Analysis of the Transmission Spectrum of Flat Glass from Near-infrared to the Ultraviolet

Hongjun Hu[*]

Teensen Genesis School, Nanchang, China

*Corresponding author: writing@pathacademics.org

Abstract. Contemporarily, glass windows have a great impact on human beings' daily life. It is crucial to design a glass with a reasonable thickness with a high transmission of visible light as well as a high reflection of near infrared light. In general, reflection from the glass surface and absorption of light waves by the glass material are important features for transmission. Therefore, for UV-visible near-infrared light waves, the greater the thickness of the glass, the greater the light absorption loss and the lower the transmission rate. However, it is believed that there are multiple reflections of light waves in flat glass and that the losses caused by reflections should also be related to the refractive index of the glass and the wavelength of the incident light. On this basis, this study has developed theoretical models of transmittance versus incident light wavelength and glass thickness, refractive index and absorption coefficient. According to the theoretical analysis, the thickness of the glass has a significant effect on the transmission spectrum of sunlight. To experimentally verify this theoretically predicted anomaly, this paper designed the experimental and measurement route and built the experimental test rig. A variety of glass samples in the thickness range of 1mm-10mm were designed and prepared for this project, and the UV-Vis-NIR transmission of the glass was scanned and measured, while the final measurement results observed anomalies in the variation of transmission with thickness. The experimental results, therefore, provide valid support for the theoretical model of this paper.

Keywords: Glass; transmission spectrum; anomalies.

1. Introduction

As a matter of fact, the high indoor temperatures in summer are mainly caused by the sun's near-infrared wavelengths entering the room, so people need to run the air conditioning 24 hours a day to maintain a comfortable indoor temperature, using a lot of electricity. There have been many attempts to reduce the amount of near-infrared energy coming through the windows to cool the room. There are plenty of studyies that focuses on evaluating the performancing of glass to inhibit temperature growing [1-4]. In 2018, Zhongyuan Yuchen (Beijing) Construction Planning Company Limited conducted an in-depth study on the thermal insulation performance of low-E glass [1]. They investigated the effect of raw glass on the thermal insulation performance, and found that increasing the thickness was not effective in reducing the K-value of insulating glass. Unexpectedly, however, they found that the single silver high transmittance type of LOW-E glass had a light transmittance of 83% [5, 6]. Based on this research of Ref. [1], they found that the position of the coating surface also affects the thermal insulation performance, with the second or third layer of glass having the lowest heat transfer coefficient and the first layer of glass having the highest heat transfer coefficient. They also concluded from their research that the laminated gas in the original insulating glass is also a very important factor, because the lower the gas conductivity of the laminated gas, the better the insulating properties of the insulating glass.

In 2021, 3M China Ltd. also conducted a study on light transmission, where they tested the NIR-blocking performance of multilayer optical films, metal coatings, and ceramic insulating films at a light transmission of about 70% [7]. It was found that the multilayer optical films had light transmittance of 30% to 70% for visible light and only 0% to 2% for infrared light from 800nm to 1200nm, which is the lowest of the three films mentioned above and can block infrared light very well. However, the transmittance of sunlight in the 1200nm to 1500nm wavelength range is 5% to 20%, which is much higher than the other two films with a transmittance of 2% to 10%. Metal

coatings have a slightly higher transmittance of visible light, 30% to 72% [8]. A much higher transmittance of infrared light in the 800nm to 1200nm range, 10% to 20%, than multi-layer optical films. Ceramic films have the highest visible light transmission of the three films at 30% to 80%, while the 800nm to 1500nm transmission is similar to that of metal coatings [9].

As can be seen from the above description, the transmittance of all three films in the visible band is less than 70%, which affects the light transmission effect. Therefore, it is important to research and develop a material with high transmittance in the visible band and high reflectance in the near infrared band, which can be expected to have important applications in our daily lives. This study therefore starts with the interaction of optical radiation in the ultraviolet, visible and near infrared wavelengths with glass. Subsequently, it will focus on the physical mechanism of the effect of glass thickness on transmission rates.

