Energy performance of thermochromic smart windows in office buildings in different climate zones

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Abstract
As a completely passive technology, the applicability of thermochromic smart windows is closely related to climate zones. Whether it can produce certain energy-saving effects in various climate zones remains to be explored. This paper uses EnergyPlus software to conduct building simulations in nine typical cities in China. The energy consumption performance of thermochromic windows with different transition temperatures was investigated compared to LowE windows and ordinary windows. The results show that thermochromic windows with a higher phase change temperature (40°C) can achieve energy-savings in all climate zones but not more than 4%. Thermochromic materials should have a higher visible light transmission in the tinted state to optimize their energy efficiency. It is hoped that this paper will provide a reference for the practical application and performance improvement of thermochromic smart windows.

Key innovations
- The suitability of thermochromic windows for various climatic zones is evaluated
- The effect of phase transition temperature on the application performance of thermochromic windows is investigated
- The development path for performance enhancement of smart windows is discussed

Practical implications
The paper uses EnergyPlus to simulate the energy efficiency of thermochromic windows with different phase change temperatures in office buildings in nine cities in China. In addition, performance enhancement paths for thermochromic materials are proposed, such as increasing the visible light transmittance in the tinted state and developing materials with higher phase change temperatures.

Introduction
The building sector is a huge gateway to social energy use. As the proportion of curtain walls in urban buildings increases, solar radiation entering the interior through the transparent envelope becomes the dominant factor affecting the annual energy consumption (Hong et al. 2021). The most commonly used energy-efficient glazing on the market is LowE windows. The research related to LowE windows has been mature enough, but the constant static optical properties of LowE windows throughout the year may make their energy performance less than ideal. Based on the limitations of traditional static glazing, a variety of emerging smart adjustable windows have been proposed, such as thermochromic (Cui et al. 2018), electrochromic (DeForest et al. 2013), photochromic (Al-Qahtani et al. 2022) and even mechanochromic (Wang et al. 2022) and magnetochromic (Zhou et al. 2021) windows. These technological developments provide new ideas for dynamic façades with adjustable performance.

VO2 is a typical thermochromic material that responds to changes in external temperature and undergoes a reversible phase transition between a metal and a semiconductor around 68°C. During the phase transition, the transmittance in the infrared band changes significantly and is therefore of increasing interest in the field of smart windows. In practical applications, the temperature of the window surface is difficult to reach this trigger temperature, so the development of VO2-based thermochromic materials is aimed at reducing the phase transition temperature, in addition to optimizing properties such as visible light transmission, solar radiation modulation capability and durability. The performance enhancement strategies of VO2 materials have been intensively investigated through elemental doping (Outón et al. 2023), multilayer structures (Zheng et al. 2015) and anti-reflective (Chen et al. 2011) layers. With tungsten elemental doping, the phase transition temperature of VO2-based films can reach a level of around 27°C (Wang et al. 2021). Another promising thermochromic material is hydrogels, which show transmittance changes in visible and near-infrared bands before and after a lower critical solution temperature of around 33°C, and their advantages of easy preparation through a solution and high transparency pave the way for their development in the field of smart windows.

Although the material field has identified promising thermochromic materials for use in building smart windows through sustained development exploration, the
climatic conditions and specific application scenarios that require thermochromic materials to perform in practice are still not clear (Saeki et al. 2010). A wealth of research has been carried out by those working in the building field to bring advances in materials into line with their architectural applications.

Liang et al. (2018) modeled the energy and daylight performance of thermochromic windows in five typical cities in China, using a cell office with only the south wall exposed in a multi-story building. Allen et al. (2017) investigated the suitability of thermochromic windows in three climates and explored the effects of material concentration and window inclination. Aburas et al. (2021) studied the effects of thermochromic windows on building performance in three hot climates. Mann et al. (2020) analyzed the energy efficiency of composite glazing consisting of static glass and thermochromic glazing compared to ordinary glazing and provided recommendations for the application of glazing systems for three-storey dwellings in 10 climatic zones. However, the material properties of the envelope were not modified accordingly for each climate zone, which should be changed in reality. Hoffmann et al. (2014) explored the climate applicability of hypothetical near-infrared switching thermochromic glazing.

