THERMAL AND VISUAL COMFORT ANALYSIS OF AN OFFICE WITH THERMOCHROMIC SMART WINDOWS APPLIED

R Liang; Y Wu; R Wilson

Department of architecture and built environment, University of Nottingham, Nottingham, NG7 2RD, UK

ABSTRACT

Although windows are important for providing daylight and solar heat gain control, they are also a direct cause of about 50% energy loss through convection, conduction and radiation through what is typically a heavily insulated envelope within which they sit. Hence improving the performance of windows is critical for saving energy consumption of buildings. Thermochromic (TC) smart windows, which change colour and optical properties in response to temperature variations, are one of the most promising technologies for regulating energy consumption in buildings. In this paper, an office room with two different types of TC smart windows were studied at three different climatic conditions (Harbin, Guangzhou and London) using building simulation software Energyplus. The selected two TC smart windows are W-doped VO_2 film and VO_2 nanoparticles coated double glazing with transition temperatures of 20°C and 40°C, respectively. The results show that there is an over 50% reduction in cooling loads of the office building with the W-doped VO_2 TC smart window installed, and approximately 15% of annual total energy saving, compared with the office with normal double glazing installed at the same climatic condition - mild and humid climate, however, due to TC windows having a relatively lower visible transmittance (e.g. For the VO_2 nanoparticles coated TC glazing, the visible transmittance is 63% below the transition temperature and 60% above the transition temperature), the total annual artificial lighting energy consumption is increased. In hot climates, W-doped VO_2 film TC window induces a nearly 9.7 % increase of cumulative thermal comfort hours. In terms of thermal comfort, it is concluded that TC smart windows are suitable to be applied in regions with very hot summer and warm winter. It is also found that TC windows reduce illuminance below a comfortable range, therefore, increase the use of indoor artificial light, however, it reduces the appearance of glare. A comprehensive understanding of TC windows performance at various climatic conditions will benefit their future application on practical buildings.

Keywords: Thermochromic materials, Simulation, Thermal comfort, Visual comfort, Energy consumption

INTRUDUCTION

The Building is one of the major energy consuming sectors – In the UK, buildings currently account for approximately 40% of its national energy consumption. While in terms of buildings, windows are significant for providing daylight and solar heat gains of the internal environment, they are also responsible for over 50% energy loss. [1] Hence improving the performance of windows is critical for saving energy consumption of buildings. Thermochromic (TC) smart windows, one of the most promising chromogenic technologies for moderating energy consumption in buildings, have been widely investigated. They are designed to regulate the amount of transmitted solar radiation in response to an applied stimulus – heat. When above the transition temperature (hot state), a thermochromic smart window transmits visible light, but reflects the majority of Near Infrared Radiation (NIR, ~43% of total incident solar radiation). This also leads to the colour change of the glazing (tinted). The reduction in solar radiation entering a building in hot seasons will reduce the air conditioning load. During cooler weather, with the glazing in its clear state below the transition temperature (cold state), both visible and NIR parts of the solar spectrum are transmitted through the window, providing daylighting and passive heating for the building. Vanadium dioxide (VO_2) is most researched TC materials.[2] Most of the recent studies of the TC windows were focused on improving the performance of TC (suitable transition temperature, improving visible transmittance, etc.), using hypothetical or ideal TC windows for building simulation.[3,4] Few studies used the practical developed TC materials to optimise the building energy performance.[6,7] In this work, building energy simulations with practical developed TC windows at various climatic conditions were carried out. It has the potential to provide a guidance on using the TC windows in buildings.

METHOD

In this section, building simulation software – EnergyPlus was used to study the building energy performance of a typical office room at different climatic conditions, where various types of thermochomic smart windows and a standard double glazing window were applied.

