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Comprehensive assessment of advanced solar facade: thermal, optical and economic assessment

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Comprehensive assessment of advanced solar facade: thermal, optical and economic assessment

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Abstract. In order to improve the enegy saving in building, development of glazing system has been widely conducted. CdTe PV window system has the feature of energy generation and adjustment on thermal and visual comfort, in this paper, the thermal performance of a glazing system integrated with semi-transparent CdTe solar cells with different transparency (10% and 50%) under different temperature conditions were investigated by experimental measurement (undertaken in a large climate chamber). The U-value of each PV window has been calculated. Moreover, the spectral transmittance within visible has been measured by spectrometer. This study provided comprehensive fundamental information of different CdTe PV window system for their further investigation on energy and visual comfort.

Keywords: CdTe semi-transparent PV window; Climatic Chamber; Thermal Performance

1. Introduction

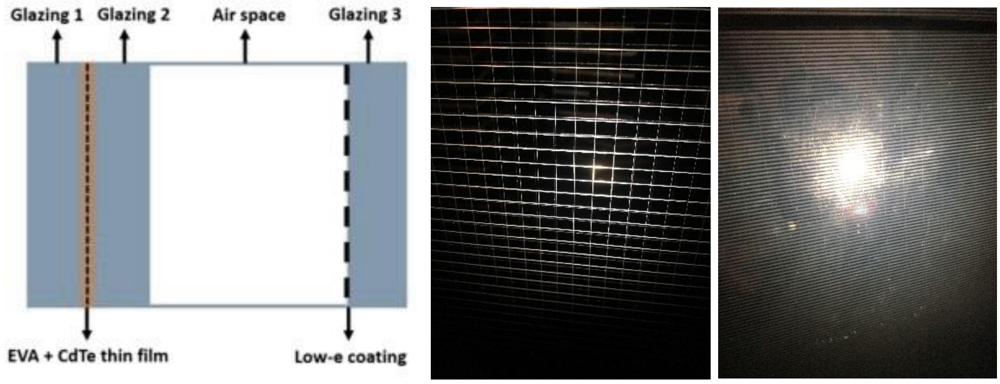
For the purpose of improving the performance of glazing systems, generating power on-site and achieving building energy conservation, photovoltaic (PV) glazing has been widely investigated and proposed to be integrated into buildings [1]. Semi-transparent PV (STPV) as one of the most promising PV types has the feature of power generation and daylight adjustment [refs]. Solar cells on a semi-transparent PV glazing partially absorb solar radiation incident on the window surface to generate electrical power, meanwhile block the oversupplied solar energy penetrated into interior space. Therefore, the overall thermal performance of the window system has been affected. This study aims to explore the thermal characteristics of Cadmium Telluride (CdTe) PV windows with different transparency[2, 3]. The U-value of CdTe PV glazing systems under a standard condition was explored through experiments, as well as the thermal resistance under conditions over a range of different mean temperatures of two glazing panes and a range of temperature differences between the surfaces, respectively, to allow a comprehensive picture of heat transfer through STPV window unit. Additionally, the optical properties were measured as well.

2. Methodology

Experimental studies of the selected glazing systems were carried out at the Laboratory at the Energy Technology Building, University of Nottingham. The characteristics (i.e., surface temperatures, heat flux, and spectral transmittance) of semi-transparent CdTe PV window with 10% transparency and 50% transparency, respectively, were measured under a series of controlled temperature conditions.

2.1. Test samples

As illustrated in Figure 1, the construction of these two PV window units consist of five layers in total, from outside to inside, listed as 3.2mm laminated glazing, 0.4 mm conventional series ethylene vinyl acetate (EVA) and CdTe film, 3.2 mm laminated glazing, 20mm Argon-filled gap, and 4mm toughened soft coat low-e glazing. 10% or 50% transparency means that there is 10%/50% percent of total window area that was not covered by solar cells.



(a) Layers of PV glazing Unit (b) 10% transparency CdTC PV (c) 50% transparency CdTe PV

Figure 1: Structure of the CdTe PV window unit

2.2. Apparatus

Figure 2 (a) shows a TAS series 2 LTCL600 climatic chamber that was used to measure the thermal performance of the glazing units in this study, which comprises two well-insulated walk-in rooms, providing a steady and cyclic simulation of the climatic environment. Each enclosure can be individually controlled. Therefore, it is possible to simulate external climate conditions in one room, whilst mimic internal conditions in the other one. One of the rooms is physically fixed on the ground, while the other can be wheeled to one side to allow the construction of a 'Test Wall'. Once the wall constructed, the two rooms were enclosed together to sandwich the 'Test Wall'. During the test, integral air conditioning units were used to control the two-room temperatures within the range from -25℃ to +60℃ and the relative humidity between 10% and 95%. In this experiment, CdTe PV glazing unit was installed in the 'Test Wall' as is shown in Figure 2 (b), resulting in measurement of various parameters, such as surface temperature, air temperature and heat flux of the glazing unit, can be obtained during operation.

