Daylighting simulation and experimental validation of granular aerogel glazing system

Dongmei Zheng\textsuperscript{1,2}, Youming Chen\textsuperscript{1,2}
\textsuperscript{1}College of Civil Engineering, Hunan University, Changsha, Hunan 410082, China
\textsuperscript{2}Key Laboratory of Building Safety and Energy Efficiency of the Ministry of Education, Hunan University, Changsha, Hunan 410082, China

Abstract
Windows have great effects on daylighting, visual comfort, and energy-saving. As an innovative glazing, the daylighting simulation accuracy of the granular aerogel glazing system (AGS) has not been validated. In this study, the optical properties of AGS were tested and the haze of AGS was calculated. The bi-directional scattering distribution function (BSDF) data of AGS were generated by the Radiance tool genBSDF. The 3-phase method in Radiance was used to simulate the daylighting performance of AGS. An in-field experiment with an AGS window was conducted to validate the simulation accuracy. Besides, the influence of haze on the daylighting simulation was discussed. The results showed that the accuracy of the introduced daylighting simulation method for AGS is reliable. The relative mean bias error (rMBE) and the relative root mean square error (rRMSE) of the simulated illuminance were within 8.6\% and 14.5\%, respectively. Additionally, the haze may have a great influence on the daylighting simulation, especially for the AGS with lower haze.

Highlights
- A daylighting simulation method considering the haze of aerogel glazing is introduced.
- An in-field experiment with an aerogel glazing window was conducted.
- Daylighting simulation method for aerogel glazing was validated by experiment.
- The influence of haze on daylighting simulation was discussed.

Introduction
Daylight has positive effects on productivity, satisfaction, visual comfort, well-being, and the energy-saving of artificial lighting (Galasiu and Veitch, 2006). In buildings, windows play the most important role in daylighting, visual comfort, and energy conservation. Therefore, special attention should be paid to the daylighting performance of windows.

Aerogel glazing system (AGS) is an innovative window with excellent thermal insulation performance, moderate translucent properties, specific acoustic properties, good durability, and aesthetic characteristics. AGS is constructed by filling granular or monolithic silica aerogel into the middle cavity of the double-glazed system.

Although the visible transmittance of granular AGS is lower than that of monolithic AGS (Buratti and Moretti, 2012), and the external vision of granular AGS is limited, granular AGS remains popular due to its commercialization. Due to the three-dimensional network nanoporous structure of silica aerogel, AGS has special scattering optical properties, which distinguishes it from other conventional glazings.

The daylighting performance of AGS was commonly investigated by experiment and simulation. Cotana et al. (2014) evaluated the lighting performance of granular AGS by monitoring the average horizontal illuminance in a prototype building in Perugia, Italy. Moretti et al. (2019) investigated the daylighting performance of AGS by comparing the horizontal illuminance in 2 measuring points. Zheng et al. (2020) investigated the daylighting performance of granular AGS skylights by comparing the horizontal illuminance close to the skylights. These experimental studies only investigated the daylighting performance of AGS in limited measuring points, limited locations, and periods. Monitoring the annual illuminance distribution of AGS in different regions by experiment poses significant challenges as it is expensive and time-consuming.

Simulation is more efficient in evaluating the daylighting performance of AGS. Garnier et al. (2015) used the daylight factor method and the CIE overcast sky model to calculate the indoor illuminance of AGS. However, the building sites, climate, and periods can not be considered by the daylight factor method. Belloni et al. (2021) simulated the illuminance of aerogel glazings with hollow silica by EnergyPlus. However, the daylighting simulation accuracy of EnergyPlus has been validated to be poor, especially in positions close to the window (Ramos and Ghisi, 2010). Huang and Niu (2015) simulated the horizontal illuminance of offices by Radiance. Khaled Mohammad and Ghosh (2023) simulated the illuminance distribution of AGS by Ecotect. However, there were no detailed simulation settings regarding the special optical scattering properties of AGS. Moreover, the accuracy of these simulation tools to simulate the daylighting performance of AGS has not been validated by experiment.

In this study, a daylighting simulation method for AGS was introduced and validated. The optical properties of a
granular AGS were tested. The bi-directional scattering distribution function (BSDF) data of AGS were generated by the Radiance tool genBSDF. The 3-phase method in Radiance was used to simulate the daylighting performance of AGS. The haze of AGS was considered in the simulation. An in-field experiment with an AGS window was conducted. The simulated horizontal illuminance in the front, middle, and back positions away from the window, as well as the vertical illuminance at eye level, was validated by the experiment. The relative mean bias error (rMBE) and the relative root mean square error (rRMSE) were used as statistical indicators to evaluate the simulation accuracy. Finally, the influence of haze on the daylighting simulation of AGS was discussed.