Properties of Thermochormic Windows

Two typical types of VO_2 glazing are chosen for this study, and their optical properties are given in Table 1. Glazing A is a VO_2 nanoparticles coated double glazing, it has T_{vis} of ~60% on both cold and hot state, while glazing B is W-doped VO_2 film coated double glazing with T_{vis} of only 39%, which is much lower than the normal glazing and also glazing A. However, the transition temperature (T_t) of glazing B (20^{o}C) is lower than that of glazing A (~40^{o}C). And the transition temperature range from cold to hot state for TC glazing A and glazing B is 8^{o}C. Glazing C is a standard double glazing unit used as reference. A common office room installed with these three types of windows respectively was studied in the following section. The U-value of each double glazing unit was defined as 2.7 W/m^{2}k.

Properties	The glass panel with VO_2 nanoparticles coated of glazing A		The glass panel with W-doped VO_2 film coated of glazing B		6mm single panel of glazing C
	Cold state	Hot state	Cold state	Hot state	
Transition temperature (T_t)	~ 40^{o}C		20^{o}C		
	Start at 36^{o}C, complete at 44^{o}C		Start at 16^{o}C, complete at 24^{o}C		
Solar transmittance (T_{sol})	0.69	0.57	0.44	0.39	0.78
Visible transmittance (T_{vis})	0.63	0.60	0.39	0.39	0.88
Solar reflectance	0.05	0.06	0.18	0.20	0.08
Solar absorptivity	0.26	0.37	0.38	0.42	0.14
Front & back side emissivity	0.84	0.84	0.84	0.84	0.84

Table 1. Properties of two typical VO_2-based TC glazing [3,4,8].

Simulation Set Up

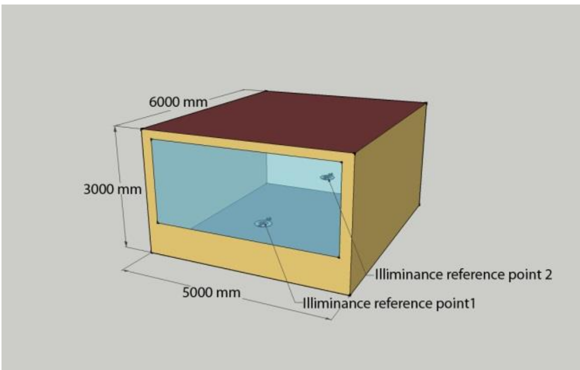


Fig. 1. Dimensions of the selected office room where three types of glazing were installed

Previous studies have indicated that EnergyPlus is promising software for building energy simulation and is also suitable to evaluate the performance of smart windows. Therefore, EnergyPlus was chosen in this work. One mid-floor common office room in a multi-story office building was selected and developed in EnergyPlus, where three types of glazing were studied respectively. The internal dimensions of this office room are 6m×5m×3m, with a southern facing window and window-to-wall ratio of 60%. It is assumed that the adjacent rooms to this selected room were under the same environmental conditions, therefore, there is no heat transfer through the internal walls, ceiling and floor but only the southern external wall with U-value of 0.18. [5] According to the ASHRAE90.1-2010 energy efficiency code, the following parameters were used in the simulation: 1) Occupant density was defined as 18.6m^2/person, 2) loads of office equipments were 13W/m^2, and 3) lighting loads were 9W/m^2. Working Schedule for occupants, equipment and lighting was defined from 9:00am to 5:00pm on weekdays, and HVAC follows the same schedule. For the HVAC system, the setpoint temperature for heating is 21^{o}C and 24^{o}C for cooling. Continuous dimming mode of artificial lighting was also applied in the simulation to evaluate the energy saving potential of TC windows. With that, the lighting can be dimmed to meet the setpoint illuminance level of 500lux. Two illuminance reference points were set as detect sensors at distance of 1m and 5m from the window and with a height of 0.8m above the floor, respectively.

Three different climatic conditions shown in Table 2 representing cold (Harbin), mild (London) and hot (Guangzhou) weather were used for the building energy simulation. Heating and cooling degree hours for each climate are illustrated in Fig. 2. From Fig. 2 it can be seen that in London, heating is almost required throughout the year, but cooling is rarely needed in the summer months. In Harbin, substantial heating is required in winter (over 15000 degree hours in Jan, Feb and Mar respectively), and there are also over 1500 cooling degree hours in summer months. There is no heating requirement in Guangzhou, but the large cooling load is required.