2. Theoretical Analysis

2.1. Transmission of Glass with a Semi-infinite Thickness

Sunlight shines into a semi-infinite thick glass and, according to the boundary conditions, the tangential electric and magnetic fields at the air-glass interface are continuous. Based on Faraday's law, Snell's Law and boundary conditions, one derives the reflection and transmission equations:

$$R_{\parallel} = \frac{|E_{ro,\parallel}|^2}{|E_{io,\parallel}|^2} = |r_{\parallel}|^2 \tag{1}$$

$$R_{\perp} = \frac{|E_{ro,\perp}|^2}{|E_{io,\perp}|^2} = |r_{\perp}|^2 \tag{2}$$

$$T_{\parallel} = \frac{n_2|E_{to,\parallel}|^2}{n_1|E_{io,\parallel}|^2} = \frac{n_2}{n_1}|t_{\parallel}|^2 \tag{3}$$

$$T_{\perp} = \frac{n_2|E_{to,\perp}|^2}{n_1|E_{io,\perp}|^2} = |t_{\perp}|^2 \tag{4}$$

if only vertical incidence is considered, i.e., $\theta = 0°$ the case of

$$R = R_{\perp} = R_{\parallel} = \left(\frac{n_1-n_2}{n_1+n_2}\right)^2 \tag{5}$$

$$T = T_{\perp} = T_{\parallel} = \frac{4n_1n_2}{(n_1+n_2)^2} \tag{6}$$

Where the parameters are defined as presented in Fig. 1 These are the reflectance and transmittance for infinitely thick glass, but in real life, as all glass has a thickness, the reflection of light within the glass must be taken into account, as well as the attenuation as it propagates through the glass.
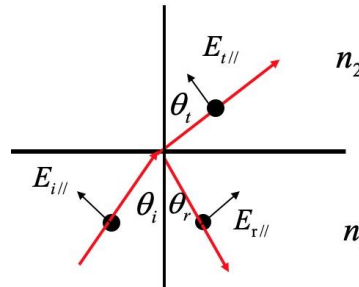

Fig. 1 The derivation of the expressions for the transmission and reflection coefficients.

Inside the glass, for each electromagnetic wave propagating to the right, some passes through the right reflector, the rest is reflected by the flat mirrors on either side and the new electromagnetic wave continues to propagate to the right. After one revolution, the electromagnetic wave is superimposed on the original wave to produce a new waveform. As it propagates through the glass, light is still lost, and one has to consider the effect of the optical attenuation coefficient [10]. If a beam of light with an intensity of P after passing through dx a length of glass is attenuated by dP, then one can define

the attenuation coefficient, which is the ratio of the intensity of light propagating through the glass attenuated per unit length as $\alpha dx = dP/P$. So the single field intensity of the light after one round trip and the superposition of the original light $E_0 + E_0 e^{2\alpha L} r^2 e^{-j2kL}$, where E_0 is the amplitude of the original wave, and r is the reflectivity of the electromagnetic wave, and $k = n_2 2\pi/n_1\lambda$, λ is the wavelength at incidence, and L is the thickness of the glass, α is the attenuation coefficient of the electromagnetic wave, which is a negative value. Similarly, the new electromagnetic wave will continue to propagate back and forth between parallel planes a number of times before superimposing on the original electromagnetic wave to form an infinite number of steps.

