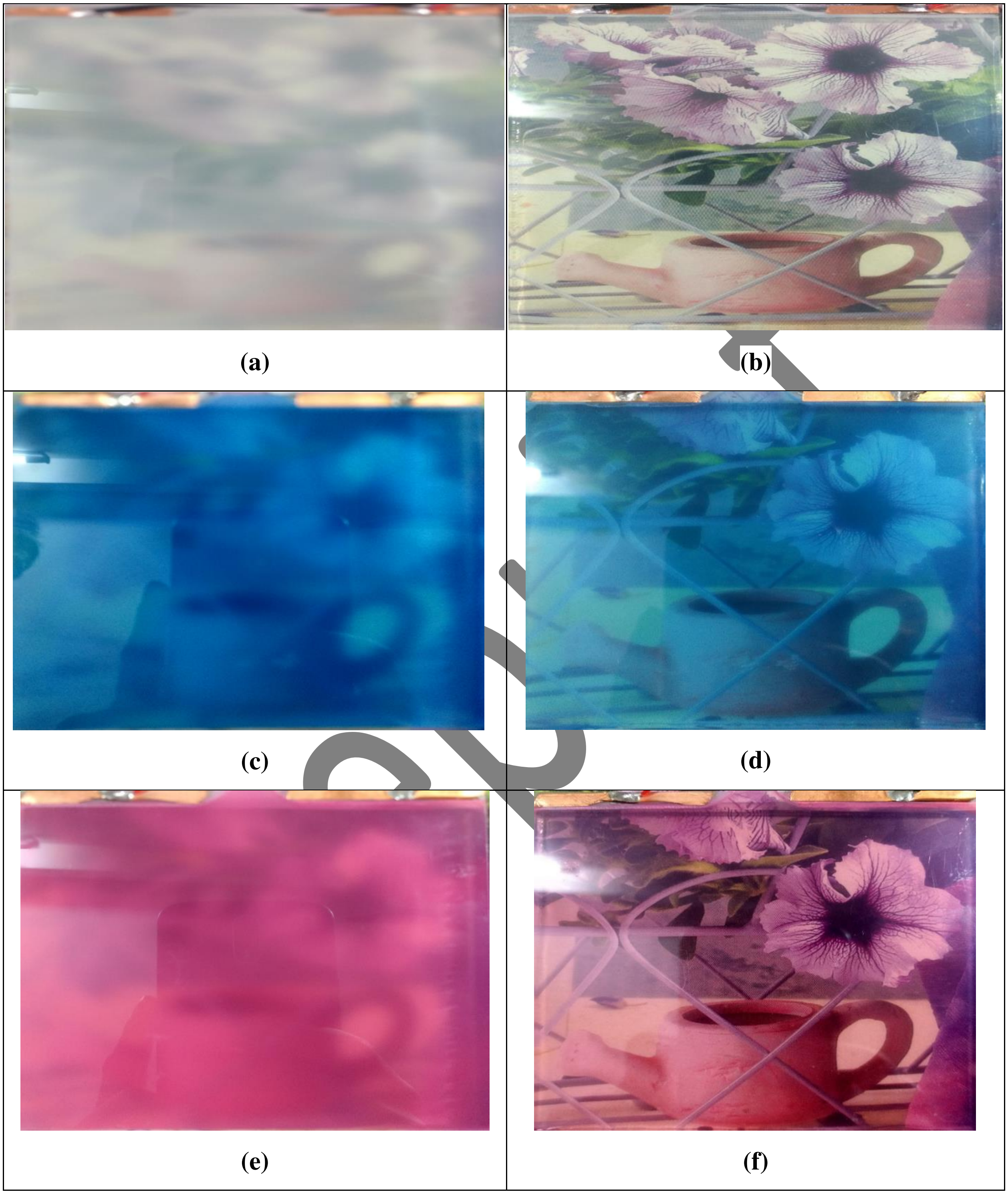

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(g)	(h)

Fig. 2 Smart PDLC film glasses a) WSPG (NV) b) WSPG (V) c) BSPG (NV) d) BSPG (V) e) PSPG (NV) f) PSPG (V) g) YSPG (NV) h) YSPG (V)

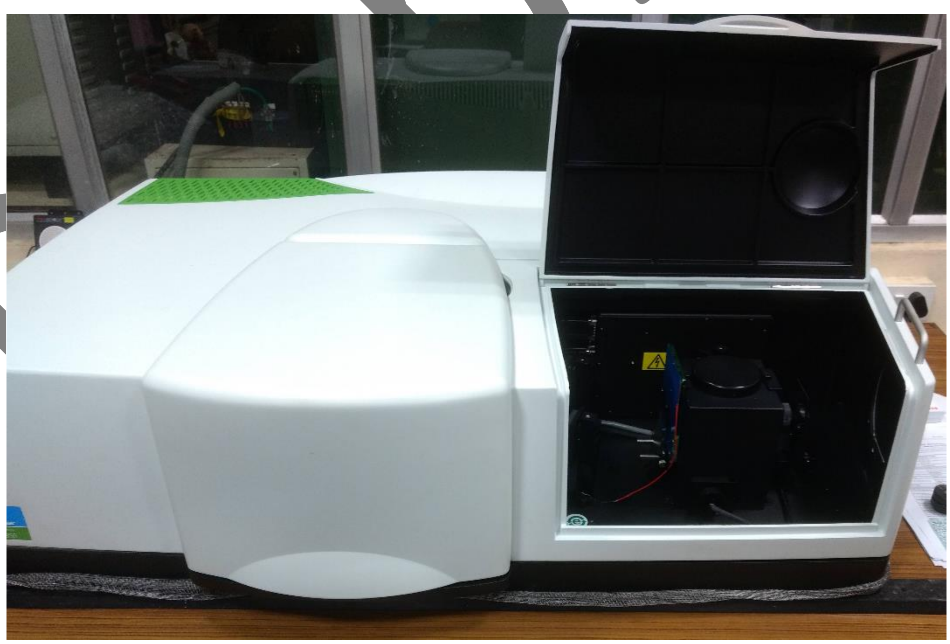

Fig. 3 Integrating sphere spectrophotometer (Perkin Elmer 950) with UV-WinLab software

