Applied Energy Symposium 2020: Low carbon cities and urban energy systems
October 10-17, 2020
Paper ID: D-160

Study on the Performance of Photovoltaic Electrochromic Window System and Impact on Indoor Lighting Environment

Xin Wu[1], Wei Zhang[1]*, Lingzhi Xie[2], Oufan Zhao[1], Mo Chen[1], Zihao Li[1], Jianhui Li[1]
1. College of Architecture and Environment, Sichuan University, Chengdu, China; 610065
2. Institute of New Energy and Low-carbon Technology, Sichuan University, Chengdu, China; 610065
*Corresponding Author Email: xskin821@163.com (Wei Zhang); Tel: +8618683682165

ABSTRACT

A photovoltaic electrochromic window was developed by combining electrochromic glass with photovoltaic window. The photovoltaic electrochromic window is installed with a solar cell layer photovoltaic module on the surface, which is connected with the inner electrochromic glass layer chromic module. It can not only be self-sufficient to achieve the purpose of energy conservation, but also can use the energy generated by the photovoltaic module to freely control the working condition of the color-changing module to achieve the regulation of the indoor lighting environment. In order to study the system performance of the new designed photovoltaic electrochromic windows under different working conditions, a test platform for the comprehensive performance of power generation and lighting was established. According to the test results, it has been shown that PV electricity supplied for color window change can be satisfied with the discoloration modules needed. Under the fading condition, the transparent transmission rate is 13%, and the transmittance under shading condition is much smaller. It means that completely shading mode have a better control on the indoor lighting environment in sunny day compared with transparent fading. In order to deeply analyze the influence of photovoltaic electrochromic windows on indoor lighting environment, a comparative test was conducted between ordinary windows and photovoltaic electrochromic windows under various climatic conditions, and the test data was analyzed through the dynamic evaluation index of lighting environment, including the percentage of total natural lighting time DA and effective lighting illumination UDI. The comparison test results showed that photovoltaic electrochromic windows, compared with ordinary windows, can create a better lighting environment in sunny days under different working conditions. The coupling of photovoltaic modules and electrochromic modules enables photovoltaic electrochromic windows to regulate indoor light environment more flexibly.

Keywords: Photochromic glass, Photovoltaic Windows, Lighting environment, Daylighting performance, BIPV

NONMENCLATURE

Abbreviations	
DA	Daylight Autonomy
UDI	Useful Daylight Illumination
BIPV	Building Integrated Photovoltaics

1. INTRODUCTION

Lighting environment design is one of the important elements of interior design. Reasonable lighting environment can have a positive impact, while unreasonable lighting environment can not only make people feel uncomfortable psychologically, but also directly harm people's physical health [1]. The evaluation of lighting environment is mainly reflected in lighting quality. As one of the basic technical indicators to measure lighting quality, the uniformity and stability of spatial illumination is very important [2]. Electrochromic glass, which is easy to adjust and stable to use, is one of the means to control the illumination level in the room. Electrochromic glass (EC) refers to the glass that can be driven by electric field to realize the stable and reversible adjustment of light transmittance, absorption rate and reflectivity. It can not only make full use of renewable energy, but also effectively regulate the indoor lighting environment that we use electrochromic glass as the building window and solar energy as the color control energy. In recent years, the related research has also attracted the attention of many researchers.