The intensity of the final light is obtained and expressed as

$$I_{cavity} = \left|E_{cavity}\right|^2 = \frac{I_0}{(1-Re^{2\alpha L})^2 + 4Re^{2\alpha L}\sin^2(kL)} \tag{7}$$

Whereas the incident sunlight needs to pass through the contact surface of the glass and air once, if the intensity of the incident light is I_i, one has $I_0 = I_i(1-R)$. When the sunlight finally leaves the glass it has to pass through the contact surface between the glass and the air again, if one uses I_t to express the intensity of light passing through the glass $I_t = I_{cavity}(1-R)$. So, one ends up with an equation for the intensity of light passing through glass with thickness.

$$I_t = I_i \frac{(1-R)^2 e^{2\alpha L}}{(1-Re^{2\alpha L})^2 + 4Re^{2\alpha L}\sin^2(kL)} \tag{8}$$

There is also the transmittance formula.

$$\text{T} = \frac{I_t}{I_i} = \frac{(1-R)^2 e^{2\alpha L}}{(1-Re^{2\alpha L})^2 + 4Re^{2\alpha L}\sin^2(kL)} \tag{9}$$

If one has n different thicknesses of glass, their thicknesses are L_i. Then their transmittance would be:

$$T_i = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(kL_i)} \tag{10}$$

If these glasses are combined, their total transmittance is $\text{T} = T_1 \cdot T_2 \cdot T_3 \cdot ... \cdot T_n$.

2.2. Effect of the Thickness of a Single Layer of Glass on the Transmission Spectrum

Electromagnetic waves of different wavelengths also possess different refractive indices, and the relationship between wavelength and refractive index is described by the Corsi dispersion formula, i.e.,

$$n = a + \frac{b}{\lambda^2} + \frac{c}{\lambda^4} \tag{11}$$

where n is the refraction coefficient, and λ is the wavelength, and a, b, c are the three Cauchy dispersion coefficients, which relate only to the medium in which they are incident. One can find the three Cauchy dispersion coefficients for glass by simply finding the refraction coefficients for the three different wavelengths of electromagnetic waves: $\lambda = 600\,nm$ with $n = 1.5163$; $\lambda = 800\,nm$ with $n = 1.5108$, $\lambda = 1000\,nm$ with $n = 1.5075$. Thus one obtains a ternary equation, that $a = 1.5004544762$, $b = 7799.52381$, $c = -754285714$.

Based on the parameters and coefficients, the reflection spectra for glass thicknesses of 1 mm and 2 mm have 23 and 24 peaks above 0.1 respectively. The reflectance spectra when the glass thickness is 3mm and 4mm are as above, with 28 and 25 peaks over 0.1 respectively The reflectance spectra for glass thicknesses of 5mm and 6mm have 27 and 23 peaks above 0.1 respectively. the reflection spectra when the glass thickness is 7mm and 8mm have 26 and 19 peaks over 0.1 respectively. The reflectance spectra for glass thicknesses of 9mm and 10mm have 26 and 21 peaks above 0.1 respectively. According to the data, it can be seen that 3mm thick glass reflects the most sunlight.

2.3. Effect of Laminated Glass Thickness on Transmission Spectrum

Regardting to effect of insulating glass thickness on transmission spectrum, as a single layer of glass has the best reflective properties at a thickness of 3mm, the effect of the thickness of the second layer of glass on the reflectance spectrum is examined over and above the 3mm thickness chosen for the first layer. In the reflectance spectrum with a second glass thickness of 1mm, there are 17 peaks above 0.2. When the second layer of glass is 2mm thick, the reflectance spectrum has 20 peaks above 0.2. When the second layer of glass is 3mm thick it has 27 peaks over 0.2 and when the second layer of glass is 4mm thick it has 13 peaks over 0.2. When the second layer of glass is 5mm thick it has 21 peaks over 0.2 and when the second layer of glass is 6mm thick it has 23 peaks over 0.2. When the second layer of glass is 7mm thick it has 24 peaks over 0.2 and when the second layer of glass is 8mm thick it has 13 peaks over 0.2 When the second layer of glass is 9mm thick the reflection spectrum it has 16 peaks over 0.2 and when the second layer of glass is 10mm thick the reflection spectrum has 16 peaks over 0.2. Based on the results, the highest level of sunlight reflection is when the second layer of glass is 3mm.

