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Research Article

Investigation of Mg-Y coated gasochromic smart windows for building applications

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Abstract

In the purpose of improving indoor comfort and achieving building energy conservation, significant efforts have been made to improve the performance of window systems. Smart windows have been increasingly considered as an efficient technology with adjustable control of their thermal and/or optical properties in response to instant changes of the environment. This paper explores the potential of using a durable Mg-Y based switchable mirror gasochromic (GC) material for building window applications. The selected Mg-Y based GC window provides a degree of flexibility to reflect the undesirable incident solar radiation rather than the other types of GC windows, which absorb the solar heat that might eventually go into the indoor space through convective, conductive and radiative heat transfer. Building simulations were carried out for a typical office with Mg-Y GC window applied using EnergyPlus. The characterization of the selected gasochromic smart window and its impact on building performance was comprehensively studied under 5 diverse climates in China. In addition, various control strategies in response to different environmental conditions or indoor comfort criteria are also considered. The results indicated that Mg-Y based films with excessively low transmittance at the reflective state are not beneficial from the perspective of building energy conservation, while potentially developed Mg-Y windows with relative higher transmittance and larger transmittance modulation can yield energy conservation of up to 27% when compared with standard double glazing. Overall, the work presented in this paper may be seen as offering potential advice and guidance on further development of switchable mirror GC material that seek to be applied into building windows for amplifying improvements in energy efficiency and occupant comfort.

Keywords
gaschromics,
energy consumption,
daylight performance,
SHGC,
switched hours

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1 Introduction

Window systems, which account for up to 60% of the total energy consumption of a building (Jelle et al. 2012; Peng et al. 2013), significantly affect the buildings' performance and occupant comfort through determining the penetration of solar energy and daylight, influencing the heating and cooling energy consumption and controlling the view into and out of a building (Huang et al. 2014; Mangkuto et al. 2016; Sun et al. 2017; Wang et al. 2016). Many efforts have been made to improve the building performance of window systems, and these are mainly in two directions: (1) for increased thermal resistance, such as using inert gases as cavity fill, multiple glass panes, low emissivity coatings, vacuum glazing and aerogel glazing; and (2) controlling solar radiation and daylight entering the room by introducing tinted coatings, reflective coatings, shading devices and switchable glazing (e.g. electrochromic (EC), thermochromic (TC) and gasochromic (GC)) (Sun et al. 2018; Zhang et al. 2016; Peng et al. 2015; Liang et al. 2018). Amongst all the technologies that control solar radiation, switchable glazing shows advantages as their thermal and/or optical properties are variable, which makes them capable of reacting to environmental changes. Electrochromic (EC) glazing is the most common and mature practice as its transmittance adaption is easily controlled by voltage. Commercial products

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can be found from companies such as View Inc., Sage Electrochromics Inc., EControl Glass GMnH. However, the complicated five-layer structure of a typical EC (i.e. transparent conduction oxide (TCO) layer/ion-storage layer/ion-conducting layer (electrolyte)/EC layer/TCO layer) and the expensive TCO layer results in an overall high fabrication cost, which becomes the main barrier to large-scale commercialization. Current EC window costs estimated at \$50–\$100 per ft^2, in comparison with low-e, argon filled windows that are around \$16 per ft^2 (Gillaspie et al. 2010).

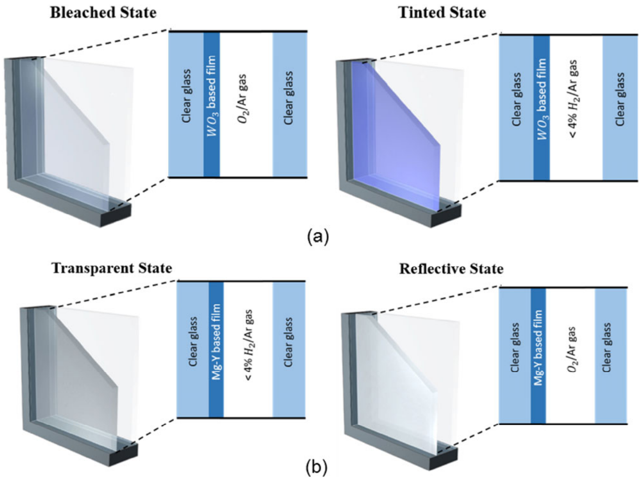


Fig. 1 Configuration of gasochromic windows with (a) metal oxide and (b) metal hydride materials

Gasochromic (GC) glazing has a simpler configuration than EC glazing, in that the GC materials can be coated directly onto a transparent glass or plastic substrate without using the expensive transparent conductive layer. Therefore, GC has potential for large glazing building facades implementation due to its advantageous simple configuration and low cost. The configuration of a typical GC double glazed window is shown in Fig. 1. The GC material, which can reversibly change its optical properties, is coated on the inner surface of the outside glazing pane. The cavity between two glazing panes is connected to devices that can pump in diluted hydrogen (H_2) or oxygen (O_2) gases. H_2 and O_2 gases may be produced by a small electrolyser within a closed loop (Casini 2018). These GC films can typically be categorised into two groups, metal oxides (as shown in Fig. 1(a)) (e.g. WO_3 (Georg et al. 2000a,b) and NiO (Yaacob et al. 2011)) and metal hydrides (as shown in Fig. 1(b)) (e.g. transition element and rare earth-based alloys (Griessen et al. 1997) and Mg-based alloys (Bao et al. 2012; Tajima et al. 2014; Granqvist 2014), in conjunction with a thin catalytic layer of Pd or Pt. When exposed to diluted hydrogen, the metal oxide GC materials change from a transparent state to an absorbing colored state, while metal hydride type GC transforms from a reflective state to a transparent state, hence it has also been named a "switchable mirror". Compared to conventional metal oxide GC windows, the switchable mirror has the advantage in energy-saving potential as it controls reflection and transmission rather than absorbing solar radiation which has the potential to enter the room through conductive, convective and radiative heat transfer. However, the commercial application of switchable mirror smart windows suffers from poor stability and switching durability (Wittwer et al. 2004; Baetens et al. 2010). For example, the Mg_4Ni thin films capped with a Pd layer shows a wide range of optical modulation (Yoshimura et al. 2006) but lower switching cycle life, with the optical modulation decreasing to 10% after 170 cycles (Yoshimura et al. 2007). The degradation results from the combined effect of the damage to the protective Pd layer, and Mg migration to the surface to form oxides that blocks the diffusion of hydrogen (Yoshimura et al. 2007, 2010). Most Mg-based alloy hydride, for example Mg-Ni (Yoshimura et al. 2007), Mg-Ti (Tajima et al. 2008), Mg-Gd (Janner et al. 2001), and Mg-Zr (Bao et al. 2012), GC thin films have a typical life of 100 to 1000 cycles. Inserting a buffer layer between the alloy and Pd layer (Bao et al. 2006) or coating a polymer protective layer could improve the durability to 450 and 1000 cycles (Bao et al. 2008), respectively. However, this is still far from commercial application which requires 100,000 cycle durability for smart windows and 10,000 to 100,000 cycles for anti-glare rearview mirrors (Alesanco et al. 2018). Mg-Y thin films are exceptions; the Pd-capped $Mg_{(1-x)}Y_x$ alloy thin films have a superior switching durability of over 10,000 cycles when the Y content is greater than 50 at.% ($x > 0.5$) and promising optical properties with visible transmittance values of *ca.* 35% in the colour-neutral transparent state ($0.27 < x < 0.7$) (Yamada et al. 2013, 2014; La et al. 2017).

