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Case study: Energy savings from solar window film in two commercial buildings in Shanghai

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ABSTRACT

The objective of this study was to understand the energy savings from applying solar window films in a commercial building with large, curtain wall areas in Shanghai, China. eQUEST was used to simulate the annual building performance with and without the solar window film. The simulation model was calibrated against the measured monthly and daily electrical consumption. The simulation results indicated that two factors significantly influence the effect of the window film. These factors include the position of the installed window film and the configuration of the original glazing system. The effect of the window film on the performance of the curtain wall glazing system varies greatly, depending on the type of film and how it is applied. The film can decrease the shading coefficient and solar heat gain coefficient by 44% and 22% if applied on the outside and inside of the existing windows, respectively. For a double pane, low-E glazing system, the building cooling load through the windows on design day is reduced by 27.5% and 2.2% for outside and inside window films, separately. Adding the window film inside of the curtain wall was not effective because the increased window conductive heat transfer offsets the decreased cooling load from solar radiation.

1. Introduction

With continuing economic growth in China, energy consumption from buildings is on the rise. Promoting energy efficiency and reducing the carbon emission rates of buildings on a nationwide scale are a top priority for the Chinese government, especially given the country's large population. The annual energy consumption of buildings in China accounts for about 25% of the total energy consumption in the country [1]. The annual building energy consumption in China increased from 0.243 billion tce (tons of standard coal equivalent) in 1996 to 0.563 billion tce in 2006 [2]. Different retrofit projects are sponsored and advocated by the government to alleviate the status quo of energy consumption in China. For example, the retrofit of existing residential buildings of 0.15 billion m^2 regulated in the 11th five-year plan (2006–2010) was finished successfully in 2010 [3]. Because this task occurred on such a large scale and involved so many participants, several challenges were anticipated [4,5].

In recent years, a number of large commercial buildings in China have been built with high window-to-wall ratios to achieve an artistic effect, visual perception, and energy savings from natural ventilation and the integration of daylight and artificial light. Large window areas allow more daylight into the building to reduce the energy required to light the buildings. In hot climate areas, the cooling load from windows accounts for the majority of the total building cooling load for large commercial buildings. The benefits from daylight may be penalized by the increased solar heat gain through the windows. It is reported that the heat dissipated from glazing systems in northern China accounts for approximately 40–50% of the total heating load in winter, while the cooling load caused by the glazing systems accounts for approximately 20–30% of the total cooling load in summer. The situation is even worse in southern China [6].

In western countries, there have been prior studies on window heat transfer and its energy-saving impact on buildings. Michael established the model to calculate the heat transfer and optical performance of glass in 1982 [7,8]. ASHRAE also provided detailed information on the theoretical calculation of glass heat transfer and optical performance [9]. Other studies on new energy-saving technology have also been conducted. Green roofing is a passive cooling technique that stops incoming solar radiation from reaching the building structure. A research team led by Castleton studied the building energy savings and the potential for retrofit of green roof technology [10].

In China, Zhang et al., from South China University of Technology, have conducted dynamic tests on total thermal resistance and the shading coefficient of the glazing system [11]. Chen et al. achieved important results by using experiments to study the

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thermal performance of building glazing systems [12]. Wei and He from Nanjing University of Technology, have made contributions to the study of energy savings analysis of the glazing system by employing computer simulations [13,14]. Pu et al., from Shenzhen Building Science Research Institute, evaluated the impact of the glazing system on the HVAC load and the energy consumption of the whole building [15]. Yang and Di, from Tsinghua University, conducted research on the energy efficiency of low-E glazing systems [16].

Several studies have also been conducted to demonstrate the effect of solar control window films on reducing the annual energy consumption and peak demand load in summer. Noh-Pat et al. developed a mathematical model for the natural convection of air on the vertical canal in a double glazing unit to study the effects of a solar control film. It was found that heat gains through windows can be reduced by 55% with solar control films outside the inner window compared to the traditional glazing system without solar control films [17]. Li et al. studied the lighting and cooling energy performance for a fully air-conditioned, open-plan office to evaluate the effects of solar control films together with lighting controls. It was found that solar film coatings coupled with light dimming controls can reduce the electricity usage and the lighting and cooling energy consumption by 21.2% and 6.9%, respectively [18]. Li et al. also conducted field measurements of solar control window films in an air-conditioned office building, and the results indicated diffuse solar radiation can be reduced by 30% using the window film coating [19].