For effects of the triple thickness of the glass on the transmission spectrum, as the second layer of glass has the best reflective properties at a thickness of 3mm, the second layer of glass should also be 3mm thick. With this in mind, the study of the effect of the thickness of the third layer of glass on the reflectance spectrum continues.When the third glass thickness is 4.1 mm the reflection spectrum, it has 23 peaks over 0.25 and when the second glass thickness is 4.2 mm the reflection spectrum has 24 peaks over 0.25. When the third layer of glass is 4.3mm thick it has 28 peaks over 0.25 and when the second layer of glass is 4.4mm thick it has 33 peaks over 0.25. When the third glass layer is 4.5mm thick the reflection spectrum has 27 peaks over 0.25 and when the second glass layer is 4.6mm thick the reflection spectrum has 30 peaks over 0.25. When the third glass layer is 4.7mm thick the reflection spectrum has 27 peaks over 0.25 and when the second glass layer is 4.8mm thick the reflection spectrum has 24 peaks over 0.25. When the third layer of glass is 4.9mm thick it has 25 peaks over 0.25 and when the second layer of glass is 5.0mm thick it has 22 peaks over 0.25. To sum up, it can be seen that the third layer of glass reflects the most sunlight when it is 4.4mm thick.

For influence of the thickness of the four layers of glass on the transmission spectrum, as the third glass layer has the best reflective properties at 4.4mm, the third glass layer should also be 4.4 mm thick. In this case, the study of the effect of the thickness of the fourth glass layer on the reflectance spectrum is continued. When the fourth glass layer is 5.1 mm thick the reflection spectrum, it has 29 peaks over 0.3 and when the second glass layer is 5.2 mm thick the reflection spectrum has 31 peaks over 0.3. When the fourth glass layer is 5.3 mm thick the reflection spectrum, it has 31 peaks over 0.3 and when the second glass layer is 5.4 mm thick the reflection spectrum has 27 peaks over 0.3. When the fourth glass layer is 5.5 mm thick the reflection spectrum has 28 peaks over 0.3 and when the second glass layer is 5.6 mm thick the reflection spectrum has 26 peaks over 0.3. When the fourth glass layer is 5.7 mm thick the reflection spectrum has 25 peaks over 0.3 and when the second glass layer is 5.8 mm thick the reflection spectrum has 28 peaks over 0.3. When the fourth glass layer is 5.9mm thick the reflection spectrum it has 31 peaks over 0.3 and when the second glass layer is 6.0mm thick the reflection spectrum has 31 peaks over 0.3. Although there are 31 peaks greater than 0.3 in the reflectance spectrum for the fourth layer of glass at 5.4mm, 5.9mm, and 6.0mm, this paper has chosen the fourth layer of glass at 5.9mm because the average reflectance spectrum is higher at 5.9mm.

For effect of five glass thicknesses on the transmission spectrum. as the fourth glass layer has the best reflective properties at 5.9mm, this study chose a glass thickness of 5.9mm for the third layer. On this basis, the study of the effect of the thickness of the fifth glass layer on the reflectance spectrum was continued. When the fifth glass layer is 6.1 mm thick the reflection spectrum, it has 33 peaks over 0.35 and when the second glass layer is 6.2 mm thick the reflection spectrum has 31 peaks over 0.35. When the fifth glass layer is 6.3mm thick the reflection spectrum has 30 peaks over 0.35 and when the second glass layer is 6.4mm thick the reflection spectrum has 33 peaks over 0.35. When the fifth glass layer is 6.5 mm thick the reflection spectrum has 29 peaks over 0.35 and when the second

glass layer is 6.6 mm thick the reflection spectrum has 30 peaks over 0.35. When the fifth layer of glass is 6.7 mm thick the reflection spectrum, it has 31 peaks over 0.35 and when the second layer of glass is 6.8 mm thick the reflection spectrum has 30 peaks over 0.35. When the fifth layer of glass is 6.9mm thick it has 34 peaks over 0.35 and when the second layer of glass is 7.0mm thick it has 31 peaks over 0.35. Overall, when the thickness of the fifth layer is 6.9mm, sunlight reflection is at a maximum.