The building performance of applying metal oxides (i.e. WO_3-based) GC window has already been numerically studied by Feng et al. (2016). The authors used WINDOW and eQUEST to predict an office building integrated with GC window and other advanced window systems under the climate of Shanghai, China. Their results showed that applying GC window can reduce HVAC energy consumption by 11.5% when compared to a normal double glazed window under the same environmental conditions. Little research has been conducted to explore the energy performance of applying metal hydrides materials, especially using building simulation tools to predict its dynamic performance under varying climate conditions. The only example of applying switchable mirror window into buildings was conducted by Yoshimura et al. (2009). The result from their experimental work indicated that the Mg_4Ni switchable mirror window can save 34% of the cooling load energy consumption on sunny days when compared to a normal double glazed window. However, further understanding the optical and thermal performance of GC smart windows integrated with

Mg-Y switchable mirror thin films, and their effects on buildings performance are required to assist and guide future developments of this potential material.

In this paper, the optical and thermal performance of a GC smart window based on durable Mg-Y switchable mirror thin film and its effect on building performance has been investigated *in silico*. The following research questions have therefore been explored:

(1) How does Mg-Y switchable mirror thin film influence the heat transfer through the window unit?

(2) Can the Mg-Y GC window facilitate energy saving when compared with a normal double glazed window or other advanced switchable window systems? If so, can it provide benefits independent of climate?

(3) How does the Mg-Y GC window impact on the daylight performance of the space it serves?

(4) What effects does the control strategy of gasochromic alteration have on the building's overall energy consumption?

2 Research methodology

The thermal and daylight performance of a typical office served by a GC smart window integrated with durable Mg-Y switchblade mirror thin film was simulated, which was compared to an ordinary double glazing and WO_3 metal oxide GC smart window.

EnergyPlus was used for predicting their annual energy and daylight performance under five diverse climates in China. The switch of filled gas (diluted H_2 or O_2) was automatically controlled according to one of the following triggers: outdoor temperature, outdoor solar irradiation and cooling load.

2.1 Gasochromic materials

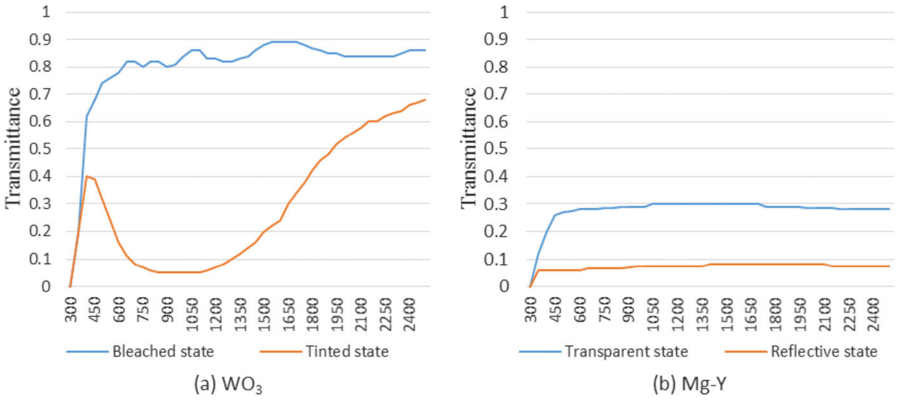
Optical properties of Mg-Y (Yamada et al. 2013) and WO_3 (Nishizawa et al. 2017) thin films were obtained from literature. The spectral transmittance of the magnesium-yttrium (Mg-Y) alloy and WO_3 based thin films are shown in Fig. 2.

Exposing tungsten trioxide (WO_3) film to diluted H_2 (e.g. 4% H_2 in Argon) at room temperature leads to hydrogenation (tinted state) with a blue tinting in 5 seconds, while exposing to diluted O_2 is dehydrogenation process, resulting in the increase of transmittance (bleached state). The WO_3 film with catalytic Pt layer (Fig. 2(a)) has a high transmittance at bleached state (*ca.* 73%) and decreased transmittance (averagely 17%) at tinted state (Nishizawa et al. 2017). The reduction of transmittance during the tinted state is mainly caused by the increase of absorbed fraction of the incident solar energy. The switching durability of WO_3 films was preserved to be more than 1500 cycles. Unlike metal oxides film, the transmittance of magnesium-yttrium (Mg-Y) alloy thin film increases during the hydrogenation process to reach a transparent state, accompanied with a reduction of reflectance. However, the transmittance of Mg-Y film at transparent state is relatively low (*ca.* 30%) (Yamada et al. 2013) as shown in Fig. 2(b). After the process of dehydrogenation, which is typically completed within 15 seconds (Yoshimura et al. 2009), the reflectance increased while transmittance reduced to *ca.* 6%.

In this simulation, the gasochromic windows were specified as an external layer of 6 mm clear glass pane with the GC film coated on the inner surface, a 16 mm gas gap and a 6 mm inner clear glass pane. The gas gap was connected to the device supplying H_2 or O_2. Argon gas was specified as the hydrogen carrier gas, reducing hydrogen concentration to less than 4%, and in so doing simultaneously reducing the risk of explosion and thermal conductivity of the gas-filled cavity.

2.2 Climates

Five different cities within China were selected to represent distinct geographical and weather conditions such as



(a) WO_3 (b) Mg-Y

Fig. 2 Spectral transmittance of WO_3 based and Mg-Y based gasochromic films temperature and solar altitude angle. These five cities represent five typical climatic zones, which are defined in the building regulation GB5017-2016, with Harbin, Beijing, Hangzhou, Kunming and Guangzhou representing a severe cold zone (SCZ), a cold zone (CZ), a hot summer and cold winter zone (HSCWZ), a temperate zone (TZ) and a hot summer and warm winter zone (HSWWZ), respectively. Detailed location and climatic properties for each city are shown in Table 1.

