Analysis of the Overall Transmittance of Self-cleaning Photovoltaic Glazing

Jiachen Cui\textsuperscript{1,2, a}, Qinghua Lv\textsuperscript{1,2, b}, Hasila Jarimi\textsuperscript{3}, Hui Lv\textsuperscript{1,2, *}, Chenben Yuan\textsuperscript{1,2}, Shijie Dong\textsuperscript{1,4}, Yuehong Su\textsuperscript{1,3} and Saffa Riffat\textsuperscript{1,3}

\textsuperscript{1}Hubei Collaborative Innovation Center for High-efficient Utilization of Solar Energy, Hubei, Wuhan, 430068, China
\textsuperscript{2}School of Science, Hubei University of Technology, Hubei, Wuhan, 430068, China
\textsuperscript{3}The Department of Architecture and Environment Build, Faculty of Engineering, University of Nottingham, University Park, and Nottingham NG7 2RD, UK
\textsuperscript{4}Hubei University of Economics, Hubei, Wuhan, 430205, China

*Corresponding author e-mail: lvh@aovenergy.com, a480682950@qq.com, blinsa080@126.com

Abstract. This paper provides a simple calculation method of multilayer glazing system based on transfer matrix method. A new self-cleaning photovoltaics (PV) modules technology is analyzed, which transmittance of self-cleaning PV glazing, the theoretical result was then validated against the transmittance experiment of the PV modules using a Spectrophotometer. The result shows that the average visible light transmittance of self-cleaning PV glazing is about 13%, the average infrared light transmittance of self-cleaning PV glazing is about 29%, and the overall average transmittance of self-cleaning PV glazing is about 21%.

1. Introduction
Transfer matrix method has been extensively studied in the literature of different methods [1, 2]. These methods are derived from the classical study of eigenmatrices that connect electromagnetic field elements to an interface and apply the method to thin films and laminated glass optical models [3]. The laminated glass optical models are based primarily on the separation of real optical glazing systems in optical elements (interfaces, glazing substrates, films and coatings), defined by transfer matrices that connect energy flows on both sides of the elements has been previously studied by Baenas and Machado, according to the classical transfer matrix method [4]. In many countries, the increasing energy consumption of commercial and residential buildings, and it has exceeded the needs of the transport and industrial sectors [5, 6]. Thus, in order to alleviate the energy problem, a lot of attempts have been made to develop low-cost, efficient and environmentally friendly building components [7, 8]. Therefore, PV technology has developed rapidly, and photovoltaic glazing has been widely used. PV glazing as an energy-saving and environmental-friendly building material, which has been regarded as one of the most advanced and cutting-edge representatives in building glazing [9, 10].

Because PV glazing directly used in the building, in order to enhance the visible light indoor lighting, the analysis of the transmittance is very important. Baenas and Machado [4] provided
theoretical developments broadening the scope of previous optical simulation models for multilayer glazing systems, the condition relating the symmetry of the transmittance of its optical components was studied. Chae et al.[11] started from optical measurement, building energy simulation was conducted to study the influence of optical characteristics on the overall energy performance of photovoltaic windows. This paper mainly studies the optical properties of the self-cleaning PV glazing, the transmission formula of the self-cleaning PV glazing is derived.

Figure 1. Basic structure of photovoltaic triple glazing

2. Theoretical Modeling

Although the definition of the transmission matrix is varied, all the forms are equivalent, resulting in the same algebraic relationship between the spectral reflectivity and transmission of the optical system elements [4]. In the most commonly used definition [12], the transmission matrix (M) is related to the external (f-front) and internal (b-back) irradiance (I) and luminosity (J). The transmission characteristics of solar radiation in parallel optical systems are analyzed, which avoids the purpose of solving optical equations related to incoherent positioning of short-wave radiation and describing energy characteristics by complex numerical methods for modeling of multilayer glazing system, sandwich glazing, and photovoltaic module [13]. Under this framework, Baenas and Machado applied the classical transfer matrix method [14] to give a closed analytical expression of the short-wave energy (transmittance, reflectivity, absorptivity). These expressions do not include angle-dependent optical properties [15, 18], light diffusion or shadow elements [18]. In the article Baenas and Machado [2] follow the definition convention given by Maestre [18], the relation between irradiance and radiosity was of the type. From the above definition, the explicit expression of the transfer matrix is:

$$M = \frac{1}{\tau_f \tau_b - \rho_f \rho_b} \begin{pmatrix} -\rho_b & 1 \\ \tau_f \tau_b - \rho_f \rho_b & \rho_f \end{pmatrix}, \quad U = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

(1)

Where the general asymmetric case $\tau_f \neq \tau_b$.

In the transfer matrix of a glazing system, $M_{1,n}$, $n$ is the number of system components, is obtained as the ordered product (front to back) of the transfer matrix of each optical component of the catalogue. This matrix relates the incoming and outgoing irradiance and radiosity pairs of the all optical system as [4],

$$\begin{pmatrix} I_{1,f} \\ J_{1,f} \end{pmatrix} = M_{1,n} \begin{pmatrix} I_{n,b} \\ J_{n,b} \end{pmatrix}, \quad M_{1,n} = M_{c,1} M_{c,2} \cdots M_{c,n}$$

(2)

$$M_{1,n} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \frac{1}{T} \begin{pmatrix} -R_b & 1 \\ T^2 - R_f R_b & R_f \end{pmatrix}$$

(3)
\[ T = m^{-1}_{12}, \quad R_i = m_{22}m^{-1}_{12}, \quad R_b = -m_{11}m^{-1}_{12} \quad (4) \]

The multilayer coatings photovoltaic glazing system applied here is based on the separation of a real optical glazing system in an optical component (interface, glazing substrate, film), which is defined by a transfer matrix that connects the short-wave energy fluxes (irradiance or incident energy) on each side of the component.

3. The Formula Derivation

**Table 1.** Catalogue of optical components and transfer matrices

| Component                  | Symbol | Transfer matrix | Matrix structure                        |
|----------------------------|--------|-----------------|------------------------------------------|
| Glazing air interface      | ]      | \[
\begin{pmatrix}
1-r_s & -r_s^2 & r_s \\
-1 & 1 & 0 \\
1-r_s & 0 & 1
\end{pmatrix}
\] | \[ M_1 = \begin{pmatrix} \rho_1 & \tau_s \\ \tau_s & \rho_1 \end{pmatrix} \] |
| Glazing substrate          | S      | \[
\begin{pmatrix}
0 & 1 \\
\tau_s & 0
\end{pmatrix}
\] | \[ M_s = \begin{pmatrix} \rho_s & \tau_s \\ \tau_s & \rho_s \end{pmatrix} \] |
| Air glazing coating        |        | \[
\begin{pmatrix}
1 & -r_{0f} \\
r_{0f} & 1
\end{pmatrix}
\] | \[ M_f = \begin{pmatrix} \rho_f & \tau_f \\ \tau_f & \rho_f \end{pmatrix} \] |
| Film (no reflectivity)     | ![+][   | \[
\begin{pmatrix}
0 & \rho_L \\
1 & 0
\end{pmatrix}
\] | \[ M_{f1} = \begin{pmatrix} \rho_{1L} & \tau_{1L} \\ \tau_{1L} & \rho_{1L} \end{pmatrix} \] |
| Film (with reflectivity)   | ![+](   | \[
\begin{pmatrix}
1-r_{1L} & -r_{1L}^2 & r_{1L} \\
-1 & 1 & 0 \\
1-r_{1L} & 0 & 1
\end{pmatrix}
\] | \[ M_{f2} = \begin{pmatrix} \rho_{2L} & \tau_{2L} \\ \tau_{2L} & \rho_{2L} \end{pmatrix} \] |

The transmissivity and reflectivities for each component see Fig. 2a, Fig. 2b.

