

A Review of the Impacts of Shading Technologies on Building Performance

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Abstract: Against the backdrop of advancing the “dual carbon” goals and the growing urgency of building energy conservation needs, shading technology, as a key means to regulate the indoor light-thermal environment of buildings and reduce building energy consumption, is of great significance for improving the comprehensive performance of buildings. This paper systematically reviews the impacts of shading technologies on building performance, defining the research scope to cover four core dimensions: performance evaluation indicators of shading technologies, testing methods, energy-saving characteristics, and impacts on architectural design and aesthetics. Research shows that dynamic external shading and comprehensive external shading have significant energy-saving advantages, while internal shading and intermediate shading have wide adaptability. The energy-saving effect of various shading technologies is closely related to climate zone characteristics and component materials. This paper also points out the current deficiencies of shading technologies and looks forward to the future development direction of green low-carbon, intelligent and efficient. This review can provide theoretical support and practical reference for building energy-saving design, shading product research and development, and the formulation of relevant standards, helping the construction industry achieve green and low-carbon transformation.

Keywords: Building shading; Shading coefficient; Solar heat gain coefficient; Building energy conservation; Green building

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1. Introduction

Under the background of the global energy crisis and the advancement of “dual carbon” goals, building energy consumption, as an important part of total social energy consumption, has an increasingly urgent demand for energy conservation and consumption reduction. According to statistics, building operation energy consumption accounts for more than 20% of the total energy consumption of buildings and the construction industry, and indoor overheating caused by solar radiation is one of the core factors leading to the surge in air conditioning energy consumption^[1]. As a key means to regulate the indoor light-thermal environment of buildings, shading technology can effectively block solar radiant heat from entering the

room, reduce air conditioning load, and at the same time optimize indoor lighting conditions, reduce artificial lighting energy consumption. It has important practical significance for improving building energy utilization efficiency and indoor thermal comfort. In addition, with the popularization of green building and ultra-low energy consumption building concepts, shading technology has become one of the core elements of building energy-saving design. Conducting a review study on the impacts of shading technologies on building performance can provide theoretical support and practical reference for building energy-saving design, shading product research and development, and the formulation of relevant standards, helping the construction industry achieve green and low-carbon transformation.

This paper focuses on the correlation between shading technologies and building performance, systematically sorting out the performance evaluation indicators, standardized testing methods of shading technologies, and their impacts on building energy-saving rate and aesthetics. Through a multi-dimensional review, it comprehensively clarifies the impact mechanism of shading technologies on building performance, providing comprehensive reference for the scientific application and optimization and upgrading of shading technologies.

2. Performance evaluation indicators of shading technologies

The performance of shading technologies directly determines their effectiveness in improving the comprehensive performance of buildings. Constructing a scientific and systematic performance evaluation indicator system is the core premise for accurately measuring shading effects and guiding the selection and optimal design of shading technologies. The indicators of shading technologies should fully cover the key dimensions related to building performance. This paper will clarify the connotation, calculation methods and application value of the main indicators as one of the key contents of performance impact.

2.1. Shading coefficient

The shading coefficient Sc (Shading Coefficient) refers to the ratio of the total solar transmittance of glass to that of standard 3 mm ordinary transparent glass^[2]. It is the core indicator for measuring the ability of shading components to block solar radiant heat from entering the room, and also the most commonly used and critical parameter in shading performance evaluation. The shading coefficient Sc reflects the heat transfer through glass by solar radiation, including the heat directly transmitted by solar radiation and the secondary radiation heat from glass to the room after heat absorption. A lower Sc value indicates less solar radiant energy transmitted through the glass. In practical engineering applications, the SC value needs to be reasonably controlled in combination with the climate conditions and building orientation of the building location. It is one of the key indicators to be considered in green building energy-saving design, and must comply with the requirements of relevant national and industrial standards.