Many previous studies focused on the improvement of the electrochromic glass and its effect on indoor lighting environment. Other studies also show that the control effect of electrochromic glass on indoor lighting environment is closely related to the operation control method. Pilkington, Germany developed a new type of electrochromic glass used in construction, which is coated with an ultra-thin tungsten oxide coating that changes its oxidation state when it is subjected to a low voltage. Therefore, through voltage control, the glass can be completely transparent to dark blue and other color changes. When outdoor light is too strong, the color of the glass gradually darkens, which prevents the indoor temperature from getting too hot. It also helps to reduce the glare on human eyes, such as computer monitor screens. When the sunlight outside is weak, the glass will gradually become transparent to increase the transmittance [3]. In order to test the specific impact of electrochromic glass on indoor light comfort, Zhengrong Li took electrochromic glass (5.7mm) + argon (12.7mm) + ordinary white glass (5.7mm) as the test object to test the control of electrochromic glass on indoor lighting environment of an office building in Shanghai. The test results show that electrochromic glass can significantly improve the stability of indoor lighting environment in sunny days, while the illumination level falling within the comfort zone increases by nearly 3 times [4]. Paulo Tavares of Portugal [5,6] compared the energy saving effect of EC glass in the Mediterranean region when solar radiation intensity and indoor and outdoor temperature were used as control parameters, and analyzed the energy saving effect of EC glass in different orientations with different control thresholds when solar radiation intensity was used as control parameters. Sbar et al [7] conducted a simulation study on the annual energy consumption of commercial buildings in three regions with dry heat, cold and extreme cold and hot weather, and the results showed that the electrochromic glass window controlled by the joint control of outdoor illumination and glare was 45% more energy-saving than the ordinary single-layer glass window. Jonsson [8] proposed that the regulation of EC glazing should be based on the use state of the room, indoor illumination when occupied, and thermal environment demand when not occupied. Lee [9-10] studied the EC glass window divided into upper and lower parts for separate control, which can better meet the requirements of indoor lighting and reduce glare.

In order to further improve the energy-saving effect of the electrochromic window, the solar thin-film cell layer was used as the outer layer of the window and the inner layer of the electrochromic glass layer to form a new photovoltaic electrochromic window. The innovation of this project is that the solar thin-film cell layer as the external structure can directly provide electricity for the color-changing glass. At the same time, it also reduces the floor space of the equipment and makes installation easier. The electrochromic glass is composed of inorganic color changing material polysiloxane as electrochromic layer. The electrochromic glass has excellent optical performance, and its transmittance is as high as 82% in "faded and transparent state". In the "fully colored state", the parallel light transmittance is less than 1.5%. Such photovoltaic electrochromic window combines photovoltaic and indoor lighting environment control, meets the demand of energy conservation and environmental protection, and makes indoor lighting environment better controlled. Especially in sunny days, it has obvious effect on the improvement of indoor light comfort. The coupling of photovoltaic modules and electrochromic modules enables photovoltaic electrochromic windows to regulate indoor light environment more flexibly.

In this paper, the optical performance of photovoltaic (PV) chromotropic Windows under different working conditions is mainly studied, and the indoor lighting environment under different conditions is analyzed through dynamic lighting environment indexes, so as to study the influence of photovoltaic (PV) chromotropic Windows on indoor lighting environment. Based on that data, the effective control scheme of photovoltaic electrochromic Windows in sunny days is explored to provide a more comfortable lighting environment.

2. RESEARCH METHODOLOGY

2.1 Photovoltaic Electrochromic Windows

The structure of the new photovoltaic color changing window is shown in Figure 1, which is mainly composed of two parts: the outer layer of solar thin film battery layer and the inner layer of electrochromic glass layer, with the size of 1200mm * 1200mm. The outer layer of the solar thin film cell is shown in Figure 1. The film mainly provides power for the inner layer of electrochromic glass layer, so that the electrochromic glass can carry out the conversion between the transparent fading state and the fully colored state according to the indoor lighting environment requirements; the inner layer of the electrochromic glass layer is shown in Fig. 2. The internal structure of electrochromic glass consists of 6 layers: PET protective film, ITO film, liquid crystal molecular layer, ITO film, self-adhesive surface, PET protective film -- PET protective film is known as polyethylene terephthalate protective film, transparent and colorless, often used as the protective film of liquid crystal screen; Liquid crystal molecules are carbon-centered compounds that have special optical properties and are sensitive to electromagnetic fields; ITO film is called ITO conductive film glass, namely indium-tin Oxide transparent conductive film glass, is a semiconductor device. The optical performance parameters of the two states of electrochromic glass are shown in Table 1.

