RESEARCH ON THE ENERGY-SAVING EFFECT OF COMPOSITE FILM MATERIALS ON SMART WINDOWS BASED ON OPTICAL PROPERTIES

by

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As the industrial and economic level continues to develop, the urban heat island effect is then serious. In order to control the indoor temperature in life and production and improve the indoor environment in summer, the study was conducted on composite film materials for smart windows for buildings. An optical analysis of the cooling requirement was conducted first, and then the material was modified based on this, and a composite film material based on polydimethylsiloxane (PDMS) and Ag coating was made. The test results show that the composite film can change the spectral absorption of the object and reduce the temperature of the object by 16.7 °C under the same light scenario. Tests on commonly used low-e glass show that the composite film material can reduce room temperature with increased sunlight transmission. Finally, a cooling test on PV panels used for building energy efficiency effectively reduced the operating temperature of the units, although it could not directly affect the power generation efficiency. This shows that the PDMS composite film based on optical properties can reduce the indoor temperature, thus reducing the power of electric cooling. The energy saving effect has positive significance for building windows.

Key words: *optical properties, smart window, composite film, energy saving effect*

Introduction

With the advancement of urbanization and the increasingly active social production activities, extremely hot weather occurs frequently. This also makes the architectural design need to consider the demand of energy consumption. Therefore, the selection and preparation of energy-saving materials under the development of clean energy has become the future development direction [1]. Building energy efficiency can change the overall perception of occupants in terms of both design and materials, with a focus on thermal energy absorption in the north and the need for a custom design for cooling energy consumption in hot weather. Since mid to late July 2022, China has experienced widespread extreme hot weather in the middle and lower reaches of the Yangtze River. This phenomenon has had an impact on human production and life, in which building refrigeration accounts for a huge share of electricity consumption [2]. As a large population country, the per capita energy consumption level of building cooling is far below that of developed countries. The development of building mate-

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rials with energy-saving properties has become one of the solutions to this problem. In view of this, scholars have studied windows for buildings based on optical properties in terms of heat transfer mechanisms, and then used this as a basis for finding and developing new composite materials [3]. The optical cooling principle of smart window has been developed for a long time, but its practical application is still in the stage of development due to the strict preparation process and use conditions. With the progress of technology, new materials are gradually developed and applied. The new material can reduce the absorption of the wave band under various conditions when the sunlight is reflected and transmitted, which promotes the application and development of cooling technology. The intelligent window based on this can achieve cooling effect by keeping the indoor temperature lower than the outdoor temperature under direct sunlight [4]. At the same time, some energy control departments as well as companies are gradually developing clean energy sources such as solar power. But the relevant units face high temperature conditions in summer, which can have a negative impact on battery life as well as power generation efficiency. Therefore, the development of cooling materials with optical properties to achieve cooling without affecting the light has become a research direction. Compared to traditional materials that can only be used at night, optically based transparent radiative cooling materials expand the range of applications. As a result, the research will be based on optical and thermodynamic principles of load materials for smart windows to promote the development of applications related to building energy efficiency.

Related work

As an important platform for building function control, scholars have incorporated new technologies and design concepts to achieve results in indoor environment optimization. Zhou's experimental team considered windows as the least energy-efficient part of the building. For solving the problem of smart regulation of solar energy by traditional smart windows, they used hydrogel-derived liquid inside the glass, which produced smart windows with excellent thermal response optical properties. The HTEST smart window they designed showed excellent performance in heating, ventilation, and air conditioning energy consumption experiments [5]. Sun's research team was inspired by chameleons to develop a temperature-responsive energy-efficient smart window. It was a design that sets the temperature as a signal source to stimulate the response of the gel, while glycol and UV absorbers act as antifreeze agents to protect the gel. Their development strategy provides a new strategy for temperature regulation of gel-based smart windows [6]. Zhou *et al*. [7] discussed all hydrogel smart windows currently available on the market, and they conducted an exhaustive study on the preparation, working mechanism, and feasibility of large-scale use of smart window materials. They concluded that gel-based materials as regulating refractive index are essential for building energy efficiency. Kim *et al*. [8] developed an electrochromic polymer to develop a capacitive window. The window introduced multiple organic molecules of blue and red ECP into a capacitive layer with a thin polyaniline film. The results showed that this smart window can display high transparency and color contrast. When multiple ECC were connected in series, energy was transferred between the windows. Their research provided ideas for the development of multi-color switching and charging smart windows. Li *et al*. [9] concluded that current color development techniques cannot meet the gaining ability of sunlight, and the development of phase change materials needs to be further promoted. Therefore, they developed a material that regulates the light scattering situation by controlling the particle size and internal structure, which optimizes the performance of temperature corresponding hydrogel. The results proved that the material can regulate the refractive index and transmittance of light at different temperatures, and this research has gone beyond the traditional scope of energy-saving smart windows. Liang *et al*. [10] concluded that thermochromic systems are ideal for energy-efficient smart windows, but this requires a considerable level of material support. For the lack of active optical control and solar modulation capability of existing materials, they proposed processing in the middle of two transparent graphenes in the processing step. The intermediate material of this preparation method possesses a phase-separated polymer framework. Tests have shown that the material has high mechanical strength and flexibility, while the optical modulation capability is also quite good.

