Energy 128 (2017) 163–182

Contents lists available at ScienceDirect

Energy

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

Modeling of solar transmission through multilayer glazing facade using shading blinds with arbitrary geometrical and surface optical properties

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ARTICLE INFO

Article history:
Received 7 December 2016
Received in revised form
24 March 2017
Accepted 3 April 2017
Available online 5 April 2017

Keywords:
Glazing façade
Solar radiation
Photovoltaic blinds
Numerical model
Guess Integer-Valued Function
Experimental validation

ABSTRACT

A system model that can accurately simulate the instantaneous solar transmittance through multilayer glazing façade (MGF) and shading device can provide a solid foundation for the thermal and daylighting performance calculation of MGF as well as indoor visual comfort evaluation. Traditional optical models for venetian blind and glazing façade meet with their limitations to analyze new prototype of shading blind like photovoltaic (PV) blind which has quite different surface optical properties compared with conventional venetian blind. The present study proposed a new system model for MGF using shading blind with arbitrary geometrical and optical features which is suitable for a wide range of applications. Three major calculation types for modeling of shading blinds cover all the possible situations in application. Guess Integer-Valued Function is adopted for delivering a general description on direct radiation transport. The direct-direct, direct-diffuse and diffuse-diffuse radiation transports are separately considered. A series of experiments were carried out to validate the model under various parameter settings and different weather conditions. Parametric study revealed some new findings in the evaluations of influence of ambient radiation situations, geometrical and optical features of blind space on both solar transmittance and solar absorption by blind layer.

1. Introduction

Multilayer glazing façade (MGF) is a general description of modern glazing façade and the frequently utilized double skin façade (DSF) is one type of MGF. MGF system has become highly popular worldwide which was originally installed in cool climate regions [1]. Modern architects are attracted by glazing structures and naturally applied it to other regions with little consideration of its energy impact. Afterwards, the engineers and researchers start to investigate the applications of different glass facades in moderate to humid climates such as Trabzon in Turkey [2], five different climatic zones of India [3] and Mediterranean climate [4]. The similar situation is also observed in the China when the energy consumption of DSF in Hot Summer and Cold Winter Zone is concerned [5]. The review research by Han et al. [6] proposed that the control of daylighting through glazings is probably the most promising one for considerable energy savings in the near future.

For engineers and architects, installation of shading devices like venetian blinds can directly and effectively reduce solar radiation penetration [7–9]. The solar transmittance through a complex system involving glass panes and shading devices is directly linked to the design and operation of air conditioning system, as well as indoor thermal and visual comfort evaluations, but the accurate simulation of this process becomes a challenge work [10–13]. For some researches in doing thermal simulation of DSF, if the solar energy penetration through MGF cannot be accurately estimated, the surface temperatures of glass, instantaneous heat gain and short-wave radiation intake also cannot be calculated. For example, Gabriel Nastase et al. [14] didn't treat the solar radiation simulation properly in the steady state heat transfer calculation of DSF and the results shown that the simulated data was obviously lower than the measured data. In another study, a simplified mathematical model of DSF was established by Hagar et al. [15]. Because the direct and diffuse radiations were not separately considered, the results by this simplified model were always larger than the results by software DIGITHON. Those examples can largely show the importance of an accurate optical model of semi-transparent MGF.

The function of an optical model of MGF is to provide or predict the dynamic information about solar radiation penetration as well

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http://dx.doi.org/10.1016/j.energy.2017.04.009
0360-5442/

as absorption. No matter it is the clear glass layer or shading blinds (Venetian blinds) layer, they are all called as semi-transparent solid layers in MGF. Generally, the studies are always concerning about the modeling of radiation transport through venetian blinds and within different solid layers. The solar radiation reflection, penetration and absorption by each solid layer of MGF are complex. The join of venetian blinds layer in this system could further complicate the analysis. If the optical property of each solid layer is obtained, Net Radiation Method [16,17] and Ray-tracing Method [18–20] are two recognized approaches for whole glazing system simulation. Besides, Jiang et al. proposed a numerical method based on the energy balance at the interface of a transparent body to calculate solar transmittance [21]. From literature reading, the Bi-directional Method [22–24] and Transfer Matrix Method [25] are suitable for the modeling of glazing system without shading blinds.