2.3 Model set up

The EnergyPlus simulation programme, which is widely used to simulate and evaluate the performance of buildings with smart windows, has been used for studies of GC windows (Crawley et al. 2008; Warwick et al. 2014; Hoffmann et al. 2014; Saeli et al. 2010). The simulation method used in this research has been validated through comparing the simulated cooling load with the measured cooling load from Ye et al. (2013)'s study while keeping the simulation model with same boundary conditions as that of the experiment. Details of the validation can be found in (Liang 2018).

A typical office room with external dimensions of 6 m × 5 m × 3 m (length × width × height) was constructed in EnergyPlus, which has a window (2 m × 4.5 m) occupied 60% of the south external wall. The room was modelled to be a mid-floor office within a multi-story building, representative of a generic office in the northern hemisphere. Therefore, only the south wall of the room was assumed to be exposed to outdoor conditions, and other room surfaces were assumed to be buffered by uniformly conditioned adjacent rooms, yielding no heat transfer.

According to the energy efficiency building standards in China (Ministry of Construction 2005), the thermal properties of building envelopes have different requirements under different climate zones. Hence the modelling options chosen were those, which satisfied the majority of thermal requirements applicable. For the settings of the building envelopes, the *U*-value of the external wall was set to be 0.43 W/(m^2·K). The *U*-values of the window systems, including the reference clear window and two types of GC windows, are all taken between 2.5 and 2.7 W/(m^2·K). The two states of each gasochromic window can be reversibly switched depending on the specified stimulus. The different stimulus-dependent control strategies are depicted in the following section. As Fig. 3 illustrates, the artificial lighting was controlled by a two-zoned automatic dimmer for complementing natural daylight, to meet the illuminance target level of 500 lux at working plane (0.8 m height from the floor) (BSI 2011). The two illuminance sensors were designated in the centres of two zones to monitor the horizontal daylight illuminance and control dimming with a distance to window of 1.5 m (Sensor 1) and 4.5 m (Sensor 2) respectively.

Internal loads and schedules were set up as follows: An occupant density is 18.6 m^2 per person and primarily occupied the room between 8 a.m. to 6 p.m. on weekdays throughout the year. Equipment loads were 13 W/m^2, and lighting loads were 11 W/m^2. Indoor temperature was controlled to be 19–24 ºC during working hours, appropriate for both winter and summer in most non-domestic building applications (CIBSE 1999).

2.4 Control strategies

In order to explore the effect of control strategies for switching GC window from bleached/transparent to tinted/reflective state on its energy performance, a series of control modes were investigated to find out the most energy effective scenarios. These include: (a) controlling switch according to outdoor temperature with thresholds of 20, 25, 30 and 35 °C, respectively; (b) controlling switch according to incident solar radiation on vertical windows with thresholds of 100, 200, 300, and 400 W/m^2, respectively; and controlling switch according to the cooling load of HVAC system with thresholds of 500, 1000, 1500, and 2000 W, respectively. For instance, for GC windows that are controlled by outdoor temperature with the threshold of 20 °C, once the outdoor temperature is above 20 °C, dehydrogenation carries out to reduce the transmittance of the GC windows.

Table 1 Climatic properties of five representative cities in different climatic zones in China (ASHRAE 2001)

	Location	Temperature (°C)		Heating/cooling period		Solar altitude	Climatic zones
		Max.	Min.	Cooling	Heating	Max	
Harbin	45.7°N 126.7°E	29	−28.4	Jun–Sep	Oct–Apr of next year	67°	SCZ
Beijing	39.8°N 116.5°E	37.1	−10.1	Jun–Sep	Nov–Mar of next year	73°	CZ
Hangzhou	30.2°N120.2°E	35.6	−1.8	Jun–Sep	Dec–Mar of next year	82°	HSCWZ
Kunming	25.0°N 102.7°E	27.4	−1.3	May–Oct	—	88°	TZ
Guangzhou	23.1°N 113.3°E	35	6.6	May–Oct	—	90°	HSWWZ

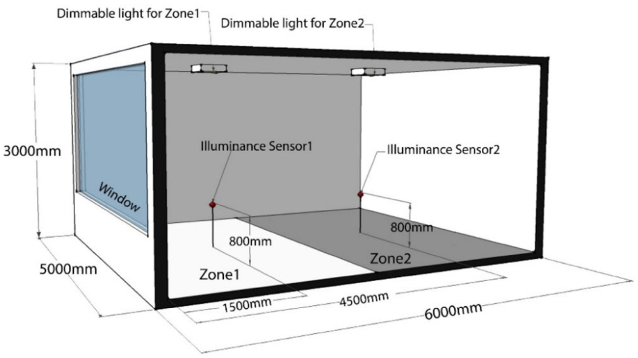


Fig. 3 Diagram of the simulated office

3 Building performance of windows integrated with Mg-Y and WO$_3$ GC films

Building performance including thermal, daylight and energy consumption have been studied on Mg-Y and WO$_3$ thin film GC windows, respectively. In order to investigate the effect of GC switch between transparent/bleached and reflective/tinted states, the building energy performance and switched hours were also discussed.

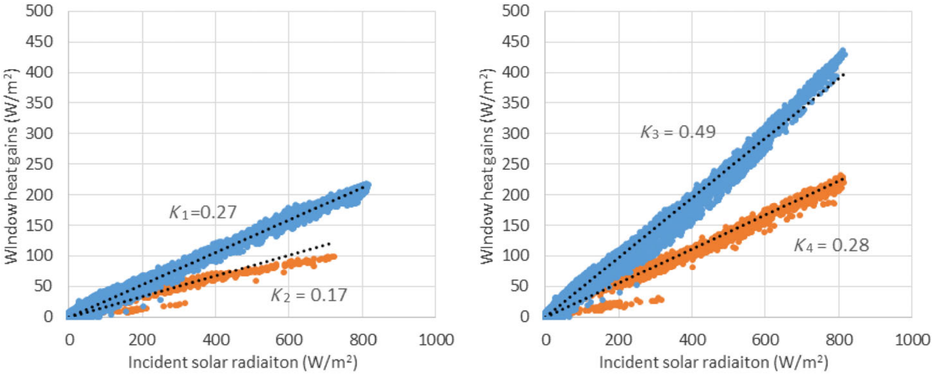
3.1 The impact of GC films on window's SHGC

Solar heat gain coefficient (SHGC) is defined as the fraction of the incident solar radiation that enters the room after passing through the window (Allen et al. 2017), which is expressed as a number between 0 and 1. A larger SHGC value indicates more solar heat transmitted into the room. The total heat gain consists of the solar radiation that is directly transmitted through the window as well as the solar radiation absorbed by the window system and subsequently released into the indoor space. Fig. 4 shows, during each timestep calculation, the window heat gain and incident solar radiation of two types of GC windows implementing under the control strategies based on temperatures (i.e. outdoor temperature is 20 °C) throughout the year under the climatic condition of Guangzhou. Each dot represents window solar heat gain and its corresponding incident solar radiation; blue dots depict GC windows at bleached/transparent state, and red dots depict GC windows at tinted/reflective state. The SHGC value is illustrated as the gradient (K) and obtained by dividing the value of window heat gain (y-axis) over the incident solar radiation (x-axis). In Fig. 4(a), the gradients of transparent and reflective state of Mg-Y based GC window is represented by K_1 and K_2, which are 0.27 and 0.17, respectively. SHGC values of the WO$_3$ based window are K_3 and K_4 (Fig. 4(b)), which is 0.49 at bleached state and 0.28 at tinted state. Thus our simulation predicts that the Mg-Y based window transfers similar solar radiation into window heat gains at its transparent state as that of the WO$_3$ window at its tinted state. However, window heat gains can be either beneficial or detrimental to energy consumption of the buildings.