(a) (b)

Figure 2. (a) External view of the climatic chamber (b) CdTe PV glazing unit installed on 'Test Wall.'

Followed International Standard ISO 9869-1:2014 for In-situ thermal resistance measurements by using heat flow meters, The measurement method was designed [4]. Informed by International Standard ISO 12567-1:2012, which determines window and door thermal transmittance using the hot-box method, the apparatus was set up [5], as is shown in Figure 3. A 300mm-thick insulated wall (U-value has been measured as no more than 0.3 W/m^2K) was sandwiched between the two rooms, forming the initial 'Test wall'. According to ISO 12567-1:2012 [5], the internal surface of the glazing unit was mounted flush with the surface of the insulated wall. Silicone sealant covered with tape was used to seal all gaps between the window and the insulated wall and hold the window firmly in their position. Additionally, in order to diminish the convection effect caused by the fans on the air conditioning units in each room, two plywood baffles were installed in both the interior and exterior chambers, respectively.

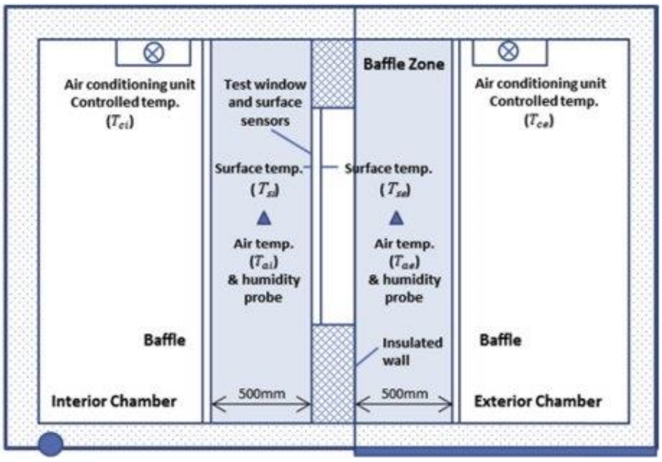


Figure 3. View of the system, the test specimen and sensors

1) External and internal surface temperature were measured by attaching 10 T type thermocouples (detector diameter < 0.3mm) on each side of the window unit [5], as is shown in Figure 2 (b), labelled as Tse (external surface temperature) and Tsi (internal surface temperature) shown in Figure 3, respectively.
2) Heat flux (q) measurement was measured by affixing heat flux meters (Hukesflux Type HFP01, thermal resistance <6.25×10-3 m-2K/W, measurement accuracy +/-5%) to the glass pane using a thin layer of thermal contact paste (Servisol, with thermal conductivity 0.77 W/mK) [4]. The thermal resistance of the heat flux meters is low enough so that the perturbation effect of the surface heat flow by positioning the heat flux meter can be negligible.
3) Air temperature (labelled as Tae and Tai showed in Figure 3) and humidity in the two baffles spaces were measured by positioning two temperature and humidity probes CS215 (accuracy +/-0.4℃ for temperature and +/-2% for humidity) closing to the window
4) Air velocities within the baffle zone were monitored by two hot wire air velocity sensors (testo 425, with measurement accuracy +/- 0.03m/s).

All of the thermocouples, heat flux meters and temperature and humidity probes were connected to a 24-channel data logger DT85, and the data were logged at 1-minute intervals.

Additionally, the Spectrometer USB2000+UV-VIS (Signal-to-noise ratio: 250:1 (at full signal), resolution: 0.1-10nm varies by configuration) was used to measure the spectral transmittance of each PV glazing window unit, and data were output by OceanView Spectrometer Operating Software.

2.3. Measurement procedure and data acquisition
Before the test, the instrumentation such as thermocouples was calibrated. At the beginning of the test, the relative humidity in the interior room was set at 30% to avoid condensation. The measured wind speed was less than 0.3m/s to represent that natural convection prevails [5]. During the test, a sufficient duration (i.e., over 72 hours) was assigned, in order to stabilise the environmental conditions in the test rooms and the heat flow through the window for each scenario, and then the measured data over a further period of 48 hours were used for analysis.

Since heat transfer between the two glass panes of the PV glazing unit is affected by both mean temperature and the temperature difference, two groups of tests containing 6 scenarios were undertaken as depicted in Table 1: group (a) has three scenarios with same temperature difference of 15 ºC, while mean temperature was controlled as 5, 10 and 15 ºC, respectively; group (b) has another three scenarios with the same mean temperature of 10 ºC, and the temperature difference was set up to be 10, 15, and 30 ºC, respectively.