2.2. Solar heat gain coefficient

The Solar Heat Gain Coefficient (SHGC) refers to the ratio of the total solar radiant energy transmitted through the glass (including the energy directly transmitted through the glass by solar radiation and the secondary radiation energy from the glass to the room after heat absorption) to the incident solar radiant energy, also known as the Solar Factor. It is a core indicator for supplementary measuring the solar radiation heat gain capacity of the combination of shading components and enclosure structures. Complementary to the shading coefficient (SC), it is more in line with the actual building engineering application scenarios. A

smaller SHGC value indicates a stronger ability of the combination to block solar radiation heat gain and a greater contribution to reducing indoor air conditioning load. Unlike the shading coefficient which focuses on the shading component itself, the solar heat gain coefficient comprehensively considers the synergistic effect of shading components and enclosure structures, and can more truly reflect the heat gain effect of the shading system in actual buildings. It is an important supplementary indicator for measuring the comprehensive performance of the shading system in green building energy-saving design. In addition, the total solar transmittance is sometimes expressed by g-value, whose value is equal to the solar heat gain coefficient. In China's basic standards and product standards, g-value is mostly used, while in building thermal application standards, SHGC is mostly used.

2.3. Visible transmittance

Visible Transmittance (T_{vis}) is an indicator for supplementary measuring the ability of shading components to allow visible light to pass through. It is defined as the ratio of the visible light flux transmitted through the shading component to the visible light flux incident on the component surface. The visible light spectrum range is 380 nm~780 nm. An excessively high T_{vis} value is likely to cause glare, while an excessively low value leads to dim indoor lighting, which needs to be reasonably controlled in combination with the building use scenario.

2.4. Daylight factor and glare index

While regulating indoor heat, shading technology also affects the indoor natural lighting effect. Therefore, indicators related to lighting performance are important supplements for measuring the comprehensive performance of shading technology, mainly including daylight factor and glare index.

The Daylight Factor (DF) refers to the ratio of the illuminance produced by direct or indirect reception of sky diffused light from an assumed and known sky brightness distribution at a point on the indoor reference plane to the sky diffused light illuminance produced by the same sky hemisphere on an unobstructed horizontal surface outdoors at the same time. It reflects the adequacy of indoor natural lighting. A reasonable shading design should ensure that the indoor daylight factor meets the use requirements, usually designed according to the minimum limit required by the General Code for Building Environment, to avoid insufficient indoor lighting due to excessive shading and increase artificial lighting energy consumption^[3].

The Daylight Glare Index (DGI) or Unified Glare Rating (UGR) is an indicator for measuring the degree of indoor glare. It reflects the ability of shading components to block direct solar light, avoiding visual discomfort caused by strong direct light, which affects human health and work efficiency. Usually, the indoor unified glare value UGR is required to be controlled at 19 or below. High-quality shading technology should achieve "shading without blocking light". Through reasonable shape and material selection, while blocking direct radiation, it allows scattered light to enter the room, taking into account both lighting performance and shading effect^[4]. For example, adjustable louver shading can flexibly control the daylight factor and glare index by adjusting the louver angle, adapting to the lighting needs of different periods^[5].

3. Standardized testing methods for shading technology performance

3.1. Material photo-thermal performance analysis and testing method

The material photo-thermal performance analysis and testing method is to test the photo-thermal performance of shading materials in various solar radiation bands in a standardized laboratory using equipment such as

spectrophotometers, emissivity testers or Fourier transform infrared spectrometers. The core is to accurately measure their transmittance, reflectance for solar radiation in the wavelength range of 300 nm–2500 nm (including ultraviolet, visible and infrared bands) and emissivity in the long-wave band. The specific test method is to fix the shading component sample in the test optical path, calculate the transmittance and reflectance at different wavelengths by comparing the spectral intensity of incident light, transmitted light and reflected light, and finally integrate to obtain the full-band average value. Moreover, the measured values are substituted into the calculation formula to accurately obtain the values of indicators such as visible transmittance and reflectance, and the total solar transmittance value. This method has high test accuracy and is suitable for precise laboratory testing. It can be used for shading material research and development and performance optimization, but the test process is complex, time-consuming, and has strict requirements on sample size.