3.2 The impact of GC windows on the building's daylight performance

Useful daylight illuminance (UDI) was used to evaluate the daylight performance affected by the two types of GC windows and reference double glazing (DG) under the five tested climatic conditions. UDI is one of the metrics used to quantify the daylighting availability through window systems and has been extensively used in previous research (Nabil and Mardaljevic 2006; Berardi and Anaraki 2015; Sun et al. 2018). UDI is expressed as the fraction of time when the indoor horizontal daylight illuminance at a specific position falls into a given illuminance range (bins); the bins were defined by splitting the analysed period into lower and upper limits. According to Nabil and Mardeljevic (2006) the UDI range limits are categorised as following:

1) Illuminance lower than 500 lux (UDI$_{<500\text{lux}}$) is classified as the undersupplied bin, which is insufficient for office environment, and may necessitate artificial lighting.

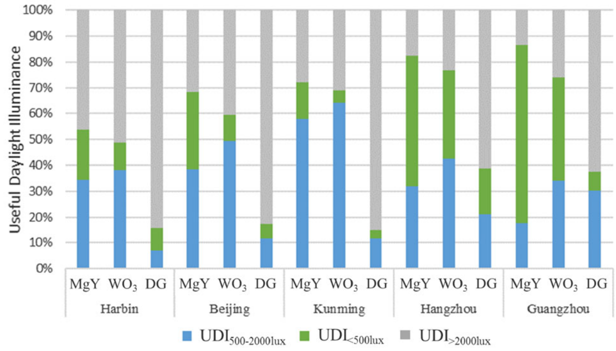


(a) Mg-Y (b) WO$_3$

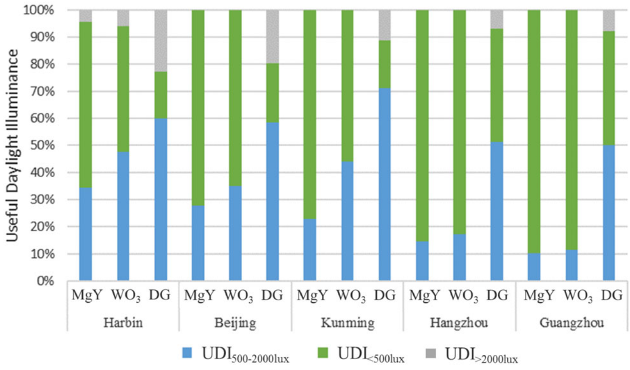
Fig. 4 Incident solar radiation rate normalised to the window heat gain of (a) Mg-Y and (b) WO$_3$

2) Illuminance of 500 to 2000 lux ($\mathrm{UDI}_{500-2000\mathrm{lux}}$) is defined as the desired bin, which is desirable or at least tolerable for occupants without requiring extra artificial lighting.
3) The oversupplied bin ($\mathrm{UDI}_{>2000\mathrm{lux}}$) quantifies the illuminance over 2000 lux, which is likely to cause visual and/or thermal discomfort.

Fig. 5 illustrates the predicted UDI at Sensor 1 and Sensor 2 during working hours, green, blue and grey columns stands for $\mathrm{UDI}_{<500\mathrm{lux}}$, $\mathrm{UDI}_{500-2000\mathrm{lux}}$ and $\mathrm{UDI}_{>2000\mathrm{lux}}$ respectively. It can be seen that both Mg-Y and WO$_3$ based GC windows result in better daylighting performance for the region close to the window (Sensor 1) under all tested climates (expect the implementation of Mg-Y based window under Guangzhou's climate). This is because a greater percentage of working hours fall into the desired illuminance range, i.e. $\mathrm{UDI}_{500-2000\mathrm{lux}}$. For example, the proportion of working hours in the desired $\mathrm{UDI}_{500-2000\mathrm{lux}}$ bin when applying Mg-Y based windows was improved from 11.7% to 57.9% in Hangzhou, when compared with DG. This improved daylighting performance of GC windows is mainly due to their switchable low visible light transmittance, which results in a significant reduction of working hours within oversupplied illuminance range, i.e., $\mathrm{UDI}_{>2000\mathrm{lux}}$. However, under all the five climates, $\mathrm{UDI}_{500-2000\mathrm{lux}}$ values of both GC windows deliver less optimal daylighting performance at the position of Sensor 2 when compared with DG. As the latitude decreases, the proportion of working hours in the undersupplied bin increases significantly with the presence of GC layers. This is due to the higher altitude angle of the sun at low latitude cities reducing penetration into the room. Therefore, GC windows are less beneficial for daylighting rooms of greater depth.



(a) Sensor1



(b) Sensor 2

Fig. 5 Useful daylight illuminance of Mg-Y and WO$_3$ GC windows compared to DG under the five climate scenarios in the simulated office at the positions of (a) Sensor 1 and (b) Sensor 2

3.3 The impact of GC windows on the building's energy performance under varying climates

Although window thermal performance is significantly affected by the integration of GC films as discussed in Section 3.1, this does not indicate whether these effects are beneficial or not. To further explore the effect of both GC films on the total energy performance of a space served by them, annual heating, cooling and lighting energy consumptions of the office under five diverse climates were predicted as shown in Fig. 6. This result indicates that, when compared with the reference DG window, WO$_3$ based GC window yields energy saving under all five climates, while the Mg-Y based GC window only provides energy saving potential under the climates of Kunming and Guangzhou. Energy savings of 24.8% and 11.1% were achieved when applying the Mg-Y based GC window under Kunming and Guanzhou's climates repectively, with cooling being the dominant mechanism through which savings can be made. In contrast, for those climates with heating requirements such as Harbin, Beijing and Hangzhou, the Mg-Y based GC window contributes to increased energy consumption when compared with the WO$_3$ based GC window and DG window. This is caused by significant increases of the heating loads as a consequence of the Mg-Y film reducing the solar heat gain transferred from the window to the room for passive heating. Beyond these observations, these results clearly demonstrated that the GC window with the current Mg-Y film is not preferrable for heating-required climates from a perspective of energy efficiency.