Additionally, many studies have been conducted to evaluate the energy performance of energy conservation measures (ECMs) using building energy simulation tools. Pan et al. developed simulation models of two office buildings with a data center, in Shanghai, China, to evaluate the energy cost savings of various ECMs compared with the baseline building [20]. Yin et al. presented the procedure used to develop and calibrate simulation models of 11 commercial buildings in California [21]. Wong et al. also used the DOE-2 energy simulation tool to evaluate the effects of rooftop gardens on the energy performance of a five-story commercial building in Singapore [22].

This study develops a procedure to estimate the energy performance of solar control window films as an energy saving retrofit to exist buildings. Using building energy simulation for the entire building, this study analyzes how the characteristics of the glazing system, with and without window films, influence energy consumption and peak demand.

2. Methodology

As shown in Fig. 1, the Lawrence Berkeley National Laboratory (LBNL) series of window software (Optics and WINDOW 6) were adopted to estimate the energy performance of the window films. Optics was used to calculate the optical properties of different types of glazing systems, such as a single clear glazing system, double clear glazing system, double low-E glazing system and a glazing system with and without low-E film, solar control window films. The glazing system database in Optics covers most types of systems that global manufacturers produce. In this study, Optics 5.1 was used to calculate the optical properties of a glazing system with and without solar control window films to provide a supplementary database of glazing systems for WINDOW 6. The optical results were imported into the database in WINDOW 6. WINDOW 6 was used to analyze the thermal and optical performance of the glazing system, which included the *U*-value, shading coefficient, solar heat gain coefficient, visible and solar transmittance, etc. The output from WINDOW 6 was saved in DOE format to be used in eQUEST.

The process of developing the building simulation model involves data collection, model development and model calibration. The collected data include architecture drawings, building envelope characteristics, occupancy, lighting and plug load power and operating schedules, HVAC system characteristics and operating schedules, measured building energy use, etc. The building's internal load parameters, such as occupancy, lighting and plug load power and operating schedules, needed to be refined and calibrated by comparing the simulated results with measured data. After the simulation models were calibrated, they were used to analyze the effect of window films on reducing energy consumption and peak power demand in summer. Since this study focuses on how the characteristics of the glazing system influence building energy consumption, some variable parameters that were unavailable were input into the model based on the building characteristics of a typical museum building.

2.1. Simulation model development

The building used in the case study is an auto-museum located in Shanghai, China, which contains approximately 27,985 m^2 on five floors used for auto exhibitions, offices and meeting spaces. As shown in Fig. 2, the building has partial shading from east-facing and west-facing window curtain walls to maximize day lighting. The *U*-values of the exterior wall and the roof are 0.48 W/m^2 K and 0.24 W/m^2 K, respectively. The internal loads with the initial simulation model give the occupancy density at 11.0 m^2 per person; the lighting density is 11.5 W/m^2, and the plug load density is 2.8 W/m^2. The HVAC system is a split heat pump with a DX coil (Direct-Expansion) system. The designed outdoor air flow rate per person is 20 m^3/h. The infiltration rate is set at grade II (0.6 m^3/m^2 h) base on the designed window curtain wall. The heating set point is 21 °C, and the cooling set point is 25 °C during the museum's operating hours.

2.1.1. Window curtain wall

The window curtain wall is composed of two types of glazing systems: an 8 + 12A + 6 double low-E glazing system and an 8 + 12A + 6 beige double low-E glazing system. There is no difference between the thermal and optical performance in these two types of glazing system. The simulation model selected the 8 + 12A + 6 double low-E glazing system as the input window type and neglected the influence of the glass sideboard that revolved around the building. Optics 5 and WINDOW 6 were used to calculate the thermal and optical characteristics of the glazing system with/without solar control window films and exported the results into DOE format files for simulation in eQUEST.

Fig. 3 shows all types of glazing system with/without window films that were analyzed with the model. Type A is the original glazing system of the actual building, type A-1 and type A-2 are optimized glazing systems with window films sticking inside and outside, respectively. Tables 1 and 2 present all thermal and optical properties of the glazing systems with/without window films. By analyzing the calculated results of the glazing systems with/without window films, the *U*-values of the type A-1 and type A-2 glazing systems were reduced by a small amount compared to the original glazing system without window films. Compared to the original glazing system, both the shading coefficient and solar heat gain coefficient for the type A-1 glazing system was reduced by 13.6%, and the relative heat gain decreased by approximately 13.1%; the shading coefficient and solar heat gain coefficient of the type A-2 glazing system were reduced by 35.7%, and the relative heat gain decreased by 34.5%. For the type A-1 and A-2 glazing systems, the visible transmittance was reduced by approximately 44–50% after sticking the window film onto the original glazing system.