![Schematics and notation for sandwich glazing system](image-url)
The transfer matrix of the self-cleaning glazing is given by:

\[ M_{1,3} = M_{1,1}M_{S,2}M_{S,3} \]  

(5)

\((r_f, r_b, t_f)\) for the glazing \(S\) front coating”, \((0,0,\tau_f)\) for the glazing sustrate”\(S\)”, \((r_s, \tau_s, t_s)\) for the glazing \(S\) back glazing”\)”. Therefore the energy coefficients of the self-cleaning glazing, from (4) can be written as:

\[ T = \frac{t_f \tau_f (1-r_f)}{1-r_s \tau_s^2} \]

(6)

Where \(T\) is the transmittance of the overall Self-cleaning coated glazing.

The transfer matrix of the self-cleaning PV glazing is given by:

\[ M_{1,6} = M_{1,1}M_{S,2}M_{S,3}M_{1,4}M_{S,5}M_{S,6} \]  

(7)

\((r_f, r_b, t_f)\) for the glazing \(S_1\) front coating”, \((0,0,\tau_f)\) for the glazingsustrate”\(S_1\)”, EVA is a film with reflectivity, \((r_r, \tau_r, \tau_L)\) for the “) + (“, \((r_f, r_b, t_f)\) for the glazing \(S_2\) front coating”\)”, \(r_{sf} = r_{sb}\), \((r_s, \tau_s, t_s)\) for the glazing \(S_2\) back glazing”\)”, \((0,0,\tau_s)\) for the glazing sustrate”\(S_2\)”. Therefore the energy coefficients of the self-cleaning PV glazing, from (4) can be written as:

\[ T = \frac{t_f \tau_f \tau_1 \tau_2 \tau_L}{\Delta} \]

(8)

\[ \Delta = 1 - \tau^2_{1b}r_{1f} + \tau^2_{1f}r_{1b}r_{2f} - \tau^2_{r1}r_{1b}r_{1f}r_{2f} - r_{sf}r_{1f}r_{2f} + r_s \tau^2 \tau^2_{1f}r_{1b}r_{2f} \]

Where \(S_1\) is the Self-cleaning coated glazing, \(S_2\) is the PV glazing

4. Results and Discussion

A lab-scale thin film PV glazing prototype was manufactured via integration of different layers of glazing using an autoclave. The prototype comprises of a layer of 400 mm×400 mm×4 mm self-cleaning glazing laminated and attached by and EVA layer to a unit of 400mm×400mm×3.2mm thin film PV glazing (TCO+750nm μc-Si film+TCO).

![Figure 3. Experimental testing of PV’s transmittance](image-url)
In Fig.3(c), AS1: single-layer self-cleaning glazing; AS2: self-cleaning glazing + ultra-white glazing (AS film is a kind of self-cleaning film, which does not contact with bonding material POE); AS3: self-cleaning glazing + ultra-white glazing, AS film is in contact with bonding material POE. AS2, AS3, although they are two different ways of contact, there is no difference in the test results.

Table 2. Transmittance of different optical components

| Component                        | T_{uv} | T_{visible} | T_{solar} | T_{ir(780-1700)} | T_{ir(900-1000)} |
|----------------------------------|--------|-------------|-----------|------------------|------------------|
| Self-cleaning glazing            | 0      | 83%         | /         | /                | 81%              |
| Self-cleaning glazing+PV glazing | 0      | 13%         | 22%       | 29%              | 31%              |

As shown in Table 2, the transmittance of the Self-cleaning coated glazing is 83%, according to formula (7) in section 3, the transmission rate of self-cleaning PV glazing is about 87%, and both the theoretical and experimental results are found to be in a good agreement. The results in self-cleaning PV glazing gives, T_{visible}, T_{ir(780-1700)} and T_{ir(900-1000)} of 13%, 29%, and 31% respectively, according to formula (9) in section 3, the overall transmission rate of self-cleaning PV glazing is 24%. The test result shows that the overall average transmittance of self-cleaning PV glazing is about 21% in Table 2, there is a good fit between the theoretical result and the test result.

