Energy and Buildings 45 (2012) 132–140

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

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

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ARTICLE INFO

Article history:
Received 13 September 2011
Accepted 31 October 2011

Keywords:
Window film
Glazing system
Electrical consumption
Commercial buildings
Building cooling load

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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0378-7788/$ – see front matter
doi:10.1016/j.enbuild.2011.10.062

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.

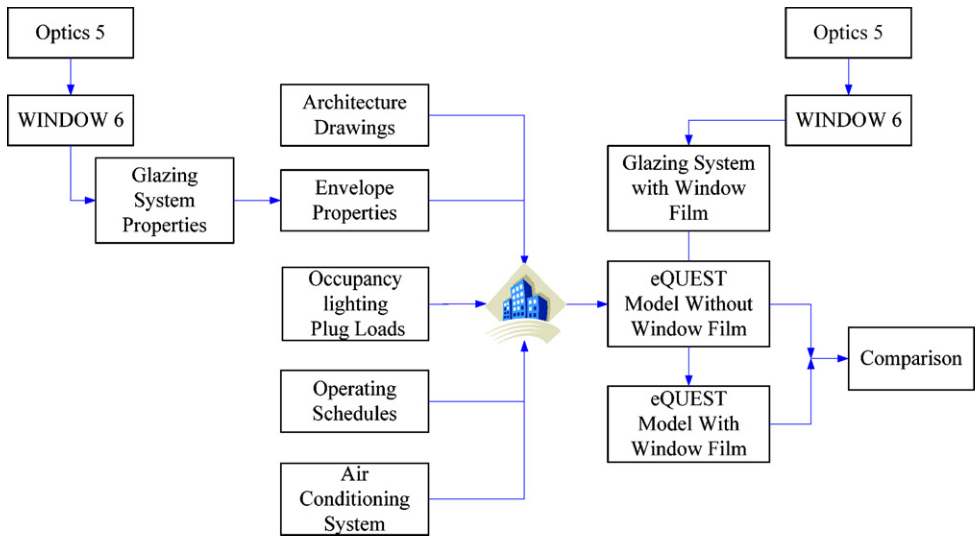

Fig. 1. Procedure to estimate the energy performance of solar control window film.

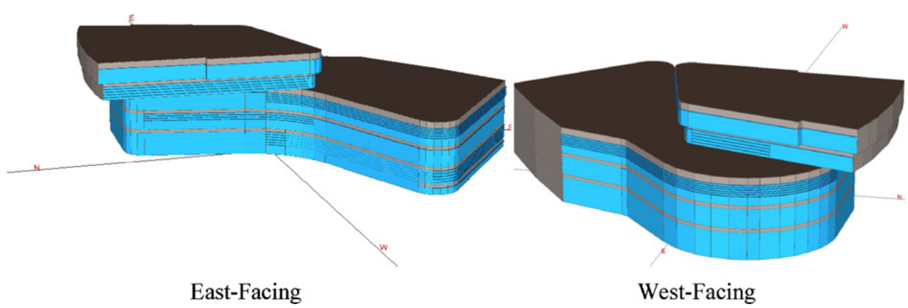

Fig. 2. eQUEST model.

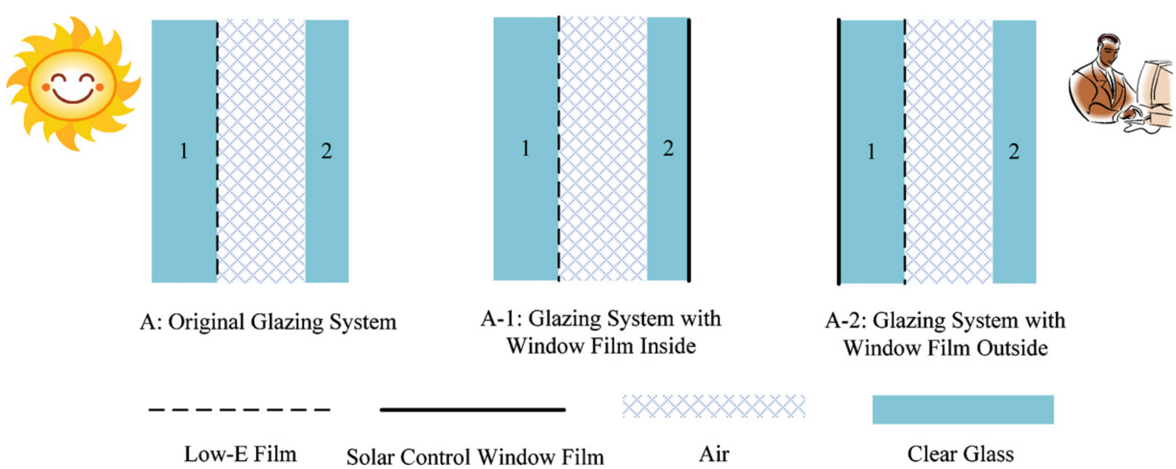

Fig. 3. Glazing systems (double low-E) with and without window films.