The literature review of the above modeling studies shows that existing studies usually model a single-cell office, but the results obtained may not apply to the whole building. Secondly, the investigation of the climatic suitability of thermochromic windows should involve a wide range of climate types for various climatic conditions, and reasonable heat transfer coefficients for the envelope and window configurations should be set separately for each climate zone to make the energy performance obtained from the simulations more reliable.

In this paper, a three-story office building is constructed in EnergyPlus software and the climatic suitability of thermochromic windows for nine typical cities in China is investigated through simulations. The effect of phase change temperature on the energy efficiency of smart windows is analyzed in detail. The development path for performance enhancement of smart windows is further discussed. The theoretical analysis based on the simulation approach will help to promote the application of smart windows and facilitate material development.

**Methods**

**Climate information**

The ASHRAE climate zoning standard (ANSI/ASHRAE, 2013) classifies climate types into moist (A), dry (B) and marine (C) based on average annual temperature and precipitation, and divides them into nine hot and cold degree zones from 0 (extremely hot) to 8 (subarctic) according to different values of HDD18 and CDD10. China is an extensive country covering essentially all ASHRAE climate zones, so we have selected nine cities in China, including cooling-dominated (Dongfang, Haikou, Guangzhou), mixed climate zones (Chongqing, Beijing, Hami) and heating-dominated (Shenyang, Harbin, Mohe). This setup allows us to define the envelope parameters for the different climatic zones according to a uniform national standard. The simulation of a wide range of climatic zones provides a reference for the practical use of thermochromic glazing in each climate zone. The climatic characteristics of the nine cities are given in Table 1. In addition, reasonable envelope heat transfer coefficients and airtightness parameters were assigned to the building models for each climate zone according to the Chinese code for energy-efficient design of public buildings (China Construction Science Institute 2015), and night-time ventilation in hot regions was taken into account.

**Table 1: Climatic characteristics and envelope parameters of 9 typical cities in China (ANSI/ASHRAE, 2013).**

<table>
<thead>
<tr>
<th>ASHRAE climate zone name</th>
<th>City</th>
<th>Max. temperature (°C)</th>
<th>Min. temperature (°C)</th>
<th>HDD18 (°C·d)</th>
<th>CDD10 (°C·d)</th>
<th>U-value of the roof (W/m²K)</th>
<th>U-value of the wall (W/m²K)</th>
<th>Airtightness and night ventilation (ac/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely hot</td>
<td>Dongfang</td>
<td>32.2</td>
<td>20.5</td>
<td>34</td>
<td>5559</td>
<td>0.5</td>
<td>0.8</td>
<td>1 from 8:00 to 18:00, 1.5 for the rest of the day</td>
</tr>
<tr>
<td>Very hot</td>
<td>Haikou</td>
<td>35.0</td>
<td>10.8</td>
<td>63</td>
<td>5234</td>
<td>0.4</td>
<td>0.45</td>
<td>0.5 for all 24h</td>
</tr>
<tr>
<td>Hot</td>
<td>Guangzhou</td>
<td>35.7</td>
<td>5.8</td>
<td>391</td>
<td>4468</td>
<td>0.25</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Warm</td>
<td>Chongqing</td>
<td>36.9</td>
<td>2.9</td>
<td>1103</td>
<td>3208</td>
<td>0.4</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Mixed</td>
<td>Beijing</td>
<td>35</td>
<td>-11</td>
<td>2790</td>
<td>2274</td>
<td>0.25</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Cool</td>
<td>Harbin</td>
<td>36.9</td>
<td>-19.1</td>
<td>3671</td>
<td>2100</td>
<td>0.25</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Cold</td>
<td>Shenyang</td>
<td>31.5</td>
<td>-22.4</td>
<td>4003</td>
<td>1763</td>
<td>0.25</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Very cold</td>
<td>Harbin</td>
<td>31.4</td>
<td>-27.7</td>
<td>5418</td>
<td>1385</td>
<td>0.25</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Subarctic</td>
<td>Mohe</td>
<td>30.1</td>
<td>-41.4</td>
<td>7927</td>
<td>704</td>
<td>0.25</td>
<td>0.35</td>
<td></td>
</tr>
</tbody>
</table>

U-value: Heat transfer coefficient

HDD18 and CDD10: The heating degree days (HDD) or cooling degree-days (CDD) are calculated as the sum of the discrepancies between daily average temperatures and the base temperature (18°C or 26°C)