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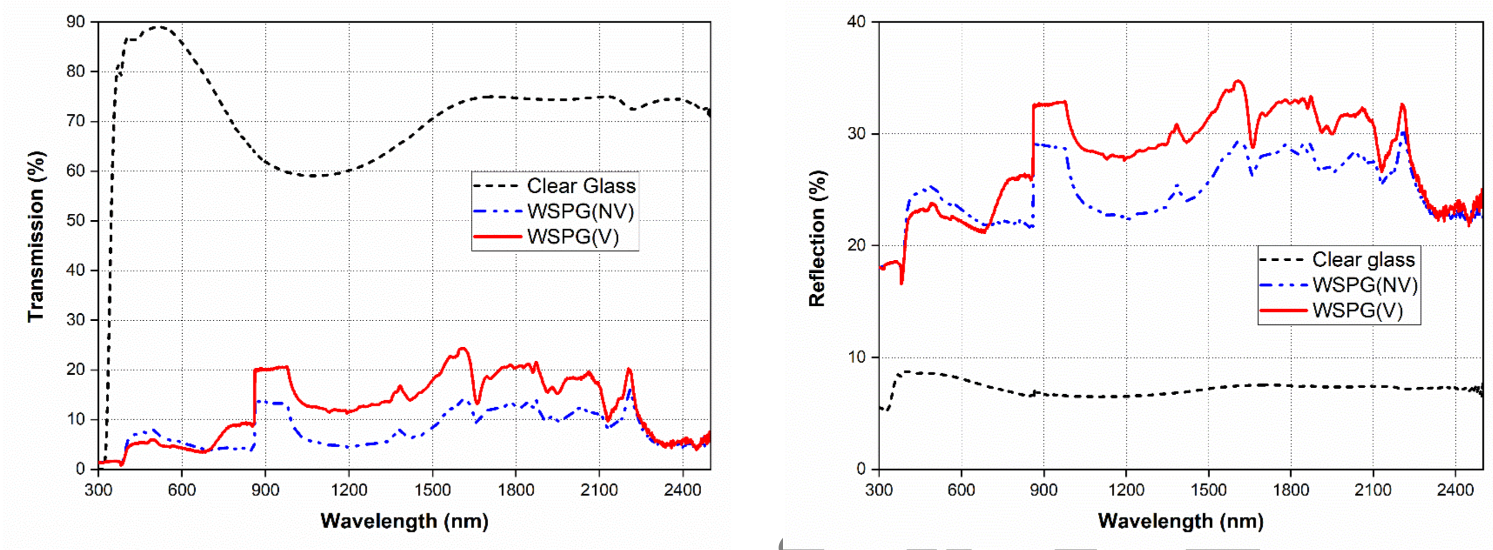
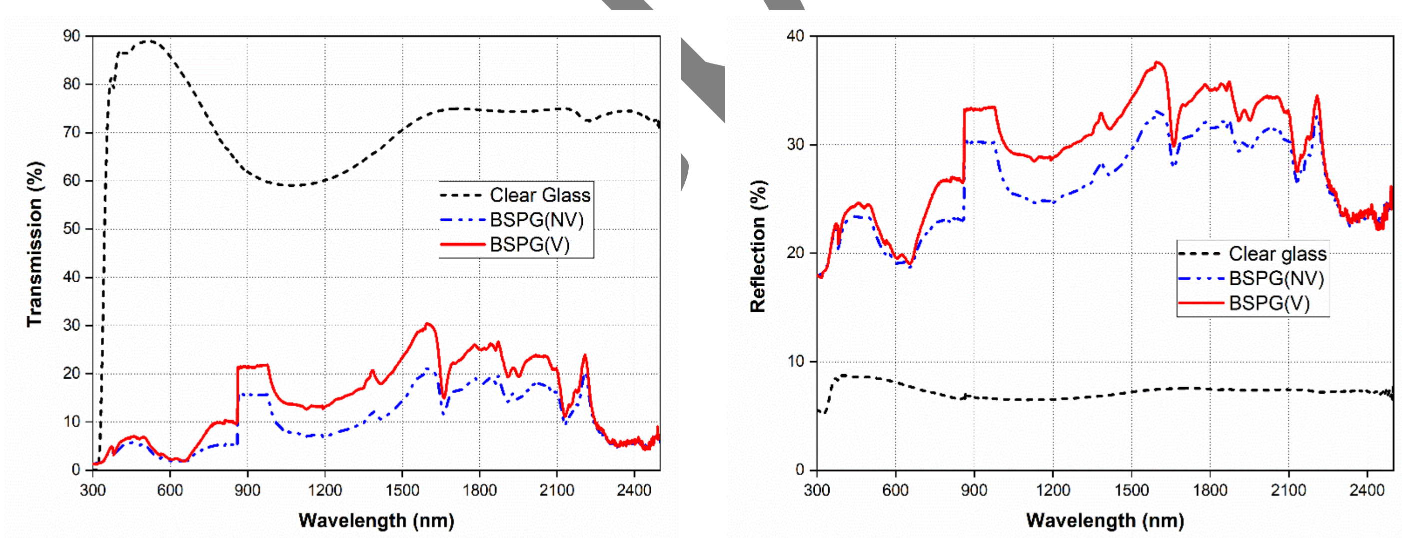


(a) (b)

Fig. 4 Spectral characteristics of White smart PDLC Film glass (a) Transmission (b) Reflection



(a) (b)

Fig. 5 Spectral characteristics of Blue smart PDLC Film glass (a) Transmission (b) Reflection

