Model of the Solar Diffuse Radiation Transmission Through Opaque Shuttle Louvers and Experimental Verification

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Abstract. The main problem of previous methods for calculating the solar diffuse radiation transmission through shading louvers is that they can only deal with flat slats. Taking the radian and dimension of louvers into consideration, a new model of solar diffuse radiation transmission through opaque shuttle louvers was established and experimentally verified in this paper. Firstly, the new calculation model was established, and then a computer program was developed with MATLAB, which can be used to study the solar diffuse radiation transmission through shuttle louvers. Secondly, an experimental set-up was built to verify the new model, and the results showed that the model predictions compared well with the experimental data. Finally, the error of the conventional calculation methods was analyzed, and the results shows that, the “flat slat model” leads to overestimation of the transmittance of diffuse radiation, and the relative error increased from 10.28% to 453.03% when the rotation angle increasing from 0 to 85°.

Introduction

Shading is a rational way of dealing with solar radiation in many conditions such as solar heat gain blocking and natural lighting of buildings [1]. There are various kinds of building shades that are commonly used, especially shuttle louvers. Compared with other kind of louvers, the obvious advantages of shuttle louvers include streamlined appearance, good strength and adjustable rotation angle [2]. Solar radiation irradiating on building envelope includes beam radiation, sky diffuse radiation, ground reflection radiation, diffuse radiation reflected from surrounding buildings, and long-wave radiation [3-4]. Parmelee and Aubele [5] developed a mathematical model for calculating the solar diffuse radiation transmission of slat. Pfommer et al. [6-7] also developed a solar radiation transmission model of slat, with the calculation method for diffuse radiation transmission similar with that in [5]. Simmler et al. [8] developed a “Simmler model”, which can be used to analyze the relationship between effective optical properties and surface reflectivity of slat, assuming that “slat was flat”. Based on the “Simmler model”, Van Dijk et al. [9-10] developed a software package named “Advanced Windows Information System” to calculate the optical and thermal properties of windows with shadings, where one of the important components was the shading model with the assumption that “slat was flat”. This method was adopted by ISO 15099-2003 [11]. Zhang et al. [12] analyzed a calculation model of solar diffuse radiation transporting through flat blinds. In general, the main problem of previous methods for calculating diffuse radiation transmission calculations is that they can only deal with flat slats. For opaque shuttle louvers, new model needs to be developed to overcome the shortcomings of the previous methods.

Many researchers studied experimental methods to verify the calculation models of shade systems. Chantrasrisalai and Fisher [13] put forward an in-situ experimental method to validate the optical model of a slat-type blind. This method was also employed by Wang et al. [14] to validate their optical model of a complex multi-glazing facades system with venetian blinds, and the model predictions agreed well with the experimental results. However, this method is not suitable for shuttle louvers, because the dimensions of shuttle louvers are bigger than those of venetian blinds, and measurement uncertainties can inevitably arises from the inhomogeneity of the blind layer and
the locations of pyranometers. Gomes et al. [15] carried out experiments to study the effect of venetian blinds on solar optical characterization of a fenestration system. The problem was that the spectral response of the LI-200 (370–1100 μm) used in the experiment did not include the entire solar spectrum, making the results unable to reflect the true solar transmission; besides, the blocking effect of irradiance sensors also led to measurement errors. Thus it is clear that new experimental method needs to be developed for shuttle louvers to solve the above-mentioned problems.

In this paper, the solar diffuse transmission mechanisms through opaque shuttle louvers are discussed, and then a calculation model is set up to describe the effect of shape, dimension, rotation angle, and surface optical properties of shuttle louvers on the solar diffuse transmission. A new experimental set-up equipped with integrating sphere was developed for studying the solar diffuse radiation transmission through shuttle louvers. The calculation results are experimentally verified, and also compared with the data in [11].

Calculation Model of the Solar Diffuse Radiation Transmission

The diffuse radiation (wavelength $\lambda_j$) reaching the opaque shuttle louver is divided into three parts [16]: $\tau_{diff}$ is transmitted through louvers into the interior environment, $\rho_{diff}$ is reflected back to the outside, and the remaining part $\alpha_{diff}$ is absorbed by the louvers. Radiation exchanging between surfaces can be analyzed by net radiation method [14], which balances the net radiation traveling directly from surface to surface. For the solar diffuse radiation transmitting through two adjacent louvers, diffuse radiation irradiating on louvers can be deduced as shown in Eqs. (1), Eqs. (2), Eqs. (3) and Eqs. (4).

