Theoreticanalysisandexperimental evaluation of the spectrum transmission coefficient of a multilayer photovoltaic vacuum glazing

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Abstract

This paper introduces an innovative thin film PV vacuum glazing (PV-VG) technology. In addition to electricity generation, the PV-VG glazing can also reduce heat loss from the building in winter and reduce heat gain in summer. In building integrated photovoltaics application, optical characterization of the PV glazing is important in determining the solar ray transmission and thermal transfer process of the glazing. This paper discusses the optical properties of the PV-VG glazing by considering the different layers of the glazing unit that includes a self-cleaning glass, a thin film PV glass and a low-e vacuum glazing. Based on the optical transfer matrix, the transmission coefficients of different film layers were deduced. The theoretical calculations were then validated against the transmission coefficient experiment of the PV-VG using an EDTM SS2450 Solar Spectrum Meter. The calculation error of the transmission coefficient of the single-layer glazing is generally within 5%, the calculation error of the transmission coefficient of the integrated PV-VG glazing is about 6%. The results show that the average visible light transmission coefficient, the average infrared light transmission coefficient and the overall transmission coefficient of PV-VG glazing are 19%, 16% and 12%, respectively. The study is important to optimize the visible light transmission of the PV-VG glazing; the optical model obtained above lays a solid foundation for further study of transmission coefficient analysis of different functional coating of PV-VG glazing.

Keywords: photovoltaic vacuum glazing; transmission coefficient; full spectrum; transfer matrix

1. INTRODUCTION

Among the total energy consumption in the world, buildings are responsible for about 40% of total world energy consumption [1–4] and glazing in buildings is largely related to this. In order to reduce energy consumption and reduce carbon emission, a lot of attempts have been made to develop low-cost, high-efficient and environmentally friendly building components [5, 6]. Therefore, building integrated photovoltaics (BIPV) has developed rapidly. BIPV is the perfect combination of photovoltaic technology and building, it is the best installation method of photovoltaic power generation system widely used in cities and can effectively reduce the pressure of the public grid [7]. The combination of traditional photovoltaic modules and buildings can only meet the needs...
of daily electricity consumption. However, due to its poor thermal performance, i.e. high heat transfer coefficient $U$ between 4–5 W/m²K, the PV glazing contributes to high heat loss of a building. To overcome this, thin film PV glass is normally installed in a building within a double-glazing unit, its $U$-value ranging between $\sim$1.6 to 2.5 W/m²K, which depends on the air gap between the glass and the type of gas used in the gap.

Vacuum glazing is an innovative glazing technology that can achieve a low $U$-value between 0.82–1.2 W/m²K. Meanwhile, with low-emissivity coating, the $U$-value of vacuum glazing can be further reduced to less than 0.6 W/m²K that implies excellent heat insulating property [8, 9]. In recent years, researchers have shown interest in the study of PV glazing and vacuum glazing technology. Among them are a group of researchers from China [10] having proposed an integration between a thin film PV glazing with a vacuum glazing. The glazing prototype was designed and manufactured in such a way that a lamination layer was sandwiched between the thin film PV glass and a vacuum glazing panel, both are independently manufactured. According to the researchers, although semi-transparent photovoltaic windows can generate electricity in situ, they also increase the cooling load of buildings significantly due to the waste heat as a byproduct. Experiment has been conducted and the results have indicated that the prototype can not only generate electricity but also help reduce the cooling load as well as improve the indoor thermal comfort. Recently, researchers [11] investigated a combined semi-transparent multicrystalline PV vacuum glazing (PV-VG). In their research, both thermal and electrical performances have been investigated. They have found that the combination of multicrystalline PV cells with vacuum glazing provide low overall heat transfer coefficient, reduces solar heat gain, generates clean electricity and allows comfortable daylight.