Cities	London		Harbin		Guangzhou	
	summer	winter	summer	winter	summer	winter
Monthly Average temperature (°C)	17	4	22	-18	28	14
Solar radiation intensity (Avg hourly) W/m^2	433	220	442	540	360	262
Location	51.15°N, 0.18°W		45.72°N, 126.68°E		23.13°N, 113.32°E	
Features	Cool winter, warm summer		Cold winter, hot summer		Warm winter, hotsummer	

Table 2. Meteorological data of three representative climates

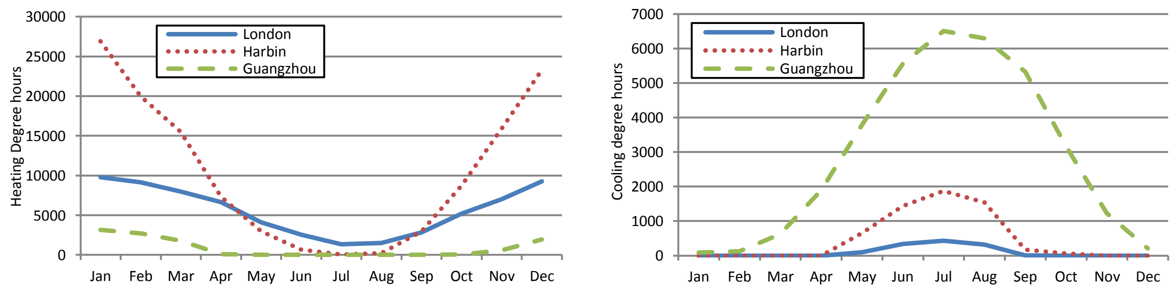


Fig. 2. Heating hours at 18 °C (left) and cooling hours at 20 °C (right) of three different climates

RESULTS AND DISCUSSION

Thermal Performance of TC Glazing Applied

In this selected typical office room, there will be a large solar heat gain through windows, due to the large window-to-wall ratio. The large window will contribute to the cooling load in summer, but might reduce the winter heating load, due to the passive heating. Indoor room temperature, heating and cooling loads are the most suitable parameters to reflect the influence of the TC window on building thermal performance. In addition, the indoor and outdoor temperature will also affect the window temperature, thus it might affect the tinted total hours of the TC window. Therefore, the simulation consists of two parts to discuss above window and building performance: HVAC off simulation mode and HVAC on simulation mode that maintains the indoor temperature between 21 and 24^{o}C during occupied time.

Firstly, indoor thermal comfort was studied under HVAC off state. The window temperature and the transmitted solar radiation through a window of consecutive three summer days in London are shown in Fig. 3 and Fig. 4, respectively. From the Figures, it can be seen that there is a sharp decrease of the solar radiation through glazing A around 12:00 on each day, it is because that the temperature of glazing A is over the transition temperature (starting at 36°C) at that time. While there is a gradual decrease of it for glazing B, due to the lower transition temperature (starting at 14°C) of glazing B. TC windows A and B both reduce indoor room temperature during daytimes, compared with the standard double glazing C, due to the reduced solar heat gains through windows. Glazing A reduces the average room temperature by approximately 1°C, while it is reduced by approximately 3°C by glazing B. This means that both TC windows perform better than normal double glazing in summer, and TC glazing B is more effective to reduce solar heat gains. Over 40% and 50% of the transmitted solar heat gain is reduced by glazing A and glazing B, respectively, when compared with reference glazing C.

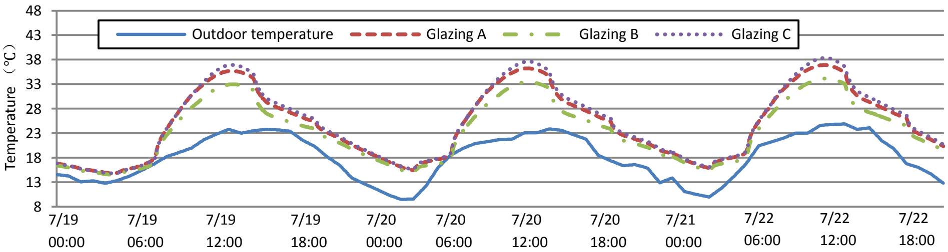


Fig. 3. Indoor temperature varies with different glazing installed.