The diffuse radiation irradiating on segment $i$ ($i=1-n$) of the upper surface of louvers can be expressed as:

$$E_{f,i}(\lambda_j) = J_0(\lambda_j) \cdot F_{0,f,i} + \sum_{k=1}^{n} E_{b,k}(\lambda_j) \cdot \rho_{b,k} \cdot F_{b,k\rightarrow f,i}$$  \hspace{1cm} (1)

The diffuse radiation irradiating on segment $i$ ($i=1-n$) of the lower surface of louvers can be expressed as:

$$E_{b,i}(\lambda_j) = J_0(\lambda_j) \cdot F_{0,b,i} + \sum_{k=1}^{n} E_{f,k}(\lambda_j) \cdot \rho_{f,k} \cdot F_{f,k\rightarrow b,i}$$  \hspace{1cm} (2)

The diffuse radiation transmitted through the louvers into the interior environment can be expressed as:

$$E_{f,n+1}(\lambda_j) = J_0(\lambda_j) \cdot F_{0,f,n+1} + \sum_{k=1}^{n} E_{f,k}(\lambda_j) \cdot \rho_{f,k} \cdot F_{f,k\rightarrow f,n+1} + \sum_{k=1}^{n} E_{b,k}(\lambda_j) \cdot \rho_{b,k} \cdot F_{b,k\rightarrow f,n+1}$$  \hspace{1cm} (3)

The diffuse radiation reflected back to the outside can be expressed as:

$$E_{b,0}(\lambda_j) = \sum_{k=1}^{n} E_{b,k}(\lambda_j) \cdot \rho_{b,k} \cdot F_{b,k\rightarrow b,0} + \sum_{k=1}^{n} E_{f,k}(\lambda_j) \cdot \rho_{f,k} \cdot F_{f,k\rightarrow b,0}$$  \hspace{1cm} (4)

The transmittance of diffuse radiance can be calculated by [11]:

$$\tau_{diff}(\lambda_j) = E_{f,n+1}(\lambda_j)/ J_0(\lambda_j)$$  \hspace{1cm} (5)

Algorithm of the Solar Diffuse Radiation Transmission and Programming Implementation based on MATLAB

Inputting Essential Factors

Essential factors needed in the program include surface optical properties, rotation angle and dimensions of louvers. Figures 1 and 2 show the geometries and coordinate systems between two
adjacent louvers before and after rotation, where \( d \) is the arc height, \( h \) is the spacing between two adjacent louvers which is controlled by the location of rotation axis of louvers, \( L \) is the louvers length, and \( \beta \) is the rotation angle.

![Figure 1. Geometries and coordinate system between two adjacent louvers.](image1)

![Figure 2. Geometries and coordinate system between two adjacent louvers after rotation.](image2)

**Coordinate Rotation Transformation**

As shown in Figure1 and Figure2, point \( O_1 \) is the original point, and \( O_1 O_2 \) is the y axis .The circular arc AB rotates around \( O_2 \) and the circular arc CD rotates around \( O_1 \) counterclockwise by \( \beta \). The coordinate values of each point after rotation can be deduced according to geometric relationships.

**Calculating View Factors**

The algebra method is used to calculate the view factors needed in transmission model. After calculating the coordinates of each point, the linear distances or arc lengths needed are calculated. Finally, the view factors are calculated, for which detailed calculating method can be found in [17] and [18].

**Listing System of Linear Equations and Solving Equations to Get Results**

The linear equations are shown as Eqs. (1)-(4),which contain \( 2n+2 \) unknowns, and correspondingly, \( 2n+2 \) linear equations. By solving the equations, the solar diffuse radiance transmitted into the interior environment, \( E_{(n+1)}(\lambda_j) \), and the solar diffuse radiance reflected back to the outside, \( E_{(0)}(\lambda_j) \), can be obtained. The transmittance \( \tau_{dif}(\lambda_j) \) of diffuse radiance can be calculated using Eqs. (6).