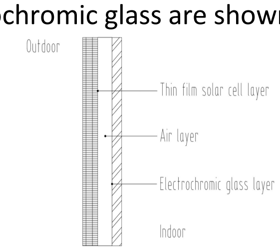
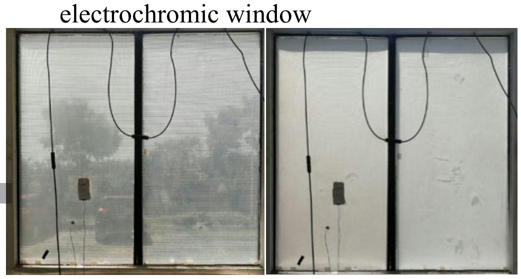


Fig. 1 Schematic diagram of photovoltaic electrochromic window

Fig. 2 Solar thin-film cell



(a) Transparent fading state (b) The fully colored state

Fig. 3 Electrochromic glass

Table 1 Optical performance of color-changing glass

Optical parameters	Model	Parameters
Visible light transmittance	Electricity	> 82%
	Without electricity	> 55%
Parallel light transmittance	Electricity	> 66%
	Without electricity	< 1.5%
Fog degree	Electricity	< 5%
	Without electricity	> 90%
Viewing Angle	Electricity	> 120°

2.2 Test rig

In order to study the optical performance of the new photovoltaic electrochromic window and its influence on the indoor lighting environment, a photovoltaic electrochromic window test rig was constructed in this paper. This test rig is located in Chengdu, Southwest China (between east longitude 102°54 '~104°53' and north latitude 30°05 '~31°26'), mainly using a room 3m (depth) ×3m (width) ×3m (height). The 75 mm thick laminated rock wool board serves as the insulation material for the wall and roof, meeting the insulation requirements of the wall and roof. The project team installed photovoltaic electrochromic windows on the south side of the room. The overall external structure of the room after renovation is shown in Fig. 4. Meteorological data, such as outdoor temperature, humidity, wind direction, wind speed and air pressure, are tested by outdoor testing equipment, as shown in Fig 5.

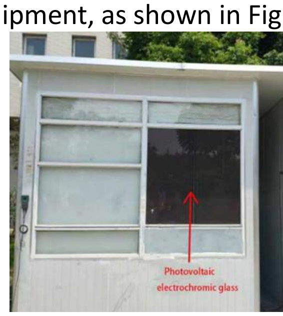


Fig. 4 Test rig

Fig. 5 Outdoor weather station

2.3 Test method

First of all, in order to record the value and change of solar radiation in real time, the radiometer as shown in Fig. 6 is used to monitor the solar radiation of the environment. The power data generated by the solar thin film battery is collected by the multi-channel PV test equipment, as shown in Fig.7. In order to monitor the internal and external surface of photovoltaic color changing windows and indoor light intensity, the wireless illuminance sensor as shown in Fig. 8 is used to record illumination data. The test range of wireless illuminance sensor is 0-100000 lux, the accuracy is 1 lux, and the error range is ± 4%. The number of illuminance sensors used in this experiment is 3, and all of them have been calibrated. The recorded illuminance data is collected and stored by the wireless illuminance host as shown in Fig. 9, and the acquisition interval is 1 min. A wireless illuminance sensor is set on the indoor 0.75m horizontal plane, the outer surface and the inner surface of the photovoltaic electrochromic window. The specific layout of each wireless illuminance sensor is shown in Fig. 10, 11 and 12. The power data generated by the solar thin film battery is collected by the multi-channel PV test equipment, as shown in Fig. 13. The total duration of the test is about one month (July 1, 2020 to August 4, 2020), and the illuminance sensor data of the inner and outer surfaces of the window and the indoor standard horizontal plane under two working conditions of transparent fading and complete coloring of the photovoltaic electrochromic window were recorded with 1 h as the test cycle at 8:00-18:00 in the day. And through the meteorological data of the meteorological instrument, the illuminance data of sunny days with similar solar radiation are selected, and the illuminance data are further analyzed.