3.2. Shading coefficient testing method with artificial or natural light source

The artificial light source method and natural light source method are two ways to test the shading coefficient. Their core principles are the same: both measure the total solar heat gain of the test piece under light source irradiation (including direct transmitted radiation and secondary heat transfer from the component to the room after absorption), then compare it with the solar heat gain of standard 3 mm transparent float glass, and finally obtain the shading coefficient. During the test, it is necessary to strictly control the edge thermal bridge and air leakage problems of the test piece installation, reasonably arrange sensors, and collect data after establishing a stable indoor and outdoor temperature difference, incident radiation and reaching thermal steady state. Among them, the artificial light source method is the mainstream standardized testing method in laboratories. It uses artificial light sources such as xenon lamps and metal halide lamps that simulate the solar spectrum, combined with a hot box and an environmental space to build a controllable environment. It can accurately control parameters such as temperature, wind speed and radiation intensity, with high test accuracy and good repeatability. It is suitable for standard test piece testing, product certification and other scenarios. However, the equipment cost is high, and the light source spectrum is different from real sunlight. Different artificial light sources have a great impact on the shading coefficient test results. The natural light source method uses real solar radiation as the light source, mainly used for on-site measurement of existing buildings and large-size components. It does not require complex laboratory equipment, has low testing cost and is closer to the actual use conditions. However, the test results are easily affected by natural factors such as weather, solar altitude, cloud cover and wind speed, making it difficult to maintain a stable thermal environment. The repeatability and accuracy are slightly lower than those of the artificial light source method. During testing, it is necessary to select periods with clear and cloudless weather and stable solar altitude to reduce the interference of external shading and air flow on the data. Based on this, Shan et al. developed an integrated testing equipment. Through a PID temperature control system for precise temperature control, it can switch working modes to realize the simultaneous testing of the heat transfer coefficient and shading coefficient of adjustable shading-window composite components in any adjustment state without disassembling the test piece, avoiding errors caused by test piece disassembly and state adjustment, and improving the testing accuracy. This equipment makes up for the technical gap in the energy-saving performance testing of adjustable shading-window composite components, provides an adaptive method and equipment support for objectively evaluating their energy-saving effects, and has

important reference significance for the promotion of such components and building energy-saving work^[6].

3.3. Daylight factor and glare index testing methods

The standardized testing method for daylight factor is a standardized method for measuring the indoor natural lighting level of buildings with unified standard environment, testing conditions and calculation processes. Usually, under a standard outdoor light environment with an overcast sky and no direct light, the receiver is placed horizontally to simultaneously measure the illuminance at a point indoors and the outdoor horizontal illuminance, and the daylight factor is calculated according to the standard formula^[7]. The test must ensure that the layout of measuring points, shading conditions, surface reflection, instrument accuracy and data collection all meet the specification requirements. It can be realized through laboratory artificial simulation of sky light source or outdoor on-site natural light illumination. The purpose is to ensure the comparability, repeatability and universality of lighting results of different buildings and different measuring points, providing a unified basis for lighting design, energy-saving evaluation and specification acceptance. The glare index is not a single value directly measured, but needs to be tested and calculated according to standards. After determining the observation position, instruments such as a luminance meter, illuminance meter and range finder are used to measure the brightness, size, distance and angle of each glare source, as well as the background brightness. Combined with parameters such as solid angle and position index in the standard formula, the glare contribution is calculated item by item and accumulated to obtain the UGR value. Then, the indoor glare degree is evaluated against the limit value. The overall process must meet the observation conditions, measuring point layout and data processing requirements specified in the standards^[8].