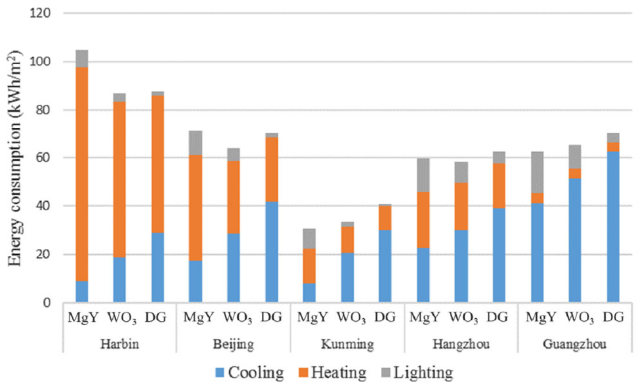


Fig. 6 Annual energy consumption of the simulated office with Mg-Y, WO$_3$ GC and DG windows under the five climate scenarios

3.4 Impact of the GC windows' switched hours on the building's energy performance

To further explore the impact of switched hours (i.e. hours spent in reflective/tinted states) on the energy performance, both GC windows were simulated for scenarios of frequent and infrequent switching. This was achieved through changing the threshold that triggers the cavity gas changeover from H_2 to O_2, once the indoor cooling load of each time-step exceeded the following thresholds: 500 W, 1000 W, 1500 W and 2000 W. A state switch transparent/bleached state to reflective/tinted states was affected at the following simulation iteration. The corresponding switched hours under each control scenario for the cooling period, defined as May to October, and the non-cooling period, defined as November to April, are expressed in Table 2. These control scenarios are labelled as "Cooling500", "Cooling1000", "Cooling1500" and "Cooling2000", respectively. Heating, cooling and lighting energy consumptions of each scenario were predicted under Guangzhou's climate (Fig. 7).

It can be seen that for both GC windows, with the cooling load threshold decreasing, the time spent in the reflective state increased sharply from 0 to 1200 hours for Mg-Y based window, and from 49 to 1401 hours for WO_3 based window. From Fig. 7(a) it is evident that Mg-Y based GC window increasing the duration spent at the reflective state results in higher overall energy consumption. Although at reflective state the GC window blocks transmittance of undesired solar heat into the room and reduces the cooling load, the corresponding lower solar transmittance reduces daylight availability, thus increasing the artificial lighting demand. The increase of lighting load reverses the decreasing trend of overall energy consumption. In contrast, Fig. 7(b) shows the favourable useful light transmittance of the WO_3 based GC window.

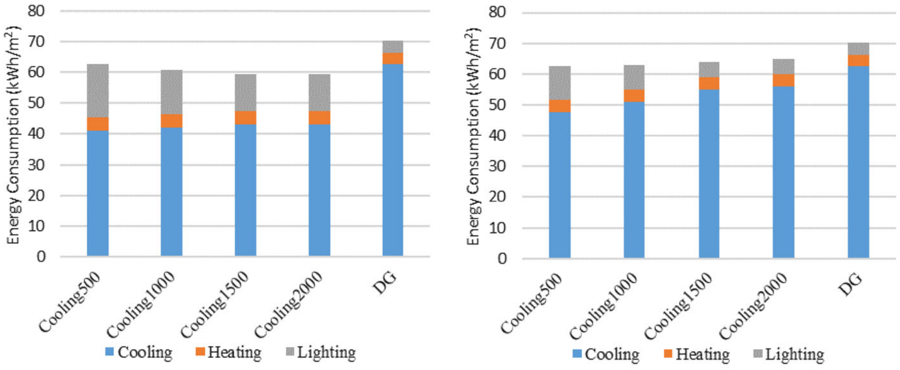
To conclude, GC window integrated with the durable Mg-Y film is most suited to energy conservation under the climate with low heating requirements. Even for the cooling dominated climate, switching to reflective state with low solar transmittance cannot benefit the energy performance for the Mg-Y GC windows when compared with the WO_3 based GC window. The conclusions drawn from these results suggest that the solar transmittance at the transparent state is sufficiently low to achieve cooling energy saving, and further reduction of transmittance is detrimental to energy consumption. When seeking to implement Mg-Y GC material on windows for achieving improvements in energy efficiency and occupant comfort, the solar transmittance at both transparent and reflective states should be increased with a relative decrease of reflectance.

4 Proposed hypothetical Mg-Y GC window with improved window applicability

The results presented in Section 3 indicated that switching from transparent state to reflective state of the original Mg-Y based GC window cannot be beneficial for energy saving due to its excessive low solar transmittance. In this

Table 2 Switched hours of Mg-Y, WO_3 GC and DG windows under the Guangzhou climate

		Switched hours (h)			
		Cooling500	Cooling1000	Cooling1500	Cooling2000
Mg-Y	Cooling period	1022	392	0	0
	Non-cooling period	178	8	0	0
WO_3	Cooling period	1066	566	566	20
	Non-cooling period	335	120	120	29



(a) Mg-Y

(b) WO_3

Fig. 7 Annual energy consumption of the simulated office with Mg Y, WO_3 GC and DG windows under the Guangzhou climate with defined cooling load thresholds section, hypothetical scenarios with increasing transmittance were proposed to explore whether it can give rise to energy saving. Additionally, three types of control strategies were discussed in order to identify the scenarios that improve energy performance under different climates.

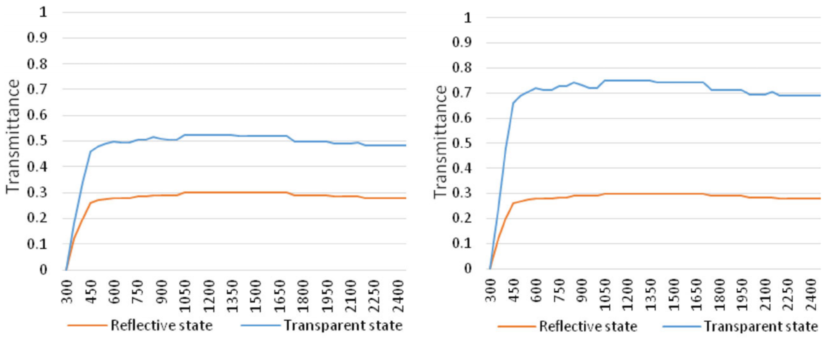
4.1 Optical and thermal properties of the proposed Mg-Y films

The performance of current Mg-Y based GC windows indicated that solar transmittance at the reflective state (*ca.* 10%) is too low for its building application, which led to excessive heating and lighting consumption. Therefore, solar transmittance of GC films is proposed to be improved through specific fabrication methods. Two hypothetical scenarios have been proposed in order to provide guidance for the development of Mg-Y based materials in window applications. As shown in Fig. 8(a), the first scenario, MgY-1, has increased solar transmittance of approximately 26% at reflective state, whilst that of transparent state is around 45%. The transmittance modulation, the difference between the transmittance at transparent and reflective states, is similar to that of original Mg-Y film shown in Fig. 2(b). In Fig. 8(b), the second scenario, MgY_2, has the same solar transmittance at the reflective state with MgY_1, while that of transparent state is assumed to be approximately 65%. The transmittance modulation is two times of that of original Mg-Y film in order to demonstrate the effect of transmittance modulation on its energy performance.