2.2. Calibration to the simulation model

Pan et al. and Yin et al. applied the ASHRAE Guideline 14-2002 to calibrate whole-building simulation models to measured data [21,23,24]. Norford et al. presented a commonsense procedure for calibrating a DOE-2 computer model of a commercial building, and they identified the major building loads, including lighting and equipment [25]. Yin et al. used the measured data for

Table 1
Thermal and optical properties of glazing systems with/without window films.

Glazing system type	K (W/m^2 K)	SC	SHGC	Relative heat gain (W/m^2)	Visible transmittance
A	1.802	0.630	0.548	411	0.714
A-1	1.778	0.544	0.473	357	0.358
A-2	1.801	0.405	0.352	269	0.399

Table 2
Other optical properties of glazing systems with/without window films.

Glazing system type	Visible			Solar					UV
	Transmittance	Reflectance		Transmittance	Reflectance		Absorptance		Transmittance
		Front	Back		Front	Back	Front	Back	
A	0.714	0.120	0.130	0.474	0.162	0.197	0.306	0.058	0.330
A-1	0.358	0.147	0.115	0.214	0.179	0.137	0.312	0.296	0.001
A-2	0.399	0.119	0.180	0.268	0.130	0.151	0.569	0.033	0.001

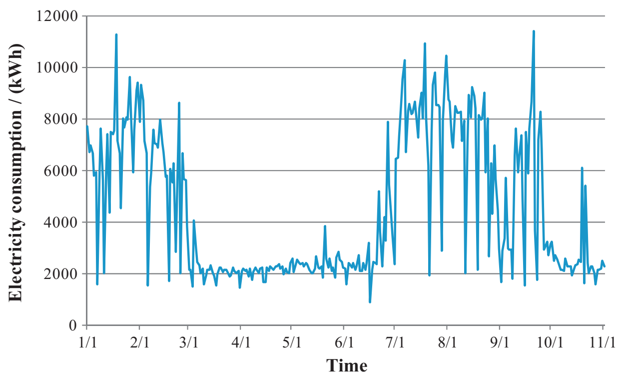

Fig. 4. Entire building electricity usage in 2008.

building electricity usage during the heating season to calibrate the lighting and plug load densities and operating schedules [21]. Paul et al. described a systematic, evidence-based methodology for the calibration of simulation models, which is intended for detailed calibration with high resolution measured data [26].

Fig. 4 shows the daily electricity usage of the entire building from January to October 2008; notice that the HVAC system did not operate from March to June, except for a few days. As shown in Fig. 5, the electricity usage on each day was almost the same, except on April 14th and April 15th, which indicated that the lighting and plug load was steady throughout the transition season. The daily average electricity usage on off-peak, mid-peak and on-peak periods was 370 kWh, 1199 kWh and 611 kWh, respectively. By evaluating the difference in electricity usage between the heating & cooling seasons and the transition season, the electricity usage of the HVAC system during the heating and cooling season could be predicted. Based on the measured electricity usage of the entire building, the lighting and plug load densities and operating schedules and the HVAC system were refined with the initial model.

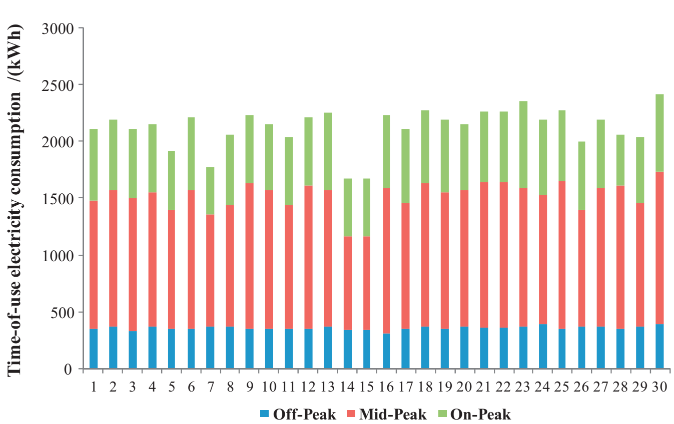

Fig. 5. Time-of-use entire building electricity usage in April.

