

Spectral investigation of solar energy absorption and light transmittance in a water-filled prismatic glass louver

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ABSTRACT

Water-filled prismatic glass louver was proposed to save energy consumptions in buildings because such innovative louvers can harvest solar energy as well as improve daylighting quality rather than “block” sunlight like traditional louvers. To enable this technology the effectiveness of ultraviolet (UV) and infrared (IR) energy harvest and visible (VIS) light transmittance was investigated via Monte Carlo simulations in this case study. The 7-band spectral model for glass and water was evaluated and adopted for several cases of solar spectra of different air mass (AM) coefficients with both direct and diffuse irradiation. Absorption and transmittance in different band regimes as well as in water and glass respectively were differentiated and compared. Practical solar data in Phoenix, Flagstaff, and Golden were utilized to demonstrate the performance of the proposed louver under different locations and realistic conditions. Results show that the device facing normally to direct sunlight can harvest around 51–54% of the total solar energy and transmit 74–76% VIS for daylighting in the range of AM1 to AM3. In particular for AM1.5, VIS transmittance reaches 76% for both direct and diffuse irradiation; UV absorption achieves 80% and 85% and IR absorption reaches 64% and 82% for diffuse and collimated irradiation, respectively. In all the three places tested, the device absorbs about 81% IR and 87% UV, and transmits about 76% VIS.

1. Introduction

The U.S. Department of Energy and Office of Planning, Budget and Analysis, Energy Efficiency and Renewable Energy estimated in 2007 that the existing building stock in the United States accounted for approximately 41% of national energy consumption, and approximately 58% was used for lighting and space heating, making the building sector the largest energy consumer. Before industrial revolution, solar energy through windows was a major source for lighting and heating. Thus, well-utilizing solar energy in building technology will lead to energy savings.

Dr. Madamopoulos at City College of New York and one current author, Dr. Guo, proposed together to National Science Foundation the liquid/nanofluid-filled hollow prismatic glass louver concept shown in Fig. 1, which serves for dual-purpose: daylighting and solar energy harvesting (see NSF Grant #ECCS-1505706). The innovative louver will utilize solar energy rather than “block” sunlight like traditional louvers. The prismatic glass shape can transmit visible (VIS) light and redirect the collimated (direct) irradiation to ceiling to eliminate the “glare effect” (Vlachokostas and Madamopoulos, 2015; Vlachokostas and Madamopoulos, 2017). The diffusely reflected light from ceiling

together with the diffuse VIS irradiation passing through the louver can illuminate room space with improved quality and comfortableness. The absorbed solar energy, mostly infrared (IR) and ultraviolet (UV), in the glass and water can be stored as thermal energy and harvested via the flowing water/nanofluid.

A prior work of the present authors has investigated collimated solar radiation of AM1.5 spectrum through a water-filled louver (Cai and Guo, 2018). However, solar irradiation through windows contains both comparable direct and diffuse components, and a very small portion of circumsolar and horizon brightening. Under cloudy condition the diffuse component increases. The impact of the diffuse irradiation is different from that of the direct irradiation. The solar spectrum for the diffuse component generally differs from the direct one. The spectrum also varies with location, weather, season, day, and even time.

The present study will take both direct and diffuse irradiation and both energy absorption and transmittance into account to enable the practical use of the proposed louvers, i.e., daylighting as well as energy harvesting. The Monte Carlo (MC) method for collimated irradiation (Cai and Guo, 2018) will be extended to incorporate diffuse irradiation. The brightening radiation is neglected as its data are not provided in the AM models selected in this case study. It is noticed that Wojcicki (2015)

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Nomenclature

E	solar heat flux, W/m ²
H	height, m
L	photon flight distance, m
N	number of photons absorbed in an element
n	refractive index
$\vec{n}$	normal direction outward a surface
$NRAY$	number of total emission photons
Ph	possible hitting parameter
P	optical property in a discrete band
Q	divergence of heat flux in an element, W/m ³
Q'	normalized energy harvest, m ⁻¹
R	random number
rd	diffuse component ratio
$\vec{r}$	ray vector
S	cross-sectional area of an element, m ²
W	width, m
w	weight factor
X, Y, Z	coordinates

Greek symbols

α	absorption coefficient, m ⁻¹
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β	extinction coefficient, m ⁻¹
ϵ	solar energy absorption efficiency
λ	wavelength, nm
$\varnothing$	circumferential angle, °
ρ	reflectivity
σ_s	scattering coefficient, m ⁻¹
ω	scattering albedo
θ	azimuthal angle, °
τ	thickness, m

Subscripts

O	initial condition
a	refraction
c	collimated
cr	critical
d	diffuse
i	surface index
in	incoming direction
k	element index
l	reflection
r	refraction
λ	spectral

derived the effective beam radiation incidence angles for diffuse and reflected solar radiation for single or double glazed flat plate. Nevertheless, MC method is very flexible and can easily treat radiation from any direction. Different diffuse ratios and various air mass coefficients will be adopted to demonstrate the feasibility and capability of the prismatic louver deployment under various weather and environmental conditions. Discrete spectral bands for different AM spectra will be calculated. We further use practical solar irradiation data at three locations in the US to calculate the solar energy absorption efficiency and VIS transmittance through the water-filled prismatic glass louver. Absorption in water and glass will be scrutinized and differentiated.

It is critical to properly model the respective contribution of diffuse and direct irradiation. Differences between diffuse and direct irradiation exist not only in terms of incident angle and photon penetration path, but also of AM spectrum. [Kirm and Topic \(2017\)](#) addressed the contribution of diffuse and direct solar irradiance separately to achieve higher accuracy in power rating photovoltaic modules and systems. [Aler et al. \(2017\)](#) improved the separation of direct and diffuse solar irradiation using the gradient boost machine learning technique. [Rossi et al. \(2018\)](#) described the correlation between global, diffuse and direct daily solar radiation of the total spectrum and the IR spectrum.

Spectral consideration is also necessary as the solar spectrum spans a wide wavelength range and the properties of material are wavelength-dependent ([Modest, 2013](#)). [Bird and Riordan \(1986\)](#) produced a

terrestrial spectrum between 300 and 4000 nm with a resolution of approximately 10 nm. Though line-by-line spectral calculation ([Clough et al., 2005](#)) is the most accurate, it is extremely time demanding. Therefore, it is paramount to consider band-average techniques that are based on the significance and difference of various radiation bands ([Myers, 2005](#)). [Escobedo et al. \(2009\)](#) used hourly and daily radiometric data to establish several empirical models for predicting the fractions of three bands. A solar spectrum is generally distinguished by three distinct bands, i.e., UV, VIS, and IR. Variation within each distinct band is still appreciable. Thus, a better band partition model that would be computationally efficient as well as accurate is highly desired for calculating solar radiation in glass-water systems for both direct and diffuse irradiation.

2. Simulation method**2.1. Physical model**

We consider a glazing system of water-filled glass louvers. Visible light passing through the louvers will be redirected to ceiling and diffusely reflect to room space for improved daylighting. UV and IR light will be absorbed by the water and glass for energy harvesting. The louver cross-section is shown in [Fig. 1](#), in which the three uniform silica glasses form an equilateral hollow triangle. Water flows inside the hollow louver. Each glass piece is 0.1875" thick, 3" wide and a few feet long. Thus, it has negligible end effect and a two-dimension (2D) cross-sectional geometry is considered in this study. The end effect may not be neglected only in the situation that both θ and $\varnothing$ approach 90°, which consists of a very small solid angle of solar incidence. In such a small solid angle, the solar incidence is almost negligible as $\cos\theta$ approaches zero. The solar incident surface (assuming the top one in [Fig. 1](#)) can be adjusted to face direct sunlight consisted of both collimated and diffuse irradiation.