**Verification Experiment**

![Figure 3. Sketch map of the experiment set-up for verification of the radiation transportation model of shuttle louver.](image3)
An optical experimental set-up was built to verify the solar diffuse radiation calculation model of opaque shuttle louvers, with the sketch map shown in Figure 3. It mainly consists of an artificial solar simulator, two solar radiometers, a set of opaque shuttle louvers and an integrating sphere. The average radiation intensity inside the integrating sphere can be measured at any position, and then the total luminous flux entering the integrating sphere, $\Phi_r$, and finally the solar diffuse radiation intensity of the opening, $I'$, can be obtained by calculation.

During the experiments, the input power and location of the artificial solar simulator were adjusted first, to make sure the intensity of the radiation on louvers stabilized at 600 W/m$^2$. The performance of the louvers was tested taking the rotation angle at 0°, 15°, 30°, 45°, 60°, 75° and 85°, respectively, and the values of the illuminance inside the integrating sphere meter ($E$) and the intensity of the radiation in front of the louvers ($I$) were recorded. And the total luminous flux entering the integrating sphere ($\Phi$) and the solar radiation intensity of the opening ($I'$) can be calculated by [19]:

$$\Phi_r = \frac{4\pi R^2[1 - \rho(1-f)] \cdot E}{\rho}$$

(6)

$$I' = \frac{\Phi_r}{S_1} = \frac{4\pi R^2[1 - \rho(1-f)] \cdot E}{\rho \cdot S_1}$$

(7)

and the measured transmittance $\tau_{\text{measured}} (\lambda_j)$ can be calculated by:

$$\tau_{\text{measured}} = \frac{I'}{I} = \frac{4\pi R^2[1 - \rho(1-f)] \cdot E}{\rho \cdot S_1 \cdot I}$$

(8)

**Discussions**

**Experimental Verification of Present Model**

To verify the mathematical model presented for opaque shuttle louvers in this paper, experiments were performed and the transmittance of louvers obtained when the rotation angle was 0°, 15°, 30°, 45°, 60°, 75° and 85°, respectively. The geometry size of louvers was $S=300$ mm, $h=260$ mm and $d=25$ mm, and the reflectivity of louvers $\rho_f=\rho_b=0.89$.

![Figure 4. The change of the transmittance with rotation angle of shuttle louver.](image)

Figure 4 shows the solar diffuse radiation transmittance obtained in the experiments and the model predictions. It can be seen that the model predictions compare very well with the experimental data, and in fact, the difference between them is less than 2%, and the relative errors are less than 8% when the rotation angle ranges from -60° to 60°, indicating the validity and reliability of the model presented.
Error Analysis of “Flat Slat Model” for Calculating Transmittance Through Opaque Shuttle Louvers

In order to show the error of “flat slat model” in performance calculation of opaque shuttle louvers, both “flat slat model” and “present model” are used to calculating the solar diffuse radiation transmittance of opaque shuttle louvers, with \( h=260\text{mm}, \; l=300\text{mm} \) and \( d=25\text{mm} \), and the louvers the reflectivity of louvers \( \rho_f=\rho_b=0.89 \). The “flat slat model” treats the shuttle louvers as ordinary flat slats, when it’s performed to calculate the solar diffuse radiation transmittance of above louvers, \( d=0 \text{mm} \). The calculation results are shown in Table 1.

| Rotation angle | 0° | 15° | 30° | 45° | 60° | 75° | 85° |
|----------------|----|----|----|----|----|----|----|
| Transmittance of “flat slat model”(%) | 58.91 | 57.14 | 51.87 | 43.29 | 31.69 | 17.60 | 7.30 |
| Transmittance of “present model”(%) | 53.42 | 51.55 | 45.99 | 36.96 | 24.81 | 10.37 | 1.32 |
| Absolute error(%) | 5.49 | 5.59 | 5.88 | 6.33 | 6.88 | 7.23 | 5.98 |
| Relative error(%) | 10.28 | 10.84 | 12.79 | 17.13 | 27.73 | 69.72 | 453.03 |

It can be seen from Table 3 that the “flat slat model” can cause distinct error, for which the reason is that it neglects the blocking effect and variation of view factor caused by the radian of the shuttle louvers. The relative error increases significantly with the rotation angle, from 10.28% to 453.03% when the rotation angle increasing from 0 to 85°.