Fig. 9 shows the window heat gain and coresponding incident solar radiaiton of MgY_1 and MgY_2 windows during each timestep throughout the year under the climatic condition of Guangzhou. As illustrated in Section 3.1, the gradient (K) of the regression linear of blue and red dots, repectively, represent values of SHGC, which shows the capability of GC windows for transferring incident solar radiation on the window to window heat gains at two states. For MgY_1 and MgY_2 windows, same SHGC is shown as $K_6 = K_8 = 0.28$ at reflective state, while at transparent state, SHGC of MgY_1 is $K_5 = 0.37$, and that of MgY_2 is $K_7 = 0.46$.

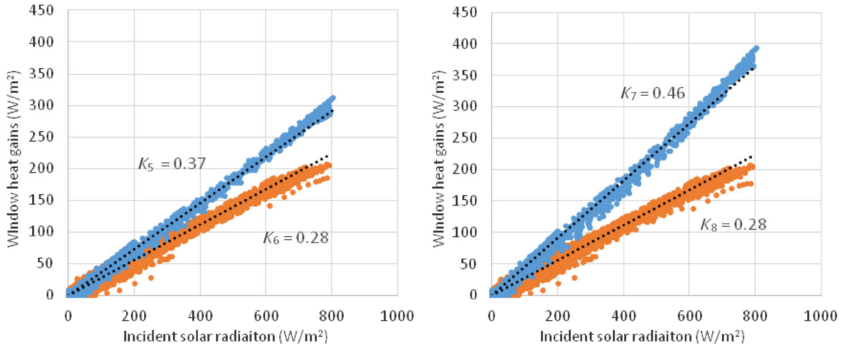
4.2 Energy consumption under the five climates with the modified Mg-Y GC windows

To explore the effect these proposed GC windows with theoretical solar transmittance values have on building energy performance, the total energy consumptions of the office served by MgY_1 and MgY_2 GC windows under five climates have been predicted and shown in Fig. 10. The



(a) MgY_1 (b) MgY_2

Fig. 8 Spectral transmittance of two types of Mg-Y based GC windows with modified solar transmittance values



(a) MgY_1 (b) MgY_2

Fig. 9 Solar heat gain coefficient (SHGC) for two Mg-Y based GC windows with modified solar transmittance values in the transparent state (blue dots) and reflective state (red dots)

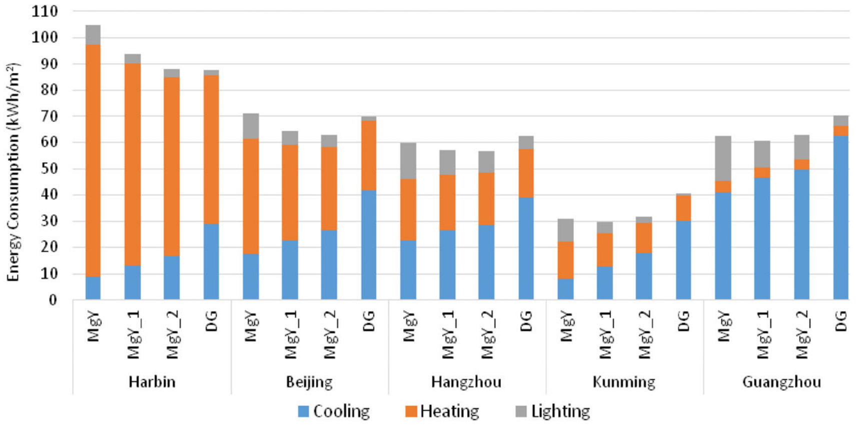


Fig. 10 Total energy consumption of the simulated office including heating, cooling and lighting, classified by different climatic conditions (Harbin, Beijing, Kunming, Hangzhou and Guangzhou), with switching controlled by the outdoor temperature with threshold of 25 °C

switch from transparent to reflective state is controlled by the outdoor temperature with a threshold temperature of 25 °C.

It can be seen that under all climatic conditions except Kunming, MgY_1 and MgY_2 windows result in lower energy consumption when compared with the original Mg-Y windows, and the reduction is up to 11.2% (MgY_2, Beijing). Meanwhile, both MgY_1 and MgY_2 GC windows are more energy efficient than DG windows under all the tested climates except Harbin, and the largest energy saving is 27% given by applying MgY_1 GC window under the Kunming climate. In Beijing and Hangzhou, the MgY_2 window reduces overall energy consumption further than the MgY_1 window. However, in Kunming and Guangzhou, the use of MgY_2 gave rise to greater energy consumption when compared with MgY_1. The results indicate that increasing the solar transmittance from that of the original Mg-Y based film to that of the proposed materials is able to yield potential energy savings for a wider range of climates. Of these two prototypes, MgY_2 with its greater solar transmittance modulation between transparent and reflective states is more efficient in permitting solar heat gain during cold days, which is desirable under the climates with a relatively long heating demand period (see Table 1) such as Beijing and Hangzhou. Whilst under the climates dominated by cooling demand, such as Kunming and Guangzhou, greater solar transmittance at the transparent state is not beneficial.

4.3 Effect of control strategies on the energy performance of GC windows with the proposed Mg-Y films

Besides the optical characteristics of GC films, control strategies for switching the GC windows between transparent and reflective states also play important roles in the building energy performance. In this section, three types of control strategies were discussed under two representative climates Beijing and Guangzhou triggered by: outdoor temperature, outdoor solar irradiation and cooling load.

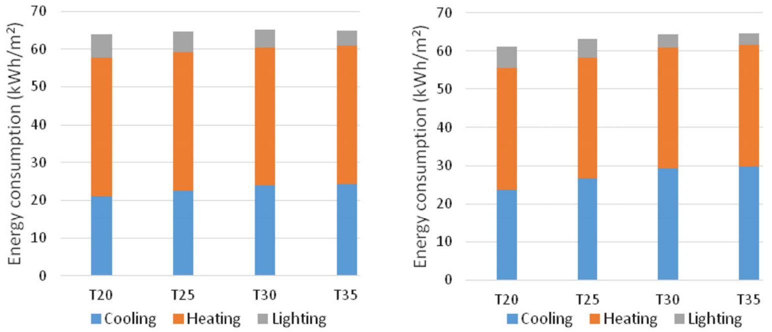
4.3.1 Control based on outdoor temperature

The thresholds of outdoor temperature that triggers the variation from transparent state to reflective state are set as 20, 25, 30 and 35 °C, and labelled as T20, T25, T30 and T35 respectively. Fig. 11 shows the energy consumption for each scenario with MgY_1 and MgY_2, whilst Table 3 presents hours spent at reflective state (switched hours) during cooling and heating/non-cooling period respectively, which is climate-dependent.