Methodology

Optical measurements

The research object of this study is the granular silica AGS with particle size (~2.5 mm) and structure (8 mm float glass + 14 mm aerogel interlayer + 8 mm float glass). Two pieces of AGS with different sizes were supplied by an advanced material technology company from China. The size of the small AGS sample is 0.15 m × 0.15 m, as shown in Figure 1. The size of the AGS installed in the in-field experiment is 1.57 m (width) × 1.26 m (height), as shown in Figure 5.

![Figure 1: Small granular AGS sample.](image)

To characterize the optical properties of the granular AGS, a Perkin Elmer Lambda 1050 spectrophotometer with a 150 mm diameter integrating sphere was used. The total and diffuse transmittance or reflectance were measured by controlling the transmission or reflection port close or open (American Society for Testing and Materials, 2013). The spectral transmittance and reflectance of the AGS are shown in Figure 2. The total and diffuse visible transmittance and reflectance of the AGS are 0.43, 0.41, 0.13, and 0.07, respectively.

The haze is defined in Equation (1), which reflects the reduction in contrast of objects viewed through it (Zhao et al., 2019). The material is the perfect Lambertian diffuser when the haze is equal to 1. Conversely, the material is transparent and specular when the haze is equal to 0. The haze of the AGS is 0.967, indicating that AGS has great scattering optical properties.

\[
haze = \frac{T_{\text{diffuse}}}{T_{\text{total}}} \tag{1}\]

where \(T_{\text{total}}\) is the total transmittance; \(T_{\text{diffuse}}\) is the diffuse transmittance.

![Figure 2: Spectral transmittance and reflectance of the granular AGS sample.](image)

Experimental setup

To validate the accuracy of the daylighting simulation method for AGS, an experiment platform was built on the roof of a building at Hunan University located in Changsha, China (112.9E, 28.22N). The internal dimensions of the test room are 2.03 m × 2.14 m × 2.49 m in width, depth, and height. The size of the AGS window is 1.57 m (width) × 1.26 m (height). The height of the window sill in each room is 0.8 m. There is a long parapet (with a thickness of 0.5 m and a height of 0.7 m) at 2.4 m in front of the test room. The reflectance of the wall, ceiling, carpet, and parapet were about 0.65, 0.65, 0.12, and 0.1, which were simply measured by an illuminance meter T-10A. The positions of all measuring points are shown in Figure 3.

![Figure 3: Arrangement of measuring points (dimensions in meters).](image)

In monitoring the outdoor environment, as shown in Figure 4, solar pyranometer TBQ-2, diffuse solar pyranometer TBD-1, and illuminance meter TBQ-6 were placed on the outdoor platform to measure the outdoor total horizontal irradiance, diffuse horizontal irradiance, and total horizontal illuminance. The indoor view of the AGS test room is shown in Figure 5. Three TBQ-6...
illuminance meters were placed horizontally at the height of 0.75 m in front, middle, and back positions (away from the window by 0.5 m, 1.0 m, and 1.5 m, respectively). An illuminance meter T-10A was positioned vertically toward the window at the eye height of seated persons, i.e., 1.2 m. The specification of the test instruments is listed in Table 1. Sensing signals from all sensors, except for the illuminance meters T-10A, were collected automatically by an Agilent data logger to a laptop every minute from 7:00 AM to 18:00 PM when the outdoor illuminance is relatively higher. The illuminance of the illuminance meter T-10A was collected automatically every minute by a specific software offered by the Konica Minolta on the same laptop. The data acquisition time was synchronized.

Simulation method

Dynamic daylighting simulation is essential for evaluating the annual hourly daylighting performance of different windows in different regions and orientations. To balance the simulation accuracy and speed, the three-phase method (McNeil, 2014) based on matrices in Radiance was used in this study. Radiance is a physically accurate software tool employing the light-backwards ray-tracing algorithm and irradiance caching algorithm (Ward and Shakespeare, 1998). The three-phase method divides the flux transfer into three phases according to the opposite process of the light penetrating: The internal space to the interior of fenestration; Transmission through fenestration; The exterior of fenestration to sky. A matrix is used to characterize each phase of light transport. The illuminance values are calculated by the following equation (McNeil, 2014):

\[ I = VTDS \]

where \( I \) is the matrix containing the time series of illuminance; \( V \) is the view matrix, represents the flux transfer from the internal space to the interior of fenestration; \( T \) is the transmission matrix, represents the flux transfer transmitting through fenestration; \( D \) is the daylight matrix, represents the flux transfer from the exterior of fenestration to sky; \( S \) is the sky matrix.