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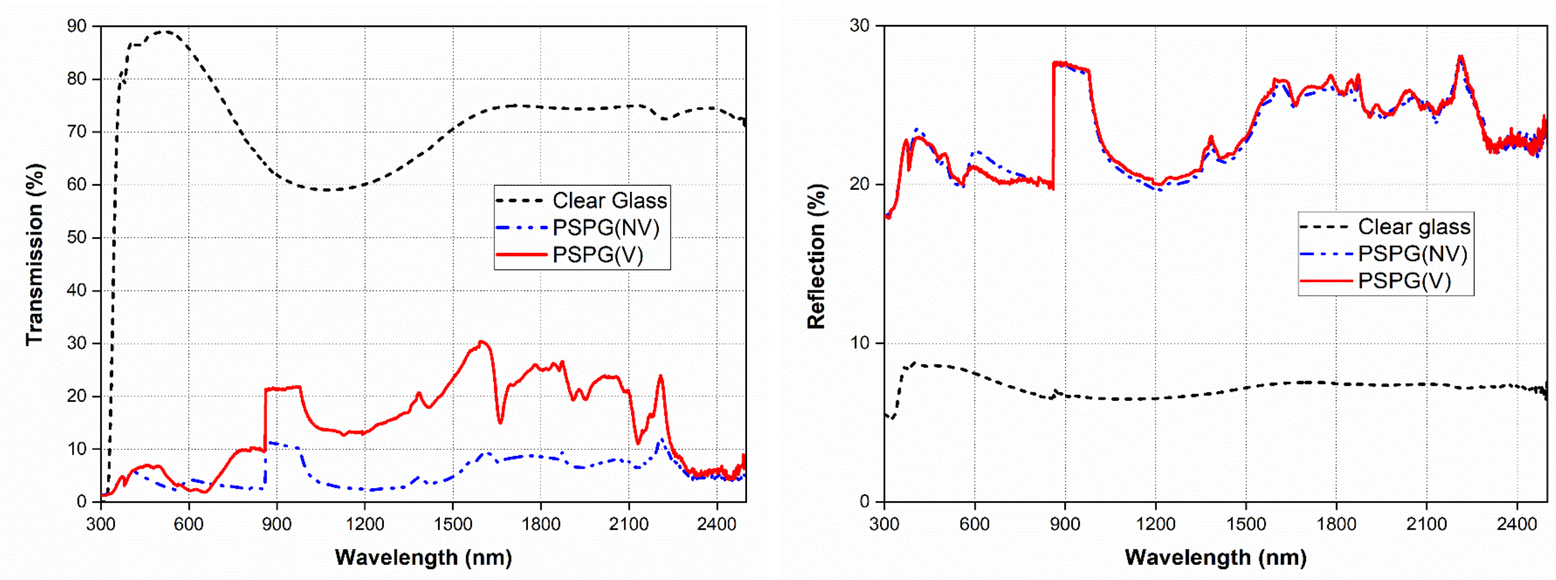
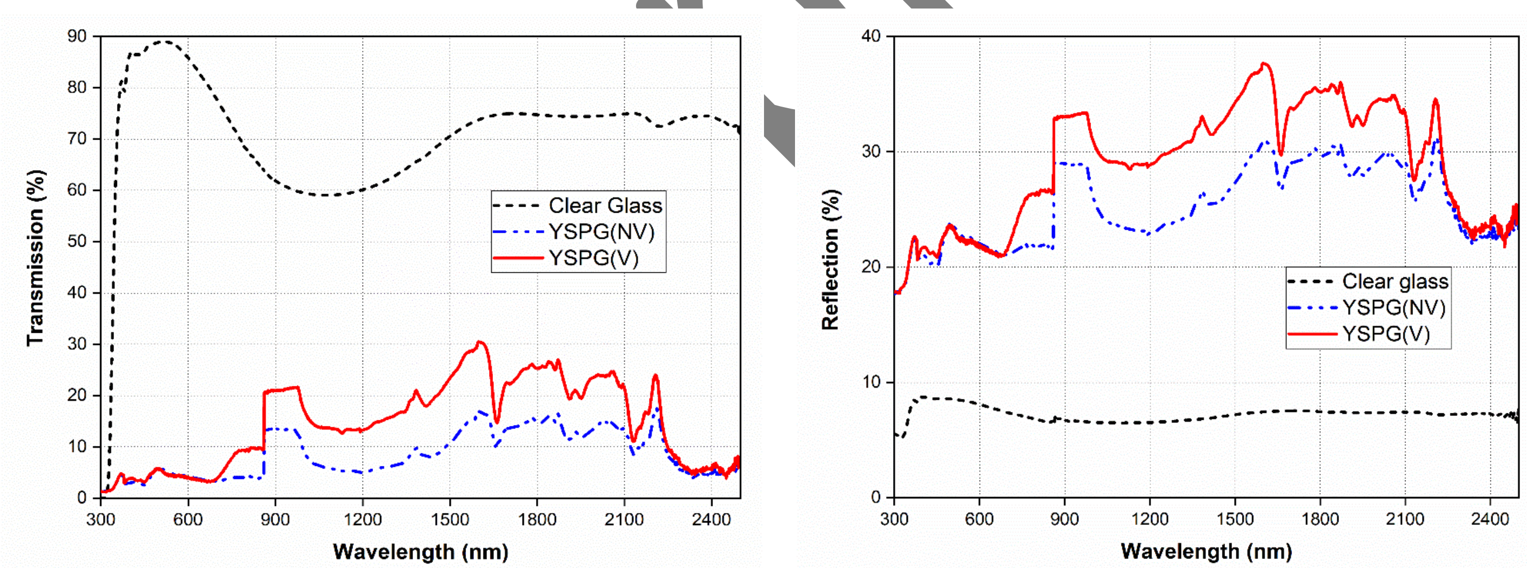


(a) (b)

Fig. 6 Spectral characteristics of Pink smart PDLC Film glass (a) Transmission (b) Reflection



(a) (b)

Fig. 7 Spectral characteristics of Yellow smart PDLC Film glass (a) Transmission (b) Reflection