3. Results & Discussion

A sketch of the experiment setup is shown in Fig. 2. As for experimental equipment, the UV-vis absorption spectra were recorded using a UV-2450 Shimadzu Vis spectrometer (Hitachi, Japan). 14 pieces of 1cm*5cm glass of 1mm thickness, one piece each of 2mm-10mm thickness, and 20 pieces of 0.5cm*1cm glass of 1mm thickness are used. During the experiments, it examined the absorption spectra of nine monolayer glasses ranging in thickness from 2mm to 10mm and a total of four multilayer glass combinations consisting of two to five layers of 1mm thickness. A multilayer glass consists of a number of identical 1mm thick glasses and a 1mm thick layer of air that separates these glasses from each other. The experimental approach is as follows.

Prepare a 0.5cm*1cm piece of 1mm thick glass and dip one side in double-sided tape, then remove the insulation from the surface of the double-sided tape and stick it to one end of a 1cm*5cm piece of 1mm thick glass, then repeat this method to stick another 0.5cm*1cm piece of 1mm thick glass to the other end of a 1cm*5cm piece of 1mm thick glass.

Finally, stick the two smaller pieces of glass together with double-sided tape, remove the insulating layer and stick a piece of 1cm*5cm glass of 1mm thickness on top, so that the two pieces of glass are stuck together and have a layer of air of 1mm thickness to separate them.

Other multiple layers of glass can be joined in this way.

When testing in the apparatus, the glass should be placed lightly in the test slot of the experimental apparatus, but always with the glass in a vertical position.

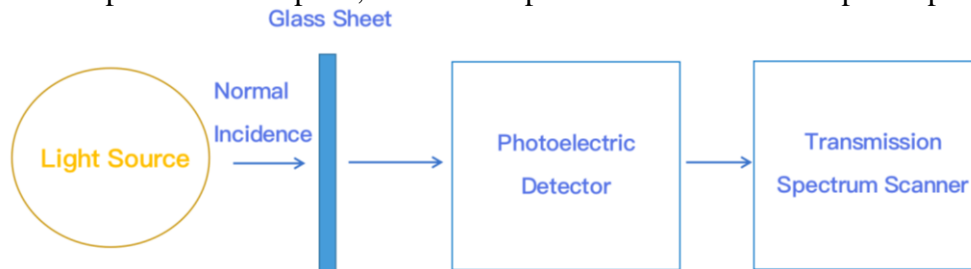When the above process is complete, run the computer and draw the absorption spectrum.

Fig. 2 Schematic diagram of the system for the measurement of the transmission spectrum of flat glass.