For building energy control, scholars have also made considerable progress in the study of insulation and cooling type materials and systems, the application of these materials has some significance for energy saving needs. Rasta and Suamir [11] studied water-based phase change materials for cold energy storage. They used a mixture of vegetable oil and water as a candidate for PCM. The test results proved that the vegetable oil ester has a large upgrade to water solubility. The nucleating agent made in this way can reduce the freezing point. Although this study has some upgrades to PCM, the scope of application is near the freezing point, so it is difficult to use for building energy consumption. Varvagiannis *et al*. [12] summarized solar cooling system in the building. Among many options, they chose PV driven vapor compression chiller, in a semi-dynamic intergroup model unit PCM combined with RPW-HEX to replace the traditional evaporator. The model performance evaluation simulation results showed that this system has a lower cooling peak than the conventional chiller and the solar energy percentage is increased. Li *et al*. [13] studied the cooling load of commercial buildings and they considered thermal inertia transfer of cooling load as an important strategy. For this purpose, they also developed a coupled model of commercial building and air conditioning system. The validation results showed that the thermal inertia transfer of air conditioning system during the cooling period can achieve a demand reduction boost and the coupling results with high accuracy. Liu et al. [14] have studied magnetically cooled zero-dimensional clusters and co-ordination polymers in recent years. They first explored the relevance of such materials to find structural principles and also compared in situ generated ligands, metal ions and magnetically cooled templates and finally provided insights from the application side. Their research has pushed this class of substances into the building cooling perspective. Li *et al*. [15] argued that building energy control can reduce the related consumption and their solution was to use energy storage materials in building facades. In the implementation path, the building energy consumption is first simulated and then the wall with energy storage coating is simulated by software. The results verified that this type of PCM has a good insulation function and a good improvement in thermal and cooling load saving.

Scholars have mostly studied smart windows in terms of thermal reserve as well as optical control, with little research on cooling loads in building energy control. With the development of real demand and material science, the thermal insulation and cooling system of smart windows in buildings can be constructed and studied using materials and systems based on relevant technologies in other fields.

Optical properties and preparation of composite film materials for architectural smart windows

Radiation cooling basis of smart window composite film material

The selection of smart window materials for the purpose of cold load reserve requires thermodynamic considerations. According to the Second law of thermodynamics, it is known that heat can be transferred from high to low temperature substances in several ways. In the production of architectural smart windows, thermal radiation should be considered as a mode of transfer and upgraded and applied in this way [16]. Thermal radiation is the process of transferring energy outward in the form of electromagnetic waves and the process is applicable to all non-zero-degree substances. The energy calculation can be calculated by the blackbody radiation law as:

$$\mu(\lambda,T)=\frac{2hc^2}{\lambda^5}\frac{1}{\mathrm{e}^{\frac{hc}{\lambda k_T}}-1} \tag{1}$$

where temperature T is that when the energy density spectrum of blackbody radiation is expressed, specifically, the radiated energy per unit wavelength per unit surface area and per unit stereo angle, λ is the electromagnetic wave wavelength, c – the speed of light, h and k – the Planck's and Boltzmann's constants, respectively. The derivation in terms of wavelength integral yields:

$$P=\sigma T^4 \tag{2}$$

Equation (2) is also known as the Stepan-Boltzmann law, where P is the total power of the thermal radiation of the blackbody and σ – the Stepan-Boltzmann constant [17]. The wavelength of the radiation center can be calculated according to the Wien displacement law:

$$\lambda=\frac{b}{T} \tag{3}$$

where b is the Wien displacement constant and T is the Kelvin temperature. Since the absolute blackbody is only an ideal model, the radiated power of an actual object is always less than the blackbody power. The heat radiation capacity of the object can be expressed as the ratio of the actual power to the blackbody radiation power. According to Kirchhoff's law of thermal radiation, the equilibrium conditions of heat absorption and radiation are equivalent:

$$\alpha(\lambda,\theta)=\beta(\lambda,\theta)=\frac{\mu}{\mu_B} \tag{4}$$

where θ is the azimuth angle, α and β – the absorbance and emissivity, and μ_B and μ – the blackbody radiant energy and the actual radiant energy of the object. The optical material of the smart window needs to emit energy to the outside world by a special design, thus reducing its own temperature. In accordance with the radiation characteristics of the sunlight received in China, it is known that the heat radiation exchange can be carried out through $8\,\mu\text{m} < \lambda < 13\,\mu\text{m}$ wavelength interval. The sun is abstracted as a huge blackbody. The absorption and radiation of the known mid-latitude are shown in fig. 1.

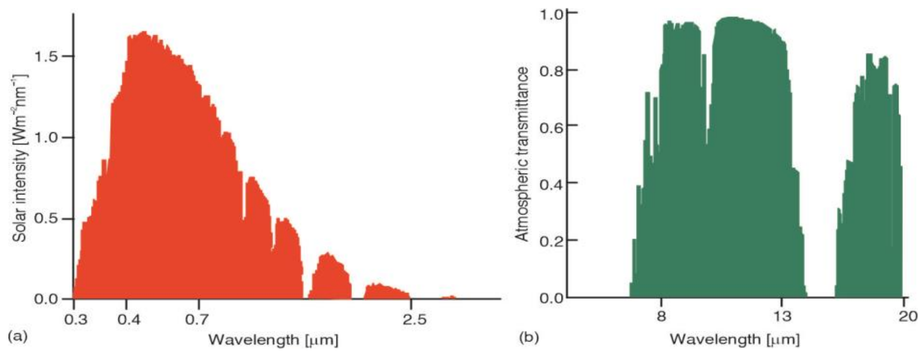

Figure 1. Atmospheric transmittance and sunlight intensity at mid-latitudes; (a) solar intensity and (b) atmospheric transmittance

According to the light intensity and wavelength transmitted by the sun in fig. 1, it is known that the temperature of the smart window control material should be lower than the ambient temperature. It needs to have enough low absorptivity in the solar band and high emissivity in the atmospheric window band. Therefore, the material cooling power of the optical composite film is as:

$$P_c = P_r - P_a - P_S - P_n \tag{5}$$

where P_c is the cooling power, P_r – the total power of thermal radiation at a fixed temperature, P_a – the total power of absorbed atmospheric radiation, P_S – the total power absorbed from the sun, and P_n – the radiation of the object to the environment. The P_r can be calculated:

$$P_r = 2\pi\int_0^{\frac{\pi}{2}} \tau \mathrm{d}\sin\tau\cos\tau \int_0^{\infty} \mathrm{d}\lambda\mu(\lambda, T)\varepsilon(\lambda, \tau) \tag{6}$$

where

$$2\pi\int_0^{\frac{\pi}{2}} \tau \mathrm{d}\sin\tau\cos\tau$$

is the stereo angle integral and $\varepsilon(\lambda,\tau)$ – the emissivity. The P_a is calculated:

$$P_a = 2\pi\int_0^{\frac{\pi}{2}} \tau \mathrm{d}\sin\tau\cos\tau \int_0^{\infty} \mathrm{d}\lambda\mu(\lambda, T)\varepsilon(\lambda, \tau)\varepsilon_a(\lambda, \tau) \tag{7}$$

where $\varepsilon_a(\lambda,\tau)$ is the atmospheric emissivity at a fixed angle and wavelength, calculated:

$$\varepsilon_a(\lambda, \tau) = 1 - a(\lambda)^{\frac{1}{\cos\tau}} \tag{8}$$

where $a(\lambda)$ is the atmospheric transmittance in the vertical direction. According to the climate, it is known that the absorption in the atmospheric window is mainly through water vapor, so the transmittance is related to the humidity. The calculation of P_S is shown:

$$P_S = \int_0^{\infty} \mathrm{d}\lambda\mu(\lambda, T) I(\lambda) \tag{9}$$

where $I(\lambda)$ is the incident intensity of sunlight, which includes radiation and scattering. The stereo angle integral cannot be brought in because the incident angle is not uniform. The P_n is the calculation:

$$P_n = K(T_r - T_a) \tag{10}$$

where K is the thermal conductivity, T_r – the radiation temperature of the object, and T_a – the absorption temperature. According to the previous principle, the temperature of the material can be lower than the ambient temperature when the object absorbs sunlight at a lower wavelength and emits infrared at a higher wavelength. When the temperature of the object decreases, P_r will decrease and P_n will increase. A zero cooling power means that the material is in thermal equilibrium. Based on the cooling principle, SiO_2 will be selected for the study and organosilicon PDMS will be selected as the candidate material for the composite construction. When light is incident on the object, the energy distribution is:

$$X(\lambda) + Y(\lambda) + Z(\lambda) = 1 \tag{11}$$

where $X(\lambda)$ is the transmittance of light, $Y(\lambda)$ – the absorbance of light, and $Z(\lambda)$ the reflectance of light. When the incident mode is normal incidence, the reflectance $Z(\lambda)$ is calculated:

$$Z(\lambda) = \frac{[\eta(\lambda) - 1]^2 + l^2(\lambda)}{[\eta(\lambda) + 1]^2 + l^2(\lambda)} \tag{12}$$

where η is the intrinsic refractive index and l – the extinction coefficient, which is related to the absorption coefficient of light:

$$A(\lambda)=\frac{2\lambda l_2(\lambda)}{c} \tag{13}$$

where $A(\lambda)$ is the absorption coefficient, which also indicates the light intensity attenuation magnitude at the light range of $1/A$. The optical constant complex refractive index of the material is calculated:

$$R(\lambda)=\eta(\lambda)+il(\lambda) \tag{14}$$

where $il(\lambda)$ is the imaginary part. The whole calculation process requires the measurement of the material absorption intensity. Since SiO_2 has difficulty in absorbing sunlight while the molecular bonds stretch and vibrate, there is strong absorption and emission in the sunlight band, resulting in a cooling effect.

Improvement and preparation of composite film materials

The basis for the selection of cooling materials was considered under the principles of optics and thermodynamics, and PDMS was finally selected as the smart window composite film material. Consideration of practical application scenarios revealed that the molecular bonding in the material determines the advantages of the material, while the scholars also optimized this material to increase the performance level. When micro-structures are added to SiO_2, the mutual scattering between the structures increases the overall emissivity, thus eliminating the reflection effect. But this optimization increases scattering, which is contrary to the specifications for building materials [18]. In view of this, the study will modify the optical properties of the material through molecular bonding, which will further reduce the reflection effect in the absorption band. Lorentzian oscillator model allows the calculation of the complex refractive index of the materials. Moreover, the motion state of the SiO_2 molecular bond can be abstracted as a simple harmonic dipole oscillator with periodic dynamics, which is used as the electric field of the incident light. At this time, the relationship between dielectric constant and complex refractive index is:

$$\beta(\lambda)=1+\frac{\dfrac{Ne^2}{\beta_0 m}}{{\lambda_0}^2+i\lambda\Gamma-\lambda^2} \qquad \beta(\lambda)=\left[\eta(\lambda)+il(\lambda)\right]^2 \tag{15}$$

where β is the dielectric constant of the composite film material, λ_0 – the vacuum dielectric constant, N – the number of oscillators per unit volume, and the damping coefficient of oscillators is Γ. The relationship between refractive index and extinction coefficient and incident light frequency can be qualitatively obtained from eq. (15). As a rule, the material absorbs most at the maximum of the intrinsic frequency, but based on the material properties also produces strong reflection. Therefore, molecular bonding needs to be introduced to reduce the value of N, when the enhanced bonding ability also increases the value of Γ. Finally, new polymers are constructed by adding duplicate molecular bonds. This eventually leads to the expansion of absorption peak and absorption band, which is the key to enhance the cooling load of composite membrane materials. The preparation of the polymer needs to consider the light absorption of the chemical bonds. The high energy of the UV and visible bands incident by sunlight can easily lead to electron leap, so such chemical bonds should be avoided in composite films [19].

Figure 2 shows the spectral absorption distribution of some chemical bonds as a reference for polymer preparation.