Fig. 6 Radiometer

Fig.7 Multi-channel PV test equipment

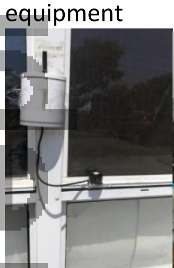


Fig.8 Wireless illumination sensor

Fig 9 Wireless illuminance host

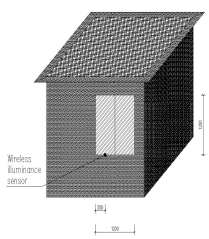


Fig 10 External test point

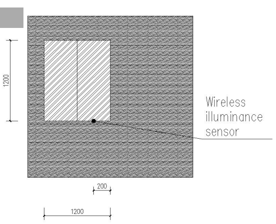


Fig.11 Internal test point

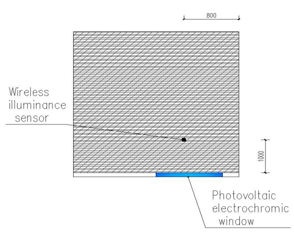


Fig. 12 Internal test point of Room (floor plan)

2.4 Analysis of optical properties and lighting environment

(1) Visible light transmittance analysis

According to the results of the data, we can get the transmission contrast of the two states. Transmittance is used to express the degree of light transmission through a transparent body. The ratio of the luminous flux after transmission to the incident luminous flux is usually used to characterize the light transmission property of the object. It was calculated using the following [11]:

$$T = \frac{E_A}{E_B} \quad (1)$$

Where T is the transmittance, EA is the luminous flux after transmission (lx), and EB is the luminous flux before incident (lx).

(2) Lighting environment analysis

The percentage of total natural lighting time DA and effective natural lighting illumination UDI are mainly used as the main evaluation indexes, and the percentage of total natural lighting time 300 lux is used as the minimum standard of indoor illumination. It was calculated using the following [12]:

$$DA_{300} = \frac{t_{300}}{t} \quad (2)$$

Where DA300 is the percentage of time spent on full natural lighting, T300 is the time occupied by indoor illumination greater than 300Lux (h), and T is the total test time (h).

The standard value of natural illumination in general rooms of office buildings is 300 lx, and that in design rooms, drawing rooms and other rooms is 600 lx [13]. Therefore, in this test, the effective natural lighting illumination UDI is divided into three sections according to the illumination value, namely UDI < 300, udi300-600 and UDI > 600 respectively. It was calculated using the following [14]:

$$\mathrm{UDI} = \frac{t_x}{t} \quad (3)$$

Where UDI is the effective natural lighting intensity, t_x is the time taken by indoor illumination in a specific range, and t is the total test time.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Visible light transmittance of photovoltaic electrochromic window

In this paper, the above platform was used for one month's experimental test. During the test process, the average outdoor temperature was 26.1 ℃, the average relative humidity was 0.69, the average outdoor wind speed was 0.6 m / s, the outdoor daytime illumination range was 15000-30000 lx, and the average solar irradiance was 413.6 W/ ㎡. The working power of the electrochromic glass is 5 W / ㎡. In this experiment, the power generated by thin-film solar cells in sunny days is generally more than 7 W / ㎡, which means the power generation capacity of thin-film solar energy battery could meet the requirements of discoloration of electrochromic glass. In order to study the influence of transparent fading state of photovoltaic electrochromic window on indoor lighting environment, it is necessary to understand the optical properties of two states of photovoltaic electrochromic window. In this paper, two days that outdoor illumination is large were selected to analyze the results.