The transmittances of different thicknesses of glass is presented in Fig. 3. when the wavelength of the electromagnetic wave is 200nm. As can be seen from Fig. 3, the transmittance spectrum of glass has the highest transmittance at wavelengths below 1000nm for 10mm thickness and the lowest transmittance at 6mm and 8mm respectively, reflecting the anomaly of light wave transmittance at wavelengths below 1000nm. According to the results of Fig. 4, the theoretical transmittance is lowest for the 6mm and 8mm thicknesses and higher for the other thicknesses. The experimental values also have the lowest transmittance at the same thicknesses and higher transmittance at other thicknesses. The predictions of the theoretical model are therefore confirmed by the experimental results.
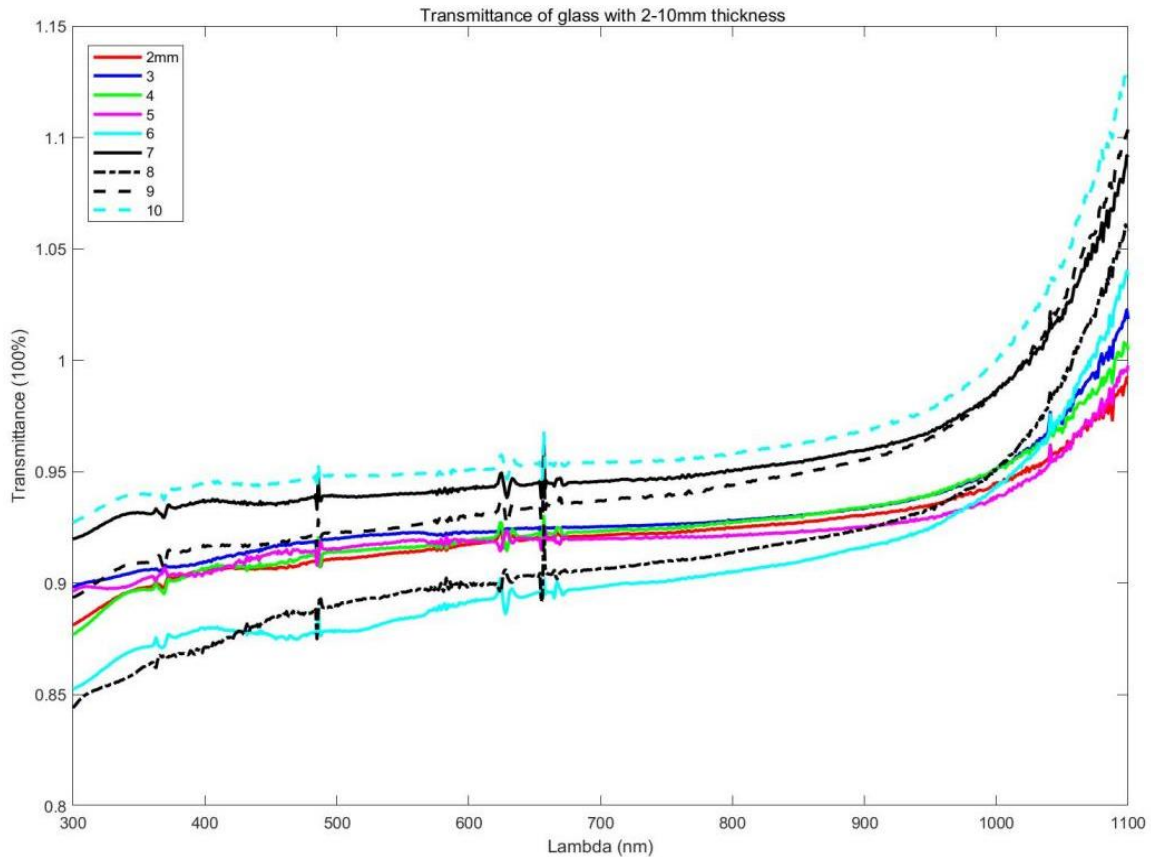
Fig. 3 Transmission spectra of monolayer glass of different thicknesses from 2-10mm and wavelength range 300-1100nm.
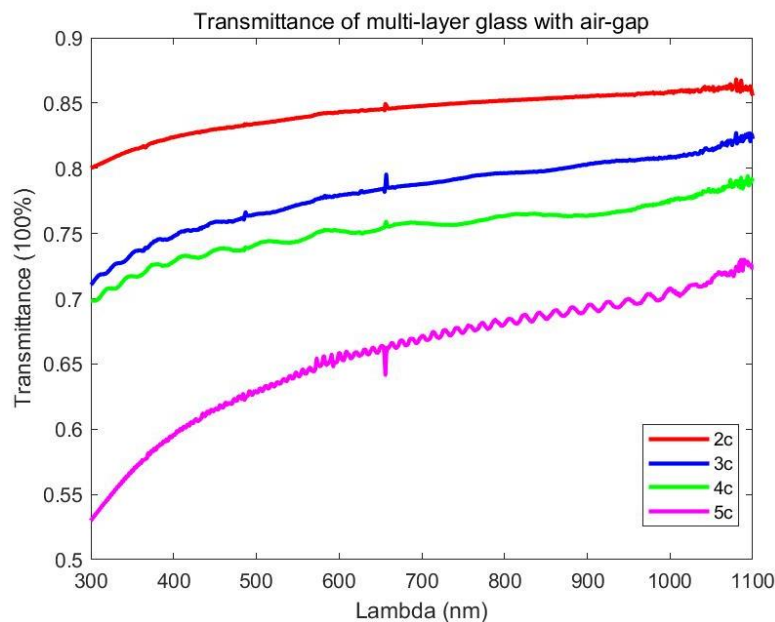

