SMART WINDOW - A WINDOW FOR DYNAMIC CONTROL OF BUILDING ENERGY PERFORMANCE

Kaitlin Allen and Yupeng Wu

Architecture and Built Environment, Faculty of Engineering, University of Nottingham, University Park, Nottingham, UK NG72RD

ABSTRACT

Thermochromic (TC) and Thermotropic (TT) glazing theoretically has the potential to significantly reduce the energy demand in buildings, by allowing transmission of visible light for daylighting but passively controlling solar gains; heat gains are minimised during the cooling season while allowing useful solar gains in the heating season.

In this study, a thermotropic layer made of hydroxypropylcellulose (HPC) and Sodium Chloride (NaCl) was synthesized and tested by the Evolution 201 UV-VIS spectrophotometer. The developed thermotropic layer has a transition temperature of 32-33˚C. Below the transition temperature visible transmission ranges between 65-95% while solar transmission ranges between 40-90%. Above the transition temperature visible transmission ranges between 5-35 % while solar transmission ranges between 10-50%.

In addition, simulations of a typical office with the developed TT and a TC installed were carried out using simulation software Energy Plus. The chosen TC window has a transition temperature of 20-21°C, constant visible transmission of 65% and solar transmission of 80% below the transition temperature and 15% above the transition temperature. From an annual energy prediction, exploring how the ambient environmental conditions affected the state of the TC, it was found that the incident solar radiation plays a large role in the tinting of the window, as heat gain within the film was predominately due to radiation, and was less reliant on convection. The performance of the TC was compared to a standard double glazing unit (DG); the use of the TC in comparison to the DG resulted in a 14.4 kWh/m2 –floor, 32%, reduction in HVAC energy annually but a 3.87 kWh/m2 –floor, 30% increase in lighting energy. Overall the TC saved 21% of combined energy annually; a significant reduction in energy use. The solar heat gain coefficient (SHGC) of the TC when tinted was 0.31 almost half that of the DG at 0.56; as the majority energy demand comes from cooling loads, this reduction in transmitted radiation, at peak temperatures greatly reduces this load. The results indicate that the TC technology would work best in areas with high levels of incident solar radiation and hot climates.

1. INTRODUCTION

Internationally the operation of buildings accounts for 30-40% of global energy consumption, leading to 30% of greenhouse gas emissions [1]. Windows themselves are extremely thermally weak components within the envelope and contribute to over 20% [2] of energy lost from buildings. It is imperative that new technology is developed to improve window thermal properties, while maintaining the visual and thermal comfort of the occupants.

Although technology that aims to stabilise the temperature of a highly glazed room has been improved many are still either steady state and inflexible, or dynamic control is given but at an energy cost. Therefore there is an opportunity to explore technologies being developed to provide passive, dynamic control of heat gain/loss through glazing, in order to reduce the energy consumption. In this project, the energy performances of a typical office building with thermochromic and thermotropic smart window applied were investigated.

2. THERMOCHROMIC AND THERMOTROPIC WINDOWS

Traditional methods for improving windows provide many benefits and energy savings but they still suffer from problems such as glare, reduction in passive heating during winter, etc. Variable transmission glazing (VTG) are smart windows where the transmission properties vary to achieve the optimum luminous and thermal environments. One of the main types of VTG are chromogenic coatings, coming from the Greek, meaning colour creating. There are two methods of switching, passive devices which respond to changes in the environment and active devices which respond to a sensor input.

Thermochromics (TCs) are passive VGTs relying on temperature to dictate the switch between clear and coloured states. The TCs have certain temperature, $T_{t,}$ which is the threshold between states; under this temperature the window appears clear, with a monolithic structure that is semiconducting and non-absorbing in the IR spectrum. Above, the structure transforms into a metallic one, reflective in the IR spectrum. This means that during hot summer days incident solar radiation is rejected maintaining a cooler internal temperature while during cold winter days all incident radiation is allowed to enter.