4. Impact of shading technologies on building energy-saving rate

The energy-saving effect of shading technology is mainly reflected in the reduction of building air conditioning energy consumption, but due to its adverse impact on lighting, it may lead to an increase in lighting energy consumption and winter heating energy consumption. There are significant differences in the energy-saving rates of different forms of shading technologies, which are greatly affected by factors such as building orientation, climate conditions and component materials. According to the installation position, shading types can be mainly divided into external shading, internal shading and intermediate shading. By sorting out the existing research results and engineering measured data of various shading technologies, this paper analyzes their influencing factors and applicable scenarios, and compares the differences in energy-saving effects of shading technologies in different climate zones, providing data support for the scientific selection and optimal application of shading technologies.

4.1. Statistics of energy-saving rate and influencing factors of external shading technology

External shading technology mainly includes four forms: horizontal external shading, vertical external shading, comprehensive external shading and dynamic external shading. A large number of scholars have completed data statistics on the energy-saving performance of various forms through engineering measurement and theoretical research. Zha used Design Builder software to conduct annual energy consumption simulation to explore the impact of horizontal shading panels on the comprehensive energy consumption of office buildings^[9]. It was found that horizontal shading panels on the south and west

facades have the best energy-saving effect, with energy-saving rates of 11.92% and 9.17% respectively, and the effect on the north facade is the least obvious. In specific cold regions, the overhang length in the range of 0~1.1m makes the most significant contribution to energy saving. Zhou et al. simulated indoor energy consumption based on Grasshopper's plug-in Honeybee and found that the energy-saving rate of a certain office building room in Nanjing using horizontal shading can reach 12.87%, while the energy-saving rate of comprehensive shading is only 1.69%. The main reason is that comprehensive shading blocks solar radiation in winter, increasing heating energy consumption. Wu et al. used DOE-2 software to conduct detailed composite simulation analysis and estimated the energy-saving potential of different buildings and external shading types. It was found that the relative energy-saving rate of active louver shading is generally higher than that of fixed shading. When using fixed shading, the relative energy-saving rates of horizontal shading and vertical shading can reach 5.96% and 3.62% respectively. The fixed comprehensive shading has a higher energy-saving rate of 8.43%, while the relative energy-saving rate of active horizontal louver shading can reach up to 12.62%. Mao et al. obtained orthogonal test results through energy consumption simulation with DeST software, exploring the impact of external shading louvers on the energy-saving rate of residential buildings in Guangzhou. The results show that for each 0.1 decrease in the comprehensive shading coefficient, the building energy-saving rate can be increased by about 8%. Tzempelikos et al. used DOE-2 to simulate and analyze the impact of external shading roller shutters on energy consumption in the Montreal area. It was found that external shading roller shutters with 20% light transmittance can reduce cooling energy consumption by 50% and annual total energy consumption by 12%. Zhang's research found that under the climatic conditions of Tianjin, the energy-saving effect of horizontal external shading louvers on the east and west facades is better than that of vertical external shading louvers, and the energy-saving rate of horizontal external shading on the west facade can reach 8%~14%. Compared with fixed shading, dynamic external shading can effectively reduce heating energy consumption and lighting energy consumption, thereby reducing total energy consumption^[10].

4.2. Statistics of energy-saving rate and influencing factors of internal shading technology

Internal shading technology is a shading form installed inside the indoor window openings of buildings. With indoor light-thermal regulation as the core function, it is widely used in various residential, office and existing building renovation scenarios due to its advantages of convenient installation, low cost and wide adaptability. Although its overall energy-saving effect is lower than that of external shading, relevant scholars have clarified its energy-saving performance and application characteristics through a large number of studies. Song used DeST software to conduct energy consumption simulation to explore the energy-saving benefits of combining internal shading with Low-E glass in hot summer and cold winter regions^[11]. It was found that the greater the short-wave reflectivity of internal shading curtains, the better the energy-saving effect in hot summer and cold winter regions. Song confirmed through research that selecting thin curtains for offices in hot summer and cold winter regions has the optimal energy-saving benefit^[12]. In summer, solar radiation heat gain is reduced by 49%, cumulative cooling load is reduced by 60 kWh, and it can balance lighting and air conditioning energy consumption. Gao et al. found that adding internal shading can reduce the annual total energy consumption of buildings by 7%, and the energy-saving rate can be further improved through behavioral regulation. Cui et al. analyzed the impact of shading renovation with different materials and structural forms on the energy consumption of the library atrium based on DesignBuilder and Ecotect

software. It was found that the shading scheme using high-reflection and low-transmission roller shutter materials has the best effect on reducing the total building energy consumption and the indoor temperature of the atrium.