Fig.13 shows the indoor illumination curve under the transparent fading state of photovoltaic electrochromic window. It can be seen from the figure that the maximum indoor illumination is 632 lx, which appears around 11:30 a.m., and the minimum illumination is 41 lx, which appears around 17:30 p.m. Fig. 14 shows the indoor illumination curve of photovoltaic electrochromic window in fully colored state. It can be seen from the figure that the maximum indoor illumination is 733 lx, which appears around 13:00 at noon; the minimum illumination is 15 lx, which appears at 8:00 a.m. From the above two figures, it can be found that from the overall point of view, the variation trend of indoor illuminance curve in these two days is firstly increased and then decreased, reaching the maximum illumination at noon. This may be due to the high solar radiation at noon and the large outdoor illumination, thus affecting the indoor illumination. Comparing the two figures, it can be found that the indoor illumination in the transparent fading state is much larger than that in the fully colored state. This may be due to the fact that the transmittance of the photochromic glass in the fully colored state is lower than that in the transparent fading state. The coupling of photovoltaic modules and electrochromic modules enables photovoltaic electrochromic windows to regulate indoor light environment more flexibly. The following figures show the transmittance curve of photovoltaic electrochromic window under different working conditions.

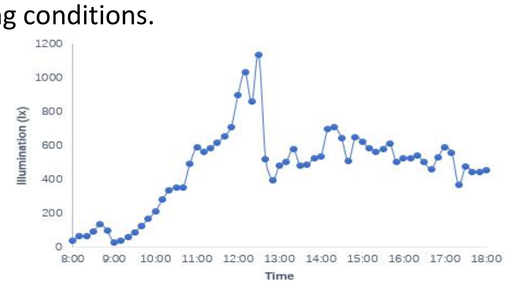


Fig. 13 Indoor illumination under transparent fading state

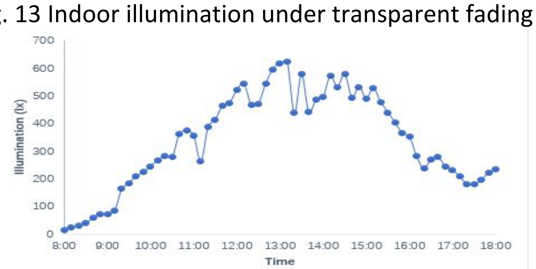


Fig. 14 Indoor illumination in fully colored state

Fig. 15 shows the transmission test results of the transparent fading state of the photovoltaic color changing window. It can be seen from the figure that during the test of this day, the transmission curve is constantly fluctuating. The maximum transmittance appeared around 15:00 p.m., which is 17.94%; the minimum transmittance appeared around 9:30 a.m., which is 8.93%. In other time, the transmission curve fluctuates in the range of 10-16.00%, that is, it fluctuates around 13.00%.

Fig. 16 shows the transmission test results of photovoltaic color changing window in fully colored state. As can be seen from the figure, similar to the transparent state, the transmission curve is also changing during the day. The maximum transmittance was 9.92% around 17:00 p.m. and the minimum transmittance was 1.98% around 11:00 am. At other times, the transmission curve fluctuates around 6.00%.

It can be seen from the above figure that the transmission curves of the two states fluctuate in a certain range in the experimental test. This may be due to the variation of the wavelength of sunlight at different times of the day, as well as the interference of other indoor and outdoor light sources. But the two curves also fluctuate in a certain range. The transmittance fluctuates around 13.00% under the transparent fading state, and fluctuates around 6.00% in the fully colored state. Obviously, compared with the transparent fading state, the full tinted photovoltaic window has lower transmittance. This means that when the outdoor light is strong, the fully colored state can prevent more light from entering the interior, creating a better lighting environment.