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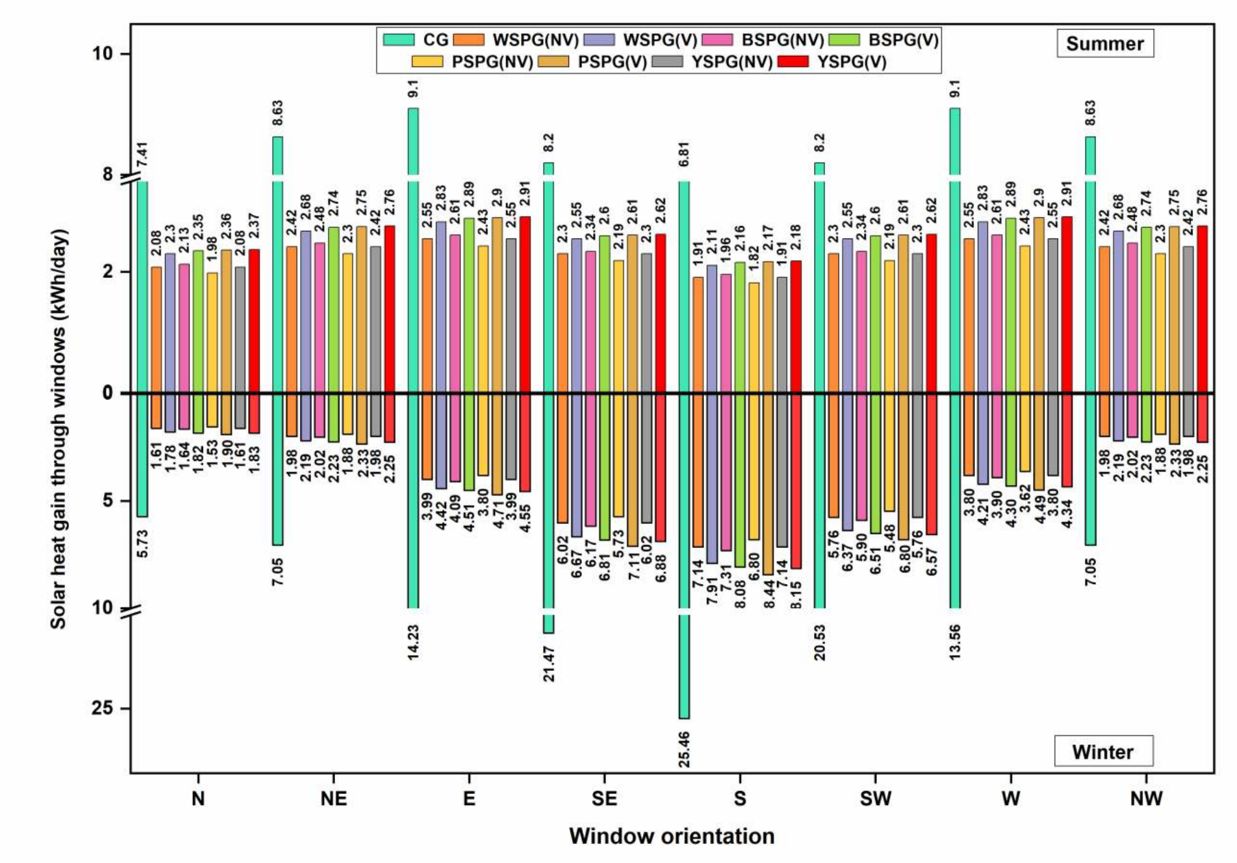

Fig. 8 Heat gain through various smart PDLCs film glazing in different orientations of hot and dry climate (Jodhpur).

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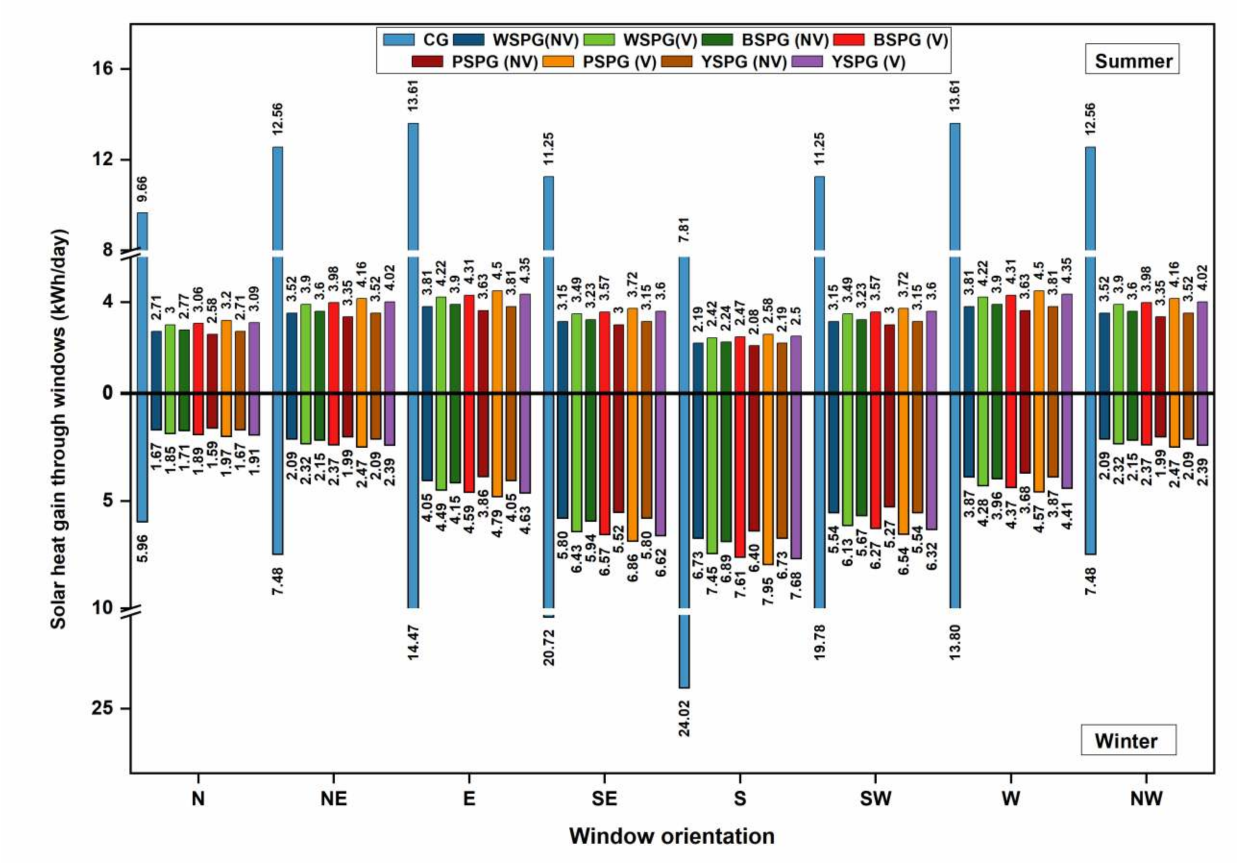

Fig. 9 Heat gain through various smart PDLCs film glazing in different orientations of warm and humid climate (Mumbai).

