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Establishment and Verification of Solar Radiation Calculation Model of Glass Daylighting Roof in Hot Summer and Warm Winter Zone in China

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Abstract

In this paper, solar heat gain through glass daylighting roof is deeply studied by theoretical calculation method, taking Guangzhou in the Hot Summer and Warm Winter (HSWW) zone as an example. The direct solar radiation is calculated by Bouguer formula whereas the diffuse solar radiation is calculated by Berlage formula, representing the basis for the calculation method of the solar radiation intensity through the glass daylighting roof. Through the establishment of solar radiation calculation model, the solar heat gain of the commonly used glass types has been calculated and analyzed, especially comparatively analyzing of Low-E cored-glass with double-coated silver and 6+12A+6 insulating glass. Then, comparison between solar heat gain as calculated and measured by field measurement tested the indoor solar radiation heat gain distribution by using adjacent rooms with different glass types in a hot summer area, with the aim of demonstrating the effectiveness of the model. The research in this paper is expected to further improve the calculation accuracy of both thermal load and indoor temperature.

Keywords: Solar radiation; Indoor solar radiation heat gain; Glass daylighting roof.

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1. Introduction

Guangzhou is a solar energy resource rich area whose annual global solar radiation is 4279.58 MJ/m2 on average. The solar radiation is abundant in summer and less in winter, being the global solar radiation in summer 1.57 times higher that of winter. The average monthly radiation in July is as high as 475.22 MJ/m2, and the radiation intensity from 10:00 to 14:00 is more than 1.45 MJ/m2 (Liu Aijun et al. 2014[1]).

Glass daylighting roof has been widely used in shopping malls, airports and railway stations in recent years because of some benefits such as a free view to the outdoor, good visual effect, reduced light loads and short installation period. The major drawbacks are mainly due to overheating and high energy consumption for space cooling. Research by Dong Zizhong et al. (2003)[2] shows that solar radiation is the primary cause of worsening indoor temperature and increase of thermal loads in the hot summer area.

The outdoor solar radiation intensity and the optical parameters of the glass are important factors affecting indoor thermal comfort. Therefore, the indoor solar radiation heat gain through glass daylighting roof in summer solstice is obtained in this study by theoretical calculation, and then is compared with that of four common glass types, in order to provide useful suggestions for designing the optimal glass daylighting roof solution.

2. Radiation on the Earth's Surface in Sunny Days

The solar radiation received by a generic wall is related to the position of the sun in the space as related to that of the wall. In this paper, the solar radiation of earth surface in a sunny day is calculated by determining the position of the sun and the solar incident angle.

2.1. Position of Sun

Solar elevation β is the angle between the sun's rays and the horizontal plane, solar azimuth A is the angle between the projection of the sun to the ground and the local meridian (Zhu Yingxin et al.2005)[3].

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

$$\sin A = \frac{\cos\delta\sin h}{\cos\beta} \tag{2}$$

where φ is the geographical latitude of observation point, δ is declination angle indicating the change of season or date and h is hour angle showing the change of time.

$$\delta = 23.45\times\sin\left(360\times\frac{284+n}{365}\right) \tag{3}$$

$$\mathrm{h} = \left(T_m \pm \frac{L-L_m}{15} + \frac{e}{60} - 12\right)\times 15 \tag{4}$$

where n is serial number of the calculated date in a year, T_m is mean solar time zone, L is longitude of local meridian, L_m is longitude of the time zone's central meridian, e is the time difference, that is, the difference between the local true sun and the local mean sun.

The summer solstice day (June 21st) has been chosen as calculation date, and e is equal to two minute and twenty-three seconds.

The solar altitude angle and azimuth angle at any time can be calculated through the above formula. Taking Guangzhou as an example in this paper, the solar altitude angle and azimuth of the summer solstice day (June 21st) is calculated in Table.1, and it is consistent with the typical meteorological data.