**Model settings**

In this study, a 3-story office building was constructed in EnergyPlus with a single-floor dimension of 20×12×3m.
The building simulated open office space on each floor with working hours from 8:00 to 18:00 Monday to Friday. The indoor load was set at an occupancy density of 10 m²/person, a lighting power density of 9 W/ m² and an equipment power density of 15 W/ m². A lighting control strategy of linear/off was set so that if the illuminance at 0.8m on the indoor working surface fell below 300lux during working hours, then turned on artificial lighting to meet the illuminance requirement. The heating and air conditioning temperatures in the room were set to 20°C and 24°C respectively to ensure a suitable environment. In this paper, the heat pump system is selected for summer cooling and winter heating, and the coefficient of performance (COP) of both equipment systems is 2. The heating season is selected from October 1 to March 31, and the cooling season is selected from April 1 to September 30.

Window settings

There are many methods to realize thermochromic simulation modeling, such as EnergyPlus, BuildingEnergy, TRNSYS, ESP-r. Among them, EnergyPlus is the most widely used (Aaturas et al. 2019). It defines thermochromic spectral characteristics through the built-in module "WindowMaterial: GlazingGroup: Thermochromic" and has good interaction with DesignBuilder modeling tool. In this paper, the dynamic optical properties of thermochromic glass are based on five spectra. The thermochromic process is simulated by assigning a specific temperature range to each spectral property. At each time step, EnergyPlus calculates the temperature of the glass surface and assigns it the closest thermochromic property. The transmittance of thermochromic glass decreases gradually with the increase of outdoor temperature to shield solar radiation.

As a passively adjustable façade technology, phase transition temperature and transition gradient width are particularly important to the performance of thermochromic windows. The former determines the temperature threshold at which the phase change is triggered and the latter determines the progressive transition temperature range of the thermochromic material. Warwick et al. (2014) have pointed out that the transition temperature has a greater impact on the energy performance of the glass than the transition gradient width.

This paper aims to investigate the effect of the magnitude of the phase transition temperature on the effectiveness of thermochromic windows for applications in various climate zones from extremely hot to subarctic. Therefore, the transition gradient width was set at 5°C and a sensitivity analysis was carried out using the phase change temperature as a univariate. Three types of thermochromic windows were defined: 20_5 TC (thermochromic) window, 30_5 TC window and 40_5 TC window. 20_5 TC window indicates that the thermochromic window has a phase transition temperature of 20°C, meaning that the window is transparent below 17.5°C and in a fully tinted state above 22.5°C. In the range 17.5-22.5°C, the window state gradually changes from Thermochromic glazing 1 to Thermochromic glazing 5 in the five spectra given in Figure 2.

Figure 1: Model of a three-storey office building.

Figure 2: Spectral properties of thermochromic glass.

This paper analyzes the energy performance of thermochromic windows with different phase transition temperatures compared to ordinary windows and discusses the differences in suitability between static energy efficient LowE windows and dynamic thermochromic windows. Ordinary glass is the baseline double or triple-glazed insulating glass, with smaller glass thicknesses and air layers in hot regions, and thicker glass, inert gas fillings, and additional layers in cold regions to meet the climatic conditions for the heat transfer coefficient of the envelope. The LowE window coating is applied to the glass near the inner side and the thermochromic functional layer of the dynamic smart window is located on the outer side.

The transmittance performance of the different types of glass is shown in Figure 3. For normal windows, the high year-round visible light transmittance (T_VIS) may result in excessive solar radiation entering the room through the
window in summer and causing overheating. For LowE windows, the coating gives better thermal insulation, but the small year-round solar heat gain coefficient (SHGC) values may lead to limited passive solar heating in winter. Compared with static glasses, the dynamic regulation of light and heat by thermochromic glass enables it to have stronger environmental adaptability and greater energy-saving potential. We divided the nine cities into three types: cooling-dominated, considering both cooling and heating, and heating-dominated. Three cities of the same type use the same glass materials and structures. The structures and thermal properties of windows are listed in Table 2.