2.2. Monte Carlo method

Monte Carlo (MC) method is a useful simulation tool for investigating radiative transfer in complex systems ([Yang et al., 1995](#); [Farmer and Howell, 1998](#); [Guo et al., 2000](#); [Wang et al., 2017](#)).

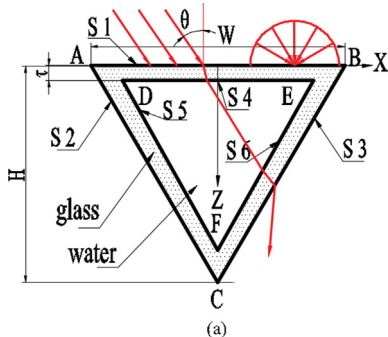


Fig. 1. Sketch of louver cross-section with direct and diffuse irradiation.

Advantages of using MC include easy handling of complicated physical processes and conditions based on statistical distributions, and easy coding in the construction of computer program without use of any governing equations. Ray tracing of a large bundle of photons can be employed to find radiative energy redistribution. However, many MC ray tracing methods (Shuai et al., 2008; Wang et al., 2013; Gong et al., 2017) in the literature for solar radiation excluded spectral consideration and collimated consideration. A recent study of the authors (Cai and Guo, 2018) has considered the spectral properties of glass and water and focused on collimated irradiation. Here, we have extended the MC method to include both collimated and diffuse irradiation and introduced a new hitting surface justification strategy to speed up the calculations. Other innovations in this study include use of various AM spectra and associated band averaging data, practical solar data and realistic conditions in three places, and VIS transmittance, etc. The ray tracing process is same for diffuse and collimated irradiation. A difference is that the direct irradiation has an initially fixed incident direction, while the diffuse one has a distribution. Their initial reflectance from the incident surface and solar spectrum are also different. In the present study, diffuse irradiation is assumed to be isotropic, ignoring circumsolar and horizon brightening. Such irregularity could be dealt with by the MC method if data were available.

The initial direction (θ_0, ϕ_0) of the diffuse irradiation is randomly generalized as follows:

$$\theta_0 = \sin^{-1}(\sqrt{R}), \quad \phi_0 = 2\pi R, \quad (1)$$

where R is the random number. A photon bundle is initiated from a position (X_0, Y_0, Z_0) at the solar incident surface of a uniform distribution:

$$X_0 = WR - W/2, \quad Y_0 = 0, \quad Z_0 = 0. \quad (2)$$

The photon flight distance is

$$L = \frac{1}{\beta_\lambda} \ln \frac{1}{R}, \quad (3)$$

where β_λ is the spectral extinction coefficient of the medium from which the photon is initiated; β_λ is a sum of the spectral absorption coefficient, α_λ , and the spectral scattering coefficient, $\sigma_{s\lambda}$.

There are six interfaces in the louver as shown in Fig. 1, S1–S6. It is necessary to justify which interface a photon will hit or whether it is absorbed/scattered inside the medium. Thus, there are seven possible flight distances, L_i , and associated end positions:

$$\begin{cases} X_i = L_i \sin \theta_0 \cos \phi_0 + X_0 \\ Y_i = L_i \sin \theta_0 \sin \phi_0 + Y_0 \\ Z_i = L_i \cos \theta_0 + Z_0 \end{cases} \quad i = 1, 2, \dots, 7. \quad (4)$$

For interaction with S1:

$$Z_1 = 0. \quad (5a)$$

For interaction with S2:

$$Z_2 = \sqrt{3}X_2 + H. \quad (5b)$$

For interaction with S3:

$$Z_3 = -\sqrt{3}\left(X_3 - \frac{W}{2}\right). \quad (5c)$$

For interaction with S4:

$$Z_4 = \tau. \quad (5d)$$

For interaction with S5:

$$Z_5 = \sqrt{3}(X_5 + 0.5W - \sqrt{3}\tau) + \tau. \quad (5e)$$

For interaction with S6:

$$Z_6 = -\sqrt{3}(X_6 - 0.5W + \sqrt{3}\tau) + \tau. \quad (5f)$$

For absorption/scattering in medium:

$$L_7 = L. \quad (5g)$$

The ray vector is set as:

$$\vec{r} = (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta). \quad (6)$$

For each surface i (from 1 to 6), we set a possible hitting parameter Ph_i as:

$$Ph_i = \vec{r} \cdot (-\vec{n}_i), \quad i = 1, 2, \dots, 6, \quad (7)$$

where $\vec{n}_i$ is the normal direction outward a surface.

The interfaces 4–6 are tested first: if $L \geq L_4 > 0$, $Ph_i > 0$ and $X_D \leq X_4 \leq X_E$, the photon will hit S4; if $L \geq L_5 > 0$, $Ph_i > 0$ and $X_D \leq X_5 \leq X_F$, it will hit S5; if $L \geq L_6 > 0$, $Ph_i > 0$ and $X_F \leq X_6 \leq X_E$, it will hit S6. Then, the interfaces 1–3 are examined: if $L \geq L_2 > 0$, $Ph_i > 0$ and $0 \leq X_2 \leq X_C$, it will hit S2; if $L \geq L_3 > 0$, $Ph_i > 0$ and $X_C \leq X_3 \leq X_B$, it will hit S3; if $L \geq L_1 > 0$, $Ph_i > 0$ and $0 \leq X_1 \leq X_B$, it will hit S1; otherwise, it will be absorbed or scattered in the glass medium.

If a photon starts inside the water medium due to scattering, the following is justified: if $L \geq L_4 > 0$ and $X_D \leq X_4 \leq X_E$, the photon will hit S4; if $L \geq L_5 > 0$ and $X_D \leq X_5 \leq X_F$, it will hit S5; if $L \geq L_6 > 0$ and $X_F \leq X_6 \leq X_E$, it will hit S6; otherwise, the photon will be absorbed or scattered in the water medium.

If a photon hits a surface, we need to consider whether the photon will reflect or transmit. For reflection, specular reflection condition is adopted as the glass and water surfaces are smooth. For refraction, Snell's law is employed:

$$n_{in} \sin \theta_{in} = n_r \sin \theta_r, \quad (8)$$

where n_{in} and n_r are refractive indices of medium in the incoming and refractive sides, θ_{in} and θ_r represent the incident angle and angle of refraction, respectively.

If $n_{in} > n_r$, there exists a critical angle, θ_{cr} , defined by

$$\theta_{cr} = \sin^{-1} \left(\frac{n_r}{n_{in}} \right). \quad (9)$$

When $\theta_{in} \geq \theta_{cr}$, the incident radiation is totally reflected with specular reflection condition.

The reflectivity, ρ , of incident radiation on an interface is given by Fresnel equation:

$$\rho = \frac{1}{2} \left[\frac{\tan^2(\theta_{in} - \theta_r)}{\tan^2(\theta_{in} + \theta_r)} + \frac{\sin^2(\theta_{in} - \theta_r)}{\sin^2(\theta_{in} + \theta_r)} \right]. \quad (10)$$

If $R < \rho$, the photon will reflect; otherwise, it will transmit.