Currently the T_t of TCs are too high (≈70°C) [3] for practical applications meaning further research into lowering this temperature needs to be done. The primary material in TCs is vanadium dioxide, VO_2, replacing some of this with other elements, such as tungsten, or doping, can lower the switching temperature to a more practical level.

Thermotropics (TTs) are similar to TCs; they are dependent on temperature to indicate switching however while TCs switch the optical properties, TTs switch the light scattering properties. This means that the view through the window becomes obscured becoming translucent instead of consistently transparent with changing tints.

The ideal transmission properties according to previous research [3] provide constant visible transmittance and reflectance at 60% and 17% respectively while the infrared transmittance changes from 80% to 15% with the reflectance changing from 12% to 77%. A transition temperature of 20 - 21°C is recommended [4].

At present, TC and TT windows do not meet these requirements with the largest solar transition given by 'RF sputtered CeO_2-VO_2 bilayers on SiO_2 substrates' changing from 37% to 20% [3]. Pure VO_2 crystals transition at 68°C with a brown/yellow film colour [4]. This transition temperature is far too high for practical applications in the built environment; via fluorine doping this transition can be brought down to a temperature of 25°C. Although practical the film colour remains brown/yellow, an extremely unappealing window colour for windows. The film colour can be changed to blue/green via gold nanoparticle doping, which also has a positive effect on the transition lowering the temperature to 15 -20°C. However doping using gold nanoparticles is an extremely expensive method and too costly for commercial availability. Considering this, the best option is therefore tungsten doping, providing a blue film colour with a transition temperature of 20 -25°C, at a reasonable price for commercial products [5].

3. BUILDING ENERGY PERFORMANCE SIMULATION

Building simulations have been carried out using Energy Plus software; a developed TT and a potential TC have been tested against a reference double glazed window to determine their viability and effect on energy saving.

A typical office room with dimensions 5m x 4m x 3m was used with a window of dimensions 2m x 1.5m (25% of the wall), placed centrally. The room is considered as part of a larger façade and building meaning that only the south wall of the room is exposed to external conditions while the other surfaces of the room are buffered by mechanically conditioned spaces and therefore experience no heat loss. The simulations have been run assuming the building is located in London, England; a marine west coast climate. This type of climate requires mainly heating in the winter and cooling in the summer. The annual average temperature is 10°C with a maximum temperature of 27°C and a minimum of -5°C. Daylight controls were used to ensure that 500lux of light was provided either naturally or via artificial lighting. The external wall has a U-Value of 0.15 w/m^2K, while the reference double glazing has a U-Value of 2.7 W/m^2K with T_{vis} = 88% and T_{IR} = 78%. A viable thermotropic layer has been developed, at the lab in the Energy Technologies Building, University of Nottingham, UK, using the cellulose derivatives hydroxypropylcellulose (HPC) and hydroxyethylcellulose (HEC) as well as sodium chloride (NaCl) which allows for the transition temperature to be controlled based on the amount added. The use of organic compounds reduces the cost as well as the hazard of toxicity. The optical performance of the developed TT was tested by the Evolution 201 UV-VIS spectrophotometer. A potential TC has been formulated from 'ideal' spectral performance [3].

Both the TC and TT have a U-Value of 1.8 W/m^2K with their transmission spectra shown in Figures 2 and 3, respectively. The transition points, T_t are 21°C and 32-33°C respectively.