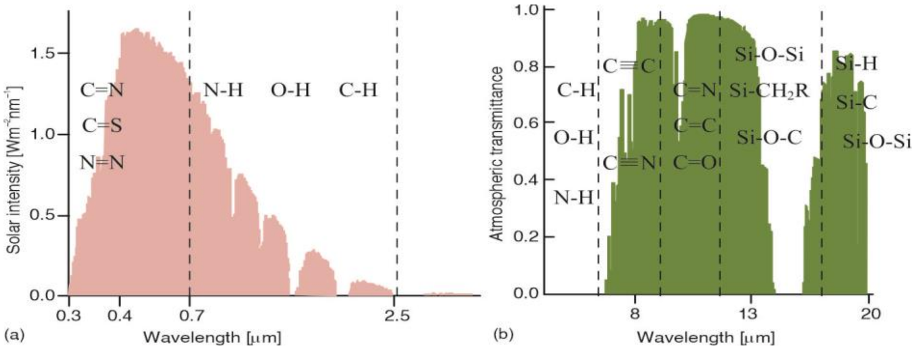

Figure 2. Spectral distribution of partial bonds; (a) light intensity and bond distribution and (b) atmospheric transmittance and chemical bond distribution

As in the spectral distribution in fig. 2, the composite film materials are mainly selected for chemical bonds near the infrared band. The absorption peaks in this band are mainly C-H, N-H, and O-H ground state jumps, which are unavoidable for most organic-like polymers. However, the jump energy of such bonds will not lead to cooling effect, so the composite film materials selected for the study will use such chemical bonds as the modified molecular bonds. The polymers generated are hydroxymethylbilane, dimethyl siloxane, and benzyl siloxane, where dimethyl siloxane as a monomer does not affect the absorption of light in the wavelength band. The resulting polymer is PDMS, which not only increases the damping coefficient but also ensures low refractive and reflective indices in the low wavelength band. In practice, the material can meet the flexibility requirements of smart window fabrication, and the fit also meets the window adhesion. the fabrication of PMDS requires the assistance of precursors and co-agents, and the main reaction is shown in fig. 3.

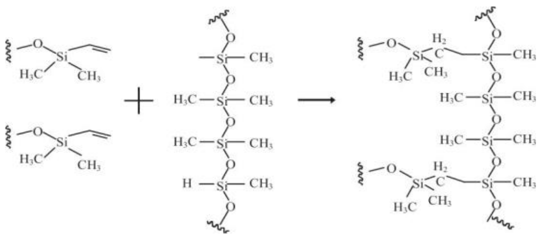

Figure 3. Main reaction of PDMS

As in fig. 3, the reaction conditions are 80 °C. After mixing, platinum-based catalysis is needed to complete the addition of molecular bonds, and the new Si-C bonds are generated and then heat-treated to produce the desired film. In the specific preparation, it is necessary to mix the precursor and the cross-linker first, stir them evenly and then leave them to stand. When the mixture is completely free of air bubbles and coated on the PET substrate, the PDMS cured film will be completely generated after 1 hours. Large-scale production of PDMS can be achieved by industrial roll-to-roll technology. The precursor and crosslinking agent are applied to the surface of the adhesive material and placed in the PET interlayer in a high temperature environment, and the protective film is removed during use [20]. Before testing, the study was conducted to characterize and calibrate the fabricated composite film materials to ensure that the generated products conform to the PDMS characteristics. The characterization tests were performed under spectrophotometer for whiteboard calibration and infrared band was characterized by Fourier transform in spectrometer. The spectral results will be analyzed under the calculation of optical principles. The molecular bond is the key to determine the radiation cooling effect, and the proportion of the precursor crosslinking agent is one of the factors that affect the molecular bond. Therefore, the preparation also needs to control the ratio of the two, and test the best ratio based on cooling through repeated experiments. The actual results show that the molecular bonds of 20:1, 10:1, and 5:1 polymer are different and there are slight differences in performance, but they can all meet the cooling requirements. The fabrication ratio is determined at 10:1 based on the strength and flexibility considerations of the smart window.