5. Conclusion

In this paper, a closed analytical expression of the overall transmittance of an optical model based on the transfer matrix method is presented. It has been used to derive the overall transmittance of self-cleaning glazing and self-cleaning PV glazing. The results of the optical model have been compared with those obtained from direct experimental determination of the transmittance of self-cleaning glazing and self-cleaning PV glazing, there are a good fit between the theoretical results and the test results. The test result shows that the overall average transmittance of self-cleaning PV glazing is about 21%. The model formulas and experimental results lay a solid foundation for further research on the transmission rate analysis and performance evaluation of photovoltaic sandwich glazing.

Acknowledgements

This work was supported by International Science & Technology Cooperation Program of China (No. 2016YFE0124300) in collaboration with Innovate UK.

References

[1] Centurioni, E. Generalized matrix method for calculation of internal light energy flux in mixed coherent and incoherent multilayers, Appl Opt. 44, (35) 2005., 7532-7539.
[2] Baenas, T., Machado, M. Optical simulation of laminated glazing, Proc glazing Performance Days 2009. Ed. GPD-Glaston Finland Oy, pp. 742-745.
[3] Epstein, L.I. The design of optical filters. J. Opt. Soc. Am. 1952, 42 (11), 806-810.
[4] Baenas, T., Machado, M. Optical model for multilayer glazing systems: application to laminated glazing and photovoltaic modules, Sol. Energy. 125 (2016), 256–266.
[5] Pérez-Lombard, L.; Ortiz, J.; Pout, C. A review on buildings energy consumption information, Energy Build. 40 (2008), 394-398.
[6] Nuria Martin-Chivelet. Comparative performance of Semi-Transparent PV modules and electrochromic windows for improving energy Efficiency in buildings, Energies. 11 (2018), 1526.
[7] Bojic M, Yik F, Leung W. Thermal insulation of cooled spaces in high rise residential buildings in Hong Kong, Energy Conves Manage. 43 (2002), 165-83.
[8] Cuce E, Young CH, Riffat SB. Performance investigation of heat insulation solar glazing for low-carbon buildings, Energy Conversion and Management. 88 (2014) 834-841.
[9] YZ Hou. Application of Photovoltaic Vacuum glazing in Building Energy Saving, Wall
[10] YQ Zhang. Development and Application of Integration of Structure and Function of PV glazing and Vacuum glazing Used for Architecture, The world of Building Materials. 04, (2017).

[11] Chae, Y.T., Kim, J., Park, H., Shin, B. Building energy performance evaluation of building integrated photovoltaic (BIPV) window with semi-transparent solar cells, Appl. Energy. 129 (2014), 217-227.

[12] Harbecke, B. Coherent and incoherent reflection and transmission of multilayer structures, Appl. Phys. 1986; B 39, 165-170.

[13] Machado M, Baenas T. Optical model for multilayer glazing systems: Experimental validation through the analytical prediction of encapsulation-induced variation of PV modules efficiency, Solar Energy. 135 (2016), 77–83.

[14] Maestre, I.R. Modelo optico y termico de acristalamientos complejos, Phd. Dissertation, 2000 University of Sevill.

[15] Maestre, I.R., Molina, J.L., Ross, A., Coronel, J.F. A single-thin-film model for the angle dependent optical properties of coated glazings, Sol. Energy. 81 (2006), 969–976.

[16] Rubin, M. Solar optical properties of windows, Energy Res. 6 (1982), 123–133.

[17] Rubin, M., Rottkay, K.V., Powles, R. Window optics, Sol. Energy. 62 (1998), 149–161.

[18] [Finlayson, E.U., Arasteh, D.K., Huizenga, C., Rubin, M.D., Reilly, M.S. Window4.0: Documentation of calculation procedures. Lawrence Berkeley Laboratory, University of California (1993).]