The ray vector after reflection, $\vec{r}_1$, is

$$\vec{r}_1 = \vec{r}_{in} + 2(|\vec{r}_{in}| \cos \theta_{in}) \cdot \vec{n}_i, \quad (11)$$

where $\vec{r}_{in}$ is the incoming ray vector. The ray vector after refraction, $\vec{r}_r$, is

$$\vec{r}_r = \frac{\tan \theta_r}{\tan \theta_{in}} [\vec{r}_{in} + \vec{n}_i (\vec{r}_{in} \cdot \vec{n}_i)] - \vec{n}_i (\vec{r}_{in} \cdot \vec{n}_i). \quad (12)$$

To trace the reflected/refracted photon, a reduced flight distance is used and calculated as the difference between the originally-calculated flight distance and the flight distance between photon initiating and hitting surface. If refraction occurs, transformation between two different media is calculated by

$$L'_1 \beta_{\lambda 1} = L'_2 \beta_{\lambda 2}, \quad (13)$$

where L'_1 is the reduced flight distance in medium 1, and L'_2 is the reduced flight distance in medium 2. For scattering, a new flight distance will be calculated based on Eq. (3).

If a photon is absorbed or scattered, we use the scattering albedo to determine whether the photon is absorbed or scattered. If $R < \omega$, in which ω is the scattering albedo, the photon would scatter; otherwise, it would be absorbed. The new scattering direction is determined by isotropic scattering condition in this study, as water scattering is very

weak and glass scattering is negligible, given by:

$$\theta = \cos^{-1}(1 - 2R), \quad \varnothing = 2\pi R, \quad (14)$$

2.3. Absorption efficiency

The louver is meshed into many small elements (Cai and Guo, 2018). The spectral divergence of heat flux, $Q_{\lambda k}$ for an element k , due to solar diffuse irradiation is calculated by

$$Q_{\lambda k} = \sum_{j=1}^{N_{\lambda k}} (1 - \rho_{j\lambda}) \frac{W \times E_{d\lambda}}{S_k \times NRAY}, \quad (15)$$

where $N_{\lambda k}$ is the absorbed spectral photon number in the element; S_k is the cross-sectional area of the element; $NRAY$ is the total photon bundles number refracted from the inward surface of solar incidence; $E_{d\lambda}$ is the spectral diffuse solar heat flux incidence on the out surface of the louver; and $\rho_{j\lambda}$ is the spectral surface reflectivity of the j -th absorbed photon from air to silica glass. The total divergence of heat flux for the diffuse irradiation, Q_{dk} , is an integral of the spectral value, i.e., the sum of contributions from all the solar bands:

$$Q_{dk} = \frac{W \times E_d}{S_k} \sum_{\lambda=280\text{nm}}^{4000\text{nm}} \sum_{j=1}^{N_{\lambda k}} \frac{(1 - \rho_{j\lambda})}{NRAY} w_{\lambda}, \quad (16)$$

where E_d is the total diffuse solar heat flux onto the louver and w_{λ} is the energy weighting factor of a spectral band.

Since the solar heat flux varies depending on location, season, day and time, it would be more convenient to show the energy absorption in terms of normalized energy harvest Q'_{dk} defined as:

$$Q'_{dk} = \frac{Q_{dk}}{E_d}, \quad (17)$$

The energy absorption efficiency for diffuse irradiation, ϵ_d , is defined as:

$$\epsilon_d = \sum_k \sum_{\lambda=280\text{nm}}^{4000\text{nm}} \sum_{j=1}^{N_{\lambda k}} \frac{(1 - \rho_{j\lambda})}{NRAY} w_{\lambda}. \quad (18)$$

We compare absorption efficiency in the glass and water, respectively. The efficiency for the whole louver is a sum from these two media.

Similarly, the collimated solar irradiation can be calculated. Suppose the ratio of the diffuse component to the total irradiation is rd , and Q_{ck} is the contribution due to collimated irradiation, then the local divergence of heat flux, Q_k including both direct and diffuse irradiation, for an element would be

$$Q_k = Q_{ck} + Q_{dk}. \quad (19)$$

The total normalized energy harvest Q'_k would be

$$Q'_k = rd \times Q'_{dk} + (1 - rd) \times Q'_{ck}. \quad (20)$$

And the total efficiency ϵ_{total} for both direct and diffuse irradiation would be:

$$\epsilon_{\text{total}} = rd \epsilon_d + (1 - rd) \epsilon_c, \quad (21)$$

where ϵ_c is the absorption efficiency corresponding to the collimated irradiation. Similarly, we can calculate the total transmittance accounting the photons passing through the louver excluding those that directly reflected from and transmitted out of the solar incident surface.

2.4. Band-averaging method

Solar irradiation is highly spectral, and so are the properties of water and glass in the whole solar spectrum ranging from 280 to 4000 nm. Both glass and water are highly absorbing medium for solar irradiation. Scattering in the glass is negligible and extremely weak in water. Further, spectral variation in refractive index should be counted for both glass and water. There exists mismatch of refractive indices in

the interfaces between glass/air and glass/water. For each partition band in the solar spectrum, band-averaged properties are calculated by:

$$P_{\lambda 12} = \frac{\int_{\lambda_1}^{\lambda_2} P_{\lambda} I_{\lambda} d\lambda}{\int_{\lambda_1}^{\lambda_2} I_{\lambda} d\lambda}, \quad (22)$$

where P_{λ} represents a spectral property, I_{λ} is the spectral solar intensity, and $P_{\lambda 12}$ can be the band-averaged scattering or absorption coefficient, or refractive index in a discrete band between wavelengths λ_1 and λ_2 .

3. Results and discussion

3.1. Validity of the 7-band model

All the present MC simulations were run in a laptop equipped with an Intel Core i-7-4720HQ 2.60 GHz CPU. Computational accuracy and efficiency depend on the band division, element division, and photon number. We divide a solar spectrum into discrete bands, and band-averaged properties are used in our calculations. The spectrum was divided in a way such that property profiles are relatively smooth within each band. Another consideration was that each partition band contains a similar amount of solar energy; and thus, the bandwidth of each band is different: in the region with condensed energy, such as the VIS and near-infrared (NIR) regions, bandwidth is narrower; while in the IR region, bandwidth is wider.

Unless otherwise specified, the AM1.5 spectrum from [ASTM Standard G173-03 \(2003\)](#) was adopted as a standard in calculating the solar irradiation on earth's surface. Details about the bands' division with AM1.5 spectrum for collimated irradiation were described in [Cai and Guo \(2018\)](#), in which a grey 1-band model, 3-, 7-, 20-, and 40-band models were considered and compared. The 7-band model was recommended as a compromise of balance between computational accuracy and efficiency. Though the AM1.5 spectrum for diffuse irradiation is somewhat different, we can use the same band partitions as the difference is not remarkable. Regardless, the band-averaged properties are different between the collimated and diffuse irradiation and for different AM models. Thus, we examine the band models for diffuse irradiation at first.

The CPU times used for calculations under different photon numbers, element numbers and band numbers for diffuse and collimated irradiation are listed in [Table 1](#) for comparison. The CPU time consumed is generally longer for diffuse irradiation than for collimated irradiation. Comparing the current CPU times for collimated irradiation with those listed in our previous study ([Cai and Guo, 2018](#)), the new photon hitting justification strategy introduced in this study has shortened the calculation time by 30–40%. In agreement with our previous finding for collimated irradiation, we also found that CPU time was not sensitive to element division and 10^8 photons were sufficient to obtain accurate results for diffuse irradiation. Therefore, 7140 elements and

Table 1
CPU times.