The installation of shading device like venetian blinds can reduce solar heat gain in practice but also bring a challenge to simulation work. Radiosity Method [19,26–33] is frequently used by researchers and simulation software like EnergyPlus and DOE-2, which takes adjacent flat-shaped blinds as modeling object and divides the slats into several pieces for the balance equations establishment of both direct and diffuse radiation. The radiosity method was derived from a clear physical concept of energy balance but it is not practical for analyzing direct-direct reflection within two adjacent blinds with specular characteristics. The analysis by Loutzenhiser et al. [34] has shown that the average simulation error by EnergyPlus and DOE are 119.2% and 114.1% respectively, which indicate the necessity of developing new models. Yahoda and Wright [35] established a mathematical model to calculate the optical performance of venetian blinds taking both specularspecularr and diffusive reflection on the slat surface and this model was compared with other models and experiment data from cited literature. Similar work was recently done by Wang and Chen [16] in their optical modeling and experimental validation. Chan and Tzempelikos [30] proposed a hybrid method which combined ray-tracing and radiosity method and solved by Monte-Carlo Algorithm. This simulation reached a high accuracy but the calculation is quite time-consuming. Another advance in the simulation study of venetian blinds is the modeling of curved slat while considering the thickness of slat by Chaiyapinunt et al. [28,36,37]. The basic method in Chaiyapinunt's work is radiosity method but the specific radiation reflection between adjacent curved slats was modeled.

The development of simulation models always come along with the advent of new systems or structures. The optical properties of both upper and lower surfaces of commonly used venetian blind are identical and all the previous models are established on this basis. But recently, a prototype of photovoltaic (PV) blinds used as external shading device was investigated at the technological and economical aspect [38,39]. The absorption coefficient of the upper surface of PV blind is large while the optical property of another side of PV blind is highly reflective, which is the first unique characteristic of PV blinds. Secondly, the PV module is capsuled by glass layer on two side surfaces of slat, which makes much higher the proportion of specular reflection than conventional venetian blinds. In previous study, only 4 inter-reflections were considered in beam-beam radiation transport [16], however, the present work can give a unified formula for more general situation applications.

This paper is going to present a comprehensive modeling work on multilayer glazing façade using shading blinds with arbitrary geometrical and surface optical features. This work can not only deliver an accurate physical model for the glazing system installed with new prototype blinds like PV blinds, but also suitable for conventional venetian blinds with different settings of blinds spacing or width. In order to test the robustness of proposed model, experiment about glazing façade integrated with PV blinds were conducted for model validation. Because the optical property of front and back side of PV blind are different, no existing model was used for model comparison. In addition, the system parametric study is carried out based on the validated model and the results revealed some new findings about MGF system which can promote our understanding and system design.

2. System model

The center philosophy of complex model establishment is to clearly figure out the input and output parameters of the target system. The general guide line is to divide a complex model into several sub-models which can be independently built and then connected and coupled through the data flow of inputs and outputs. We treat each single sub-model as a module function.

The purpose of the present model is to dynamically calculate the solar absorption and penetration through multilayer glazing façade (MGF). The basic steps of system modeling work are: 1) to build a solar module which can accurately simulate solar position and radiation intensity on vertical plane if the solar radiation measurement on vertical plane is not available; 2) to build a glass module which can specifically give the direct and diffuse radiations transmittance of single clear glass; 3) to build a blinds module which can calculate direct-direct, direct-diffuse and diffuse-diffuse radiation transport though blinds layer in terms of different situations; 4) to collectively calculate the solar energy transmission through MGF using previously established solar module, glass module and blinds module.

2.1. Solar position and radiation

Accurate computation of solar position plays a fundamental role in solar energy applications [40]. For building envelope, the instantaneous heat gain is closely linked to solar position. Solar altitude angle h (Degree) and wall-solar azimuthal angle ε (Degree) are two important parameters in calculations. The inputs are calculation date, time step, local latitude φ, longitude L, hour angle w, wall surface inclination angle β, facade oriantiation γ (this value is zero for south-facing facade). The solar azimuthal angle α is a intermediate variable. The correlations between those inputs and h and ε are expressed by Eqs. (1)–(3), which could be found in some researches on solar position simulations [40–44].

$$\sin h = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos w \tag{1}$$

$$\cos\alpha = \frac{\sinh \sin\varphi - \sin\delta}{\cos h \cos\varphi} \tag{2}$$

$$\varepsilon = \alpha - \gamma \tag{3}$$

The solar transmittance though MGF is a one-dimensional process in net radiation method. In this and other previous studies [16,28], the modeling target is the vertical wall and the direct and diffuse solar incidences on vertical plane are necessary. However, only the data of solar radiation intensity on the horizontal plane is available except for some typically vertical installed solar pyranometers in experiment rig. There are all sorts of different mathematical models for the estimation of vertical direct and diffuse radiation from measured data on horizontal plane [45–48]. The major difference of those models is the estimation of diffuse radiation fraction received by inclined surface ($R_d = G_{dif,v}/G_{t,v}$). According to the comparison conducted by Khalil and Shaffie [48], the model derived by Skartveit [49], and Perez [50,51] have higher simulation accuracy. We tested the both Skartveit's model and Perez's model by comparing with the field measurement in Changsha, Hunan province, China for different period of time. The