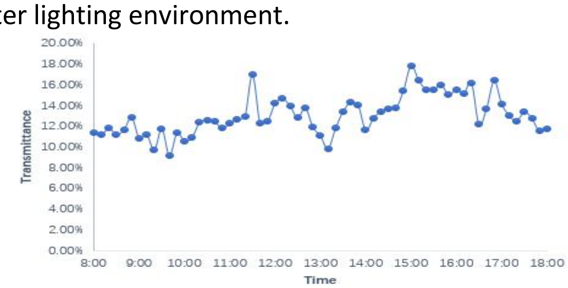


Fig.15 Transmittance of photovoltaic electrochromic window in transparent fading state

Fig. 16 Transmittance of photovoltaic electrochromic window in fully colored state

3.2 Comparison of the influence of photovoltaic electrochromic window and ordinary window on indoor lighting environment

In order to further study the influence of photovoltaic electrochromic window on indoor lighting environment under different working conditions, on the basis of the above platform, a two-week comparative experiment was carried out between ordinary window and photovoltaic color changing window with the same area. In this paper, we choose two days in which the outdoor illumination is large and can better analyze the lighting environment indicators.

Fig. 17 shows the comparison of the lighting environment indexes between the transparent and fading state of photovoltaic electrochromic window and ordinary window. It can be seen from the figure that, compared with ordinary windows, although DA decreased from 85.45% to 77.73%, correspondingly, the percentage of UDI > 600 decreased from 79.28% to 21.08%, decreased by about 60.00%; while UDI300-600, that is, the appropriate lighting range increased from 17.77% to 56.65%, increased by about 40.00%, which greatly improved the indoor lighting environment.

Fig. 18 shows the comparison of the lighting environment indexes between the fully colored photovoltaic window and the ordinary window. It can be seen from the figure that, compared with ordinary windows, although DA has further decreased, from 89.09% to 54.28%, the percentage of UDI > 600 has decreased from 83.89% to 5.23%, which is about 80%, which is 20.00% lower than that under transparent fading state; while UDI300-600, that is, the appropriate range of daylighting is increased from 5.20% to 49.08%, which also improves the indoor lighting environment.

Comparing the influence of the two working conditions on the indoor lighting environment, it can be found that both working conditions can improve the indoor lighting environment. However, in transparent fading state, the percentage of appropriate time for daylighting increases more than that in fully colored state, and the inhibition of excessive daylighting under complete coloring state is larger than that in transparent fading state. Therefore, when using the photovoltaic color changing window, the transparent fading condition is adopted when the external illumination is moderate or small, while the full coloring condition is adopted when the external illumination is large.

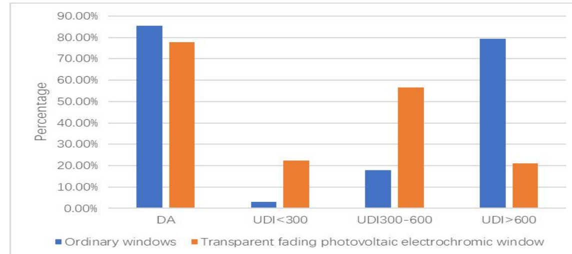


Fig. 17 Comparison of lighting environment index between transparent fading state and ordinary window

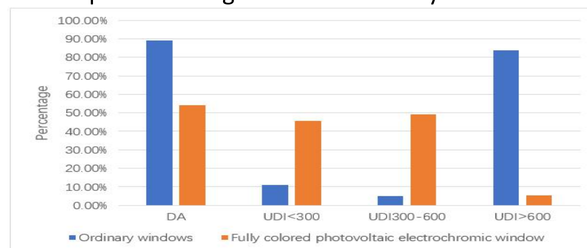


Fig. 18 Comparison of lighting environment indexes between fully colored windows and ordinary windows

4. EXPERIMENTAL RESULTS AND ANALYSIS

In this paper, a new type of photovoltaic electrochromic window is studied, and the performance of the window and its influence on indoor lighting environment are studied. The coupling of photovoltaic modules and electrochromic modules enables photovoltaic electrochromic windows to regulate indoor light environment more flexibly. The research includes the following aspects: the optical performance test of the new photovoltaic color changing window, and the influence of different working conditions on the indoor lighting environment. The conclusions collected in this paper are as follows:

(1) In this paper, the new photovoltaic window is mainly composed of two parts: the outer layer of solar thin film cell and the inner layer of electrochromic glass connected with it. Through such a structure, the photovoltaic electrochromic window can not only realize the color changing function of traditional electrochromic window, but also reduce the occupied area of the equipment. It can also be self-sufficient through the solar cell module to achieve the effect of energy saving.