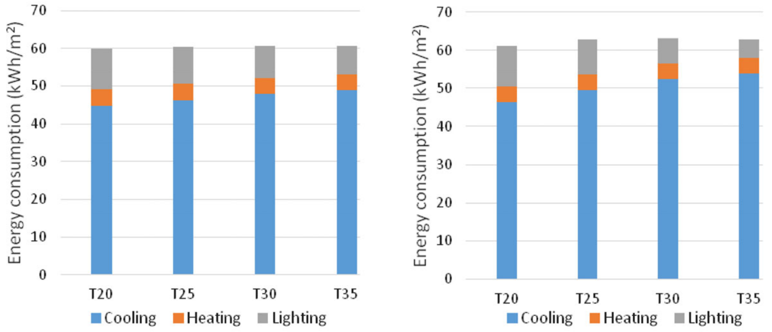
The results show that under the control of outdoor temperature, the number of switched hours during cooling period is dramatically more than that of heating/non-cooling period. With the decrease of temperature threshold from 35 to 20 °C, both MgY_1 and MgY_2 have more switched hours during cooling periods under both climatic conditions, which leads to decrease of the overall energy consumption mainly due to the reduction of cooling energy demand. The lowest energy consumption in Beijing can be observed when applying MgY_2 with 20 °C trigger temperature (i.e. 61.2 W/m^2), and that of Guangzhou is 59.9 W/m^2 caused by MgY_1 with the same trigger temperature.

4.3.2 Control based on solar radiation incident on vertical window surface

Fig. 12 shows the predicted building energy consumption affected by solar radiation based control strategies, with MgY_1 and MgY_2 changing to reflective states when the incident solar radiation exceeds thresholds of 100, 200, 300 and 400 W/m^2, labelled as Solar100, Solar200, Solar300 and Solar400, respectively. The corresponding switched hours during heating/non-cooling and cooling periods are presented in Table 4.



(a) MgY_1 in Beijing (b) MgY_2 in Beijing



(c) MgY_1 in Guangzhou (d) MgY_2 in Guangzhou

Fig. 11 Energy consumption of a simulated office with GC windows using modified Mg-Y films, MgY_1 and MgY_2, controlled by the outdoor temperature with threshold of 20, 25, 30 and 35 °C in Beijing and Guangzhou

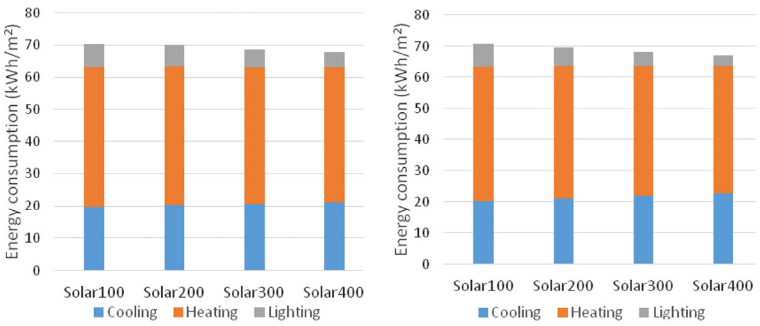
Table 3 Annual hours spent at the reflective state of both MgY_1 and MgY_2 during cooling and heating/non-cooling period of Beijing and Guanghzou under outdoor temperautre based control strategies

		Switched hours (h)			
		T20	T25	T30	T35
Beijing	Cooling period	2869	1378	299	11
	Heating/non-cooling period	100	10	0	0
Guangzhou	Cooling period	4310	3400	794	13
	Heating/non-cooling period	1323	263	16	0

Table 4 shows that under both climates, the number of switched hours within the heating/non-cooling period is higher than that of the cooling period except in the scenario of "Solar100". The solar incident angle is lower in cold days than that of hot days, which means that solar radiation is more intense on the vertical window surface during heating/non-cooling period, resulting in GC windows' transition from transparent to reflective state. Fig. 12 shows the decease of overall energy consumption with the increase of solar radiation from scenario "Solar100" to "Solar400" is predominantly due to the reduction of lighting energy consumption, which can be attributed to a decrease in time spent at the reflective state throughout the year. Due to the relatively high solar incident angle of Guangzhou (see Table 1), the penetration of solar radiation into the office via the window is lower; consequently minimising the impact of the GC window's state transition on artificial lighting requirements. Scenario "Solar400" with the MgY_2 window gave rise to the lowest energy consumption (i.e. 67 W/m^2) in Beijing, while the most energy efficient scenario is "Solar300" with MgY_2 window applied under the climatic condition of Guangzhou with energy consumption of 56 W/m^2.

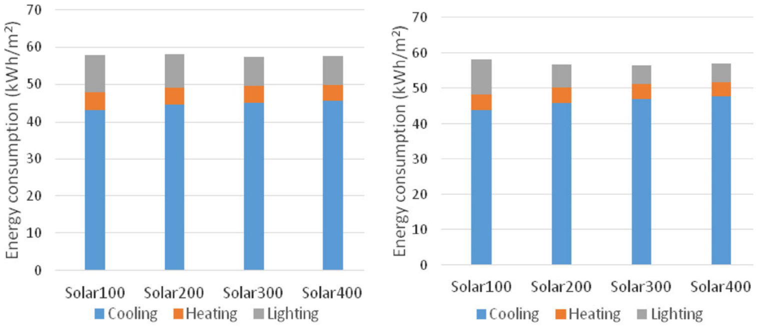
4.3.3 Control based on cooling load

According to the cooling load output within each timestep calculation, the values of 500, 1000, 1500 and 2000 W cooling load were selected as the thresholds for control of the gasochromic switch, labelled as Cooling500, Cooling1000, Cooling1500 and Cooling2000 respectively. Once the cooling load was detected to be higher than the threshold of each scenario, GC windows are proposed to be switched to the reflective state. Fig. 13 shows the energy consumption predicted under different scenarios, and Table 5 presents the



(a) MgY_1 in Beijing

(b) MgY_2 in Beijing



(c) MgY_1 in Guangzhou

(d) MgY_2 in Guangzhou

Fig. 12 Energy consumption of a simulated office with GC windows using modified Mg-Y films, MgY_1 and MgY_2, with GC state transition controlled by the incident solar radiation on the window with thresholds of 100, 200, 300 and 400 W/m^2 respectively in Beijing and Guangzhou