The combined PV and vacuum glazing is very challenging to manufacture. It lies in the fact that transparency intrinsically conflicts with the concept of photonic absorption. Under the influence of solar radiation, the PV layer absorbs a fraction of the incoming photons and converts them into useful electrical power; meanwhile, its transparency indicates the percentage of transmitted photons through the glazing. The transmission coefficient of PV-VG glazing mainly depends on PV glass, the traditional way to increase the PV glass transmission coefficient is by using AR film. However, the result of using AR film is that the total thickness of the glazing, the weight of the glazing window increases [12]. Husain et al. analyzed the transmission coefficients of eight different photovoltaic materials. There is a certain contradiction between the power generation efficiency and the transmission coefficient of photovoltaic materials (e.g. the transmission coefficient of the thin film PV glass increases while its power generation efficiency decreases). [13–15]

From previous studies, it can be found that it is difficult to achieve a cost-effective photovoltaic vacuum glass glazing that has both satisfactory transmission coefficient and high power generation efficiency. Therefore, this paper introduces an innovative multilayer thin film PV-VG glazing with multi-functions and high comprehensive efficiency. The design of the PV-VG glazing is discussed in Section 2. The main aim of this paper is to analyze the transmission coefficient of the different layers of the PV-VG in different range of wavelengths in the full spectrum. The study is important to optimize the visible light transmission and improve power generation efficiency of the PV-VG glazing. The expected results will provide a valuable reference for the future development of the multilayer PV-VG glazing [10].

2. METHODOLOGY

2.1. The structure of the thin film PV-VG
The basic structure of PV-VG glazing is shown in Figure 1. The PV-VG glazing consists of the following layers in order: a vacuum glazing element that is formed with two glass panes with a narrow vacuum gap, a thin film PV layer deposited on a glass, an EVA (ethyl vinyl acetate) layer and a self-cleaning coated glass. When the PV-VG glazing is imposed by solar radiation, a portion of solar radiation will be reflected while some will be transmitted through the different glazing layers depending on the transmission property of each layer. It is important to note that solar radiation comprises of electromagnetic waves of a wide spectrum; longer wavelengths have less energy (for instance infrared) than shorter ones, such as visible light or UV. Crystalline silicon cells are only sensitive for wavelengths between 0.3 μm and 1.1 μm. Therefore, the polycrystalline thin film PV cells in the designed PV-VG glazing are transparent to the wavelengths beyond 1.1 μm, and the electrical performance of the thin film PV cells is not sensitive to the wavelengths beyond 1.1 μm.

2.2. Theoretical modeling
The propagation of solar radiation through complex glazing systems has been discussed by Baenas and Machado in 2009. They presented a method for the systematic formulation of the equations for determination of the optical coefficients of a glazing system [16]. The closed analytical expressions of short-wave energy magnitudes that characterize it (transmission coefficient, reflectivity, absorptivity) of a glazing system were derived by applying classical traditional matrices [17–19].
The parameters are defined as: $T$ - transmittance, $R_f$ - front and $R_b$ - back reflectances, $\tau_{m}$ - transmission coefficient of the $m$-th substrate, $(t_n, r_{nf}, r_{nb})$ - the transmission coefficient, front and back reflectivity of the $n$-th component with reflectivity.

The transfer matrix of the glazing system, $M_{1,h}$, $h$ being the number of components, is obtained as the ordered product of the transfer matrix of each optical component. This matrix relates the external (f-front) and internal (b-back) outgoing irradiance ($Q$) and radiosity ($P$) pairs of all the optical system as,

$$(Q_{1,f}, P_{1,f}) = M_{1,h} (Q_{h,b}, P_{h,b}), \quad M_{1,h} = M_{d,1}M_{d,2} \cdots M_{d,h}$$

where $d$ represents the type of component following Table 1, and the reflectivity, transmission coefficient and transfer matrix of different components are unique.