Table 1. The arrangement of mean temperature and surface temperature difference for glazing systems.

Group	**(a) Same Temperature Difference**			**(b) Same Mean Temperature**		
Scenario	1	2	3	4	5	6
Mean temperature (T_{si} +T_{se})/2 ºC	5	10	15	10	10	10
Temperature difference (T_{si} -T_{se}) ºC	15	15	15	10	15	20

2.4 Analysis of the data

Based on the measured glazing surface temperatures (Tsi and Tse) and heat flux (q) in the experiments, Data was analysed by average method [4], and the thermal resistance of the glazing system was calculated by using Equation (1):

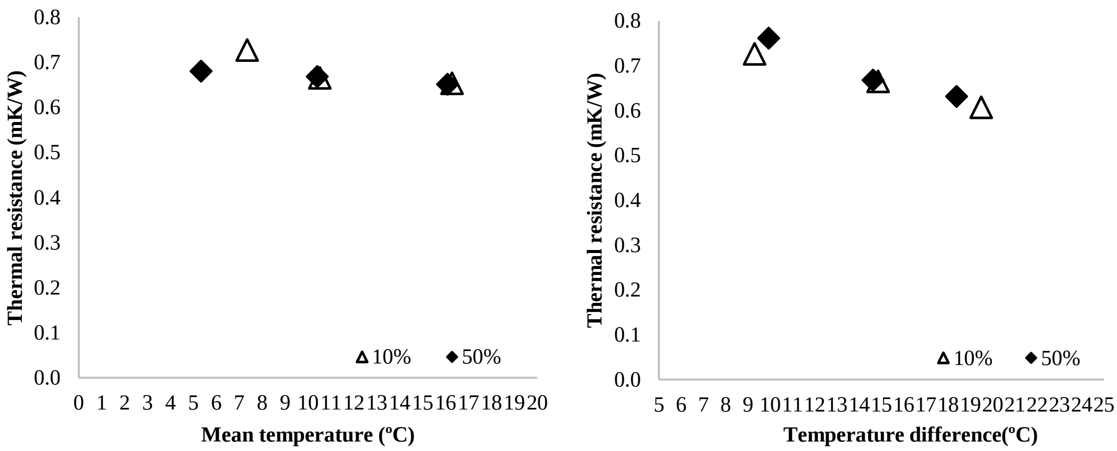
$$R_T = \frac{\sum_{j=1}^{n}(T_{sij}-T_{sej})}{\sum_{j=1}^{n} q_j} \quad (1)$$

Where, the index j enumerates the individual measurement. The heat transmittance, U, can be obtained by using the calculated thermal resistance RT and the empirical values determined according to EN673[6].

3. Measurement results and discussion

3.1. Thermal resistance under varying temperature conditions

According to the surface temperatures and heat flux of each CdTe PV glazing unit (with the transparency of 10% and 50%) tested under the first three scenarios, the corresponding thermal resistance was calculated, and shown in Figure 4 (a). In these scenarios, the temperature difference between the interior and exterior surfaces of the PV glazing unit was controlled at constant 15 ºC. As can be seen, with the increase of mean temperature difference from 5 ºC to 15 ºC, the calculated thermal resistance is slighting decreasing from approximately 0.68 to 0.65 (i.e., difference of 3%) for 50% transparency PV glazing. Although there is a deviation caused by experimental errors, the tendency of that for 10% transparency PV glazing is similar to the 50% one.



(a) Same temperature difference (b) Same mean temperature

Figure 4. Calculated thermal resistance under the six scenarios of 2 groups

Figure 4(b) shows the relationship between thermal resistance and temperature difference, in which, a constant mean temperature of 10 ºC across each glazing system was kept, within the three scenarios in the group (b). Increasing the mean temperature from 10ºC to 20ºC leads to a decrease of the thermal resistance by up to 13%. To sum up, compared with temperature difference, the mean temperature has a more significant influence on the thermal resistance of these PV glazing systems.

3.2. U-values of semi-transparent CdTe PV window units

Based on the standard boundary conditions from EN 673[6], where the temperature difference between two glazing panes is 15 ºC, and the average glazing pane temperature is 10 ºC, the overall heat transfer of the glazing system is calculated, and U-value is presented in Table 2. It can be seen that the experiment almost restored the standard conditions, and the corresponding U-value was calculated as 1.673 for CdTe PV glazing unit with 10% transparency, while 1.666 for that with 50% transparency. This means that increasing covered area with solar cells might improve heat transfer.