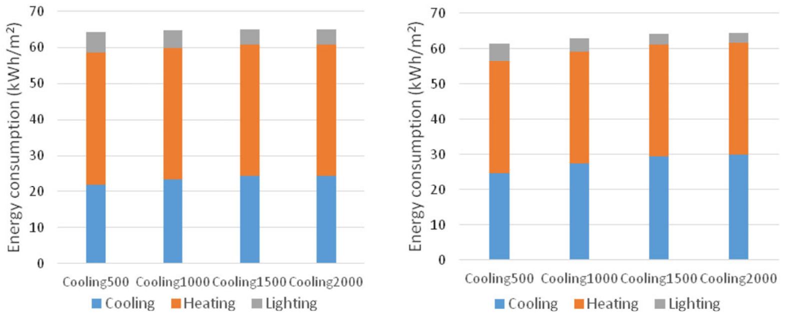
Table 4 Annual hours spent at the reflective state for GC windows using modified Mg-Y films, MgY_1 and MgY_2, during cooling and heating/non-cooling period of Beijing and Guanghzou under different solar radiaion based control stratigies

		Switched hours (h)			
		Solar100	Solar200	Solar300	Solar400
Beijing	Cooling period	1462	937	645	425
	Heating/non-cooling period	1318	1027	855	712
Guangzhou	Cooling period	1249	448	203	119
	Heating/non-cooling period	850	550	418	332

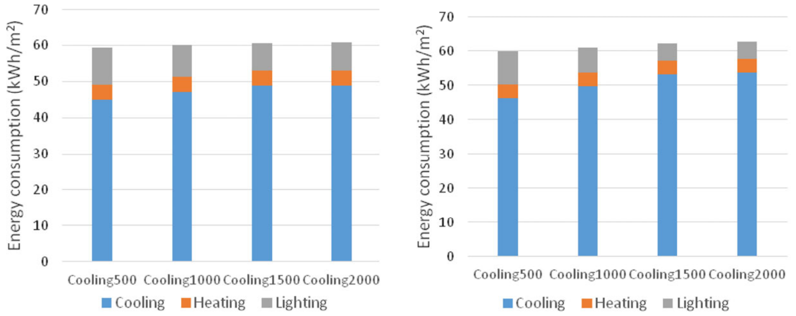
corresponding switched hours during heating/non-cooling and cooling periods. Cooling load is not only climate-dependent, but also affected by the use of GC windows, therefore, four groups of switch hours were simulated under both climates.

It can be seen in Table 5 that switched hours mainly occur during the cooling period, which is beneficial for reducing solar heat gains within hot days. With the increase of cooling load threshold from 500 to 2000 W, the total number of switched hours decreased to zero. Results shown in Fig. 13 indicate that both MgY_1 and MgY_2 windows controlled with lower cooling threshold (i.e. larger number of switched hours in cooling period) lead to decrease of overall energy consumption, which is due to the sharp reduction of cooling energy demand. Under the climatic condition of Beijing, MgY_2 window with control scenario "Cooling500" gave rise to the lowest energy consumption to 61.5 W/m^2. However, in Guangzhou, the most energy efficient scenario is "Cooling500" of MgY_1 window (59.4 W/m^2).

To summarise, control strategies based on outdoor temperatures or cooling load are effective to achieve significant energy saving under both climates. It is because their proposed thresholds (e.g., 25 °C/1000W) are predicted to be easily achieved during cooling demand period, but not during heating/non-cooling period, which reduces the cooling energy consumption by blocking undesirable solar heat gains during hot days, whilst admitting solar heat for passive heating on cold days. However, our simulation predicts that control strategies based on incident solar radiation on windows is only suited to climates such as Guangzhou which have no cooling demand throughout the



(a) MgY_1 in Beijing (b) MgY_2 in Beijing



(c) MgY_1 in Guangzhou (d) MgY_2 in Guangzhou

Fig. 13 Energy consumption of a simulated office with GC windows using modified Mg-Y films, MgY_1 and MgY_2, with GC state transition controlled by cooling load with threshold of 500, 1000, 1500, and 2000W respectively in Beijing and Guangzhou

Table 5 Annual hours spent at the reflective state for GC windows using modified Mg-Y films, MgY_1 and MgY_2, during cooling and heating/non-cooling period of Beijing and Guanghzou under different cooling based control stratigies

		Switched hours (h)			
		Cooling500	Cooling1000	Cooling1500	Cooling2000
Beijing_MgY_1	Cooling period	609	202	6	0
	Heating/non-cooling period	11	0	0	0
Beijing_MgY_2	Cooling period	654	253	29	0
	Heating/non-cooling period	25	0	0	0
Guangzhou_ MgY_1	Cooling period	1057	494	7	0
	Heating/non-cooling period	277	45	5	0
Guangzhou_ MgY_2	Cooling period	1060	529	15	0
	Heating/non-cooling period	314	90	16	0

year, obtaining the lowest energy consumption amongst all three control strategies.

5 Conclusions

Gasochromic windows have potential to improve both building energy performance and visual comfort when compared with standard double-glazed window. Mg-Y switchable mirror thin film is a durable GC material with the potential to be applied on building windows. This research developed a comprehensive analysis derived from simulation of Mg-Y based GC windows across a range of diverse climatic conditions in China. Based on a typical office room, the thermal and optical as well as energy performance of Mg-Y windows was investigated, comparing with commonly studied WO_3 based GC windows and standard double glazed window. Moreover, potential development of Mg-Y materials and gasochromic control strategies were discussed. The following conclusions can be summarised:

1) Mg-Y based GC windows have lower SHGC than WO_3 GC window and DG window, indicating lower capability of transferring solar radiation into window heat gains even at the transparent state.
2) GC window integrated with the current durable Mg-Y film can only provide energy conservation under climates with negligible heating requirements when compared to the DG window.

3) Mg-Y based GC window provides improvements in the daylight performance, for the zone near the window, over DG (except Guangzhou). However, the performance was suboptimal compared to WO_3 based GC window due to the low transmittance at both transparent and reflective states. For the zone away from the window, desired $UDI_{500-2000lux}$ was reduced by both GC windows.
4) The current Mg-Y film provides better energy performance than WO_3 film under specific climatic conditions: those dominated by cooling demand (i.e., Kunming and Guangzhou) due to its low solar transmittance at both states.
5) It is found that increasing the solar transmittance of Mg-Y is able to improve the energy efficiency. Improving the transmittance modulation between the two states is beneficial for buildings located in climates, such as Beijing and Hangzhou, where both cooling and heating are required throughout the year.
6) Control strategies based on outdoor temperatures and cooling loads for Mg-Y windows are effective at improving the building energy performance under different climates, while control based on solar radiation is only appropriate under extreme hot climates without heating demand.

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