Photon #	Element #	Band #	Diffuse, CPU (s)	Collimated, CPU (s)
10^6	7140	7	21	15
10^7			209	148
10^8			2101	1488
10^9			20,686	14,951
10^8	3192	7	2100	1510
	7140		2038	1488
	12,656		2152	1504
			1	89
10^8	7140	3	907	644
		7	2101	1488
		20	6137	4611
		40	14,046	10,594

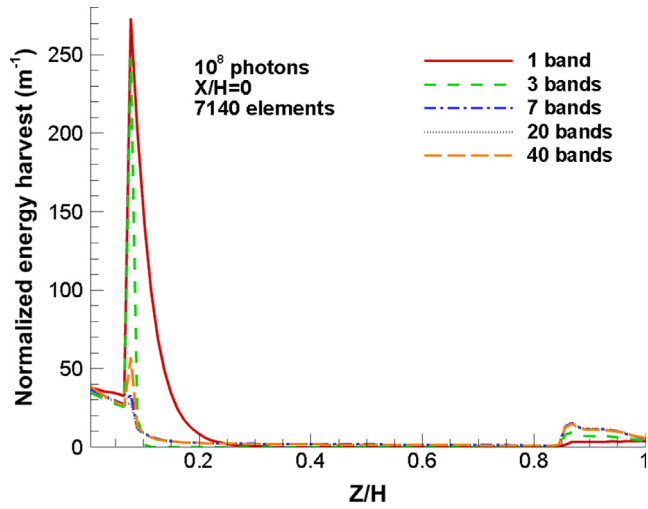


Fig. 2. Normalized diffuse solar energy harvest along the louver centreline ($x = y = 0$) for different band models.

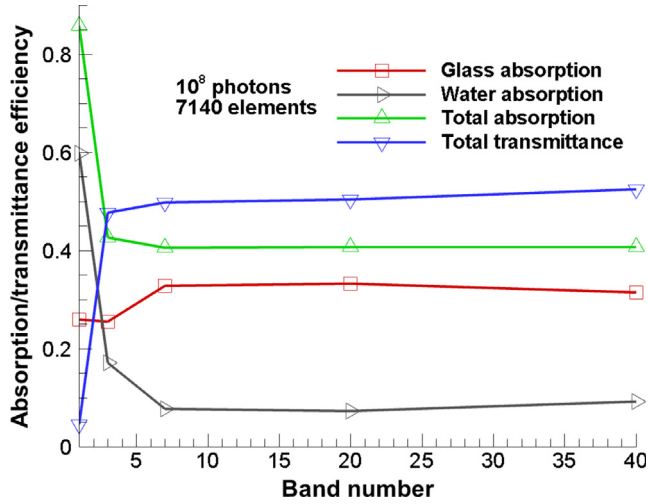


Fig. 3. Diffuse solar energy absorption and transmittance efficiencies vs. band division.

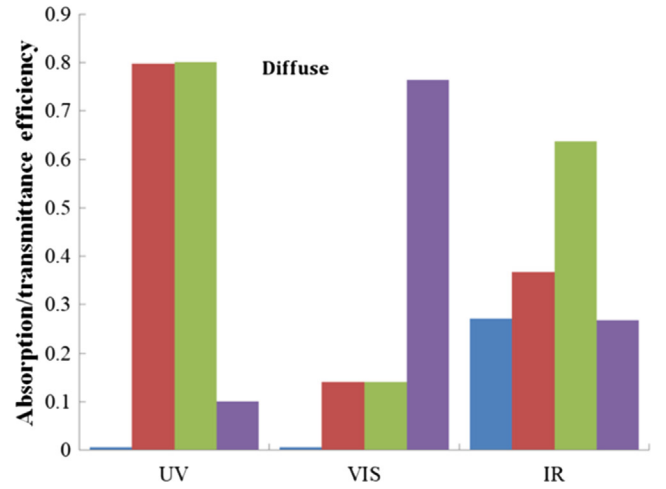
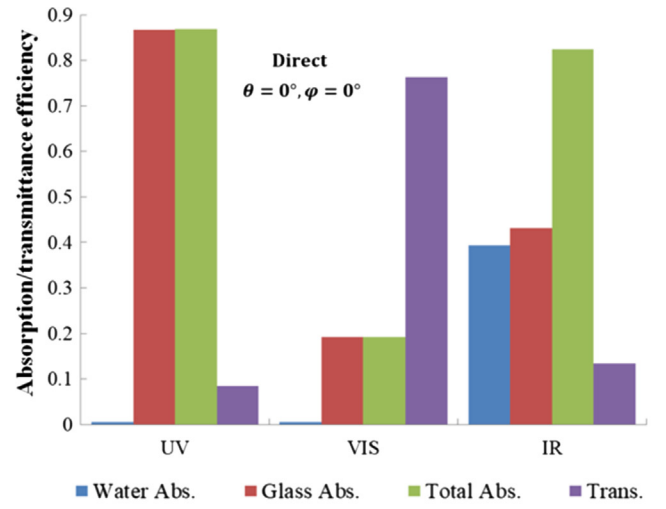


Fig. 5. Solar energy absorption/transmittance efficiencies in three distinct spectra for both diffuse and direct irradiation.

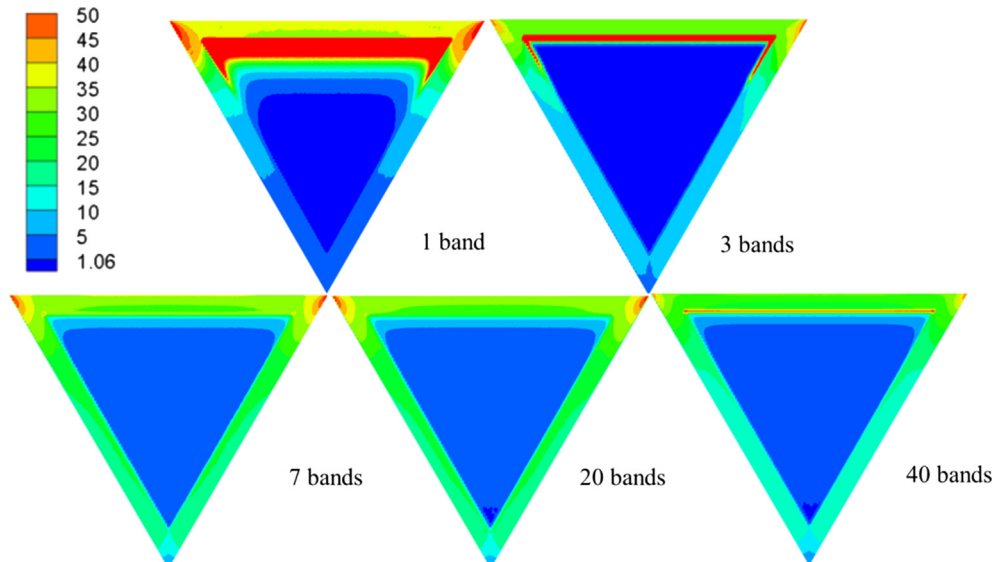


Fig. 4. Contours of normalized diffuse solar energy harvest (m^{-1}) for different spectral models.

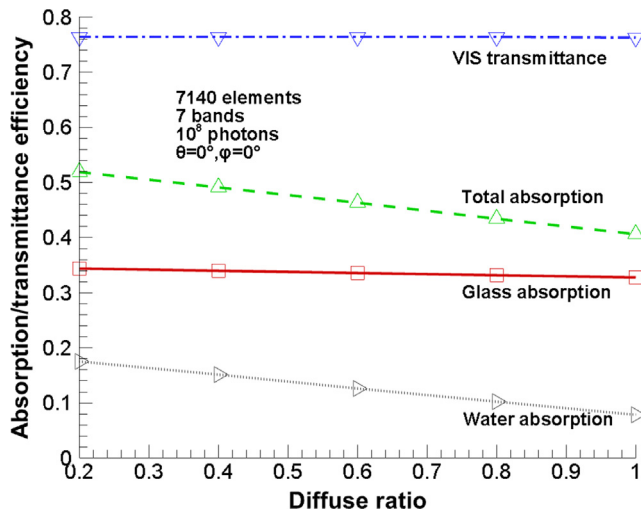


Fig. 6. Solar energy absorption/transmittance efficiencies vs. diffuse ratio.