Table.1 Solar altitude angle and azimuth of the summer solstice day

time	h	β	A
6:00	-97.33	2.78	-114.36
7:00	-82.33	15.59	-109.28
8:00	-67.33	28.78	-105.03
9:00	-52.33	42.21	-101.37
10:00	-37.33	55.80	-98.15
11:00	-22.33	69.50	-95.40
12:00	-7.33	83.26	-94.35
13:00	7.67	82.95	94.29
14:00	22.67	69.20	95.46
15:00	37.67	55.50	98.22
16:00	52.67	41.90	101.44
17:00	67.67	28.48	105.11
18:00	82.67	15.30	109.38
19:00	97.67	2.50	114.49

2.2. Solar incident angle on a generic surface

Wall solar incidence angle (θ) and wall solar azimuth angle (α) are introduced to describe the solar radiation on the wall surface, as introduced by Wu Jundi 2013[4]. θ is the angle between the direct rays of the sun and the normal surface of the wall. α is position of the sun relative to the wall, as well as the angle between the projection of the sun's rays on the earth's surface and the projection of the surface normal to the plane. These angles are exemplified in Figure 1.

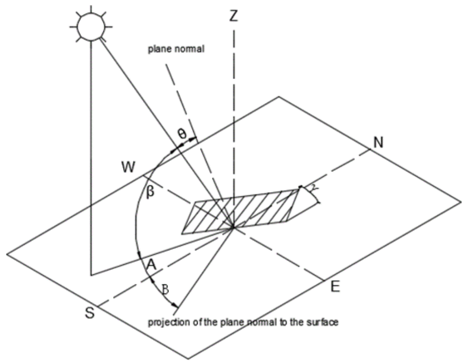

Fig. 1.angular relationship between the sun and the surface

Furthermore the angle γ is introduced (wall inclination angle), i.e. the angle between the wall and the ground plane, (a vertical plane is 90° sloped while a horizontal plane is 0° sloped). B, or wall azimuth, is the angle between the surface normal in the horizontal plane projection and South direction, being the west orientation assumed as positive and the east orientation as negative.

$$\alpha = A - B \tag{5}$$

$$\cos\theta = \cos\beta\cos(A+B)\sin\gamma + \sin\beta\cos\gamma \tag{6}$$

2.3. Solar radiation on earth's surface

Solar radiation reaching the earth surface consists of two components in cloudless sunny summer: one component is direct sunlight to the ground, called direct radiation; the other component is the atmospheric scattering to the ground, called diffuse radiation. Atmospheric longwave radiation to the ground after H_2O and CO_2 absorption is included as well in the calculation of the light received by daylighting .

According to the Bouguer formula, the direct solar radiation $I_{D\theta}$ on the surface is:

$$I_{D\theta} = I_o \cdot P^m \cdot \cos\theta \tag{7}$$

where I_o is the solar constant (1353W/m^2), P is atmospheric transparency (generally between 0.65-0.75), and m is the air quality whose analytical formulation is given by the following equation:

$$\mathrm{m} = (\sin\beta)^{-1} \tag{8}$$

According to the Berlage formula, the sky diffuse radiation I_d on the surface is:

$$I_d = \frac{1}{2} I_o \sin\beta \cdot \frac{1-P^m}{1-1.4\ln P} \cdot \frac{1+\cos\gamma}{2} \tag{9}$$

The ground reflected radiation Ir on the surface is:

$$I_r = \rho_g I_{S(\gamma=0)} \left(1-\cos^2\frac{\gamma}{2}\right) \tag{10}$$

where ρ_g is ground average reflectance, being typical average reflectance values of land surface between 10-35%. $I_{S(\gamma=0)}$ is defined as the total solar radiation intensity on the horizontal surface in the cloudless day.

Hence the total solar radiation intensity reaching the ground I_S is:

$$I_S = I_{D\theta} + I_{DS} = I_{D\theta} + I_d + I_r \tag{11}$$

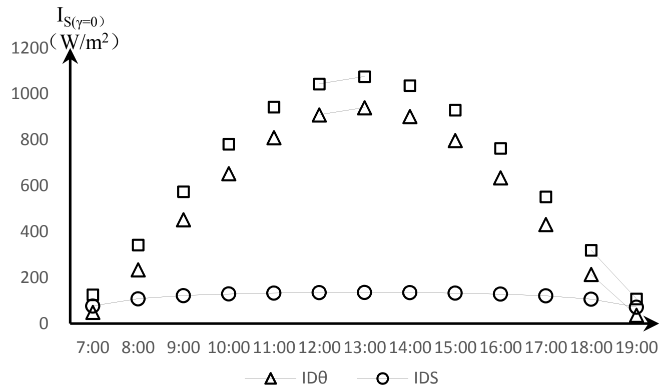

Figure 2. at the summer solstice

According to the above formulation, the horizontal solar radiation intensity received at the summer solstice has been calculated and it is shown in Figure.2. It can be seen from this figure that the solar radiation intensity of the horizontal plane is symmetrically distributed along the local noontime, and reaches the maximum value at 12:00.