Table 2. U-value calculation under standard boundary conditions simulated in the experiment

CdTe Transparency	Target Temp. diff (ºC)	Target mean temp. (ºC)	Cold side surface temp. (ºC)	Hot side surface temp. (ºC)	Temp. diff in test (ºC)	Mean temp. in test (ºC)	U-value (W/Km)
10%	15	10	3.09	17.95	14.86	10.15	1.673
50%	15	10	3.10	17.72	14.62	10.41	1.666

3.3. Spectral transmittance of CdTe PV window units

The spectral transmittance within the visible spectrum (380-780nm) of CdTe PV window unit has been measured, and results are shown in Figure 5, which is labelled as CdTe_10% for 10% transparency, and CdTe_50% for the one with the transparency of 50%. It can be seen that the peak transmittance of CdTe_50% is 30.7% at the wavelength around 610 nm, while the transmittance of CdTe_50% is no more than 5% without apparent peak value.

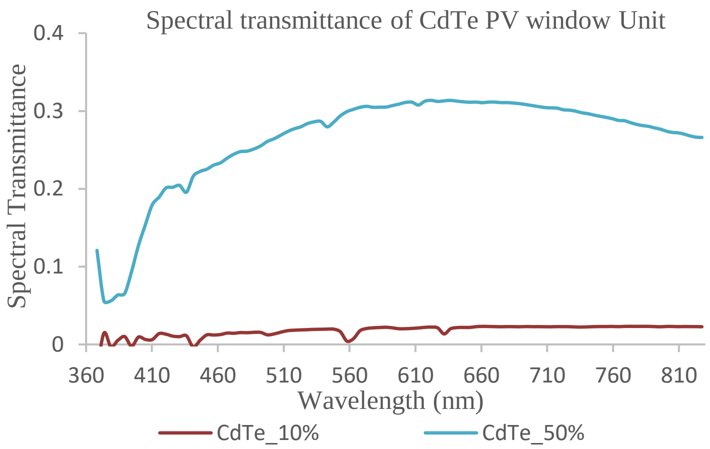


Figure 5. The spectral transmittance of CdTe PV window unit with 10% and 50% transparency

4. Economic analysis

Compared with normal double-glazing unit without low-e coated, the studied CdTe PV windows have similar U-value, as is shown in Table 3. The ones with low-e coated have lower U-value. For normal double glazing listed in the table, the price is ranging from £154 to £579 per m2 depending on the technologies they applied. CdTe technologies have the potential to achieve low cost through combing sufficient efficiency with lower module area cost. Additionally, compared with crystalline silicon modules, CdTe PV modules experience can increase their energy output by 5-9% annually[2]. The expected PV systems are between 25–30 years, CdTe PV modules can either be recycled or disposed of, when they reached their end-of-life. A CdTe PV recycling results in approximately 95% of semiconductor material recovery, and 90% of the glass can be reused[7].

Table 3. Introduction about current commercial window manufacture and products

Manufacture	**Pilkington**	
Product Name	Pilkington K Glass™ Range	Pilkington Optitherm™ S1 Plus double IGUs
Structure	Outer pane (4mm) + air space (16mm, Argon-filled 90%) + inner pane (4mm)	
Outer pane	Pilkington Optiwhite™ (low-iron extra clear float glass	Pilkington Optifloat™ Clear (float glass)

Inner pane	Pilkington K Glass™ (low-emissivity coated thermal glass, $\varepsilon = 0.16$)	Pilkington Optitherm™ S1 Plus (low-emissivity coated thermal glass, $\varepsilon = 0.013$)
U-value (W/m²K)	1.2-1.5	1.0
Manufacture	**WALSHSGLASS**	
Product Name	Twin Seal IGUs clear	Pilkington Optitherm™ S1 Plus double IGUs
Structure	Outer pane (6mm) + air space (12mm, air or argon-filled) + inner pane (6mm)	
Outer pane	Float glazing	Float glazing
Inner pane	Float glazing	Float glazing
U-value (W/m²K)	2.7 with air filled 2.6 with argon filled	1.9 with air filled 1.6 with argon filled
Manufacture	**VENTA WINDOW**	
Product Name	Free combination outside opening windows	
Structure	Outer pane (4mm) + air space (16mm, Argon-filled) + inner pane (4mm)	
Outer pane	Clear glazing	
Inner pane	Low-e glazing	
U-value (W/m²K)	1.3	

5. Conclusion

The CdTe window units with 10% and 50% transparency were investigated, respectively, by experimental measurement. Based on a series of standard, comprehensive assessment methods were developed in a controllable climate chamber. Both thermal (e.g., surface temperature, heat flux) and optical properties (e.g., spectral transmittance) were discussed. Results show that CdTe PV has a similar U-value of approximately 1.6, which is similar as the normal double glazing in the current market, and varying the temperature difference between the two surfaces of window unit has a more significant effect on thermal resistant than changing its mean temperature. Further studies about its application in the building will be conducted, including energy consumption, visual comfort and life cycle analysis.

Acknowledgement

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