In Figure 2, from an unitary incident irradiance, the symmetrical transmission $T$ and reflectances ($R_f, R_b$) of the optical system are obtained as [16]:

$$(1, 0)^T = M_{1,h} (1, T)^T, \quad (0, T)^T = M_{1,h} (0, 1)^T$$

Equation (2) can be rewritten as transfer matrix for equivalent optical interface of the glazing system ($T \neq 0$).

$$M_{1,h} = \left( \begin{array}{cc} m_{11} & m_{12} \\ m_{21} & m_{22} \end{array} \right) = \frac{1}{T} \left( \begin{array}{cc} -R_b & 1 \\ T^2 - R_f R_b & R_f \end{array} \right).$$

Therefore, from the above matrix elements, the relations between the glazing system energy coefficients ($T$, $R_f$, $R_b$) and the coefficients describing the glazing components ($t_n$, $r_{nf}$, $r_{nb}$) or ($\tau_m$, 0, 0) can be obtained:

$$T = m_{12}^{-1}$$

$$R_f = m_{12}^{-1} m_{22}$$

$$R_b = m_{21} m_{12}^{-1}.$$
Sensitive to the wavelength. Therefore, the transmission \( T \) will be expressed in three different light bands: ultraviolet light (350 nm−380 nm, \( T_{\text{UV}} \)), visible light (380 nm−780 nm, \( T_{\text{visible}} \)) and infrared light (780 nm−1700 nm, \( T_{\text{IR}} \)).

Table 2 presents some transmissivities of films (self-cleaning film, PV film, low-e film) that are obtained with the simulation of Zemax, as we did in reference [26]. These transmissivities will be applied in the calculation.

3. ANALYSIS OF THE TRANSMISSION COEFFICIENT OF DIFFERENT STRUCTURES

For comparing the characteristics of different optical structures, four types of system are analyzed.

3.1. Self-cleaning coated glass

The transmission coefficient and reflectivity of each layer of the self-cleaning coated glass is shown in Figure 3.

The corresponding equation system is obtained from expressions (1), (2) and Table 1, from which the transfer matrix of the self-cleaning coated glass is given by:

\[
M_{1,3} = M_{A_{s},1}M_{S1,2}M_{F1,3}M_{A_{c},4}M_{S3,5}M_{G_{i},6}. \tag{7}
\]

The transmission coefficients and reflectivities for each component are as follows: \((t_1, r_{1f}, r_{1b})\) for the self-cleaning coating 'Ac', \((r_{s1}, 0, 0)\) for the glass substrate 'S1', \((1-r_{s1}, r_{s1}, r_{s1})\) for the glass back interface 'Gi'. The average transmission coefficient of the self-cleaning coated glass from Equation (4) can be written as:

\[
T_{SC}(\lambda) = \frac{t_1(\lambda)\tau_1(1-r_{s1})}{1-r_{s1}r_{1b}(\lambda)\tau_{s1}^2} \tag{8}
\]

where \( \lambda \) is the wavelength of the incident light. The transmission coefficient of self-cleaning glass can be separated into three bands

\[
T_{SC-UV} = \sum_{\lambda=350nm}^{380nm} \frac{t_1(\lambda)\tau_1(1-r_{s1})}{1-r_{s1}r_{1b}(\lambda)\tau_{s1}^2}
\]

\[
T_{SC-Visible} = \sum_{\lambda=380nm}^{780nm} \frac{t_1(\lambda)\tau_1(1-r_{s1})}{1-r_{s1}r_{1b}(\lambda)\tau_{s1}^2} \tag{9}
\]

\[
T_{SC-IR} = \sum_{\lambda=780nm}^{1700nm} \frac{t_1(\lambda)\tau_1(1-r_{s1})}{1-r_{s1}r_{1b}(\lambda)\tau_{s1}^2}
\]

3.2. PV glass

The transmission coefficient and reflectivity of each component of the PV glass is shown in Figure 4.