Optical properties and energy-saving effect testing of composite film materials for smart windows

The cooling principle of PDMS is analyzed from a theoretical point of view as well as the expected effect. The study will conduct optical experiments and scenario tests to verify the energy-saving performance of the material for architectural smart windows. For practical application, the smart windows need to control temperature rather than light, so Al foil and sputtered reflective layer of Al sheet are chosen as substitutes for the architectural substrate. Meanwhile, various substances are used as the materials to be cooled down, and the cooling effect of this material is countered by pasting the film. The experiment is built with the need to first isolate the external energy convection, so the film is placed in the acrylic cavity with other substances, and the whole cavity is isolated from the ground energy by the Al foil base. The entire test process does not artificially alter the energy. The data acquisition module is composed of thermocouples and collectors, and the average value of the two thermocouples is taken as the result. Environmental parameters are measured by temperature and humidity meters. The sensor is placed near the cavity to maintain adequate ventilation and avoid instrument error. The measurement frequency is 1 hours. In the actual application scenario, there is an uneven metal structure inside the smart window, which can easily lead to the metal absorbing too much sunlight. So, the film material will be tested first under the heat situation of the metal material. The spectral emission results of the Al sheet are shown in fig. 4.

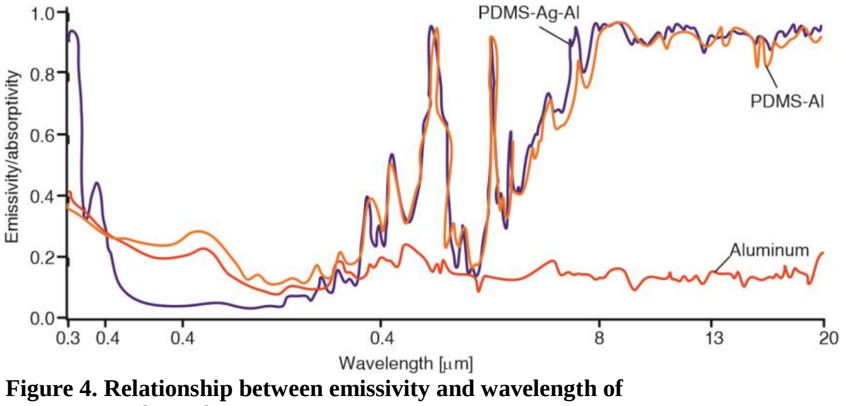

Figure 4. Relationship between emissivity and wavelength of three kinds of thin film

As the emission spectra of the film combination method in fig. 4, there is microscopic unevenness on the surface of aluminum. The average absorption in the sunlight band in the result is about 0.21, and the absorption in the infrared band is lower at 0.12, which indicates that this film composition can absorb sunlight, but cannot dissipate heat. When PDMS is added to the film material, the sunlight absorption is increased to 0.24 and the emission in the infrared band is increased to 0.89, which can meet the cooling requirement of the building windows. When the film layer is added with Ag, the emission rate of infrared band is basically un-

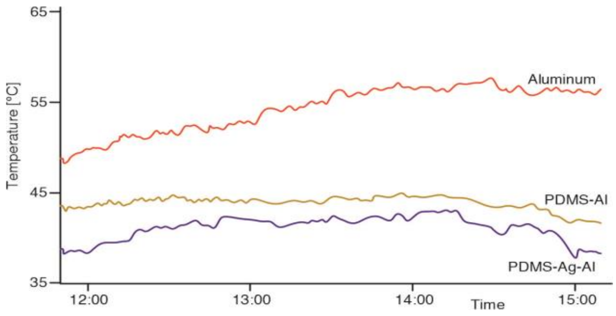

Figure 5. Refrigeration test results of three films

changed. But the absorption rate of sunlight band is only 0.07, which reduces the sunlight energy absorption in the performance of PDMS film and has positive significance for building energy saving. The cooling experimental tests were conducted on the films of the three combination methods, and the results are shown in fig. 5.

The cavity environment as in fig. 5 was tested for cooling at the time of strongest sunlight. The results showed that the temperature absorption of the aluminum sheet alone increased to 50 °C after 12 o'clock and increased with the ambient temperature. This approach obviously did not meet the demand for building cooling. When PDMS was added to the film, the temperature could be controlled below 45 °C and the film had a more significant cooling effect. At this time, when Ag coating is added, the temperature control effect is further improved. The temperature can be controlled to 40 °C or below, which is 16.7 °C lower compared to the simple Al film. This is of great significance to the temperature control of buildings and civil scenes, and also relieves the energy consumption of refrigeration. Low-emissivity (Low-e) glass is often used as an alternate material in current architectural windows. This glass has a high reflectivity in the infrared band, which can easily lead to interior heat dissipation functions. In the meantime, its own radiant heat dissipation will be greatly reduced by the Low-e design, so the film will be tested on Low-e. Figure 6 shows the spectral results of plain Low-e and the film after coating.