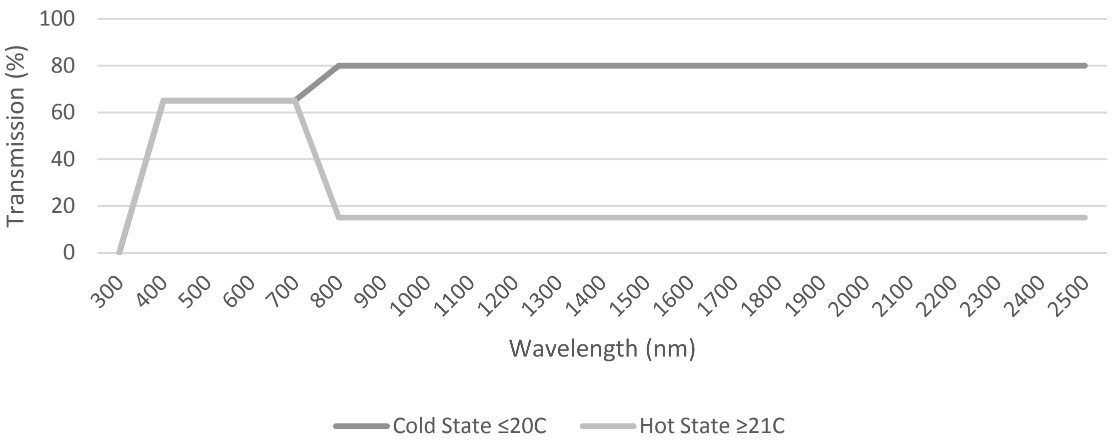


Figure 2 – Thermochormic Transmission Spectra

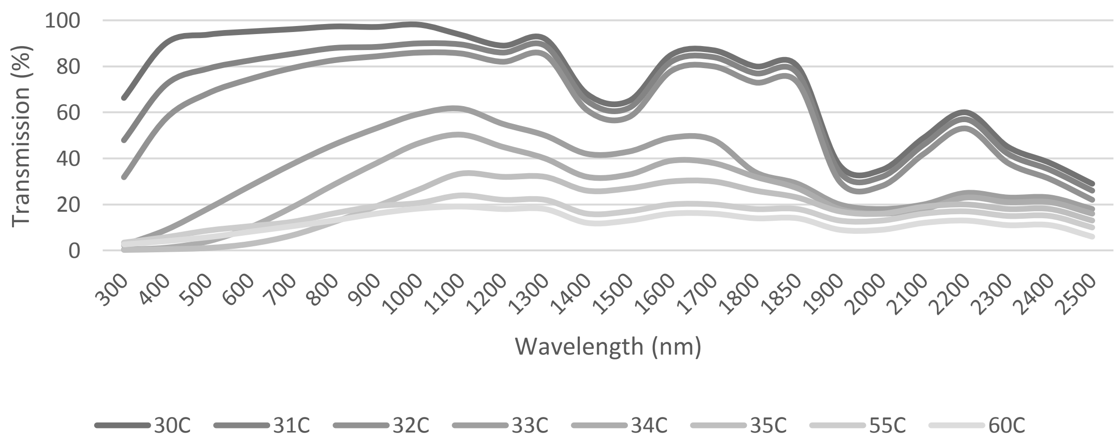


Figure 3 – Thermotropic Transmission Spectra

4. ANALYSIS

The ambient air temperature and incident solar radiation have a key role as they are what dictates room temperature but also the switching of states. There is a strong correlation of switching response to both outdoor air temperature and incident solar radiation [6]. Figure 5 shows hourly sets of data acquired through simulation for a consecutive 3 day period in winter and 3 day period in summer.