The detailed simulation method for each matrix, especially for the transmission matrix of AGS is described below:

(1) Transmission matrix. Due to the special scattering optical properties of aerogel, AGS is a complex fenestration system. The BSDF data were generated to describe the transmission matrix. Since the scanning goniophotometer used for measuring the BSDF data is very limited in the world and the measurement is expensive and time-consuming, the Radiance tool genBSDF based on the ray-tracing algorithm was used to generate the BSDF data of AGS (McNeil et al., 2013). The trans material type was used for describing the AGS. The specular transmittance and reflectance of AGS can be calculated according to the measured total and diffuse transmittance and reflectance. The surface roughness of AGS is assumed to be 0. The haze of AGS is considered in the last item of the material description. The last item is equal to 1-haze. All material primitives in Radiance are defined in a fixed syntax format. When the above parameters are known, the trans material of AGS can be created according to the calculation method in the book Rendering with Radiance (Ward and Shakespeare, 1998), as shown in Figure 6. The 7 parameters in the last row are RGB color, specularity, roughness, transmissivity, and transmissive specularity.

![Figure 4: Testing instruments in the outdoor platform.](image)

![Figure 5: Inside view of the AGS test room.](image)

Table 1: Instrument specification.

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar pyranometer TBQ-2</td>
<td>0~2000 W/m²</td>
<td>±2%</td>
</tr>
<tr>
<td>Solar pyranometer TBQ-1</td>
<td>0~2000 W/m²</td>
<td>±2%</td>
</tr>
<tr>
<td>Illuminance meter TBQ-6</td>
<td>0~20000 lx</td>
<td>±5%</td>
</tr>
<tr>
<td>Illuminance meter T-10A</td>
<td>0.01~299900 lx</td>
<td>±2%</td>
</tr>
</tbody>
</table>

Figure 6: trans material type for the AGS.

Then, a polygon with trans material type was used to generate the BSDF data of AGS by the Radiance tool genBSDF. The low-resolution BSDF is sufficient for the illuminance simulation with the three-phase method. The number of sample rays per Klem's division is set to 1000.
The number of ambient divisions is set to 7000. The example BSDF data of AGS in two incident patches is shown in Figure 7. It is observed that the haze property of AGS is considered. The transmittance in the specular patch with the same number as the incident patch is larger. Moreover, the visible direct-hemispherical transmittance is changed with the incident patch.

(2) View matrix and daylight matrix. The room model was built in SketchUp according to the actual dimensions in the experiment, and then transformed into a Radiance model through the plug-in su2rad. The ground plane with a visible reflectance of 0.12 and the exterior parapet with a visible reflectance of 0.1 were also modeled outside the room. The material type plastic was used for the wall, ceiling, carpet, and ground plane. After the geometries, materials, and indoor calculation points were determined, the view matrix and daylight matrix can be simulated by the Radiance tool rfluxmtx.

(3) Sky matrix. In the CIE sky model, the sky type needs to be chosen manually, which may be less accurate. The Perez sky model was used in this study because the luminous distribution of the sky can be automatically generated based on site longitude, latitude, meridian, time, direct-normal irradiance, and diffuse horizontal irradiance. The sky matrix can be simulated by the Radiance tool gendaymtx. In this study, the diffuse horizontal irradiance was measured; the direct-normal irradiance is calculated according to the measured total and diffuse horizontal irradiance:

\[ E_{\text{normal}} = \frac{E_{\text{total}} - E_{\text{diffuse}}}{\sin h} \]  

where \( E_{\text{normal}} \) is the direct-normal irradiance (W/m²); \( E_{\text{total}} \) is the total horizontal irradiance (W/m²); \( E_{\text{diffuse}} \) is the diffuse horizontal irradiance (W/m²); \( h \) is solar altitude angle (°).

**Validation criteria**

The relative mean bias error (rMBE) and the relative root mean square error (rRMSE) are used as statistical indicators to evaluate the accuracy of the daylighting simulation methods. According to the studies of Reinhart and Breton (2009), simulation results are considered reliable if the rMBE is less than 20% and the rRMSE is less than 32%.

\[
\text{rMBE} = \frac{\sum (I_{\text{simulation}} - I_{\text{measure}})}{\sum I_{\text{measure}}} \times 100\%  \tag{4}
\]

\[
\text{rRMSE} = \frac{\sqrt{\sum (I_{\text{simulation}} - I_{\text{measure}})^2}}{\text{Mean} (I_{\text{measure}})} \times 100\%  \tag{5}
\]

where \( I_{\text{simulation}} \) is the simulated illuminance (lx); \( I_{\text{measure}} \) is the measured illuminance (lx).

**Results and discussion**

The experiment was conducted in September. Two sunny days (September 29th-30th, 2022) near the autumnal equinox were selected as representatives. The measured outdoor diffuse horizontal irradiance, the measured outdoor horizontal illuminance, and the calculated direct-normal irradiance are shown in Figure 8.