The corresponding equation system is obtained from expressions (1), (2) and Table 1, from which the transfer matrix of the PV glass is given by:

\[
M_{1,8} = M_{A_{c},1}M_{S2,2}M_{F2,3}M_{A_{c},4}M_{S3,5}M_{G_{i},6}. \tag{10}
\]

The transmission coefficients and reflectivities for each component are as follows: \((1-r_{s2}, r_{s2}, r_{s2})\) for the glass front interface 'Ai', \((r_{s2}, 0, 0)\) for the glass substrate 'S2', \((r_{s2}, 0, 0)\) for the glass substrate 'S3', \((r_{PV}, 0, 0)\) for the PV film (no reflectivity) 'Fn', \((r_{2f}, r_{2f}, r_{2b})\) for the PV coating 'Ac', \((1-r_{s3}, r_{s3}, r_{s3})\) for the glass back interface 'Gi', \(r_{s2} = r_{s3}\). The average transmission coefficient
of the PV glass from Equation (4) can be written as:

\[
T_{PV}(\lambda) = \frac{t_2(\lambda) \tau_{s2}^{PV}(1 - r_{s2})^2}{A}
\]

\[
A = 1 + t_2^{PV}r_{s2}^{2}r_{s2}\tau_{s2}^{PV} - t_2^{PV}r_{s2}\tau_{s2}^{PV} - r_{s2}\tau_{s2}^{PV}
\]

(11)

where \(\lambda\) is the wavelength of the incident light. The transmission coefficient of self-cleaning glass can be separated into three bands

\[
T_{PV}(\lambda) = \begin{cases} 
T_{PV-UV} = \sum_{\lambda=350nm}^{380nm} \frac{t_2(\lambda) \tau_{s2}^{PV}(1 - r_{s2})^2}{A} \\
T_{PV-Visible} = \sum_{\lambda=380nm}^{780nm} \frac{t_2(\lambda) \tau_{s2}^{PV}(1 - r_{s2})^2}{A} \\
T_{PV-IR} = \sum_{\lambda=780nm}^{1700nm} \frac{t_2(\lambda) \tau_{s2}^{PV}(1 - r_{s2})^2}{A} 
\end{cases}
\]

(12)

3.3. Low-e coated glass

The transmission coefficient and reflectivity of each component of the low-e coated glazing as shown in Figure 5.

The corresponding equation system is obtained from expressions (1), (2) and Table 1, from which the transfer matrix of the low-e coated glass is given by:

\[
M_{1,3} = M_{A_{1,1}}M_{S_{1,2}}M_{F_{n1,2}}M_{S_{2,4}}M_{F_{n2,4}}M_{A_{2,6}}M_{S_{3,7}}M_{G_{8,10}}M_{G_{11,11}}.
\]

(16)

The transmission coefficients and reflectivities for each component are as follows: \((t_1, r_{1f}, r_{1b})\) for the self-cleaning coating ‘A1’, \((t_{s1}, 0, 0)\) for the glass substrate ‘S1’, \((t_{EVA}, 0, 0)\) for the polymer film ‘Fn1’, \((t_{s2}, 0, 0)\) for the glass substrate ‘S2’, \((t_{PV}, 0, 0)\) for the polymer film ‘Fn2’, \((t_{s3}, 0, 0)\) for the PV coating ‘A2’, \((t_{s3}, 0, 0)\) for the glass substrate ‘S3’, the gas space without optical function for the ‘G’, \((t_{s4}, r_{s4}, r_{s5})\) for the low-e coating ‘A3’, \((t_{s5}, 0, 0)\) for the glass substrate ‘S4’, \((1 - r_{s4}, r_{s5}, r_{s6})\) for the glazing back glass interface ‘G’.