![Figure 3: Transmittance characteristics of static windows and smart windows.](image)

**Table 2: Construction and performance of windows in different regions.**

<table>
<thead>
<tr>
<th>Region</th>
<th>Dongfang, Haikou, Guangzhou</th>
<th>Chongqing, Beijing, Hami</th>
<th>Shenyang, Harbin, Mohe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window type</td>
<td>Normal window</td>
<td>LowE window</td>
<td>Smart window</td>
</tr>
<tr>
<td>Construction</td>
<td>Clear 6mm+Air 6mm+Clear 6mm</td>
<td>Clear 6mm+Air 6mm+Clear 6mm</td>
<td>Thermo 6mm+Air 6mm+Clear 6mm</td>
</tr>
<tr>
<td>U-value (W/m²K)</td>
<td>3.094</td>
<td>2.168</td>
<td>3.091</td>
</tr>
<tr>
<td>SHGC</td>
<td>0.700</td>
<td>0.585</td>
<td>0.382~0.628</td>
</tr>
<tr>
<td>Tvis</td>
<td>0.781</td>
<td>0.745</td>
<td>0.076~0.650</td>
</tr>
</tbody>
</table>

**Results**

**Performance of windows in cooling-dominated cities**

The combined graph shown in Figure 4 gives the energy performance of different types of windows in a typical
three-story office building in a hot city with predominantly cold supply. The column-superimposed diagram corresponding to the left vertical axis compares the energy consumption of heating (E-heating), cooling (E-cooling) and lighting (E-lighting) for normal windows, LowE windows, and thermochromic smart windows with phase change temperatures of 20°C, 30°C and 40°C. The broken lines on the right axis show the energy-saving rates of heating (R-heating), cooling (R-cooling), lighting (R-lighting) and total energy-saving rate (R-total) per unit floor area for LowE and thermochromic windows relative to normal windows.

Figure 4: Energy performance of different types of windows in cooling-dominated climate zones.

Figure 5: Energy performance of different types of windows in mixed climate zones.
The broken lines in Figure 4 correspond to the right vertical axis and show the cooling, heating, lighting, and total energy-saving rates per unit of floor area for LowE and thermochromic windows relative to ordinary windows.

According to the total energy consumption and total energy-saving rate, for the three hot cities of Dongfang, Haikou and Guangzhou, the thermochromic windows with a phase transformation temperature of 40°C have the highest energy-saving rate, which is 3.65% in Dongfang, 2.17% in Haikou and 2.35% in Guangzhou, followed by LowE windows. The 30_5 and 20_5 TC windows have a negative energy-saving rate, and the 20_5 TC windows have the lowest energy-saving rate, with a 20% drop compared to normal windows. This is due to the window being colored most of the year, resulting in a huge increase in energy consumption for lighting.

Secondly, the contribution of the energy consumption and the energy-saving rate to the total energy-saving rate is analyzed by sub-component. In the three cities dominated by cooling energy consumption, the cooling energy-saving rate corresponding to the 40_5 TC window is consistent with the total energy-saving rate, which indicates that when the phase transition temperature is larger, the increase in lighting energy consumption caused by the coloring state of the thermochromic window has less adverse influence. The 30_5 TC smart windows have the largest cooling energy-saving rate, but the adverse effect of the increase in lighting energy consumption is greater, so the total energy-saving-rate is negative. LowE windows have the least impact on lighting energy consumption, but the cooling energy-saving rate is lower than the three thermochromic windows, with the total energy-saving rate for LowE falling between 30_5 and 40_5 TC windows. Therefore, for hot areas, thermochromic windows with higher phase transition temperatures are recommended, followed by LowE windows.

Performance of windows in mixed climate cities

As can be seen in Figure 5, for the three cities in the mixed climate zone of Chongqing, Beijing and Hami, the highest total energy-savings were achieved with LowE windows. The total energy-savings for LowE and 40_5 TC windows were almost all in the 1-2% range, which is not a significant energy-saving. This is followed in order by 30_5 and 20_5 TC windows. 20_5 TC windows show the lowest energy-savings, with a decrease of 24.68% in Chongqing, 20.63% in Beijing and 12.53% in Hami, caused by a huge increase in lighting energy consumption.

From the analysis of the sub-energy consumption, it can be obtained that the cooling energy-savings with 30_5 TC windows are greater in mixed climate zones than with other windows and that the cooling energy-savings with 30_5 TC windows are greater in the relatively cold cities, as shown by Hami (11.66%), Beijing (7.63%) and Chongqing (2.51%).