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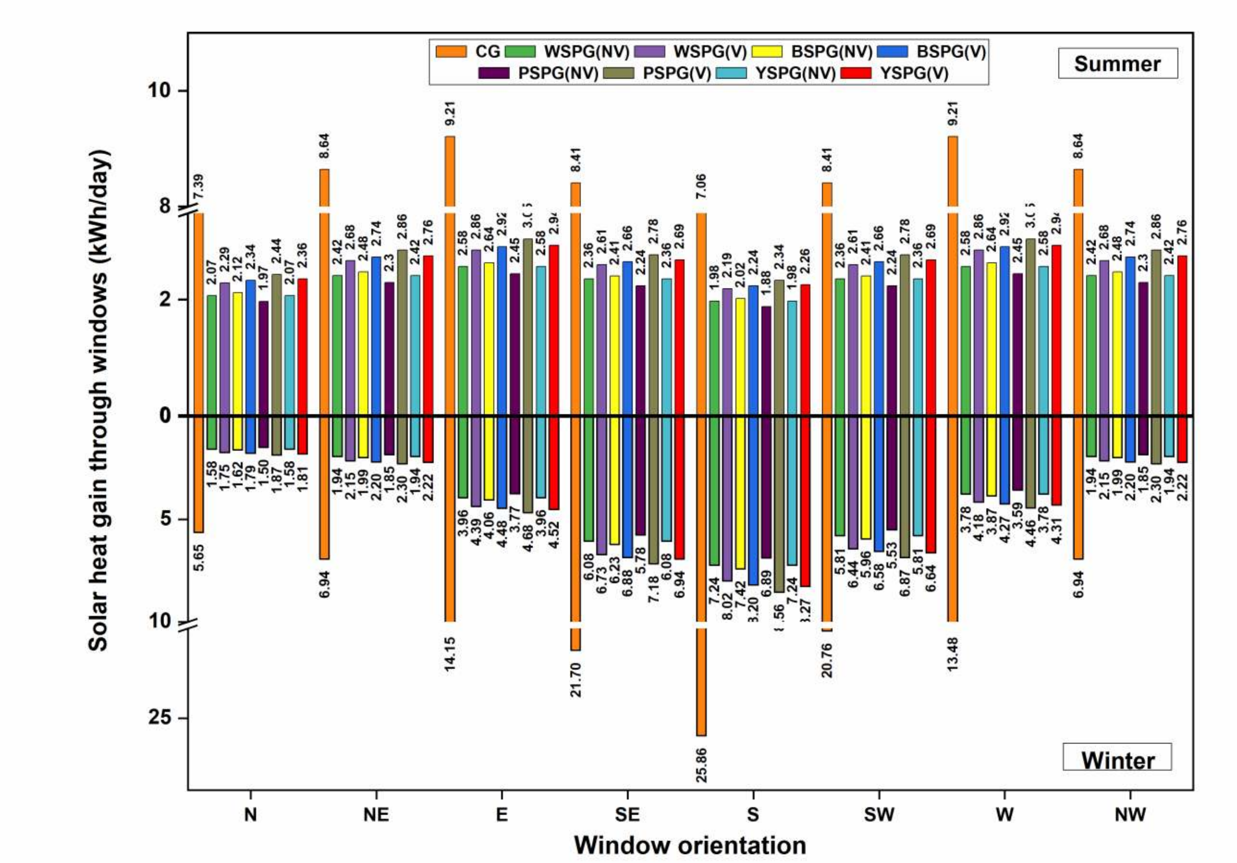

837

838 **Fig. 10** Heat gain through various smart PDLCs film glazing in different orientations of
839 composite climate (New Delhi).

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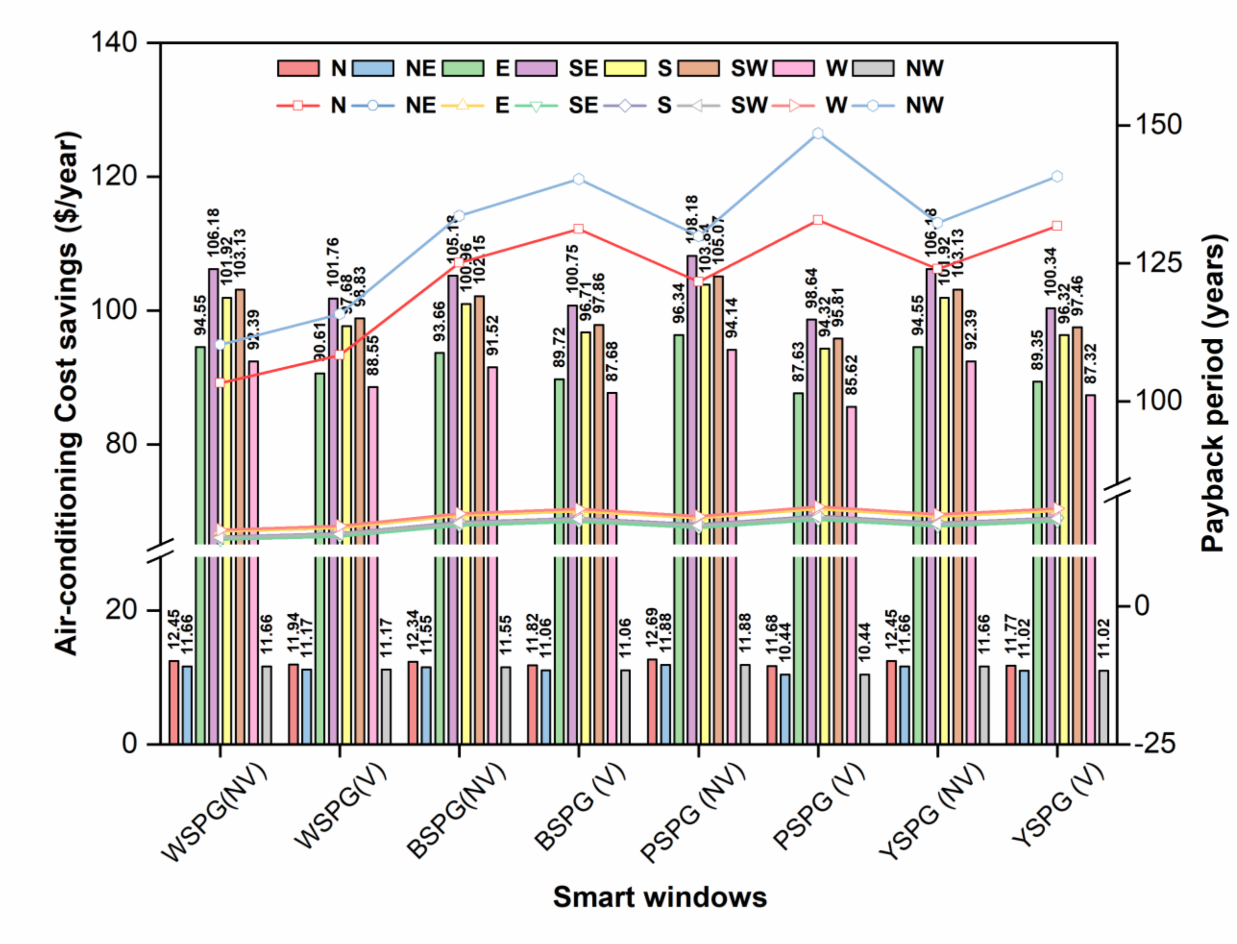

Fig. 11 Yearly air-conditioning cost savings and payback periods of smart glasses of hot and dry climate (Jodhpur).