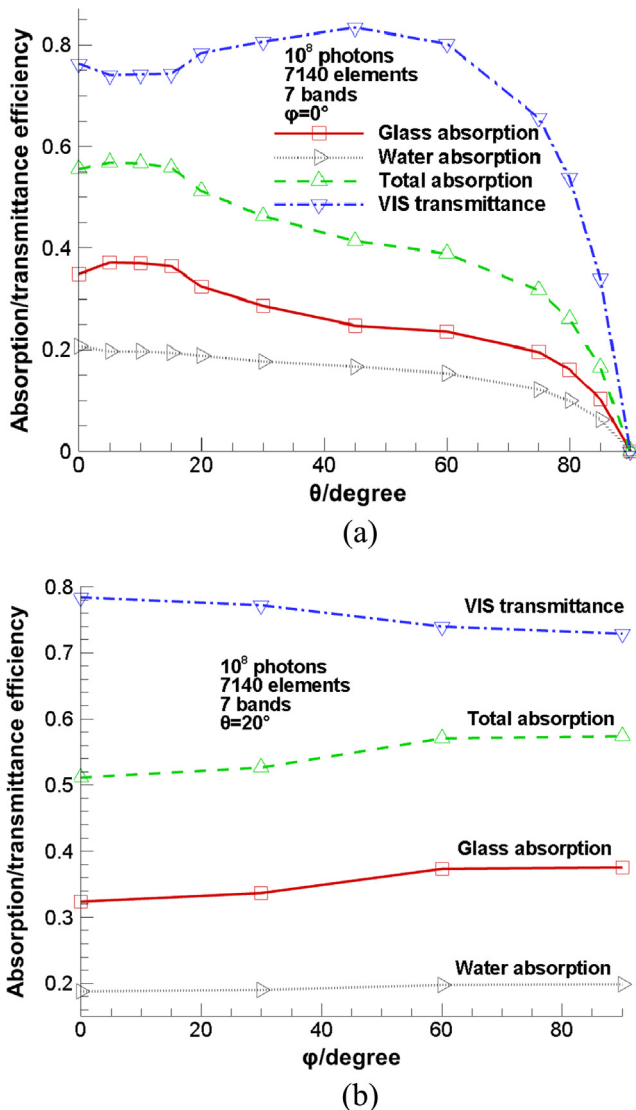


Fig. 7. Effects of incident angle of the collimated irradiation on solar energy absorption and VIS transmittance: (a) polar angle; and (b) circumferential angle.

10^8 photon bundles were adopted in all the calculations thereafter.

A proper band division of the solar spectrum is pivotal for accurate and efficient modeling of solar irradiation. In general, the larger is the band partition number, the more accurate the calculation is. However, CPU time increases with increasing band number. Fig. 2 shows the normalized diffuse solar energy harvest distributions along the louver centreline for five different band models. The results from the grey (1-band) and 3-band divisions deviate substantially from the other three models. The profiles from the 7-band and 20-band models coincide well and are in a good agreement with the 40-band model except the local peak value around $Z/H = 0.08$. In comparison with the result for collimated irradiation (Cai and Guo, 2018), the normalized solar energy harvest for diffuse irradiation is smaller. This is because the collimated irradiation under normal incidence could be attenuated more in the louver.

Fig. 3 shows the glass/water/total solar energy absorption efficiencies and the transmittance for diffuse irradiation with different band divisions. It is seen that the predicted absorption and transmittance efficiencies vary with band partition number until 7 band partitions and then almost flatten in the range from 7 bands to 40 bands. Thus, the 7-band model provides a good accuracy.

The contours of normalized diffuse solar energy harvest in the whole louver are plotted in Fig. 4. The 1-band and 3-band models predict a larger absorption in the glass, i.e., the solar irradiation is heavily attenuated by the glass layer facing solar incidence. The 7-band model is still a good choice as its result is close to the predictions of the 20- and 40-band models. The same conclusion held for collimated irradiation (Cai and Guo, 2018). Therefore, the 7-band model is justified and used thereafter for both collimated and diffuse irradiation.

3.2. Absorption/transmittance efficiency

In many practical applications, a solar spectrum is categorized by three distinct sub-spectra, i.e., UV in the range 280–400 nm, VIS in the range 400–700 nm, and IR in the range 700–4000 nm. The water-filled prismatic louver is designed to absorb solar IR and UV radiation for harvesting energy, but pass VIS light for daylighting. It would be very useful to understand the energy absorption efficiency and transmittance under these three distinct wavelength ranges. In this sub-section, AM1.5 spectrum was adopted in all the calculations.

Fig. 5 shows the absorption/transmittance efficiencies in UV, VIS, and IR, respectively, for diffuse and collimated (normal incidence) irradiation. It is observed that the glass medium absorbs the most UV and VIS light; as for the IR, both the glass and water absorb strongly. The total absorption of IR solar energy in the louver is very high, about 63.8% for the diffuse irradiation and 82.3% for the collimated irradiation. For the UV light, the absorption for both the diffuse and collimated irradiation is strong, and the total absorption reaches about 80% for the diffuse radiation and 84.9% for the collimated one. It means that UV light is well absorbed by the louver, protecting occupants in a room from overexposure to harmful UV irradiation. The absorption of VIS is weak, only about 14.1% for the diffuse light and 19.2% for the collimated light. However, VIS transmittance is quite high, about 76.3% for both the diffuse and collimated light. It well explains that most VIS light can pass through the water-filled glass louver for natural illumination.

The ratio of diffuse intensity over total irradiation (diffuse + direct) varies with location, season, day, time, and weather condition. Each air mass value carries a diffuse ratio. To simplify the problem and inspect the effect of diffuse ratio, we assumed a varying diffuse ratio from 0.2 to 1.0 in Fig. 6, in which the glass/water/total solar energy absorption efficiencies and VIS transmittance are plotted. The collimated irradiation is of normal incidence. A unity diffuse ratio represents an opaque cloud. It is seen that as the diffuse ratio increases, the water absorption efficiency decreases obviously, but the glass absorption efficiency decreases slightly, and the VIS transmittance is nearly constant at 76%.

Table 2
Spectral properties of material in the 7-band model for AM1 to AM3 spectra. (D/C = Diffuse/Collimated).