The mean value of $I_{D\theta}$ is 494.61W/m2, the mean value of I_{DS} is 106.77W/m^2, and the diffuse radiation accounts for about 18% of the total radiation.

3. Solar Radiation Heat Gain Calculation

The solar radiation heat gain (SHG) through the glass is calculated by means of the following equation:

$$\text{SHG} = \left(SG_{D\theta} \cdot x_g + SG_{DS}\right) \cdot SC \cdot x_f \cdot F = \left(I_{D\theta} \cdot g_{D\theta} \cdot x_g + I_{DS} \cdot g_{DS}\right) \cdot SC \cdot x_f \cdot F \quad (12)$$

$SG_{D\theta}$ is direct solar radiation heat gain. SG_{DS} is diffuse solar radiation gain. g is heat gain coefficient. SC is shading coefficient. F is glass area. x_g is the ratio of the sun actual area, equal to the ratio of actual area (spot area) and the glass area. x_f is glass effective area coefficient.

$g_{D\theta}$ is influenced by glass type, number of panes and so on. Its empirical polynomial function is shown below (J. Karlsson et al. 2000)[5]:

$$g_{D\theta} = g(0) \cdot \left(1 - az^{\mu} - bz^{v} - cz^{w}\right) \quad (13)$$

where z=θ/90; a=8;b=0.25/q;c=(1-a-b);μ=5.2+0.7q;v=2;w=(5.26+0.06p)+(0.73+0.04p)q.

g(0) is the direct solar heat gain coefficient for normal direction of sunrays. p isequal to the number of panes.. q is the glass type parameter, and values 1-10 according to the different glass and film.

g_{DS} approximately equal to $g_{D(\theta=60°)}$ by integral calculation, because diffuse radiation comes from all directions of the sky.

$$g_{DS} = 2\int_0^{\frac{\pi}{2}} g_{D\theta} \cdot \sin\theta \cos\theta d\theta \approx g_{D(\theta=60°)} \quad (14)$$

4. Solar Radiation Heat Gain of Difference Glass Types

Different glass forms, such as insulating glass, Low-E glass, heat reflective glass, laminated glass and so on, has been widely used in the lighting roof currently. This paper calculates and analyses solar radiation heat gain of different lighting roof glass types under the assumption of horizontal lighting roof without any shading and under sunny weather. These glass types are 6mm thick single glass, 6mm thick single toughened glass with heat reflecting film, 6+12A+6 insulating glass and Low-E cored-glass with double-coated silver. $g_{D\theta}$ is obtained by relevant parameters provided by the manufacturer together with the corresponding q value., Table.2 details all the relevant parameters used for each glazing type.

Table.2 Calculation of different glass types'

NO.	Glass type		SC	q	$g_{D\theta}$
1	6mm thick single glass	0.74	0.85	4	
2	6mm thick single toughened glass with heat reflecting film	0.70	0.80	10	
3	6+12A+6 insulating glass	0.58	0.67	4	
4	Low-E cored-glass with double-coated silver	0.38	0.44	2	

The solar heat gain coefficient of each glass at different incident angles is obtained through the above calculation, shown in Figure.3. It is found that the inflection point of all glass types' g_D value appears in the range of 50°-60°

incidence angle. The total solar radiation intensity reaching the ground at horizontal plane is greater than 600W/m2 during 9:00-16:00 when the incident angle is less than 50°.

The influence of glass type on solar radiation is mainly reflected in the solar heat gain coefficient $g_{D\theta}$ and shading coefficient SC from Equation (12). It is worth to point out that two conditions are assumed in this paper when calculating the solar radiation heat gain per unit area: (1) the horizontal glass lighting roof is without occlusions and shading devices, that is, x_g=1; (2) the exposure effective area of glass roof is the whole glass area, that is, x_f=1 . The solar radiation heat gain through glass is thus calculated and shown in Figure.4.