3. Energy analysis

3.1. Energy consumption analysis of the window curtain wall

The building loads from windows are composed of the loads from window conduction and solar radiation through the windows. During the cooling season, the cooling load from solar radiation through the windows accounts for the majority of the total building cooling load compared with the cooling load from window conduction. During the heating season, the heating load from window conduction is much higher than the cooling load from solar radiation through the windows, even though the cooling load from solar radiation could offset part of the total building heating load. To better understand the effect of solar control window films, we conducted a detailed analysis on window conduction and solar radiation through the windows, with and without window films.

Tables 3 and 4 present the detailed comparison results of the building cooling and heating load for different types of glazing system with/without window films. It can be seen that the effects of the window films on the thermal performance of the glazing system are different for glazing systems with outside and inside window films. On summer design day, the cooling load from window conduction with type A-1 increased 113% compared to that of the original glazing system type A, while no obvious difference was observed for type A-2 with window films outside the original glazing system. For type A-1, the solar absorption of the inner surface increased to 0.296, from 0.058, after sticking window film onto the inside window of the original glazing system. This led to an increase in the inner surface temperature and cooling load from window conduction. Moreover, the cooling load from solar radiation through the windows was reduced by 56% and 44% for type A-1 and A-2, respectively, due to the decrease in solar transmittance. For the building heating load from windows, there was no significant difference between the heating load from window conduction for type A-1 and A-2, while the cooling load from solar radiation decreased by 56% and 43% for type A-1 and A-2, respectively, on heating design day. The building cooling load from solar radiation on winter design day was much lower than that of summer design day and accounted for only 20% of the total building heat load from windows.

Fig. 6 illustrates the simulation results of the building cooling load for the proposed glazing system types with/without window films. For glazing system type A-1, the total building cooling load decreased slightly compared to the original glazing system type A. The reason for no obvious effect of the window film inside the glazing system is that the increased cooling load from window conduction offset the effect and potential for the window films to decrease the cooling load from solar radiation through the windows. For glazing system type A-2, even though the outside window film increased the solar absorptance of the outer window surface, there was no obvious change in the building cooling load from window conduction due to the existence of an air layer in the glazing system. Meanwhile, the building cooling load from solar radiation through the windows decreased by 44% compared to the original glazing system type A. Therefore, the simulation results for glazing

Table 3
Building cooling load from windows (window area: 6141 m^2).

Cooling load	Total building cooling load from all windows				Average building cooling load from all windows			
Peak load	Conduction (kW)		Solar radiation (kW)		Conduction (W/m^2)		Solar radiation (W/m^2)	
	Design day	Annual	Design day	Annual	Design day	Annual	Design day	Annual
A	175.08	190.92	375.22	293.30	28.51	31.09	61.10	47.76
A-1	373.25	348.91	164.69	131.25	60.78	56.81	26.82	21.37
A-2	187.02	207.30	211.68	169.10	30.45	33.76	34.47	27.54

Table 4
Building heating load from windows (window area: 6141 m^2).

Heating load	Total building heating load from all windows				Average building heating load from all windows			
Peak load	Conduction (kW)		Solar radiation (kW)		Conduction (W/m^2)		Solar radiation (W/m^2)	
	Design day	Annual	Design day	Annual	Design day	Annual	Design day	Annual
A	−253.55	−258.22	122.32	164.25	−41.29	−42.05	19.92	26.75
A-1	−246.51	−249.64	53.64	69.99	−40.14	−40.65	8.73	11.40
A-2	−252.70	−256.40	69.03	113.77	−41.15	−41.75	11.24	18.53

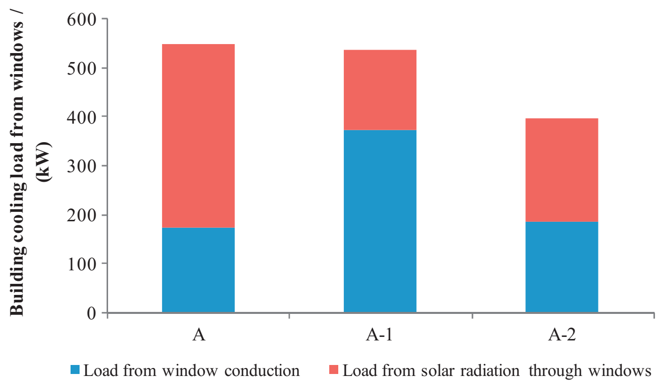

Fig. 6. Building cooling loads from windows on summer design day.

system type A-2, with window films outside, show a wide energy saving potential.