AM#	λ (nm)	$n_{\text{glass}} \text{D/C}$	$n_{\text{water}} \text{D/C}$	$\alpha_{\text{glass}} (m^{-1}) \text{D/C}$	$\alpha_{\text{water}} (m^{-1}) \text{D/C}$	w (%) D/C
1	280–400	1.5440/1.5430	1.3427/1.3421	178.8291/122.8164	0.2288/0.1957	15.8004/4.3827
	400–548	1.5302/1.5300	1.3360/1.3360	5.1404/4.9238	0.0332/0.0322	32.3281/20.9044
	548–700	1.5218/1.5225	1.3312/1.3313	12.4456/12.8232	0.2540/0.2645	21.0546/21.4920
	700–850	1.5179/1.5177	1.3292/1.3300	33.7586/34.2335	2.3779/2.4048	12.5021/15.8989
	850–1100	1.5144/1.5142	1.3265/1.3268	54.4810/54.7346	31.0781/32.5442	10.3138/16.6866
	1100–1530	1.5101/1.5105	1.3227/1.3300	52.5434/51.8163	414.4431/445.388	5.0196/10.7063
	1530–4000	1.5028/1.5004	1.3114/1.3155	36.8057/58.4255	4749.797/22228.27	2.9813/9.9291
1.5	280–400	1.5433/1.5429	1.34251.3421	140.8555/102.5293	0.2188/0.1929	14.0626/4.575
	400–548	1.5303/1.5300	1.3360/1.3360	5.1727/4.9200	0.0332/0.0276	32.2913/21.288
	548–700	1.5237/1.5220	1.3314/1.3316	12.0604/12.8230	0.2433/0.2641	21.5228/21.643
	700–850	1.5183/1.5178	1.3293/1.3294	33.4190/34.1597	2.3592/2.4007	13.3306/16.195
	850–1100	1.5163/1.5143	1.3267/1.3268	54.1478/54.6798	30.1100/32.3981	10.6064/16.673
	1100–1530	1.5117/1.5104	1.3252/1.3230	53.1602/52.0098	410.5200/435.3489	5.0399/10.088
	1530–4000	1.5032/1.5010	1.3161/1.3148	41.6509/54.7049	4820.23/16225.80	3.1464/9.538
2	280–400	1.5435/1.5421	1.3424/1.3417	117.1738/67.9990	0.2098/0.1699	12.8113/2.6517
	400–548	1.5306/1.5300	1.3362/1.3358	5.1182/4.8575	0.03310/0.03198	31.4389/18.8876
	548–700	1.5222/1.5221	1.3316/1.3316	12.7025/12.9676	0.2609/0.2684	22.1045/21.7267
	700–850	1.5179/1.5178	1.3294/1.3294	33.7639/34.3443	2.3773/2.4123	14.3591/17.0348
	850–1100	1.5144/1.5143	1.3269/1.3268	54.4287/54.7573	30.7838/32.8206	11.3487/18.1428
	1100–1530	1.5106/1.5104	1.3231/1.3230	52.6458/52.0067	405.4809/435.6416	4.9797/10.8938
	1530–4000	1.5030/1.5008	1.3120/1.3146	37.4836/54.0303	4870.0826/13482.41	2.9578/10.6626
3	280–400	1.5432/1.5415	1.3422/1.3413	93.2615/45.9273	0.1995/0.1527	10.6891/1.6294
	400–548	1.5305/1.5230	1.3362/1.3357	5.0935/4.7952	0.0329/0.0317	30.0245/16.7002
	548–700	1.5221/1.5221	1.3316/1.3316	12.9135/13.1240	0.2665/0.2723	22.8236/21.4547
	700–850	1.5177/1.5178	1.3294/1.3294	33.7399/34.4443	2.3771/2.4197	16.009/17.9592
	850–1100	1.5144/1.5143	1.3269/1.3268	54.3858/54.7717	30.5717/33.0411	12.3565/19.5219
	1100–1530	1.5106/1.5104	1.3232/1.3230	52.8145/52.1138	401.1681/431.5246	5.1041/11.2553
	1530–4000	1.5029/1.5012	1.3123/1.3140	38.1175/51.1719	5198.3048/9167.434	2.9932/11.4793

Glass absorption efficiency is much larger than water absorption efficiency. The total energy absorption efficiency increases from 40.6% to 51.9% when the diffuse ratio declines from unity to 0.2. It means that the louver performs better under clearer sky condition. The louver under overcast clouds absorbs about 22% less solar energy than that under a clear sky.

Fig. 7 depicts the absorption/transmittance efficiencies vs. the incident angle of collimated irradiation. In Fig. 7(a) the polar angle of collimated incidence varies from 0° to 90° and the circumferential angle is fixed at $\phi = 0^\circ$. It is seen that the variation of absorption efficiency is smoother in the water than in the glass. This is because the glass medium is the first incident layer of the sunlight. The glass has a larger absorption coefficient and harvests nearly twice the solar energy than the water inside the louver. Initially, the total energy absorption efficiency increases, and the VIS transmittance decreases as the polar angle grows from zero to a small value (5°). Then, both the total absorption and VIS transmittance nearly flatten until 15° . After that, the total energy absorption efficiency reduces with increasing polar angle. For the VIS transmittance, however, the efficiency starts to increase after 15° to a maximum around 45° . After that, the VIS transmittance drops with enlarging angle. Both the absorption efficiency and transmittance drop rapidly after 75° . Under normal incidence (0°), the total absorption efficiency reaches 55.5%. At 5° , the total absorption efficiency reaches a maximum of 56.8%, and remains about 56% from 5° to 15° . This is because the incident light at 5° can travel longer distance inside the glass medium than the normal and other incident angles; and thus, more energy can be absorbed by the glass layer. At 20° , the efficiency drops to 51.1%. This drop is due to the reduction of effective glass area with increasing incident angle. At 75° , the total absorption efficiency further falls to 31.7%. After 75° , an abrupt drop occurs because of the increased reflectivity in the first glass-water interface. As for the VIS transmittance, it remains around 75% from 5° to 15° , and reaches a maximum of about 83.4% at 45° .

In Fig. 7(b) the circumferential angle of collimated incidence varies between 0° and 90° and the polar angle is fixed at $\theta = 20^\circ$. Because the louver geometry is symmetric, we only need to investigate the influence on circumferential angle in one octant. It is seen that as the

circumferential angle enlarges, the glass/water/total absorption efficiencies slightly increase, but the VIS transmittance slightly falls. The water/glass/total absorption and VIS transmittance efficiencies are 19.9%, 37.5%, 57.4%, and 72.9%, respectively at $\phi = 90^\circ$, and 18.8%, 32.4%, 51.1%, and 78.4%, respectively at $\phi = 0^\circ$. This is attributed to that the incoming light travels longer distance in the glass medium when the circumferential angle enlarges.

3.3. Effect of air mass spectrum

In addition to AM1.5, we further developed the 7-band model to incorporate AM1, AM2, and AM3, and listed the spectral band-averaged properties of water and glass for the four air mass coefficients in Table 2 for both diffuse/collimated irradiation. In the calculations, we used the spectral data of water from Hale and Querry (1973) and of silica glass from Herzberger (1942) and Rubin (1985). As scattering is negligible in glass and very weak in water, the values for scattering coefficients are not listed in the table. The simple model of the atmospheric radiative transfer of sunshine (SMARTS) developed by Dr. Christian Gueymard computes clear-sky spectral irradiances. In this and following sub-section, we obtained the solar spectra data from NREL SMARTS code (<https://www.nrel.gov/grid/solar-resource/smarts.html>) and calculated the diffuse ratio for each air mass spectrum. The diffuse ratio is 0.2635, 0.2232, 0.2426, and 0.2802, corresponding to AM1, 1.5, 2, and 3, respectively.

The air mass effect on solar energy absorption and transmittance in the respective UV, VIS and IR regions is shown in Fig. 8. It is seen that both UV and IR absorption in the louver is very strong for all the four AM spectra. The IR absorption efficiency is 80.3%, 79.8%, 76.8%, and 80.1% for AM1, 1.5, 2, and 3, respectively. The corresponding UV absorption efficiency is 86.2%, 83.5%, 70.9%, and 69.8%, respectively. Thus, the influence of air mass on IR absorption efficiency is weak; but the UV absorption efficiency decreases as air mass value increases. This is because the glass absorption coefficient for UV reduces as air mass value increases. The VIS absorption in the louver is weak, all below 20% for the four AM values; but VIS transmittance is quite high, reaching 75.4%, 76.3%, 74.0%, and 74.4% for AM1, 1.5, 2, and 3,

