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Analysis of the Overall Transmittance of Self-cleaning Photovoltaic Glazing

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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.

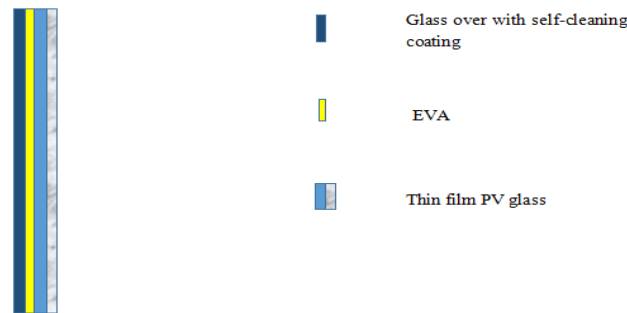


Figure 1. Basic structure of photovoltaic triple glazing

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:

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

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],

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

$$M_{1,n} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \frac{1}{T} \begin{pmatrix} -R_b & 1 \\ T^2 - R_f R_b & R_f \end{pmatrix} \quad (3)$$

$$T = m^{-1}_{12}, R_f = m_{22}m^{-1}_{12}, R_b = -m_{11}m^{-1}_{12} \quad (4)$$

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	\rfloor	$\begin{pmatrix} 1 - r_s - \frac{r_s^2}{1 - r_s} & \frac{r_s}{1 - r_s} \\ -\frac{r_s}{1 - r_s} & \frac{1}{1 - r_s} \end{pmatrix}$	$M_{\rfloor} = UM$ r_s : Glass substrate reflectivity
Glazing substrate	S	$\begin{pmatrix} 0 & \frac{1}{\tau_s} \\ \tau_s & 0 \end{pmatrix}$	$M_S = M$ τ_s : Glass substrate transmissivity
Air glazing coating	\parallel	$\begin{pmatrix} \frac{1}{t_0} & -\frac{r_{0b}}{t_0} \\ \frac{r_{0f}}{t_0} & t_0 - \frac{r_{0f}r_{0b}}{t_0} \end{pmatrix}$	$M_{\parallel} = UM$ t_{0f} : Coating transmissivity r_{0f}, r_{0b} : Coating reflectivity front, back
Film (no reflectivity)	$\rfloor + \rfloor$	$\begin{pmatrix} 0 & \tau_L^* \\ \frac{1}{\tau_L^*} & 0 \end{pmatrix}$	$M_{\rfloor + \rfloor} = UMU$ τ_L^* : Film transmissivity
Film (with reflectivity)	$\rfloor + (\rfloor$	$\begin{pmatrix} \frac{\rho_L}{\tau_L} & \tau_L - \frac{\rho_L^2}{\tau_L} \\ \frac{1}{\tau_L} & -\frac{\rho_L}{\tau_L} \end{pmatrix}$	$M_{\rfloor + (\rfloor} = UMU$ τ_L : Film transmissivity ρ_L : Film reflectivity

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

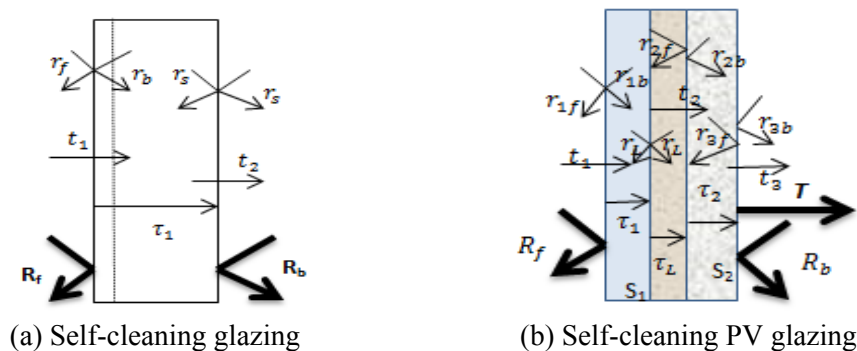


Figure 2. Schematics and notation for sandwich glazing system

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

$$M_{1,3} = M_{||,1} M_{s,2} M_{||,3} \quad (5)$$

(r_f, r_b, t_1) for the glazing S front coating”[“”, $(0,0, \tau_1)$ for the glazing sustrate”S”, (r_s, r_s, t_2) for the glazing S back glazing”]”. Therefore the energy coefficients of the self-cleaning glazing, from (4) can be written as:

$$T = \frac{t_1 \tau_1 (1 - r_s)}{1 - r_s r_b \tau_1^2} \quad (6)$$

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

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

$$M_{1,6} = M_{||,1} M_{s,2} M_{||,3} M_{||,4} M_{s,5} M_{||,6} \quad (7)$$

(r_{1f}, r_{1b}, t_1) for the glazing S₁ front coating“[“”, $(0,0, \tau_1)$ for the glazingsustrate”S₁”, EVA is a film with reflectivity, (r_L, r_L, τ_L) for the “) + “, (r_{2f}, r_{2b}, t_2) for the glazing S₂ front coating”[“”, $r_{3f} = r_{3b}$, (r_s, r_s, t_3) for the glazing S₂ back glazing”]”, $(0,0, \tau_2)$ for the glazing sustrate”S₂”. Therefore the energy coefficients of the self-cleaning PV glazing, from (4) can be written as:

$$T = \frac{t_1 t_2 \tau_1 \tau_2 \tau_L}{\Delta} \quad (8)$$

$$\Delta = 1 - \tau_1^2 r_{1b} r_L + \tau_1^2 r_{1b} r_L^2 r_{2f} - \tau_L^2 \tau_1^2 r_{1b} r_{2f} - r_{2f} r_L + r_s \tau_2^2 \tau_1^2 r_{1b} r_L r_{2b} - r_s \tau_2^2 r_{2b} + r_s \tau_2^2 \tau_1^2 r_{1b} r_L^2 - r_s \tau_2^2 \tau_L^2 \tau_1^2 r_{1b} t_2^2 - r_s \tau_2^2 r_L t_2^2 + r_s \tau_2^2 \tau_1^2 r_{1b} r_L^2 r_{2f} r_{2b} + r_s \tau_2^2 \tau_L^2 \tau_1^2 r_{1b} r_{2f} r_{2b} + r_s \tau_2^2 r_{2f} r_{2b} r_L$$

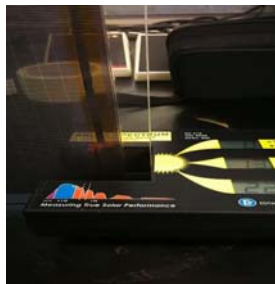
Where S₁ is the Self-cleaning coated glazing, S₂ is the PV glazing

4. Results and Discussion

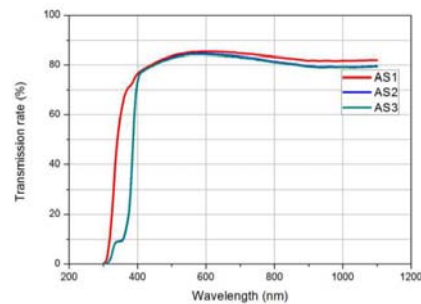
A lab-scale thin film PV glazing prototype was manufactured via integration of different layers of glazing using an autoclave. The prototype comprises of a layer of 400 mm×400 mm×4 mm self-cleaning glazing laminated and attached by and EVA layer to a unit of 400mm×400mm×3.2mm thin film PV glazing (TCO+750nm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



(a) PV model



(b) Spectral transmittance meter



(c) Test data

Figure 3. Experimental testing of PV's transmittance

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 optical model formulas and experimental results lay a solid foundation for further research on the transmission rate analysis and performance evaluation of photovoltaic sandwich glazing.

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