In mixed climate zones, heating energy-savings with LowE windows are higher than with other windows and the heating energy-savings are greater in relatively hot cities, as demonstrated by Chongqing (14.03%) Beijing (5.64%), and Hami (5.47%).

Therefore, LowE windows and thermochromic smart windows with a higher phase change temperature (40°C) have some energy-saving effects in mixed climate zones but neither is significant. Thermochromic windows with even lower phase change temperatures are even less energy efficient.

Performance of windows in heating-dominated cities

Figure 6 performs the various types of windows in colder regions. In colder climates, the highest total energy-savings with LowE windows were found in Shenyang at 2.04%, Harbin at 2.67% and Mohe at 2.24%. This is followed by 40_5 TC windows. 20_5 TC windows have the lowest total energy-savings, with -12.78% in Shenyang, -10.55% in Harbin and -4.17% in Mohe, respectively. In the three heating-dominated cities, the
highest heating energy-savings were achieved with LowE windows, 4.37% in Shenyang, 4.45% in Harbin and 3.38% in Mohe; the heating energy-savings with all other window types were negative. The use of LowE windows has the least impact on lighting energy consumption, followed by 40_5 TC smart windows. Overall, in colder regions, the best energy-savings are achieved with LowE glass but only by around 2%. The energy consumption with 40_5 TC windows is essentially the same as with normal glass, while thermochromic windows with even lower phase change temperatures are even less energy efficient.

Discussion

The ideal performance of smart windows

Therefore, from the above simulation results, it can be seen that the main reason affecting the energy-saving effect of thermochromism is that the visible light transmittance after coloring is not high enough.

In fact, for the ideal smart window, we want it to perform as follows in winter and summer: it is desired that the smart windows have a high visible and near-infrared transmittance in winter, while the long-wave infrared emissivity from the outer surface of the window is low to avoid heat loss to the outside. In addition, we want the smart windows to have guaranteed visible light and low near-infrared transmittance in summer, while the outer surface has a high emissivity to increase the radiative cooling to the outside in summer, as shown in Figure 7.

Therefore, the ideal smart window properties should be defined as: multi-band independent modulation of visible, near-infrared, and long-wave infrared light.

Independent adjustment of K and LSG

The lighting and shading performance and thermal insulation performance of smart windows can be expressed by the light-to-solar gain ratio (LSG) and heat transfer coefficient (K), respectively.

The ideal smart window should be able to achieve independent adjustment of LSG and K to enable the smart window to better adapt to a wider range of climates. Specifically, the adjustment of LSG can be achieved through the modulation of solar radiation on the premise that the visible light transmittance meets the lighting requirements. The adjustment of K can be achieved through the modulation of long-wave infrared on the premise that K meets the envelope limits of the climate zone, as shown in Figure 8.

Comprehensive evaluation of energy, environment, and comfort

Although this paper only discusses the energy performance of thermochromic windows, in order to achieve more reliable building applications, the evaluation of smart windows should not only focus on their building energy performance, but also on their impact on the creation of the building light or thermal environment, and personnel comfort.

As shown in the Figure 9, as an adaptive and transparent envelope, the integration of smart windows with renewable energy, the interconnection with indoor energy-using devices and the relationship with personnel behavior are all worthy to be deeply explored. We hope that smart windows will play a greater role and contribute to the development of smart and flexible buildings.

Conclusion

For each climate zone, LowE windows and thermochromic windows with a higher phase change temperature (40°C) can be energy efficient. In hotter climates, 40_5 TC windows are more energy efficient than LowE windows, while in mixed and colder climates the opposite is true.

Therefore, thermochromic windows are more suitable in hot areas. The reason for their low energy-saving rate is that the visible light transmittance in the coloring state is low, which causes adverse effects due to increased lighting energy consumption. When the phase change temperature is lower (20°C), the window has poor light transmission throughout the year and the adverse effects caused by increased lighting energy consumption are more pronounced. Compared to other types of windows,
LowE windows provide the best heating energy-saving rates in each city. The results also provide a reference for the performance enhancement, material selection and preparation of thermochromic smart windows. Materials for thermochromic windows should have a high visible light transmission rate in the tinted state. In addition, the phase change temperature of thermochromic materials for windows does not have to be controlled near room temperature. Thermochromic materials with higher phase change temperatures (30–40°C) can be developed, which are more suitable for a wider range of climatic zones.

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