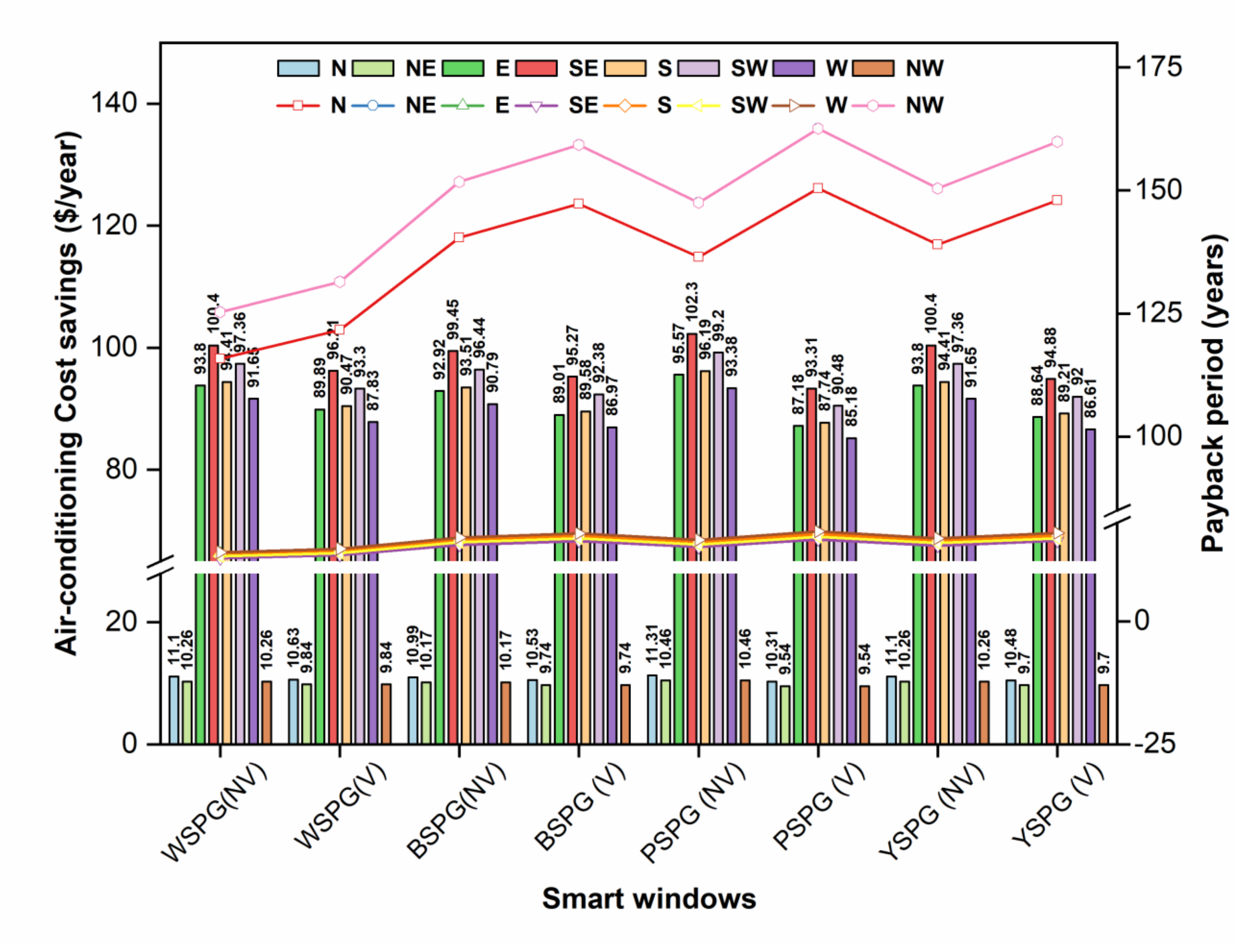

Fig. 12 Yearly air-conditioning cost savings and payback periods of smart glasses of warm and humid climate (Mumbai).