(2) The transmittance of photovoltaic electrochromic window in fully colored state is lower than that in transparent fading state, which means the fully colored state can block more light from entering the room than the transparent fading state in sunny days. Compared with ordinary windows, the percentage of suitable daylighting time in two different working conditions of photovoltaic electrochromic window is greatly increased. This shows that compared with

ordinary windows, the two working conditions of photovoltaic electrochromic windows can improve the indoor lighting environment.

(3) Compared with the transparent fading state of photovoltaic electrochromic window, the time ratio of excessive daylighting is reduced by 20% when using full coloring state. This shows that the ability of complete coloring state to restrain excessive indoor lighting is stronger than that of transparent fading state. This means that when the external illumination is moderate or small, the transparent fading condition should be adopted; when the external illumination is large, the full coloring condition should be adopted.

(4) In order to further improve the practical performance of the new photovoltaic electrochromic windows, we can try to change the coverage ratio of photovoltaic electrochromic windows in all windows in a certain direction of the building in the future; or add automatic control to make the working conditions of photovoltaic electrochromic windows automatically change with the external light conditions, so as to better regulate the indoor lighting environment.

ACKNOWLEDGEMENT

It is supported by National Key Research and Development Program of China (No. 2016YFE0124500), Sichuan Science and Technology Program (2019YFH0184), Science & Technology Department Foundation of Chengdu City, China (2017-GH02-00006-HZ) and "the Fundamental Research Funds for the Central Universities".

REFERENCE

[1] Fabio Falchi, Pierantonio Cinzano, et al. Limiting the impact of light pollution on human health, environment and stellar visibility [J]. Journal of Environmental Management, 2011,10,2714-2722

[2] Xiao Dai. Lighting environment in office space [J]. Industrial Design,2019(07):107-108.

[3] Germany developed a new type of color changing glass for building [J]. Jiangsu Chemical,2000(Z1):69.

[4] Zhengrong Li, Junling Ju. Control of indoor light and thermal environment of office building by electrochromic glass[J]. Building energy saving,2016,44(02):68-71+114.

[5] Tavares P, Bernardo H, Gaspar A, et al． Control criteria of electrochromic glasses for energy savings in Mediterranean buildings refurbishment[J]． Solar Energy，2016，134: 236-250

[6] Tavares P, Gaspar A, Martins A, et al. Evaluation of electrochromic windows impact in the energy performance of buildings in Mediterranean climates[J]． Energy Policy，2014， 67 (4): 68-81

[7] Sbar N L, Podbelski L. Yang H M, et al. Electrochromic dynamic windows for office buildings[J]． International Journal of Sustainable Built Environment，2012，1(1): 125-139

[8] Jonsson A, Roos A． Evaluation of control strategies for different smart window combinations using computer simulations[J]．Solar Energy, 2010, 84(1): 1-9

[9] Lee, Eleanor S, DiBartolomeo, et al. Monitored Energy Performance of Electrochromic Windows Controlled for Daylight and Visual Comfort[C] A share Meeting．2005

[10] Lee E S, Claybaugh E S, Lafrance M． End user impacts of automated electrochromic windows in a pilot retrofit application [J]． Energy and Buildings， 2012，47: 267-284

[11] Rubin, M. Rubin. Optical properties of windows [J] Energy Research, 6 (1982), pp. 123-133

[12] C.F. Reinhart, J. Mardaljevic, Z. Rogers, Dynamic Daylight Performance Metrics for Sustainable Building Design [J]. Leukos, 3 (1) (2006), pp. 7-31

[13] Nabil, A., Mardaljevic, J. Useful daylight illuminances: A replacement for daylight factors [J]. Energy Build,2006, 38, 905–913.

[14] Lighting design standard for buildings; Ministry of Construction of the People's Republic of China, China, 2013