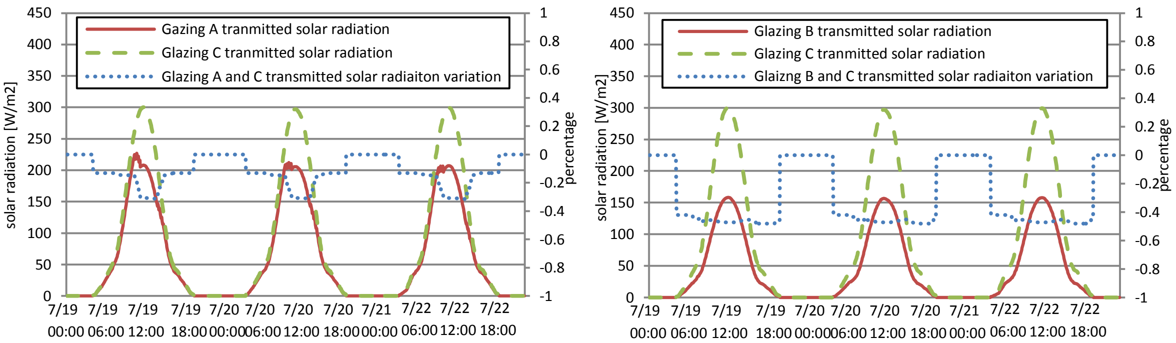
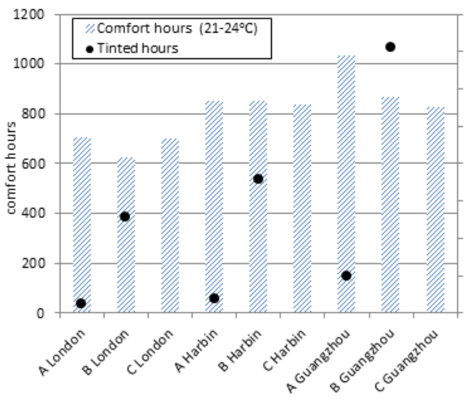
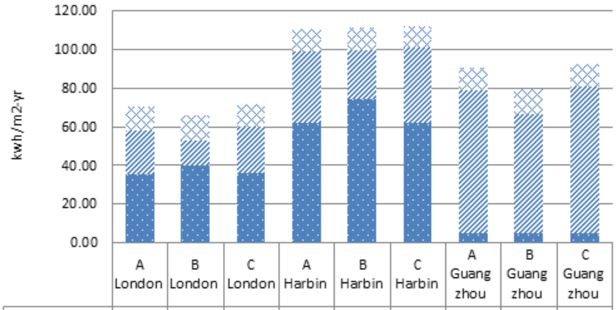


Fig. 4. Transmitted solar radiation of glazing A (left) and B (right) compared with glazing C in London summer days

The indoor annual total comfort hours and glazing tinted hours (hours when TC glazing in hot state) at different climatic conditions are shown in Fig. 5 In London, the office with glazing A has slightly more thermal comfort hours compared with glazing C. A reduction of approximately 10% in comfort hours is observed when glazing B is applied. This is because glazing B has a lower transition temperature, which has blocked a significant amount of solar heat gains during cooler seasons. In Harbin, there is no significant difference in comfort hours when these three types of glazing are installed. It might be because Harbin has a short summer, but a long cold winter. Although glazing A and glazing B both perform better than glazing C during summer, due to reduced transmitted solar radiation of their TC glass panels even at cold state, there is a decrease of comfort hours during winter. In Guangzhou, glazing A is outstanding for improving the comfort hours by 9.7% and glazing B also induces a significant increase of it. It means that, generally in terms of improving thermal comfort level, TC windows are more suitable for climates with hot summer and warm winter such as Guangzhou. It can be seen from the tinted hours points illustrated in Fig. 5, glazing B has more tinted hours than glazing A for each climate, which indicates that even in winter, glazing B can still be tinted and cause unnecessary reduction of solar heat gains through windows.