Conclusions

In order to overcome the shortcoming of “flat slat model”, a new model for calculating the solar diffuse radiation transmission through opaque shuttle louvers was established in this paper. Based on the model, a MATLAB-based computer program was developed to study the impact of shape, dimension, rotation angle, and surface optical properties of opaque shuttle louvers on the solar diffuse radiation transmission. To verify the model presented, an experimental set-up was built using artificial solar simulators and integrating sphere meter. The results show that the model predictions compare well with the experimental data, and the difference of diffuse radiation transmittance between them is less than 2%, indicating the validity and reliability of the new diffuse radiation transmission calculation model. The results also show that the conventional “flat slat model” can cause distinct error when it’s performed to calculate the solar diffuse radiation transmittance of opaque shuttle louvers, and the relative error increases with the rotation angle of the louvers.

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References

[1] Z.R. Li, Q.H. Tao, F.J. Jiang, L.Z.Hu, Optimum fixed slat angle and energy-saving potential of dynamic external louvers, Journal of Xi’an University of Architecture & Technology (Natural Science Edition), 44(2012) 767-772 (in Chinese).

[2] Q.H. Tao, Z.R. Li, J.W. Zheng, Calculation Model of Solar Diffuse Radiation Transportation Through Shuttle Louvers and Program Realization, Journal of Tongji University (Natural Science Edition), 43(2015):777-782 (in Chinese).

[3] Q.H. Tao, Z.R. Li, F.J. Jiang, L.Z. Hu, Necessity of shading on north facade and optimal selection of shading device, Journal of Chongqing University (Natural Science Edition), 36(2013) 154-161 (in Chinese).
[4] Q.H. Tao, Z.R. Li, F.J. Jiang, Y. Lu, L.Z. Hu, An improved method for generating typical meteorological years used in building energy simulating in China, Journal of Harbin Institute of Technology, (New Series), 21(2014) 21-29.

[5] G.V. Parmelee, W.W. Aubele, ASHVE research report No.1460-The shading of sunlit glass: An analysis of the effect of uniform spaced flat opaque slats, ASHVE Transaction, 58(1952) 377-398.

[6] P. Pfrommer, K.J. Lomas, CHR. Kupke, Solar radiation transport through slat-type blinds: a new model and its application for thermal simulation of buildings, Solar Energy, 57(1996) 77–91.

[7] P. Pfrommer, Thermal Modeling of Highly Glazed Spaces [D], Ph.D. Thesis, Leicester UK: De Montfort University, 1995.

[8] H. Simmler, U. Fischer, F.C. Winkelmann, Solar-thermal window blind model for DOE-2, Berkeley, CA: Simulation Research Group Internal Report, Lawrence Berkeley National Laboratory, 1996.

[9] Van Dijk Dick, Paul Kenny, Goulding John, WIS Advanced Windows Information System, WIS Reference Manual, Dublin: TNO Building and Construction Research Department of Sustainable Energy and Buildings, 1996.

[10] Van Dijk Dick, H. Oversloot, WIS, the European tool to calculate thermal and solar properties of windows and window components, Proceedings of Building Simulation, 3 (2003) 259-266.

[11] ISO 15099:2003, Thermal performance of windows, doors, and shading devices–detailed calculations, International Standards Organization, Geneva, 2003.

[12] L. Zhang, Q.L. Meng, Calculating model of solar diffuse radiation transporting through external blinds and it's program realization, Journal of Chongqing Jianzhu Uuniversity, 31(2009) 92-95(in Chinese).

[13] C. Chantrasrisalai, D.E. Fisher. An in-situ experimental method for the development and validation of slat-type blind models in cooling load calculations. Journal of Solar Energy Engineering, 2006, 128(2):189-198.

[14] Y. Wang, Y.M. Chen, Modeling and calculation of solar gains through multi-glazing facades with specular reflection of venetian blind, Solar Energy, Volume 130, 2016, 33-45.

[15] G. Gomes, A.J. Santos, A.M. Rodrigues. Solar and visible optical properties of glazing systems with venetian blinds: Numerical, experimental and blind control study. Building and Environment, 71(2014)47-59.

[16] Lawrence Berkeley National Laboratory, Energy plus Engineering Reference 2010, U.S. Department of Energy, (2010)191-202.

[17] M.F. Modest, Radiative heat transfer [M], McGraw-Hill, New York, 1993, Chaprt 5.

[18] S.M. Yang, W.Q. Tao, Heat transfer, The fourth edition [M], Beijing: Higher Education Press, (2006)398~404 (in Chinese).

[19] H.Y. Na, Integrating sphere, ACTA Energiae Solaris Sinica, 4(1983)99-104(in Chinese).