Fig. 4 Transmission spectrum of glass with 1mm thickness air layer. Here, 2c: 2-pane glass; 3c: 3-pane glass; 4c: 4-pane glass; 5c: 5-pane glass

4. Conclusion

In summary, this study invetigates transmission spectrum of flat glass from near-infrared to the ultraviolet wavelength. To be specific, this paper developed a model using Fresnel's laws of reflection and transmission. It is found that the loss of light as it propagates through the glass is small and that

it is the repeated reflection of light at different media contacts that determines how much light can pass through a section of glass of a given thickness. In the experiments, the transmittance of glass of different thicknesses is measured, which generally agreed with the theoretical values, confirming the validity of our theoretical model. Nevertheless, there are still some shortcomings in this study, e.g., only measured the transmittance of a total of nine glasses from 2mm to 10mm. Additionally, when determining how much sunlight a glass reflects, this research looks directly at the number of peaks in the comparative reflectance spectrum and do not take into account the size of the peak and the rest of the spectrum below it. This means that more experiments are needed in the future to get more theoretical data to improve the analytical model. Overall, these results shed light on guiding further exploration of transmission spectrum of flat glass.

References

[1] Cao G. Research on the application of LOW-E glass in the energy-saving design of buildings. Building Materials and Decoration, 2018, 17: 68-69.

[2] Finley J J. Heat treatment and bending of low-E glass. Thin Solid Films, 1999, 351(1-2): 264-273.

[3] Cuce E, Young C H, Riffat S B. Thermal performance investigation of heat insulation solar glass: A comparative experimental study. Energy and Buildings, 2015, 86: 595-600.

[4] Grosjean A, Le Baron E. Longtime solar performance estimations of low-E glass depending on local atmospheric conditions. Solar Energy Materials and Solar Cells, 2022, 240: 111730.

[5] Peng J, Curcija D C, Thanachareonkit A, et al. Comparative study on the overall energy performance between photovoltaic and Low-E insulated glass units. Solar Energy, 2021, 214: 443-456.

[6] Zhang W, Lu L, Xu X. Thermal and daylighting performance of glass window using a newly developed transparent heat insulated coating. Energy Procedia, 2019, 158: 1080-1085.

[7] Yang T. Comparative analysis of different types of glass insulating film applications. Building Technology, 2021, 1.

[8] Ziming C, Fuqiang W, Dayang G, et al. Low-cost radiative cooling blade coating with ultrahigh visible light transmittance and emission within an "atmospheric window". Solar Energy Materials and Solar Cells, 2020, 213: 110563.

[9] Dong J, Lu P, Ding Y. Study on the thermal insulation performance of high refractive hollow glass beads in heat reflective coatings. Silicate Bulletin, 2019, 38(7): 2191-2195.

[10] Ma W, Liu F. Effect of porosity on ultrasonic damping coefficient and mechanical properties of glass fibre composites. Journal of Composites, 2012, 5: 69-75.