	A London	B London	C London	A Harbin	B Harbin	C Harbin	A Guang zhou	B Guang zhou	C Guang zhou
Lighting Load	12.24	12.85	11.82	11.27	11.80	11.06	12.22	13.31	11.80
Cooling Load	23.04	13.11	24.07	37.41	24.96	38.97	73.99	61.25	75.95
Heating Load	35.34	39.98	36.03	62.10	74.62	61.94	4.83	5.26	5.05

Fig. 5. (left) Comfort hours and tinted hours of glazing A, B and C in different climates
Fig. 6. (right) Comparison of heating, cooling and lighting load in three typical climate. HVAC schedule: weekday deadband is 21-24°C

With simulation under HVAC on mode, energy consumption for heating and cooling as well as lighting influenced by TC windows is shown in Fig. 6. Generally, TC glazing A and B both reduce building total energy consumption compared with normal glazing C to a different extent. Especially in London and Guangzhou, glazing B induces 10% and 15% of energy saving per year respectively. It can be seen that glazing B results in an obvious decrease of cooling load and increase of heating in all three climates. And glazing A has not shown an apparent benefit on energy saving compared with normal double glazing, because of the relatively high T_t that rarely achieved. In Harbin, the cooling load is reduced by TC glazing, however, this energy saving is counteracted with increase of heating load caused by lower solar heat gains, which results in almost no change of energy consumption in total. However, considering the practical situation, few cooling devices are used in London because summer is not so hot and few heating devices are used in Guangzhou due to its warm winter. Reducing cooling load in hot climate by TC windows is more significant. Additionally, lighting loads only increases slightly because of relatively low T_{vis} of TC glazing A and B by about 1 kWh/m^2 per year.

Visual Comfort of TC Glazing Applied

When simulations are under HVAC off mode, taking glazing A as an example, the illuminance levels of reference point1 (1m away from window) and point 2 (5m away from window) were studied under three consecutive summer days and are shown in Fig. 7. It can be seen that compared with normal glazing, TC glazing A results in a delay of achieving 500lux (visual comfort threshold value) of point 2 and a reduction of the peak illuminance value of point 1 by over 50%, which means that because of lower solar transmittance, TC glazing provides better daylighting and therefore would reduce energy consumption for shading potentially.

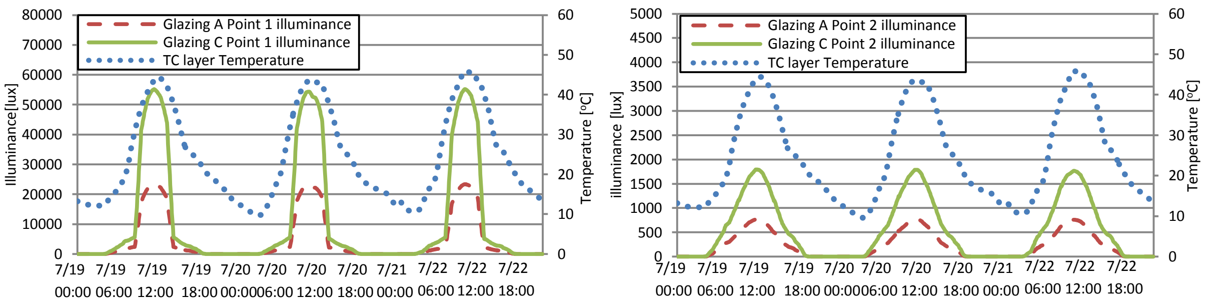


Fig. 7. Illuminance plot of point 1 (left) and point 2 (right) in three summer days

The Useful daylighting Index (UDI), a dynamic daylight performance indicator, was applied to estimate indoor visual comfort. By considering realistic climatic conditions and variables in the time, the UDI is based on work plane illuminance and is defined on hour basis absolute values of daylight illuminance. It aims to determine when daylight levels are suitable for the occupants. When illumiance <100lux, it is too dark for occupants, however, when illumiance >2000lux, it is too bright. Both are able to cause visual discomfort. Occupants can tolerate UDI 100-500lux, and feel very comfortable with UDI 500-2000lux [9]

In Table 3, the percentages of daytime hours among one year when each UDI metric was achieved are presented. It is obvious that both of glazing A and glazing B improve the percentage of UDI reaching 100-500lux and 500-2000lux compared with normal glazing. In addition, they also reduce the percentage of UDI>2000lux. In London, up to 15% of UDI 500-2000 is increased by glazing B, and 8% by glazing A, which is the most effective increase. It means that TC windows are able to improve visual comfort and reduce the risk of discomfort daylighting glare.

