Solar Energy 159 (2018) 212–225

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Multiple nonlinear regression model for predicting the optical performances of dielectric crossed compound parabolic concentrator (dCCPC)

Meng Tian, Yuehong Su*

Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK

ARTICLE INFO

Keywords:
Dielectric crossed compound parabolic concentrator (dCCPC)
Transmittance
Optical efficiency
Mathematical model
Multiple nonlinear regression
Clear sky

ABSTRACT

As a typical type of three-dimensional compound parabolic concentrator (CPC), dielectric crossed compound parabolic concentrator (dCCPC) has drawn a significant research attention in these years to explore its angular characteristics in solar collection for concentrating photovoltaics and daylighting control in buildings. Optical efficiency and transmittance are the main performance indicators to evaluate a dCCPC which may be base-coated as a receiver or non-coated for daylighting. The most common way to accurately determine the performance of a dCCPC is through ray-tracing simulation which requires advanced optical analysis software and lots of time. To facilitate the annual performance evaluation of dCCPC, this study puts forward several mathematical models for multiple nonlinear regression based on a mass of simulation results. The models can predict the transmittance of non-coated dCCPC and the both of transmittance and optical efficiency of base-coated dCCPC from several sky parameters, respectively. The agreement between predicted and simulated values is generally satisfactory. The coefficient of determination (R^2) for each model is higher than 0.94 and the mean square error (MSE) is less than 0.002. Six specific time among the whole year are selected to verify the reliability of the prediction models in practice. The limitation and significance of these models are discussed as well. The regression models provide a convenient and accurate approach to predict the optical performance of dCCPC.

1. Introduction

The compound parabolic concentrator (CPC) is one type of the non-imaging optics, which has great potential in solar energy concentration, daylighting control and illumination. CPC is a non-tracking concentrator to collect solar energy in concentrating photovoltaic (CPV) and solar thermal systems, which has been verified by many research studies (Sellami and Mallick, 2013; Li et al., 2015; Arnaoutakis et al., 2015; Karathanassis et al., 2017). In terms of traditional two-dimensional (2D) CPC, (Sun and Shi, 2010) tested the maximum short circuit current of a CPV system which was higher than twice of the flat PV panel. In the experiment conducted by Bahaidarah et al. (2014), the CPV system with cooling generated 61.9% higher electricity compared to the flat PV panel with cooling. For the lens-walled CPC proposed by Su et al. (2012a) and Li et al. (2013,2014a, 2014b), it was found that the solar energy collected by the lens-walled CPC is 20–30% more than traditional 2D CPC. For crossed CPC (CCPC), the maximum optical efficiency could reach 95% (Sellami et al., 2012). The maximum power ratio was up to 2.67 for the dielectric filled crossed CPC (Baig et al., 2014b). In a system integrating CPC, PV and tubular absorber, the total energy conversion efficiency was 20% higher than the independent PV module (Ulavi et al., 2013).

The advantages of CPC in daylighting control has been also proposed by some researchers (Walze et al., 2005; Yu et al., 2014; Zacharopoulos et al., 2000; Mallick and Eames, 2007; Sarmah and Mallick, 2015) in recent years. Due to its specific structure, CPC can receive or reject sunlight depending on the incident angle. Ulavi et al. (2014b, 2014a) designed a hybrid solar window with CPC and tubular absorber; the annual thermal efficiency ranged from 21% to 26% when it was used as skylight and 15–24% when it was used as south or east-facing windows. Yu et al. (2014) investigated the feasibility of using 2D dielectric CPC as skylight in daylighting control. It was found that the CPC provided lower transmittance at noon and higher transmittance in the morning and afternoon under clear sky, which could reduce solar heat gain significantly. PRDIEs is a smart window applied on building facade integrating CPC and photovoltaic to provide daylighting and electricity at the same time. It has been extensively investigated by many researchers (Sarmah and Mallick, 2015; Sarmah et al., 2014; Baig et al., 2014a; Mallick et al., 2004, 2006) . The average electrical conversion efficiency was 9.43% and it could reduce up to 20% in the cost of per unit power output comparing with the conventional PV module (Sarmah et al., 2014).

Two-dimensional (2D) trough CPC has a longitudinal axis and two

* Corresponding author.
E-mail address: yuehong.su@nottingham.ac.uk (Y. Su).

http://dx.doi.org/10.1016/j.solener.2017.10.090
Received 14 June 2017; Received in revised form 20 October 2017; Accepted 31 October 2017

parabolic-curved surfaces, which is the most common one in all CPCs (Welford and Winston, 1978). For the most common east-west orientation of 2D trough CPC in practice, the incident light projected on the north-south meridian forms a so-called south projection angle, which could be compared with the acceptance angle of CPC to determine its optical performance. However, this would be not suitable for a three-dimensional CPC, for example, typical crossed CPC (CCPC), also called orthogonal CPC, consists of four parabolic surfaces and two square apertures. Different from 2D CPC, the optical performance of CCPC is more complicated so that it cannot be determined using a simple south projection angle directly. Due to the complex ray path of incident light, the optical performance of CCPC can be obtained only by raytracing simulation.

The dielectric CPC (dCPC) is an alternative to the mirror CPC and has an enlarged acceptance angle owing to the refraction on air-dielectric interface and also allows transmission of light beyond its acceptance angle. As a result, the dCPC has been widely used in CPV and daylighting control systems. Welford and Winston (Welford and Winston, 1978) proposed that the actual acceptance angle of a dCPC needs to be adjusted by a certain degree for nonmeridional incident rays due to the refraction. For 2D dCPC, Yu and Su (2015) proposed a concept of inner projection angle which is the refracted projection angle of incident light inside dCPC. They found strong correlations between inner projection angles and optical performance at different solar azimuth angles of 2D dCPC based on simulation results. However, for 3D dielectric crossed compound parabolic concentrator (dCCPC), the refraction and total internal reflection owing to dielectric material should also be considered, which causes the prediction of optical performance of dCCPC becomes more complicated.