3.2. Cooling load analysis on design day

Figs. 7 and 8 show the building cooling load breakdown for the original glazing system type A and the comparison of simulation results between different glazing system types with/without window films. Notice that the cooling load from the windows account for 66% of the total building cooling load, and the cooling load from window conduction and solar radiation through the windows accounted for 44% and 20%, separately. The effects of the window film on the solar radiation through the windows have been demonstrated in the previous section. As shown in Fig. 8, the glazing system type A-2, with a window film outside, could reduce solar radiation through the windows by 44%, with little influence on the cooling load from window conduction.

3.3. Whole building energy usage

Due to the hot summer and cold winter climate in the study area, the total building energy consumption needs to be studied to evaluate the effects of window films on window curtain walls. By sticking the window film onto the original glazing system, the solar heat gain coefficient (SHGC) of the glazing system was reduced by 15–30%. This led to a reduction in the heat gain from solar radiation through the windows. On the one hand, the building cooling loads during the cooling season are reduced significantly due to the deep reduction in the cooling load from solar radiation through the windows. On the other hand, the building would benefit less from the solar radiation through the windows. By comparing the energy consumption and cost of calibrated building simulation models with/without window films, the effects of the window film on reducing the energy consumption for the entire building can be better understood.

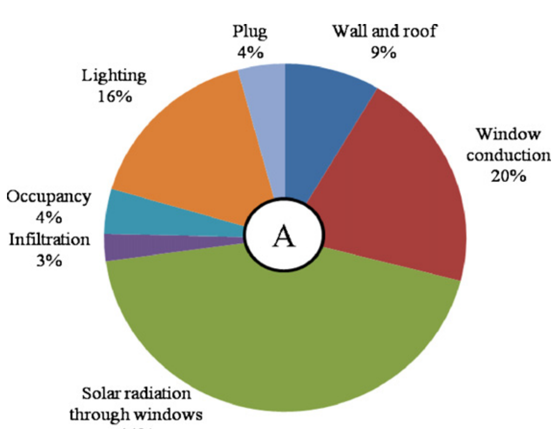

Fig. 7. Building cooling load breakdown for original glazing system Type A.

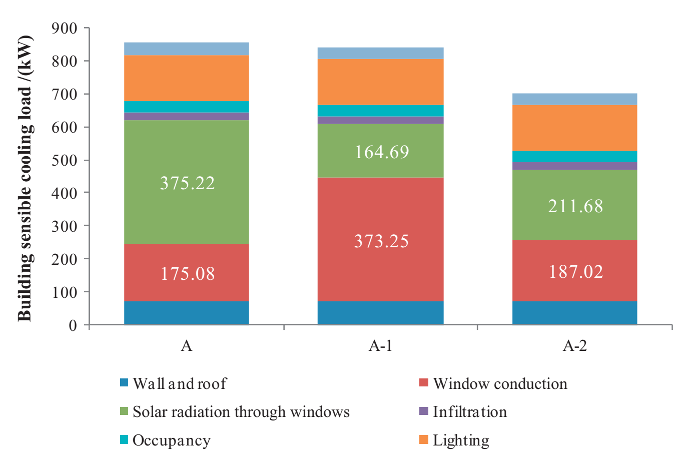

Fig. 8. Building cooling load breakdown for all proposed glazing system types.

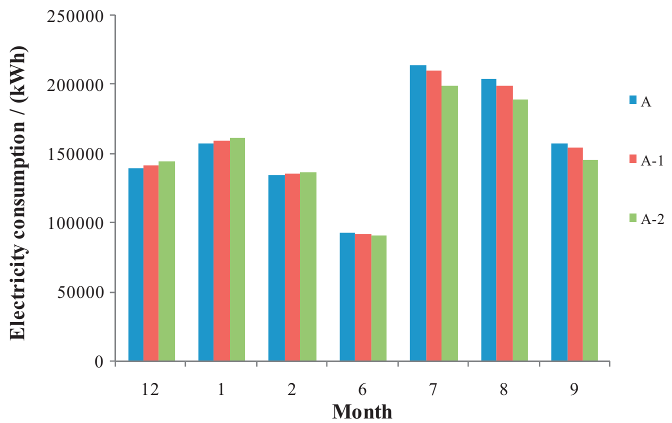

Fig. 9. Monthly whole building electricity usage for proposed glazing systems (heating & cooling seasons).