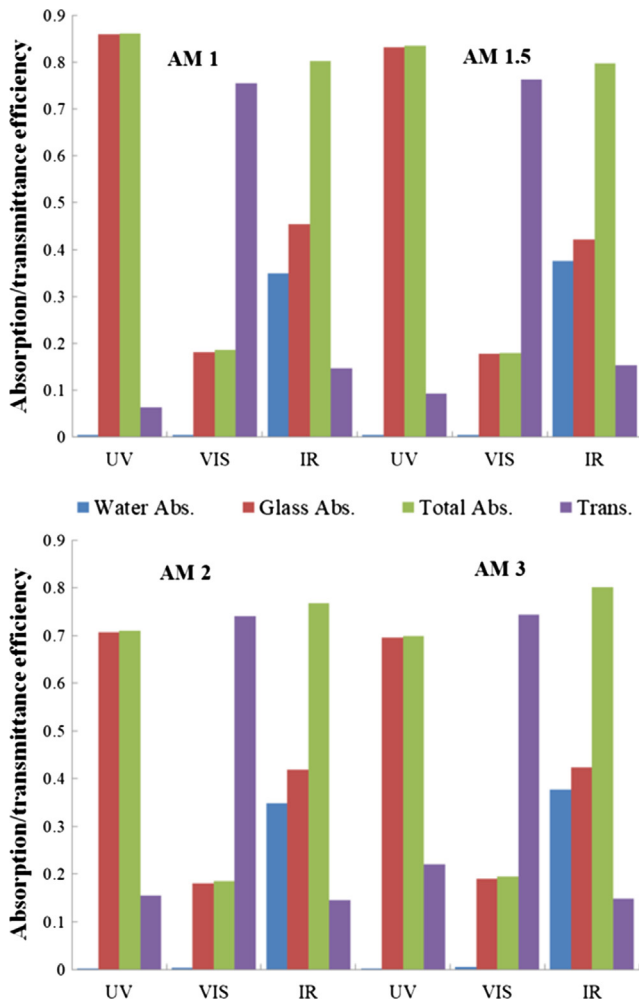


Fig. 8. Effects of air mass spectrum on solar energy absorption and transmittance in UV, VIS, and IR regions, respectively.

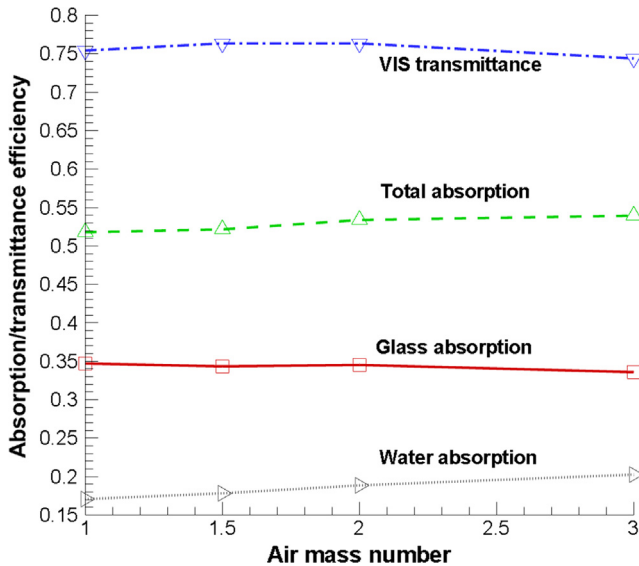


Fig. 9. Solar energy absorption efficiency and VIS transmittance vs. air mass coefficient.

respectively. Thus, the air mass does not affect much VIS transmittance.

Fig. 9 displays the effect of air mass value on water/glass/total absorption efficiencies and VIS transmittance. With increasing AM

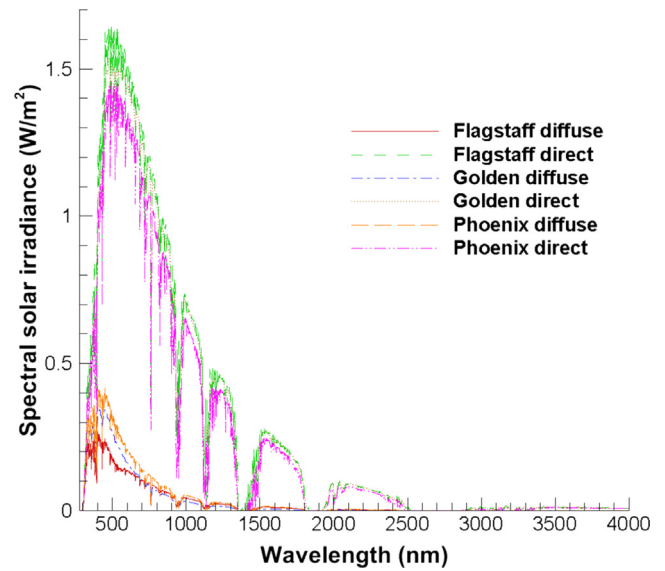


Fig. 10. Spectral solar irradiances at Flagstaff, Golden and Phoenix during summer time.

value, the water absorption efficiency increases, but the glass absorption efficiency decreases. The total absorption efficiency changes slightly, ranging from 51.8% to 53.9% for the four AM coefficients. The variation on VIS transmittance is also small. VIS transmittance varies between 74.4% and 76.3%. It should be mentioned that during the calculations, the collimated irradiation was assumed of normal incidence and the circumsolar and horizon brightening was ignored. When the louver is adjusted to face the direct sunlight, it will perform well for all air mass conditions.

3.4. Proof-of-concept study

As a proof-of-concept study to enable practical installation of the water-filled prismatic glass louvers, we calculated and compared the louver performance at three locations, i.e., Phoenix(P) and Flagstaff(F) in Arizona, and Golden(G) in Colorado, using solar data from the NREL SMARTS code. The spectral solar irradiances are plotted in Fig. 10 for both direct and diffuse irradiation. All the band-averaged properties for the three places are listed in Table 3. The diffuse ratio is 0.1046, 0.08633, and 0.1107 for P/F/G, respectively.

The solar spectrum for Flagstaff in a dry, desert-like environment was generated for AM1.2 at an elevated site at 34° latitude. The same summer atmosphere was used (20°C temperature, 30% relative humidity), but a default humidity-dependent aerosol model was selected. The UV irradiance was calculated on a receiver tilted 34° towards South (i.e., tilt = latitude). This geometry is such that near normal incidence is reached at the equinoxes. Because AM1.2 corresponds to a zenith angle of 33.59°, the incidence angle at solar noon on equinox days is 0.41°.

Solar noon time for specific mid-summer day, July 15, 2000, was considered in generating the solar spectrum for Phoenix (latitude 33.433N, longitude 112.007W). All gaseous abundances were defaulted from the reference atmosphere selected (MLS).

The spectrum for Golden was the output of a spectroradiometer under realistic conditions. The experiment took place at NREL, Golden, Colorado during the Summer of 2001. The basic atmospheric profiles were assumed to be described by the default MLS reference atmosphere. The site being relatively close to various pollution sources within the Denver urban area, the light pollution option was selected. The type of aerosol is not known, but is probably close to a rural model.