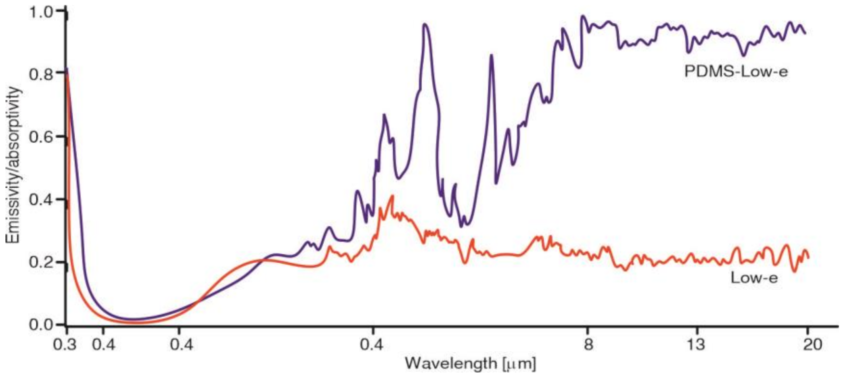

Figure 6. Spectral measurement of composite membrane bonding on Low-e

As in the spectral test in fig. 6, the absorption rate of the glass without the composite film in the sunlight band is 0.09 and the infrared emissivity is 0.21. After adding the composite film, the absorption rate of the sunlight band does not change much, but the infrared emissivity increases to 0.89. This indicates that the composite film has good heat dissipation ability and can dissipate heat through the structural gap. At this time, the sunlight transmission of the two glass structures is used in the experiment, and the results are shown in fig. 7.

As shown in fig. 7, the transmittance of the visible band of the glass without PDMS is 0.79, which increases to 0.80 with PDMS, while the temperature difference between the two is still 9 °C in the thermal imaging simulation. In other words, there is a small increase in sunlight transmission under the effect of composite film, but the temperature control maintains a certain advantage. It is important for indoor environment control and building energy control, and this cooling effect can meet the regulation needs in the southern region. The composite film and low-e glass are used in the actual scenario to test the temperature, and the results are shown in fig. 8.

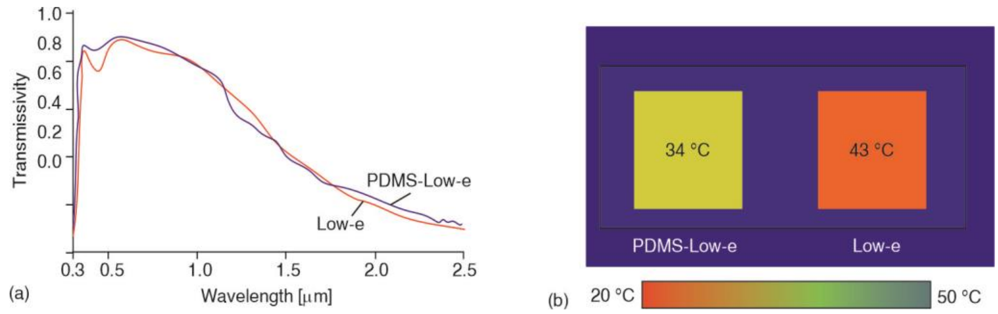

Figure 7. Low-e sunlight transmission test

As shown in the temperature test results of the real scenario in fig. 8, the highest temperature of the glass without the laminated film was 42.3 °C at 13:42 a. m. The temperature of the glass after loading was always lower than that of the glass alone. The highest temperature did not exceed 40 °C, which was 8.2 °C lower compared to the temperature of the glass. It fully demonstrated the performance of PDMS. Commercial buildings usually lay photovoltaic power generation as the energy source for cooling, but the efficiency of current photovoltaic panels is not high. The proportion of heat energy is much larger than the light energy used for power generation. As a result, battery heat dissipation becomes the key to extend the life of the panels, and the power generation efficiency is directly related to the operating temperature. The use of smart windows with cooling function for PV power generation becomes one of the solutions to the overheating problem. The study will test the cooling effect of this scenario. Since the PV cell is different from the ordinary building scenario, it needs to be processed. When the cell is prepared, its surface is a tetragonal cone microstructure to increase the contact area of light energy, and this structure makes it have certain infrared absorption characteristics. After the treatment of the energy-saving window, the results of absorption performance changes in each waveband are shown in tab. 1.