3.3.1. *Electricity consumption*

Fig. 9 shows the simulated monthly electricity usage of whole building for all types of glazing systems, with and without window films. Compared to the original glazing system type A, the electricity usage for type A-1 and A-2 did not change significantly during the heating season. In addition, the electricity usage for type A-1 and A-2 decreased by 2.0% and 8%, respectively, during the cooling season. For type A-2, with window films outside the glazing system, electricity usage of whole building decreased by 7.3–8% from July to September, and the total electricity savings throughout the cooling season was 37,191 kWh.

3.3.2. *Energy cost*

Table 5 presents the 2009 utility rates of electricity and natural gas in Shanghai. The utility rate for natural gas is a uniform rate by per cubic meter, and the utility rate for electricity includes a time-of-use energy charge and monthly peak demand charge.

Fig. 10 shows the simulated monthly energy cost of all simulation models with different glazing systems. We can see that there is no significant change in the energy cost during the heating season, and the maximum reduction in the monthly energy cost during the cooling season reached 8.0% in September. In addition, the monthly peak demand charge was reduced significantly due to a decrease in the monthly peak demand of the whole building.

Table 6 presents detailed results of the monthly energy cost for the simulation models. Compared to the original glazing system type A, the electricity cost for type A-1 and A-2 increased by 0.6–2.0% during the heating season. For type A-1 and type A-2, the electricity cost during the cooling season was reduced by 2.1–2.2% and 7.3–8.0%, separately. Significant cost savings could be observed for the simulation model with glazing system type A-1. The average energy cost saving was $2044, and the total energy cost saving throughout the cooling season was $6274. Compared to glass type A-2, the effect of the window films on reducing electricity consumption and peak demand is more obvious.

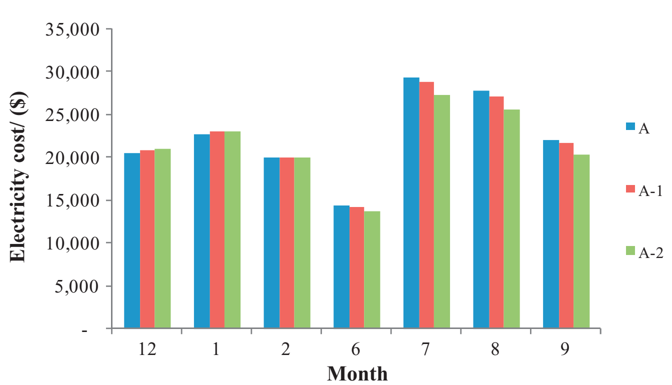

Fig. 10. Monthly simulated energy cost for models with different glazing system.

3.3.3. *Optimization of energy conservation measures with window films*

The building had a window-to-wall ratio of 90%, with 1–3 stories. With respect to the heat gain from solar radiation through the windows, the average solar radiation of the northern windows was the lowest compared to other orientations. For the northern glass curtain wall, the potential for utilizing window films for solar radiation reduction was not as obvious. The average solar radiation for the northeastern windows was also lower in the morning. Therefore, we proposed two optimization models for utilizing window films to improve the energy efficiency and economic benefits. The first optimal model (A-2-1) was to stick window films onto the glass curtain walls, except for the northern orientation; and the second model (A-2-2) was to stick window films onto the glass curtain walls, except for the northern and northeastern orientations.

Table 7 presents the monthly simulation results for the electricity cost of the optimized simulation models with window films. For the optimized simulation model A-2-1, the average monthly cost savings throughout the cooling season was $1435, which is higher than that of simulation model A-2 by $335. For the optimized simulation model A-2-2, the average monthly cost savings throughout the cooling season was $1130, which is higher than that of simulation model A-2 by $276. By comparing optimal model A-2-1 with optimal model A-2-2, the northern glass curtain wall without window films accounted for 34.5% of the total window area of the whole building; while the northern and northeastern glass curtain wall without window films accounted for 48% of the total window area. By sticking window films onto other windows, both the energy savings and economic benefits could be improved.

3.4. *Further analysis and discussion*

To study the impact of sticking solar window films onto the double-clear glazing system, the research team also created scenario series B and conducted simulation and analysis. As shown in Fig. 11, a “virtual” double-clear glazing system was proposed to study the effect of solar window films for reducing the cooling load through such windows. Tables 8 and 9 present the detailed thermal and optical properties of the “virtual” double-clear glazing system with/without window films. It can be seen that the *U*-value of glazing system types B-1 and B-2 decreased slightly compared to the double-clear glazing system without window films. Compared to the double-clear glazing system, both the shading coefficient and solar heat gain coefficient for type B-1 were reduced by 22%. In addition, the relative heat gain decreased by 21%. The shading coefficient and solar heat gain coefficient for type B-2 were reduced by 46%, and the relative heat gain decreased by 44%. For glazing systems type B-1 and B-2, the visible transmittance decreased by approximately 50% after sticking window films onto the “virtual” double-clear glazing system (Table 9).