The average transmission coefficient of the PV-VG glazing from Equation (4) can be written as:

\[
T_{low-e}(\lambda) = \frac{t_3(\lambda) \tau_{s3} \left(1 - r_{s4}\right) \left(1 - r_{s4}\right)}{1 - r_{s4}r_{s6} \tau_{s4}^2}
\]

(14)

where \(\lambda\) is the wavelength of the incident light. The transmission coefficient of self-cleaning glass can be separated into three bands

\[
T_{low-e}(\lambda) = \begin{cases} 
T_{low-e-UV} = \sum_{\lambda=350nm}^{380nm} t_3(\lambda) \tau_{s4} \left(1 - r_{s4}\right) \\
T_{low-e-Visible} = \sum_{\lambda=380nm}^{780nm} t_3(\lambda) \tau_{s4} \left(1 - r_{s4}\right) \\
T_{low-e-IR} = \sum_{\lambda=780nm}^{1700nm} t_3(\lambda) \tau_{s4} \left(1 - r_{s4}\right)
\end{cases}
\]

(15)

3.4. PV-VG glazing

The transmission coefficient and reflectivity of each component of the PV-VG glazing as shown in Figure 6.

The corresponding equation system is obtained from expressions (1), (2) and Table 1, from which the transfer matrix of the PV-VG glazing is given by:

\[
M_{1,1} = M_{A_{1,1}}M_{S_{1,2}}M_{F_{n1,2}}M_{S_{2,4}}M_{F_{n2,4}}M_{A_{2,6}}M_{S_{3,7}}M_{G_{8,10}}M_{G_{11,11}}.
\]

(16)

The transmission coefficients and reflectivities for each component are as follows: \((t_1, r_{1f}, r_{1b})\) for the self-cleaning coating ‘A1’, \((t_{s1}, 0, 0)\) for the glass substrate ‘S1’, \((t_{EVA}, 0, 0)\) for the polymer film ‘Fn1’, \((t_{s2}, 0, 0)\) for the glass substrate ‘S2’, \((t_{PV}, 0, 0)\) for the polymer film ‘Fn2’, \((t_{s3}, 0, 0)\) for the PV coating ‘A2’, \((t_{s3}, 0, 0)\) for the glass substrate ‘S3’, the gas space without optical function for the ‘G’, \((t_{s4}, r_{s4}, r_{s5})\) for the low-e coating ‘A3’, \((t_{s5}, 0, 0)\) for the glass substrate ‘S4’, \((1 - r_{s4}, r_{s5}, r_{s6})\) for the glazing back glass interface ‘G’.

The average transmission coefficient of the PV-VG glazing from Equation (4) can be written as:

\[
T_{PV-VG}(\lambda) = \frac{t_1(\lambda) t_2(\lambda) t_3(\lambda) \tau_{EVA} \tau_{PV} \tau_{s1} \tau_{s2}^2 \tau_{s4} \left(1 - r_{s3}\right) \left(1 - r_{s4}\right)}{\Delta}
\]

\[
\Delta = 1 - r_{s4} \tau_{s4} \tau_{EVA} \tau_{PV} r_{s2} - 2K_{t_{s4} r_{s4}^2}
\]

(17)
ties and reflectivities of other optical components are presented as: 

\[ T_{PV-VG} (\lambda) = \begin{cases} 
\frac{380nm}{\lambda=350nm} T_{PV-VG-UV} \\
\frac{780nm}{\lambda=380nm} T_{PV-VG-Visible} \\
\frac{1700nm}{\lambda=780nm} T_{PV-VG-IR} 
\end{cases} \]

\[ T_{PV-VG} (\lambda) = \frac{\sum_{\lambda=350nm}^{380nm} t_1(\lambda) t_2(\lambda) t_3(\lambda) t_4(\lambda) t_{EVA} t_{PV-VG} t_{UV} t_{PV-VG} t_{Visible} t_{PV-VG} t_{IR}}{\Delta} \]

\[ T_{PV-VG} (\lambda) = \frac{\sum_{\lambda=380nm}^{780nm} t_1(\lambda) t_2(\lambda) t_3(\lambda) t_4(\lambda) t_{EVA} t_{PV-VG} t_{UV} t_{PV-VG} t_{Visible} t_{PV-VG} t_{IR}}{\Delta} \]