4.3. Statistics of energy-saving rate and influencing factors of intermediate shading technology

Intermediate shading is a shading form that integrates shading components between the cavities of double glazing curtain walls or double windows, combining the convenience of internal shading and the energy-saving stability of external shading. This technology emerged relatively late, and application research is still in its infancy. Some scholars have clarified its energy-saving characteristics and application advantages through comparative measurement. Cheng et al. used Comfen software to conduct energy consumption simulation on south-facing hotel guest rooms in Beijing and found that the comprehensive energy consumption is the lowest when the opening angle of the built-in louver insulated glass is 165 degrees. Li Shengjie analyzed the energy-saving effect of insulated glass with built-in louvers. Using DeST software simulation, it was found that the annual total energy consumption of buildings is the lowest when the louvers of insulated glass with built-in louvers are closed all year round, which can reduce the annual energy consumption by about 12.5% compared with ordinary insulated glass. At present, there are few studies on the energy-saving benefits of intermediate shading, and there are still certain research gaps and deficiencies in this field^[13].

5. Impact of shading technologies on architectural design and aesthetics

Shading technology is not a simple auxiliary component for building energy conservation. Its design and application are directly related to the overall design logic and visual aesthetic effect of the building. It is not only a key means to optimize building performance, but also an important element of architectural design expression. A reasonable shading design can achieve the coordinated unification of building performance and design aesthetics. On the contrary, it may destroy the overall coordination of the building and limit the exertion of design creativity. This paper discusses the specific impacts of shading technology from the dimensions of architectural design adaptability and visual aesthetics, providing reference for the integration of shading design and overall architectural design.

5.1. Stylistic aesthetic value of shading components

As an important part of the building facade, the selection of shape, color and material of shading components directly determines the visual texture and aesthetic expression of the building, and has unique stylistic aesthetic value. In terms of shape design, shading components can enrich the layers of the building facade through various shape designs, breaking the monotony of the traditional building facade. The linear shape of horizontal shading is simple and atmospheric, which can create a stretched and stable architectural temperament, suitable for modern minimalist style buildings; the vertical lines of vertical shading are straight and neat, which can enhance the vertical sense of the building and improve the solemnity and three-dimensional sense of the building; the grid-like and block-like shapes of comprehensive shading are flexible and changeable. Through different arrangement methods, it can create a facade effect with a sense of rhythm and rhythm; dynamic shading components can adjust their shapes according to environmental changes,

adding dynamic beauty to the building. In terms of color matching, the color of shading components should be coordinated with the main color of the building and the surrounding environment. At the same time, the characteristics of the building itself can be well highlighted by reasonably using shading components of different colors. In terms of material matching, shading components of different materials present different aesthetic textures. Metal shading components are simple, smooth and delicate in texture, with a modern sense, suitable for modern buildings; wooden shading components are natural and warm, close to nature, suitable for ecological buildings and rural style buildings; fabric shading components are soft and light, which can create a soft and comfortable visual effect, suitable for residential buildings and leisure buildings; glass shading components are transparent and light, which can realize the virtual and real combination of the building facade and improve the transparency and delicacy of the building.