For type B-1, on summer design day, the total building cooling load from the windows decreased by 17.2–17.6%, and the building cooling load from transmitted solar radiation through the windows decreased by 58.0–58.8%; for type B-2, on summer design day, the total building cooling load from the windows decreased by 38.0–39.3%, and the building cooling load from transmitted solar radiation through the windows decreased by 58.0–58.4%. By comparing the calculated results for type B-1 and B-2, we found that the

Table 5
2009 utility rates of electricity and natural gas in Shanghai.

Energy source	On-peak		Mid-peak			Off-peak	Demand charge ($/kW Month)
Electricity ($/kWh)	8:00–11:00	18:00–21:00	6:00–8:00	11:00–18:00	21:00–22:00	22:00–06:00	
	0.158		0.099			0.046	5.735
Natural gas ($/m^3)	0.368						

Table 6
Comparison of energy cost between base model and models with window films.

Monthly electricity cost ($)		12	1	2	6	7	8	9
Monthly time-of use electricity cost ($)	A	16,674	18,955	16,095	10,491	25,382	24,102	18,409
	A-1	16,927	19,213	16,228	10,404	24,797	23,507	18,018
	A-2	17,281	19,494	16,375	10,203	23,526	22,208	16,978
Monthly peak demand (kW)	A	681.20	667.30	678.00	680.90	713.40	644.40	654.30
	A-1	677.70	664.80	674.60	674.00	702.80	636.90	642.70
	A-2	646.20	638.20	648.60	628.30	660.30	593.20	592.90
Demand charge ($)	A	3907	3827	3889	3905	4092	3696	3753
	A-1	3887	3813	3869	3866	4031	3653	3686
	A-2	3706	3660	3720	3604	3787	3402	3400
Monthly electricity cost ($)	A	20,581	22,782	19,984	14,396	29,474	27,798	22,161
	A-1	20,813	23,026	20,096	14,269	28,828	27,160	21,704
	A-2	20,987	23,154	20,095	13,806	27,313	25,610	20,379
Electricity cost savings ($)	A	–	–	–	–	–	–	–
	A-1	−233	−243	−113	127	646	638	457
		−1.1%	−1.1%	−0.6%	0.9%	2.2%	2.3%	2.1%
	A-2	−406	−372	−111	590	2161	2188	1783
		−2.0%	−1.6%	−0.6%	4.1%	7.3%	7.9%	8.0%

Note: Cost savings = electricity cost of simulation model with original glazing system ($) – electricity cost of simulation model with glazing system with window film ($).

Table 7
Electricity cost of the whole building with the ECM of window film.

Monthly electricity cost		12	1	2	6	7	8	9
Monthly time-of use electricity cost ($)	A	16,674	18,955	16,095	10,491	25,382	24,102	18,409
	A-2	17,281	19,494	16,375	10,203	23,526	22,208	16,978
	A-2-1	17,220	19,439	16,337	10,297	24,104	22,765	17,393
	A-2-2	17,124	19,354	16,280	10,328	24,391	23,053	17,592
Monthly peak demand (kW)	A	681.20	667.30	678.00	680.90	713.40	644.40	654.30
	A-2	646.20	638.20	648.60	628.30	660.30	593.20	592.90
	A-2-1	662.40	653.10	664.70	643.30	675.80	609.20	609.50
	A-2-2	666.60	655.50	668.30	649.80	684.20	615.80	619.30
Demand charge ($)	A	3907	3827	3889	3905	4092	3696	3753
	A-2	3706	3660	3720	3604	3787	3402	3400
	A-2-1	3799	3746	3812	3690	3876	3494	3496
	A-2-2	3823	3760	3833	3727	3924	3532	3552
Monthly electricity cost ($)	A	20,581	22,782	19,984	14,396	29,474	27,798	22,161
	A-2	20,987	23,154	20,095	13,806	27,313	25,610	20,379
	A-2-1	21,019	23,185	20,149	13,986	27,980	26,259	20,889
	A-2-2	20,948	23,113	20,113	14,055	28,315	26,585	21,144
Electricity cost savings ($)	A	–	–	–	–	–	–	–
	A-2-1	−438	−403	−166	410	1494	1540	1272
		−2.1%	−1.8%	−0.8%	2.8%	4.9%	5.3%	5.5%
	A-2-2	−367	−331	−129	342	1159	1213	1018
		−1.8%	−1.5%	−0.6%	2.3%	3.8%	4.2%	4.4%

Note: Cost savings = electricity cost of simulation model with original glazing system ($) – electricity cost of simulation model with glazing system with window film ($).