\[ T_{PV-VG} (\lambda) = \frac{\sum_{\lambda=780nm}^{1700nm} t_1(\lambda) t_2(\lambda) t_3(\lambda) t_4(\lambda) t_{EVA} t_{PV-VG} t_{UV} t_{PV-VG} t_{Visible} t_{PV-VG} t_{IR}}{\Delta} \]

\[ T_{PV-VG} (\lambda) = \frac{\sum_{\lambda=1700nm}^{350nm} t_1(\lambda) t_2(\lambda) t_3(\lambda) t_4(\lambda) t_{EVA} t_{PV-VG} t_{UV} t_{PV-VG} t_{Visible} t_{PV-VG} t_{IR}}{\Delta} \] (18)

where \( \lambda \) is the wavelength, \( T_{PV-VG glazing} (\lambda) \) is the average transmission coefficient of PV-VG glazing in the band of 350 nm – 1700 nm, which includes the average transmission coefficient of the three bands.

4. SIMULATIONS AND EXPERIMENTAL RESULTS

4.1. Simulations

The transmission coefficients of the four optical structures discussed in Section 3 are simulated by the Equations (9), (12), (15) and (18). Except the transmissivities in Table 2, the transmissivities and reflectivities of other optical components are presented as: \( r_{s1} = 0.911, r_{s4} = 0.041, r_{1b} = 0.033, r_{2d} = r_{3d} = 0.925, r_{3f} = 0.207, r_{2b} = 0.224, r_{s4} = 0.936, r_{4b} = 0.028, r_{3b} = 0.023. \) Table 3 presents the simulation results.

4.2. Experimental results

A lab-scale thin film PV vacuum glazing prototype was manufactured via integration of different layers of glazing using an autoclave, as shown in Figure 7a. The prototype comprises of a layer of 400 mm × 400 mm × 2 mm self-cleaning coated glass laminated and attached by EVA layer onto a unit of 400 mm × 400 mm × 6.4 mm thin film PV glass (TCO + 750 nm μc-Si film + TCO). The integrated self-cleaning coated glass and thin film PV glass was then attached to a vacuum glazing including a 400 mm × 400 mm × 2 mm low-e coated glass. The vacuum glazing consists of TCO glass and low-e coated glass with a vacuum gap of 0.3 mm. The integration process of the different layers of glazing was performed using an autoclave at optimum temperature and pressure. This is important to ensure that the vacuum glazing is not negatively affected during the process.

Before the complete PV-VG glazing (self-cleaning glass + PV glass + vacuum glazing) was manufactured at Hanergy Group, the optical properties of the individual components of the PV-VG glazing, the combination of a self-cleaning glass and PV glass were first measured using Brolight BIM-6001 fiber optic spectrophotometer with a test range of 300 nm–1100 nm. After being assembled, the complete PV-VG was also manufactured using the same spectrophotometer. The measured transmission coefficients with respect to the wavelength are given in Figure 8.

The transmission coefficients of the PV-VG glazing sample made by Hanergy Group measured by the optic spectrophotometer are \( T_{PV-VG-visible} = 16\% \) and \( T_{PV-VG}(780-1100) = 42\% \), while the transmission coefficients of the combination of a self-cleaning glass and PV glass are 19% and 48%, respectively.

The deviation between calculated and experimental results is about 3% for the PV-VG glazing and 5% for the combination of a self-cleaning glass and PV glass.

As shown in Figure 7b, testing of the second sample PV-VG glazing was conducted at the University of Nottingham using SS2450 Solar Spectrum Meter of EDTM. The results of spectral transmission coefficient test are listed in Table 4.
The laboratory measured $T_{sc}(380-1700)$ of the self-cleaning coated glass is 84%, close to about 87% reported in the literature [27]. $T_{low-e}(380-1700)$ of the sample low-e coated glass is 76%, compared to about 80% given in the literature [28].