**Horizontal illuminance**

The measured and simulated horizontal illuminance in the front, middle, and back positions are shown in Figure 9. It is found that the simulated horizontal illuminance in the morning and afternoon is a little higher than that of the measurement. This may be caused by the constant transmittance set in the trans material type or the error of the Radiance tool genBSDF for generating the BSDF data at larger solar incident angles. The simulated horizontal illuminance is lower than the measurement at noon. That may be caused by inadequate internal reflection in simulation. The rMBE of the horizontal illuminance in the
front, middle, and back positions are 4.8%, -3.4%, and -5.2%. The rRMSE of the horizontal illuminance in the front, middle, and back positions are 11.1%, 13.5%, and 14.5%. Therefore, the accuracy for simulating the horizontal illuminance of AGS is reliable.

and lower at noon. The rMBE and rRMSE of the simulated vertical illuminance are 8.6% and 12.9%. The accuracy of the simulated vertical illuminance is also reliable.

**The influence of haze on daylighting performance**

AGS is commonly treated as perfect Lambertian diffusers. However, the haze property of AGS is considered in the daylighting simulation in this study. To determine the effect of haze on the daylighting simulation of AGS, the horizontal and vertical illuminance of AGS with different haze were simulated and compared. Although the haze for the granular AGS may be higher, the haze of the monolithic AGS can be as lower as 0.139 (Zhao et al., 2019). Therefore, the haze of AGS was set at 0.2-1.0, with an interval of 0.2. The AGS is treated as the perfect Lambertian diffuser when the haze is set to 1. The calculated haze of the AGS from the measurement is 0.967. Other Settings are consistent with the original simulation.

The simulated horizontal illuminance in front, middle, and back positions with different haze is shown in Figure 11. It is found that the horizontal illuminance in the front and middle positions increases with the decrease of haze. However, the horizontal illuminance in the back position decreases with the decrease of haze. Moreover, the influence of haze on the horizontal illuminance in the front position is higher than that in deeper positions. Since the direct sunlight is likely to be higher in the front position, and the specular transmittance tends to be higher when the haze is lower, the horizontal illuminance tends to be higher when the haze is lower. Moreover, direct sunlight is significantly higher than diffuse sunlight. Therefore, the influence of haze on the horizontal illuminance in the front position is the largest. However, the horizontal illuminance on the back position is more likely to be influenced by indirect light. Since the scattering effect of AGS decreases with the decrease of haze, the horizontal illuminance decreases with the decrease of haze. It is also found that the hypothesis of the perfect Lambertian diffusers for AGS may have great errors. The hypothesis of the perfect Lambertian diffusers

**Vertical illuminance**

The measured and simulated vertical illuminance at eye level is shown in Figure 10. The trend of the measured and simulated vertical illuminance is similar to that of the horizontal illuminance. The simulated vertical illuminance is also higher in the morning and afternoon...
tends to underestimate the horizontal illuminance in the front and middle positions and tends to overestimate the horizontal illuminance in the back position.

The simulated vertical illuminance at the eye level with different haze is shown in Figure 12. It is found that vertical illuminance also decreases with the decrease of haze. This is because vertical illuminance is also mainly influenced by indirect sunlight. Comparing the illuminance with different haze, it is also found that the haze may have a great influence on the vertical illuminance simulation. The hypothesis of the perfect Lambertian diffusers tends to overestimate the vertical illuminance at eye level.

**Conclusion**

To better simulate the dynamic daylighting performance of AGS, a daylight simulation method based on the three-phase method in Radiance was introduced and validated by an experiment. The conclusions are drawn as follows:

- The accuracy of the simulated horizontal and vertical illuminance is reliable. The rMBE of the horizontal illuminance in the front, middle, and back positions are 5.9%, -7.4%, and 3.6%. The rRMSE of the horizontal illuminance in the front, middle, and back positions are 12.1%, 18.1%, and 11.8%. The rMBE and rRMSE of the simulated vertical illuminance are 8.7% and 13.8%.

- The haze of AGS may have a great influence on the daylighting simulation, especially for the AGS with lower haze. The hypothesis of the perfect Lambertian diffusers for AGS may underestimate the horizontal illuminance in the front and middle positions, and overestimate the vertical illuminance and the horizontal illuminance in the back position.

The research outcome of this study could provide reference and guidance for simulating the dynamic daylighting performance of AGS, which is beneficial for building designers and engineers to better promote and reasonably apply the AGS in the process of building daylighting design.

**Acknowledgement**

The authors would like to express their gratitude to the National Natural Science Foundation of China (Grant no. 51678227) and the “13th Five-Year” National Key R&D Project of China (Grant no. 2017YFC0702201) for the financial support.

**References**