5.2. Unity and coordination with architectural style

The design of shading technology should be consistent with the overall style of the building to achieve the integrity and coordination of architectural aesthetics, avoiding the disconnection between shading components and the main building, which will destroy the overall beauty of the building. Different architectural styles have different requirements for shading design, which need to be targeted and adapted to achieve the in-depth integration of shading and architectural style+. Modern minimalist style buildings focus on simple, smooth and atmospheric visual effects, and are suitable for shading components with simple shapes and regular lines, such as horizontal shading panels, vertical louvers, adjustable louvers, etc. The colors are mainly light colors and neutral colors, and the materials are preferably modern materials such as metal and glass, avoiding complex decorations to highlight the minimalist texture of the building; ecological buildings focus on integration with the natural environment, and are suitable for shading components made of natural materials such as wood and fabric. The shapes can adopt natural curves, grid shapes, etc., or be matched with vegetation shading to enhance the ecological sense and natural sense of the building; traditional style buildings focus on the cultural heritage and decoration of the building. The design of shading components needs to integrate traditional elements to achieve the combination of tradition and modernity; minimalist architecture focuses on the purity and integrity of the building. Shading components can adopt an integrated design with the main building, such as hidden shading, shading panels integrated with the wall, etc. The color and material are consistent with the main building to achieve a simple and unified building facade^[14].

5.3. Integration path of green building design goals

With the popularization of green building and ultra-low energy consumption building concepts, shading technology has become the core integration point for achieving green building design goals, promoting the transformation of architectural design towards low-carbon, energy-saving and comfortable directions. The core goals of green building design are to reduce building energy consumption, improve indoor comfort and reduce environmental impact. Shading technology exactly meets this goal. Its integration with green building design is mainly reflected in three aspects:

- (1) Integration with building energy-saving design: Through scientific shading selection and design, reduce air conditioning and lighting energy consumption, helping buildings meet the requirements for building energy consumption control in green building energy-saving standards;

- (2) Integration with indoor thermal comfort and light comfort design: Through precise regulation of shading components, optimize the indoor temperature and lighting environment, reduce glare and overheating phenomena, improve human comfort, and conform to the “people-oriented” design concept of green buildings;
- (3) Integration with low-carbon and environmental protection design: Select environmentally friendly and renewable materials for shading components, reduce carbon emissions during material production and waste disposal, and at the same time indirectly reduce carbon emissions throughout the building life cycle through the improvement of energy-saving effects, helping to achieve the “dual carbon” goals.

In addition, shading design can also be integrated with passive building design. Through reasonable shading forms, make full use of natural lighting and natural ventilation, reduce the use of active air conditioning and lighting systems, and realize the harmonious coexistence of architectural design and the natural environment^[15].

6. Conclusion

Against the background of the continuous strengthening of “dual carbon” goals and building operation energy consumption control needs, shading technology has developed from a single component-level measure to one of the key strategies comprehensively affecting building energy consumption, light-thermal comfort and facade expression. This paper systematically sorts out the core performance indicator system and standardized testing path of shading technologies, and discusses their synergistic impacts on building energy-saving rate, architectural design and aesthetics, forming a multi-dimensional and comprehensive research summary. Research shows that in terms of energy-saving impact, existing studies generally show that shading can effectively inhibit solar radiation heat gain and reduce cooling load, but its comprehensive energy-saving benefits are jointly restricted by factors such as shading position, component form, control strategy, building orientation and climate zone. It is necessary to conduct systematic trade-offs and scenario-based selection between cooling energy conservation, lighting needs and potential changes in heating and lighting energy consumption. In addition, shading is not an auxiliary technology for building energy conservation. Its shape, material and interface integration directly affect the integrity and aesthetic expression of the building facade. The coordination of performance and aesthetics should be achieved within the framework of unified architectural style and integrated structure.

In general, shading technology plays an irreplaceable role in building energy conservation and consumption reduction, comfort improvement and green transformation. The review research in this paper can provide theoretical support and practical reference for building energy-saving design, shading product research and development and the formulation of relevant standards, helping shading technology develop in a more efficient, intelligent and environmentally friendly direction, and promoting the construction industry to achieve “dual carbon” goals and sustainable development.

Disclosure statement

The author declares no conflict of interest.

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