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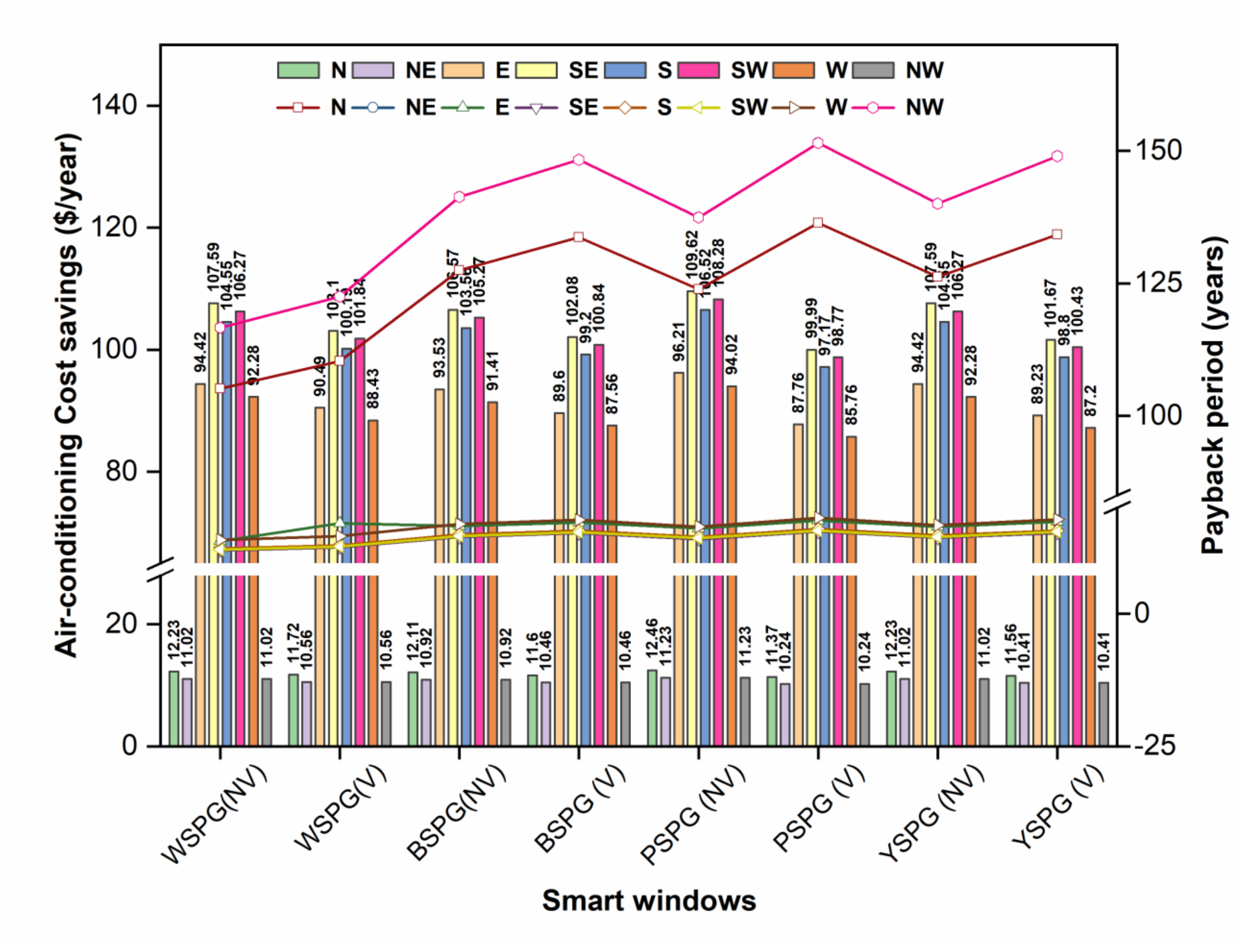

Fig. 13 Yearly air-conditioning cost savings and payback periods of smart glasses of composite climate (New Delhi).

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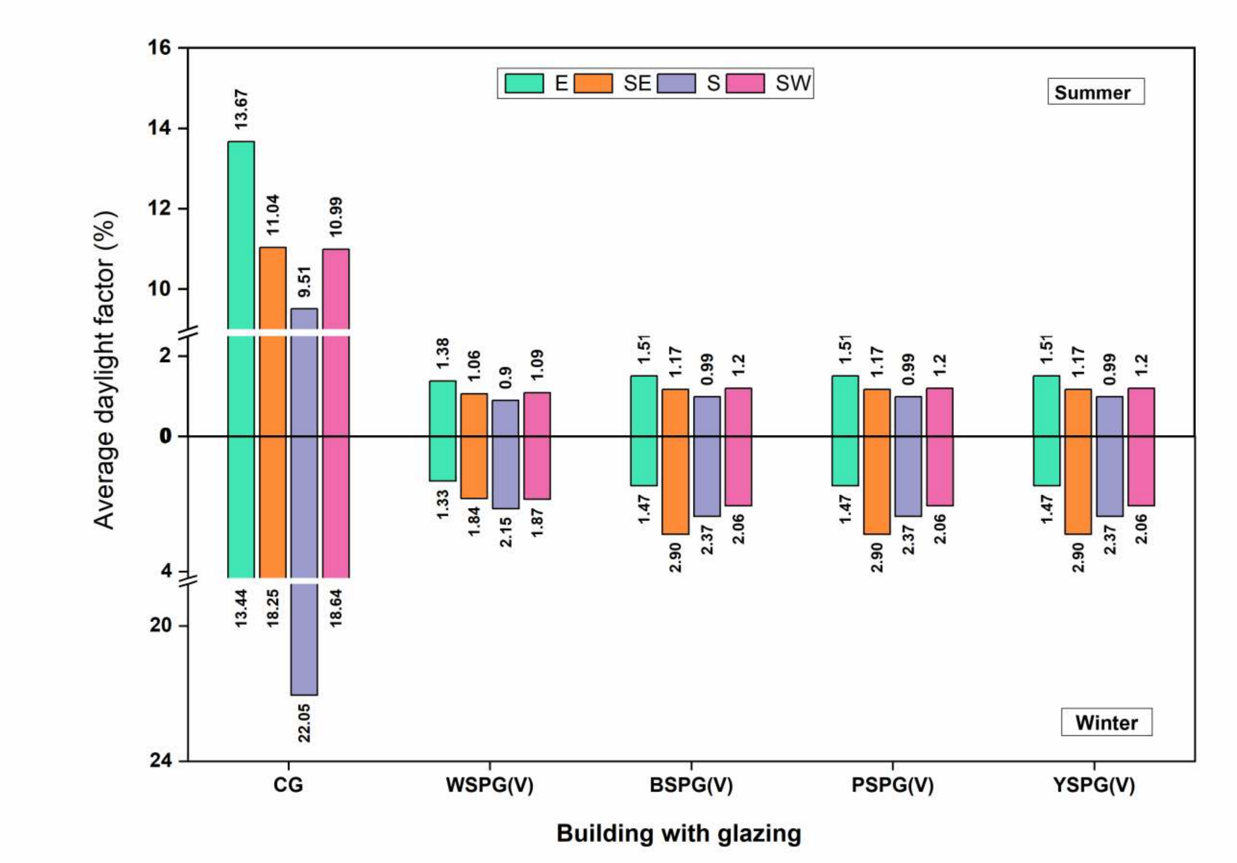

Fig. 14 Average daylight factor of various smart windows in a hot and dry climate (Jodhpur)