Table 8
Thermal and optical properties of glazing systems (double-clear) with/without window films.

Glazing system type	*K* (W/m^2 K)	SC	SHGC	Relative heat gain (W/m^2)	Visible transmittance
B	2.670	0.818	0.712	538	0.794
B-1	2.623	0.641	0.557	426	0.399
B-2	2.667	0.443	0.385	301	0.399

Table 9
Other optical properties of glazing systems (double clear) with/without window films.

Glazing system type	*K* (W/m^2 K)	SC	SHGC	Relative heat gain (W/m^2)	Visible transmittance
B	2.670	0.818	0.712	538	0.794
B-1	2.623	0.641	0.557	426	0.399
B-2	2.667	0.443	0.385	301	0.399

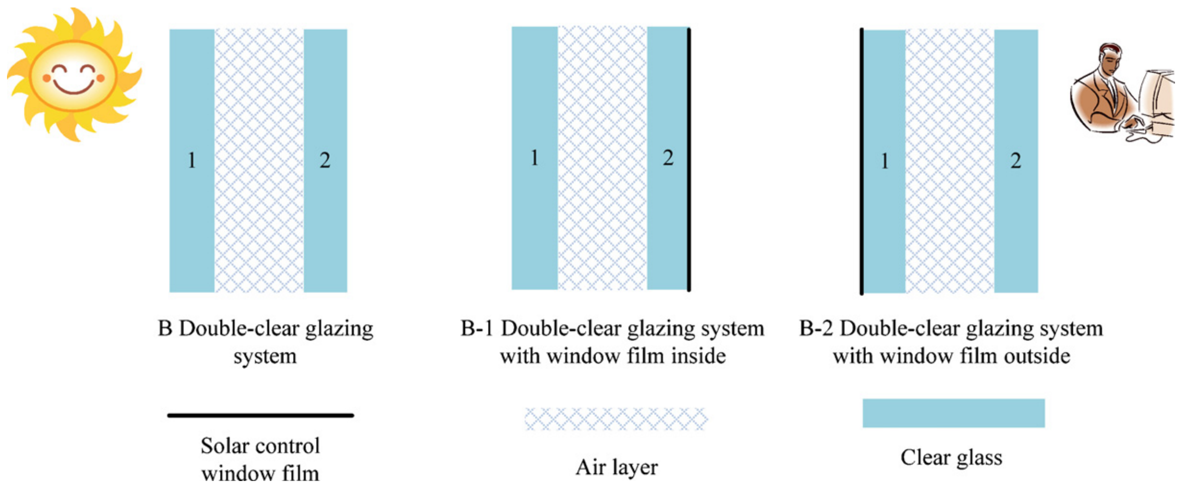

Fig. 11. Glazing systems (double-clear) with and without window films.

Table 10
Building cooling load from "virtual" windows (window area: 6141 m^2).

Cooling load	Total building cooling load from all windows				Average building cooling load from all windows			
Peak load	Conduction (kW)		Solar radiation (kW)		Conduction (W/m^2)		Solar radiation (W/m^2)	
	Design day	Annual	Design day	Annual	Design day	Annual	Design day	Annual
B	235.47	255.42	471.40	368.64	38.34	41.59	76.76	60.03
B-1	194.26	211.49	194.22	151.88	31.63	34.44	31.62	24.73
B-2	142.93	157.85	196.10	153.35	23.27	25.70	31.93	24.97

effect of window films on reducing transmitted solar energy is obvious and similar. This is due to the same effect as utilizing window films on the solar transmittance of the glazing system. However, for type B-1 with window film inside of the glazing system, no significant reduction in the total building cooling load from windows was seen. The main reason for this is the increased cooling load from window conduction, which offset the potential effects of the window film on reducing the building cooling load from solar radiation through the windows. For the glazing system type B-2, although the outside window film increased the solar absorptance of the outer window surface, no obvious difference occurred for the building cooling load from window conduction due to the existence of an air layer in the glazing system (Figs. 12 and 13 and Table 10).