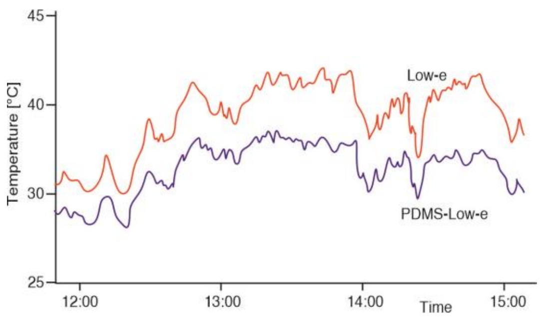

Figure 8. Temperature of Low-e and composite membrane materials in real scenes

From the results in tab. 1, the emissivity of the PV cell in the infrared band is not much different from that after using the smart window, so this composite film material has little effect on the infrared emission. However, there is a certain improvement in the absorption performance, and this treatment can optimize the

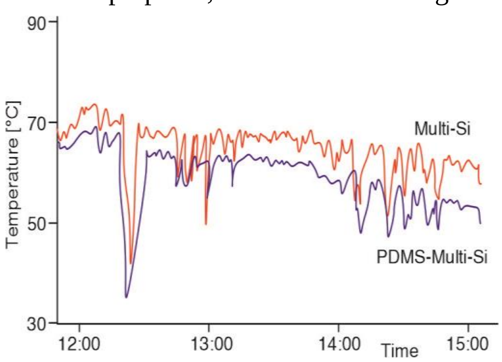

Figure 9. Temperature control of PV cells by PDMS

electric panel working condition from the temperature control aspect. Even though it cannot improve the power generation efficiency. Figure 9 shows the temperature control performance test under the real scenario.

Table 1. Optical effects of PDMS smart Windows on silicon-based PV cells

Battery type	Treatment mode	Emissivity (0.3-2.5 μm)	Absorptivity (0.3-2.5 μm)
Mono-Si	General	0.74	0.76
	+PDMS	0.74	0.92
Multi-Si	General	0.91	0.77
	+PDMS	0.91	0.91
A-Si	General	0.92	0.78
	+PDMS	0.92	0.91

As in the temperature control in fig. 9, the temperature of the simple PV panel is in the range of 65-70 °C, with a short decrease at 12:20, which is caused by the start of the panel operation. In contrast, under the studied intelligent window control, the overall temperature of the generator set is lower than that of the simple electric panel, with a temperature difference of up to 5.5 °C. Based on the working conditions of the PV electric panel, it is known that the efficiency can be improved by 0.4% for every 1 °C decrease in temperature. It means the cooling energy saving effect shown by the results is positive for both the life extension and efficiency improvement of the PV generator set.

Conclusion

With the improvement of living and production levels, temperature control inside buildings has become a common research area for the energy industry and the building industry. As a smart window of building light and heat transfer window, its cooling load control has become the focus of research. The problem of indoor temperature control in southern China urgently needs to be solved. Smart windows have been widely used and researched in other parts of the world with similar climates. In Japan, the use of hydrogel coatings has been proposed to intelligently regulate solar heat using the characteristics of hydrogels subject to temperature changes. In Singapore, the thermochromic properties of vanadium dioxide materials have been investigated and their application in smart windows discussed. Compared to conventional static windows, smart windows in these areas reduce the total energy consumption of buildings by approximately 10%, but this is not nearly enough. In view of this, the research starts from the optical properties and the light band of the atmospheric window in the region where China is located is studied to derive the preconditions for cooling. Then the molecular bonds of SiO_2 were modified to affect the extinction coefficient and refractive index by introducing other bonds to achieve the optical requirements for cooling, and this was used to make PDMS. The studied smart window composite film was made based on PDMS with Ag coating. Spectroscopic experiments on the material showed that the film material was able to increase the sunlight absorption to 0.24, increase the emission in the infrared band to 0.89. It can also reduce the average temperature by 16.7 °C, which indicates the significant cooling effect of this material. At the same time, the film modification of commonly used low-e glass showed a temperature reduction of 8.2 °C. Finally, the temperature control of PV panels was tested. The results demonstrated that the composite film can effectively reduce the unit temperature, which brings help to extend the life of the panels and improve the efficiency. However, the study needs to improve the parameter control of the film, and subsequent work will explore the optimal cooling configuration.

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