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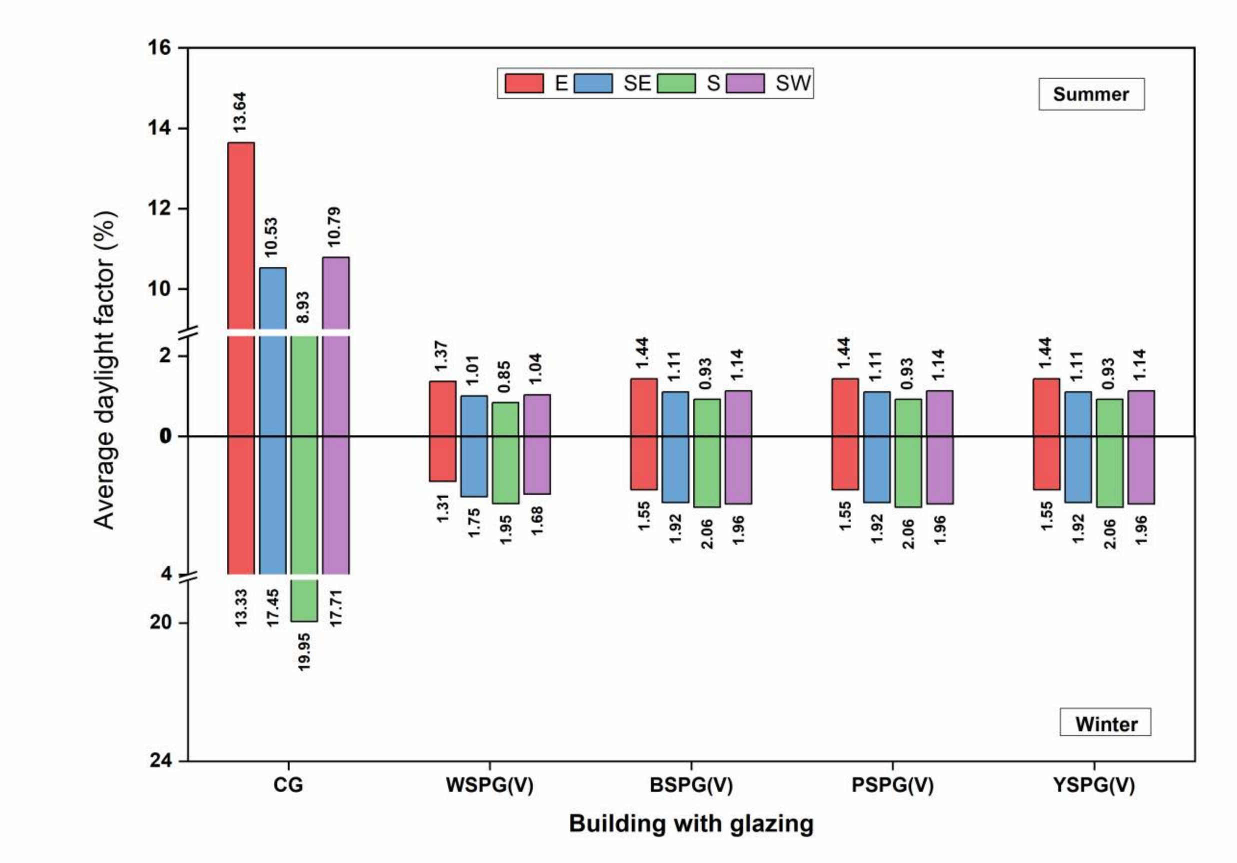

Fig. 15 Average daylight factor of various smart windows in a warm and humid climate (Mumbai)

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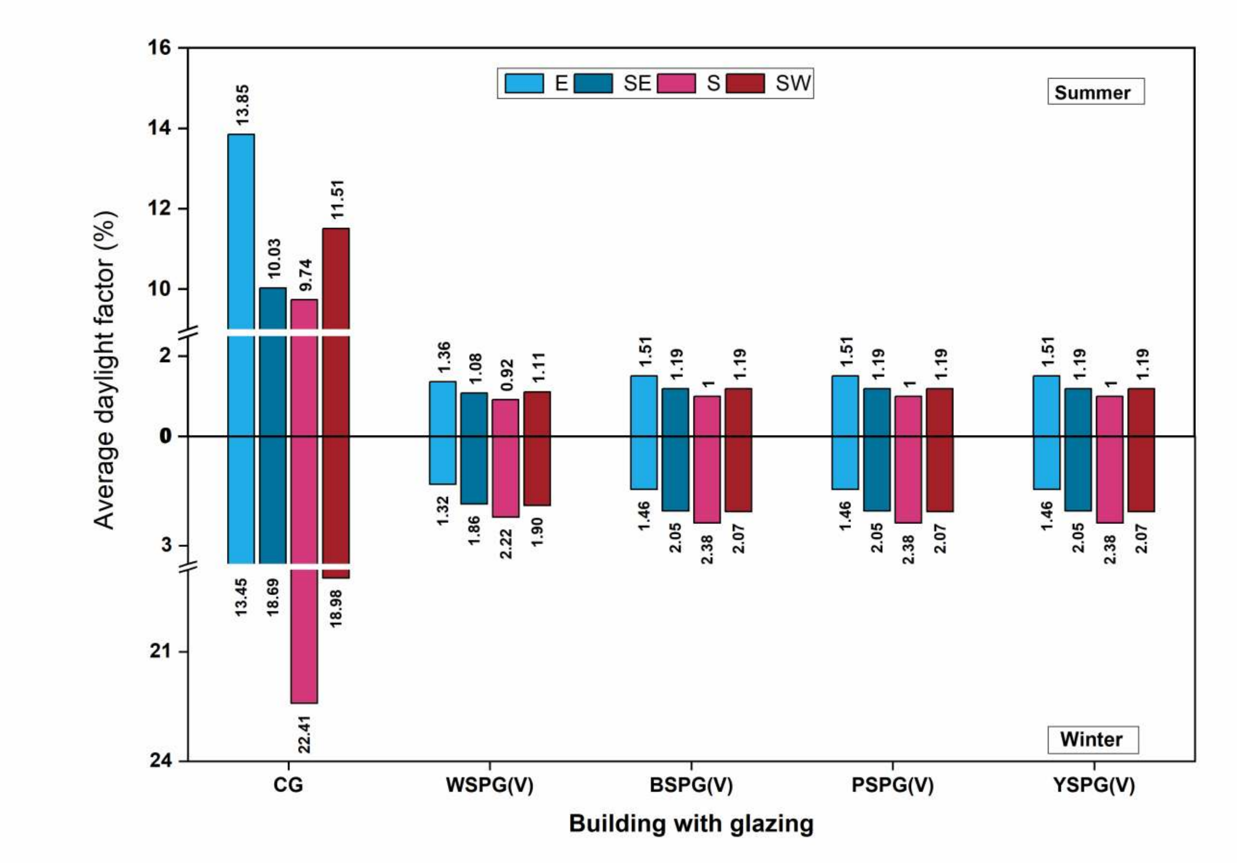

Fig. 16 Average daylight factor of various smart windows in composite climate (New Delhi)