To date, no research has been published in the literature that proposes a relatively fast and simple model to predict the optical performance of dCCPC except for simulation. In this study, several mathematical models are proposed through multiple nonlinear regression based on a mass of simulation results, in order to predict the optical performance for base-coated and non-coated dCCPC from the given solar azimuth angle, altitude angle and sky clearness factor. The validation and limitations of the models are given to discuss the feasibility and reliability of the models as well. On basis of the regression models proposed in this study, the transmittance of using dCCPC can be calculated in a fast and accurate way rather than using long time raytracing simulations. Similarly, in terms of the CPV application, the amount of light received by the PV panel attached on the base of dCCPC can also be determined in a much more convenient way.

2. Methodology

2.1. CPC models

The optical performance of dCCPC can be evaluated in two aspects: the optical efficiency and transmittance. According to previous studies (TIAN and SU, 2015, 2016), it was found that the transmittance and optical efficiency of a dCCPC are related to its dimension, sun position and sky condition. In this research, the dCCPC demonstrated in Fig. 1 is selected as an example to investigate the correlations between its performance and influencing factors. It consists of four parabolic surfaces and two square apertures, which is transformed by crossed interception of two tough dielectric CPCs. For the purpose of applying CPC to windows or facades, the dCCPC is a miniature optical structure, for example, with a height of 24.2 mm and an entry aperture of 18 mm ∗ 18 mm. The dCCPC may be filled with acrylic material, which has a refractive index of 1.5. The inner and outer half acceptance angles of the dCCPC are 14.47° and 22.02°, respectively. Two kinds of the dCCPCs in this dimension will be investigated in this study: one is non-coated dCCPC which is the normal dielectric CCPC, the other is base-coated dCCPC having black material attached on its exit aperture to simulate solar absorption.

2.2. Software settings

The optical performance of dCCPC was simulated by Photopia. It is a fast and accurate photometric analysis software which can provide liable and comprehensive evaluation for non-imaging optical systems. The calculation is based on probabilistic raytracing under numerous defined optics and light source models in its library (Photopia, n.d.). The light source models for modelling daylight input offered by Photopia are based on the IESNA RP-21 daylight equations. The luminance distribution of sky dome varies across the hemisphere as described in IESNA RP-21. The absolute illuminance from the sun (solar disk) and sky are provided automatically depending on the altitude angles and sky conditions, but they can also be adjusted manually. Both of the sun and sky model emit light onto the optical systems in order to simulate real outdoor conditions. It is worth to mention that the real sky changes all the times and the RP-21 equations represent standard conditions.

Sky clearness factor () proposed by Perez et al. (1990) is a popular way to determine the sky condition which has been used in EnergyPlus simulation (EnergyPlus, 2016) and daylight calculations (Kleindienst et al., 2008; Piderit et al., 2014). It is calculated from the horizontal diffuse irradiance, normal direct irradiance and solar zenith angle in order to describe the sky condition as shown in Eq. (1). Eight categories corresponding to the different value intervals were proposed to describe the sky conditions from overcast to very clear sky (Perez et al., 1990).

$$\varepsilon = \frac{\frac{(I_h + I)}{I_h} + kZ^3}{1 + kZ^3} \tag{1}$$

where I is direct normal solar irradiance; I_h is diffuse horizontal irradiance; k is a constant and equals 1.041; Z is solar zenith angle in radians.

However, in the optical simulation using Photopia, it is not a setting option to choose a sky clearness factor, but it allows to change the lumen or radiative outputs from the sun disk and sky dome in its sky model. The horizontal irradiance or illuminance can be then obtained from the sun and sky with complex light distribution for different solar altitudes, and the sky clearness factor can be hence calculated. It would offer a convenience in data analysis by defining a term called sunlight lumen ratio (φ_{lumen}), which is a ratio of the direct normal output from the sun disk to the diffuse output from the sky dome in the sky model, as expressed in Eq. (2). The output from the sun and sky can be set as required in Photopia. The values of sunlight lumen ratio can be controlled as constant in order to investigate the relationships among other criteria.

$$\varphi_{lumen} = \phi_{sun}: \phi_{sky} \tag{2}$$

where ϕ_{sun} is the total light output from the sun (direct light output); ϕ_{sky} is the total light output from the sky (diffuse light output).

In addition, it is important to note that each sunlight lumen ratio corresponds to an interval of sky clearness factor. Table 1 illustrates the sunlight lumen ratios used in simulation for this study, and corresponding horizontal sunlight illuminance ratio, sky clearness factors and sky conditions. The horizontal sunlight illuminance ratio is the ratio of direct horizontal illuminance and global horizontal illuminance, which can indicate the percentage of sunlight illuminance to the total illuminance on a horizontal surface. According to the classification of clearness factor, it is overcast condition when < 1.2, intermediate to clear for ≈ 2–3, and then becomes clearer towards very clear conditions as > 6.2. This research focuses on clear sky condition. Therefore the sky clearness factor is controlled above 3 by adjusting the sunlight lumen ratio. Three lumen ratios were selected corresponding to three intervals. It can be seen that with the increase of sky clearness factor, the horizontal sunlight illuminance ratio rises from 0.55 to nearly 1. It is important to mention that the sunlight lumen ratio will be used to demonstrate simulation results for better comparison and illustration, but the sky clearness factor would be used in data regression for the purpose of practical application.