Fig. 11 shows and compares the absorption efficiency and transmittance in the three places. The collimated irradiation to the louver is

Table 3
Spectral properties of material for the three selected locations.^a

Place	λ (nm)	n_{glass} D/C	n_{water} D/C	α_{glass} (m^{-1}) D/C	α_{water} (m^{-1})D/C	w (%) D/C
Flagstaff, AZ	280–400	1.5447/1.5429	1.3431/1.3420	187.7624/121.8088	0.2347/0.1966	17.375/4.550
	400–548	1.5307/1.5300	1.3363/1.3359	5.1926/4.9302	0.0334/0.03229	30.029/21.058
	548–700	1.5227/1.5221	1.3314/1.3317	12.5969/12.8139	0.2582/0.2644	19.783/21.397
	700–850	1.5179/1.5179	1.3291/1.3302	33.9149/34.2280	2.3852/2.4041	12.367/15.787
	850–1100	1.5147/1.5145	1.3275/1.3267	54.5382/54.7290	31.2725/32.5010	10.632/16.574
	1100–1530	1.5103/1.5103	1.3227/1.3229	52.1497/51.7478	430.5059/448.4718	5.542/10.793
Phoenix, AZ	1530–4000	1.5032/1.5001	1.3165/1.3156	55.9517/59.4039	22437.77/25388.48	4.272/9.841
	280–400	1.5457/1.5427	1.3427/1.3418	183.0197/122.7706	0.2307/0.1960	21.449/4.537
	400–548	1.5308/1.5296	1.3363/1.3356	5.1831/4.9229	0.0333/0.03226	40.383/21.532
	548–700	1.5225/1.5215	1.3319/1.3311	11.9715/12.8030	0.2409/0.2639	20.223/22.11
	700–850	1.5187/1.5174	1.3294/1.3290	33.4706/34.2330	2.3658/2.4073	8.981/15.992
	850–1100	1.5143/1.5141	1.327/1.3267	54.1861/54.7311	29.5140/32.6616	5.882/16.370
Golden, CO	1100–1530	1.5109/1.5103	1.3233/1.3228	53.0507/52.0093	390.3912/443.6420	2.001/9.825
	1530–4000	1.5032/1.5004	1.3129/1.3147	38.5970/55.7801	45320.17/14727.21	1.081/9.634
	280–400	1.5441/1.5429	1.3428/1.3421	177.1455/118.5965	0.2302/0.1949	19.893/4.424
	400–548	1.5310/1.5230	1.3365/1.3359	5.1493/4.9157	0.0332/0.0321	38.456/20.663
	548–700	1.5217/1.5221	1.3304/1.3316	12.1313/12.8914	0.2455/0.2665	20.450/21.299
	700–850	1.5185/1.5178	1.3309/1.3294	33.6100/34.3250	2.3641/2.4061	9.878/15.865
	850–1100	1.5138/1.5143	1.3259/1.3268	54.2891/54.7780	29.8791/32.7004	6.947/16.793
	1100–1530	1.5132/1.5104	1.3289/1.3229	52.8717/51.7180	405.2632/451.1257	2.775/10.989
	1530–4000	1.5021/1.5005	1.3132/1.3153	44.5994/57.5710	31650.01/25722.35	1.601/9.967

^a NREL SMARTS code (<https://www.nrel.gov/grid/solar-resource/smarts.html>).

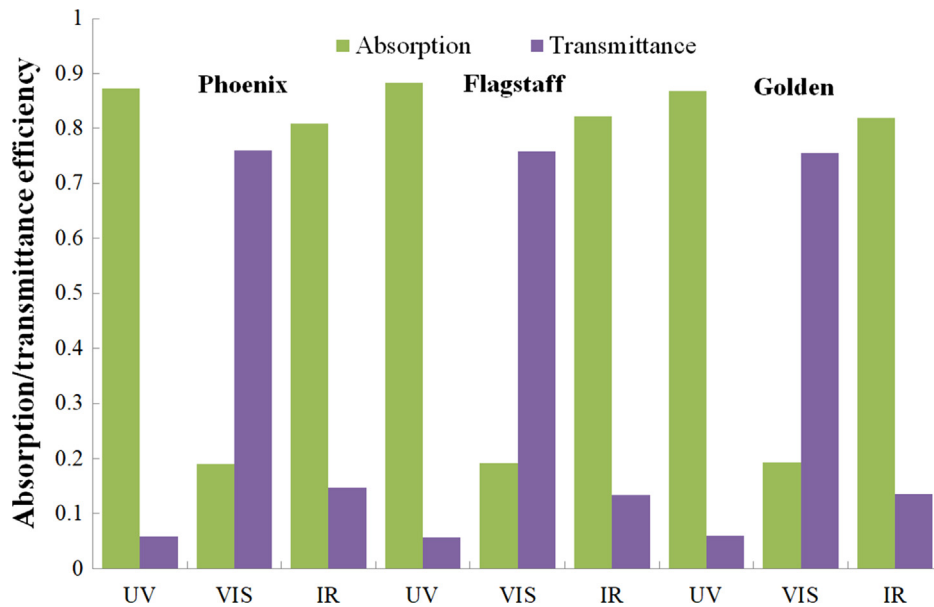


Fig. 11. Absorption/transmittance efficiencies in three places with practical solar data.

assumed to be normally incident. It is seen that the louver performs very well at all three places. The device absorbs 87.2%, 88.3%, and 86.9% UV light, and 80.9%, 82.2%, and 81.9% IR radiation in P/F/G, respectively. The VIS absorption is weak, about 18.9%, 19.2%, and 19.4% in P/F/G, respectively. The VIS transmittance is high, achieving 75.9%, 75.8%, and 75.5% in P/F/G, respectively. We also calculated the total solar energy absorption efficiency, which is 53.2%, 55.4%, and 56.1% in P/F/G, respectively.

4. Conclusions

The aim of this case study is to develop the 7-band spectral model for spectral investigation of solar irradiation under various solar spectra and conditions as well as to evaluate the performance of a water-filled prismatic glass louver to enable its practical use. The louver has dual-purpose: solar energy harvesting and daylighting. Both direct and diffuse irradiation were considered and compared. Differences of

absorption and transmission between water and glass and among the three distinct spectral regions, i.e., UV, VIS and IR, were examined and scrutinized. Performance under practical solar data at three places with realistic conditions was demonstrated. Some important conclusions can be summarized as follows:

The proposed louver can be used to harvest solar energy and improve daylighting effectively in different places under different conditions. The three practical examples in Phoenix and Flagstaff, Arizona, and Golden, Colorado show that the device can absorb 87–88% UV and 81–82% IR radiation energy, and transmit about 76% VIS light. The total solar energy absorption efficiency reaches 53–56% in the three places under testing conditions.

The influence of air mass value on the total absorption efficiency and VIS transmittance is very small. We considered AM1, 1.5, 2, and 3 spectra, and found that the total solar energy absorption efficiency ranges from 51.8% to 53.3%, and the VIS transmittance varies

between 74.4% and 76.3%. The air mass does affect the UV absorption efficiency, which is 86.2%, 83.5%, 70.9%, and 69.8% for AM1, 1.5, 2, and 3, respectively. The corresponding IR absorption efficiency is 80.3%, 79.8%, 76.8%, and 80.1%, respectively.

The change of solar energy absorption efficiency and VIS transmittance is very slight as the diffuse ratio varies. This further justifies that the proposed louver would work well in any location, season, and weather conditions.

Both the glass and water media absorb IR radiation strongly. The glass absorbs the UV strongly and some VIS light. The water absorbs little UV and VIS light. VIS transmittance is very high and the majority UV light can be blocked by the louver, reducing the risk of UV overexposure of occupants.

The incident polar angle of direct sunlight affects the solar energy absorption and VIS transmittance. The total energy absorption efficiency increases, and the VIS transmittance decreases slowly as the polar angle grows from zero to 5°. Then, both the efficiencies nearly flatten until 15°. After that, the energy absorption efficiency reduces with increasing polar angle; but the VIS transmittance starts to increase until a maximum around 45°. After that, the VIS transmittance drops with enlarging angle. In practice, a louver can be justified to face the sunlight within a small variation of polar angle (e.g., < 15°); and thus, the effect of incident angle should not be a concern. Further, the effect of the circumferential angle for the collimated incidence is not appreciable. With increasing circumferential angle, the energy absorption efficiency slightly increases, while the VIS transmittance slightly drops.

Through intensive comparisons among different spectral band models, it is certain that treating the solar spectrum as grey or simply dividing it into 3 bands is not good enough for accurately simulating solar radiation transfer through glass and water. With 20 and 40 bands, the accuracy improves, but the computation is time-consuming. The 7-band model works well as a compromise of balance between computational efficiency and accuracy.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.solener.2018.12.066>.

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