UDI	**London**			**Guangzhou**			**Harbin**		
Illumiance [lux]	Glazing A	Glazing B	Glazing C	Glazing A	Glazing B	Glazing C	Glazing A	Glazing B	Glazing C
<100 (insufficient)	3%	6%	2%	5%	7%	3%	0.9%	2%	0.3%
100-500 (tolerable)	13%	17%	11%	13%	18%	12%	10%	11%	7%
500-2000 (comfort)	28%	35%	20%	30%	33%	24%	17%	26%	13%
>2000 (discomfort)	56%	42%	67%	52%	42%	61%	72%	61%	79%

Table 3. UDI of illuminance at reference point1 with glazing A, B and C installed in three climates, respectively.

CONCLUSION

The performance of a common mid-floor office room installed with practical TC glazing A (VO_2 nanoparticles), glazing B (W-doped VO_2 film) and reference glazing C was studied with the building simulation software EnergyPlus. From the results, the following conclusions can be obtained, 1) Both types of TC glazing can improve indoor thermal comfort by reducing solar heat gains through windows in the hot season and improve comfort hours up to 9.7% for VO_2 nanoparticles in Guangzhou, while low T_t might cause indoor heat gain reduction in the cooler seasons and therefore increase the building heating loads. 2) Although the cooling load in summer is reduced, the heating load in winter increases simultaneously. This indicates that both types of TC glazing would be suitable to be used in climates with hot summer and warm winter without the requirement of heating loads. 3) Both types of TC glazing can improve indoor visual comfort and reduce the risk of glare, and glazing B shows a better performance because of relatively lower T_t that is easy to be reached, although lighting loads increase slightly. The feedback this research gives on the application of two types of potential TC glazing installed in an office room may provide guidance for the utilization of TC windows in the future.

ACKNOWLEDGEMENTS

This work was supported by the Faculty of Engineering, University of Nottingham through a PhD studentship to Runqi Liang.

REFERENCES

1. Hong, Y., Xianchun, M., Bin X.:Theoretical discussions of perfect window, ideal near infrared solar spectrum regulating window and current thermochromic window. Energy and Buildings, 49, 164–172, 2012
2. P, H., et al.: Preparation and thermochromic property of VO_2/mica pigments, Materials Research Bulletin, 46 (6) 966–969. 2011
3. Ivan P. P. et al.: Atmospheric pressure chemical vapour deposition of thermochromic tungsten doped vanadium dioxide thin films for use in architectural glazing. Thin Solid Films, 517, 4565–4570, 2009.
4. Shuyi, L.: VO_2-based Thermochromic and Nanothermochromic Materials for Energy-Efficient Windows: Computational and Experimental Studies. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology, 1095, 2013.
5. ANSI/ASHRAE/IES Standard 90.1-2010, Energy Standard for Buildings except Low-Rise Residential Buildings.
6. Hong, Y, Linshuang L. : Smart or not? A theoretical discussion on the smart regulation capacity of vanadium dioxide glazing. Solar Energy Materials & Solar Cells, 120, 669–674, 2014.
7. Manfredi, S. et al.: Energy modelling studies of thermochromic glazing, Energy and Buildings, 42, 1666–1673, 2010.
8. Yanfeng, G. et al.: Nanoceramic VO_2 thermochromic smart glass: A review on progress in solution processing. Nano Energy, 1, 221-246, 2012.
9. Michela, B. et al.: Energy saving through the sun: Analysis of visual comfort and energy consumption in office space. Energy Procedia 30, 693-703, 2012