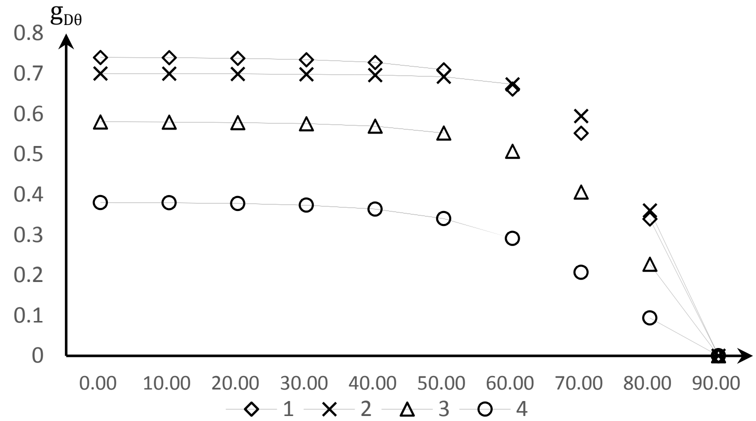

Figure.3 of glass types at different incident angles

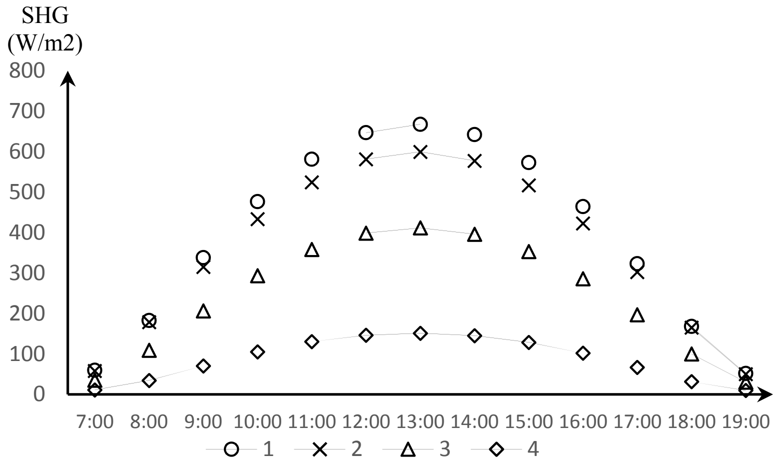

Figure.4 Solar radiation heat gain through the glass SHG of glass types

It can be seen from Figure.4 and Figure.2 that the trend of the solar radiation heat gain through the glass is the same as for that of the horizontal solar radiation intensity. The average total solar radiation heat gains of 6mm thick single glass, 6mm thick single toughened glass with heat reflecting film, 6+12A+6 insulating glass and Low-E cored-glass with double-coated silver were 375.69, 345.96, 230.36 and 81.91W/m2 respectively. The average indoor solar radiation heat gain through 6mm thick single toughened glass with heat reflecting film, 6+12A+6 insulating glass and Low-E cored-glass with double-coated silver is 0.91, 0.61 and 0.22, as much as that of 6mm thick single glass.

Ding Yong et al.(2014)[6] tested the indoor solar radiation heat gain by using adjacent rooms with different glass types in a hot summer area, and it is found that the average indoor solar radiation heat gain through the Low-E insulating glass and the ordinary insulating glass is 0.24 and 0.73 as much as that of single layer glass. The measured results are basically consistent with the theoretical analysis results in the case of the thermal insulation performance of Low-E cored-glass with double-coated silver is better than that of Low-E insulating glass. It can be seen that Low-E cored-glass with double-coated silver has better heat insulation and energy saving effect than that of 6mm thick single glass, 6mm thick single toughened glass with heat reflecting film and 6+12A+6 insulating glass.

5. Conclusions

Trend of the solar radiation heat gain through glass is found to be the same as that of the horizontal solar radiation intensity reaching the ground, thus informing the choice of the appropriate shading control strategy. For example, automatic sun shading curtain should be closed during the day 9:00-16:00 to reduce direct radiation when the summer heat insulation.

The average indoor solar radiation heat gain through 6mm thick single toughened glass with heat reflecting film, 6+12A+6 insulating glass and Low-E cored-glass with double-coated silver is 0.91, 0.61 and 0.22, as much as that of 6mm thick single glass. Low-E cored-glass with double-coated silver has better heat insulation and energy saving effect.

Solar heat gain coefficient g changes with the change of the direct radiation angle, thus affecting the indoor solar radiation heat gain. Therefore, in the calculation of indoor solar radiation heat gain, it should be considered not only glass thermal insulation properties, but also the local time distribution of the solar radiation to the glass lighting roof.

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