Comparing the transmission coefficient in Tables 3 and 4, we can find that the experimental results are well agreed with the theoretical calculation. The error of the transmission coefficient of single-layer glazing is generally within 5%. Because the transmission coefficient of multi-layer glazing system is the product of the transmission coefficients of all glazing layers, the calculation error of the transmission coefficient of the integrated PV-VG glazing is about 13%, the difference between theoretical data and test data is small.

From Table 4, it can be found that the $T_{PV}(350-1700)$ of the PV glass is about 18%, which is about 2% higher than transmission coefficient of the PV glass mentioned by Martín-Chivelet [29]. The transmission coefficient of the PV glass is higher than that of PV-VG glazing. Compared with the transmission coefficient of PV glass, $T_{PV-VG(380-780)}$ of PV-VG is 7% lower, and $T_{PV-VG(780-1700)}$ is 13% lower. The $T_{PV-VG(380-780)}$ of the PV-VG with multi-films is 19%, which indicates that PV-VG glazing allows daylight.

4.3. Testing the power generation efficiency of the PV-VG glazing

The output voltage and current at maximum power point of the PV glass in the sample PV-VG glazing were also measured under
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different light intensities and presented in Table 5. The average output voltage and current of PV-VG glazing is 53.30 V and 197.5 mA, so the electric power generation of PV-VG glazing is 10.5 W. In comparison, the average output voltage and current of PV glass is 37.10 V and 131.8 mA. The electric power generation of PV glass is 4.9 W. The enhanced power generation of PV glass in the PV-VG glazing is because the multilayer thin film PV vacuum structures and the low-e glass film which one reflects back the infrared ray to PV layer [26]. The low-e glass in PV-VG glazing reflects light onto the thin film PV layer.

Table 5. The output voltage and current at maximum power point of PV-VG glazing and PV glass under different light intensities.

| Light intensity (W/m²) | PV-VG glazing Voltage (V) | PV-VG glazing Electric current (mA) | PV glass Voltage (V) | PV glass Electric current (mA) |
|------------------------|---------------------------|------------------------------------|---------------------|------------------------------|
|                        | Voltage (V)               | Electric current (mA)               | Voltage (V)         | Electric current (mA)        |
| 800                    | 52.97                     | 1947                               | 35.78               | 1286                         |
| 810                    | 52.78                     | 1959                               | 36.18               | 1306                         |
| 820                    | 53.18                     | 1973                               | 36.74               | 1310                         |
| 830                    | 53.43                     | 1974                               | 37.52               | 1327                         |
| 840                    | 53.46                     | 1991                               | 37.88               | 1343                         |
| 850                    | 53.78                     | 2007                               | 38.23               | 1338                         |
| average                | 53.30                     | 1975                               | 37.10               | 1318                         |

5. CONCLUSION

Design of a multilayer thin film photovoltaics vacuum glazing (PV-VG) with multi-functions has been described. The optical transfer matrix has been adopted to establish an analysis model to calculate the spectral transmission coefficient of the PV-VG glazing and the contribution of its component layers. Two samples of PV-VG glazing have been prepared in China and UK respectively through a joint Innovate UK China Bridge project. The measured transmission coefficients have been used to validate the analytical model. The deviation between them is about 6% for the PV-VG glazing and within 5% for its functional component glass. The optical model obtained above lays a solid foundation for further study of transmission coefficient analysis of different functional coatings of PV-VG glazing.

The PV-VG glazing mentioned herein contains a self-cleaning coated glass and low-e coated vacuum glazing. The transmission coefficient $T_{(350-1700)}$ of the integrated PV-VG glazing is 12%, lower than the $T_{(350-1700)}$ of PV glass by absolute 6%. PV-VG glazing contains self-cleaning coated glass, which absorbs ultraviolet light to complete self-cleaning and extend the service life of thin film photovoltaic cells. In addition, the PV-VG glazing contains a low-e coated glass, which can effectively improve the power generation efficiency by reflecting the transmitted radiation back to the PV cell.

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