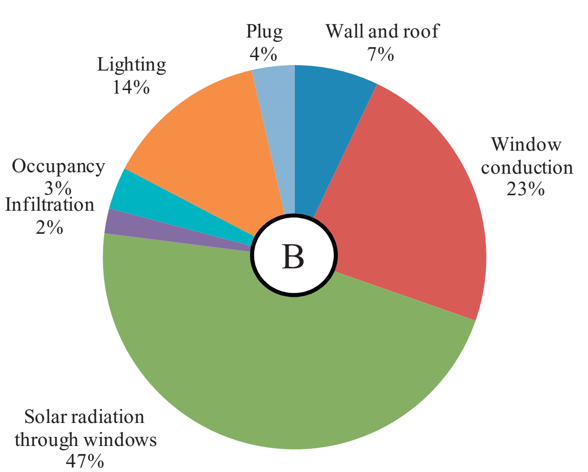

Fig. 12. Building cooling load breakdown for virtual glazing system Type B.

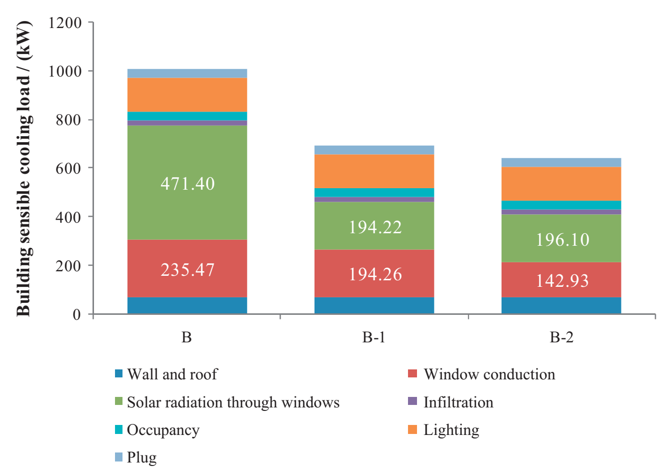

Fig. 13. Building cooling load breakdown for virtual glazing system Type B.

4. Conclusions

Based on the original glazing system of the building, the effects of sticking window films onto the glazing system are different between the outer and inner window film types. Through analyzing the thermal and optical performance of different glazing systems with window films, the glazing system type A-2, with window films outside, is found to be more effective for reducing the SHGC and SC of the original glazing system. In addition, the window films could improve indoor comfort by reducing UV transmittance to 0.001.

Building cooling loads from solar radiation through the windows decreased by 56% and 44% for type A-1 and A-2, respectively, due to the reduction in solar transmittance. Though the reduction in heat gain from solar radiation could increase the building heat load, the magnitude of the increased building heat load is much lower than the reduction of the building cooling load by utilizing window films in the Shanghai climate zone. For the original glazing system in the auto museum, there is no obvious effect for reducing annual electricity consumption of the HVAC system by sticking window films onto the inside of the glazing system. However, sticking window films onto the outside of the glazing system could reduce the annual electricity consumption of the HVAC system significantly.

Through the detailed analysis of the total building energy consumption, the effect of sticking window films onto the inside of the original glazing system is not obvious. The reason for no obvious effect is that the increased cooling load from window conduction offsets the potential for the window film to decrease the cooling load from solar radiation through the windows.

Compared to the energy performance by sticking the window film onto the inside of the original glazing system, the window film performs better in the "virtual" double-clear glazing system. The existence of the low-E film in the original glazing system type A plays a key role in the observed differences between glazing system A-1 and B-2. The heat gain from solar radiation is blocked between layers of low-E and window film, which decreases the effect of the window film on reducing the solar radiation heat gain through the windows, as shown in the "virtual" double-clear glazing system.

Simulation results indicate that utilizing window films could reduce the time-of-use electricity consumption and monthly peak demand. For glazing system type A-2, the average electricity cost savings during the cooling season could be reduced by 7.3–8.0%, which is approximately $2044 per month. With respect to the heat gain from solar radiation through the window, the average solar radiation of the northern windows is the lowest compared to other orientations, as well as the northeastern windows in the morning. We propose sticking window films onto some of the windows of the building, and then both the energy savings and economic benefits could be improved. If the area of window films is reduced by 34.5% and 48% for the northern and northeastern glass curtain walls, the average electricity cost savings during the cooling season could be reduced by $1435 and $1130, respectively.

Though window films could reduce the annual electricity consumption and monthly peak demand, the effect on day lighting by utilizing windows will decrease due to the reduction of visible transmittance. For this building, there will be no significant influence on the effect of day lighting because this building has a high window-to-wall ratio of 90%. Future work should emphasize the performance of indoor illumination levels and total building energy consumption.

Acknowledgement

The author wants to thank Shanghai Auto Museum for the support of this research.

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