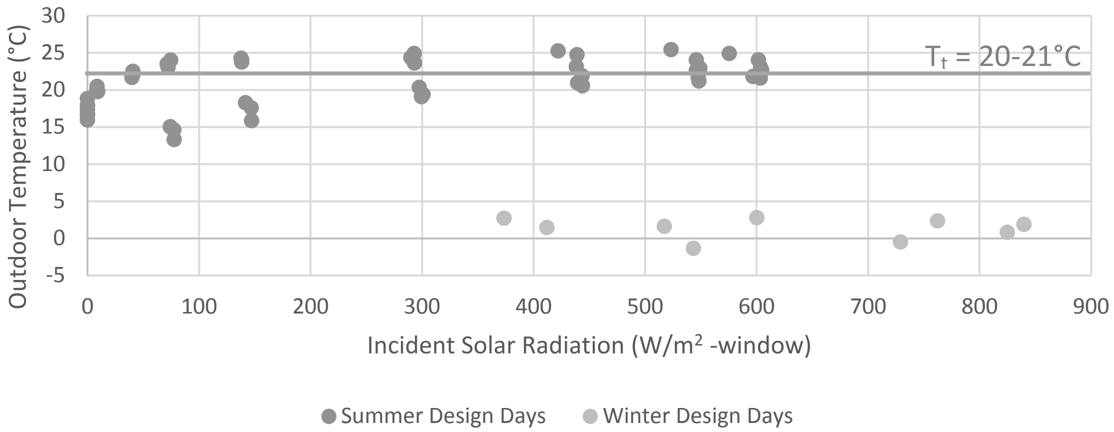


Figure 5 – Sets of outdoor drybulb temperatures and incident radiation resulting in tinting

The TC was tinted for 58 hrs of the 144 hr simulation, 40%; winter simulation tinted for 9 of 72 hrs, 13 %, while the summer simulation tinted for 49 of 72 hrs, 68%. The summer simulation shows that, for the majority of cases, tinting occurs when the outdoor temperature is near or above T_t; although tinting does occur at lower outdoor temperatures and 0 w/m^2 because of the heating effect from the HVAC system. The winter simulation shows that there are still occurrences of tinting when the outdoor temperature is much lower than the transition temperature due mainly to the high levels of incident solar radiation/ window heat gain as on a sunny winter’s day as shown in Figure 6. The construction of the window with the TC layer closer to the interior also helps to maintain a higher temperature for longer, resulting in more tinting.

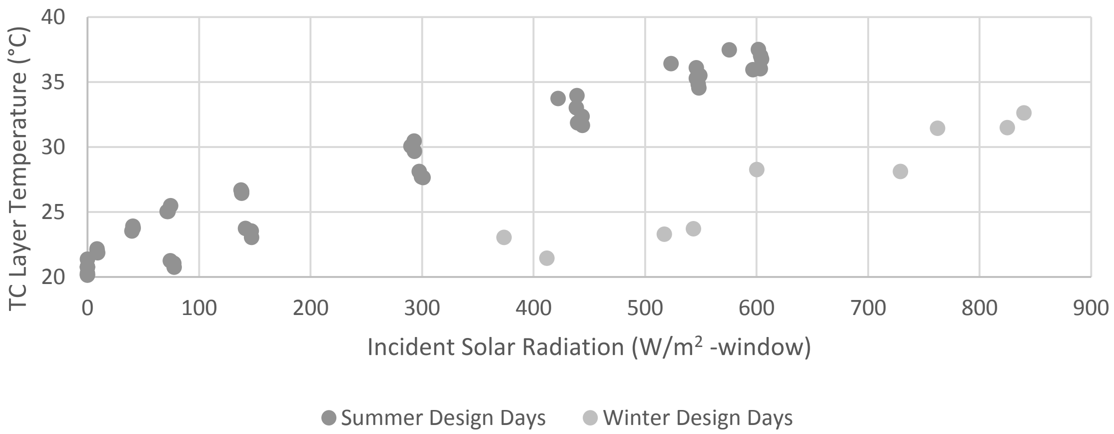


Figure 6 – Sets of thermochormic glazing temperatures and incident radiation resulting in tinting

Figure 7 shows the incident solar radiation with the concurrent window heat gains. The heat gain shown provides a balance between solar radiation, convective and long wave radiation heat transfer processes. The dotted line 'SHGC' represents the average solar heat gain coefficient, for the 6 simulated days when tinted, which can be determined by dividing the window total heat gain by the incident solar radiation, giving a value of SHGC = 0.31. By comparing the winter and summer data sets, it can be seen that window heat gain is predominantly due to incident solar radiation and is much less reliant on convection. The winter design points provide higher levels of total heat gain, showing the importance of incident solar radiation and the low significance of the outdoor temperature

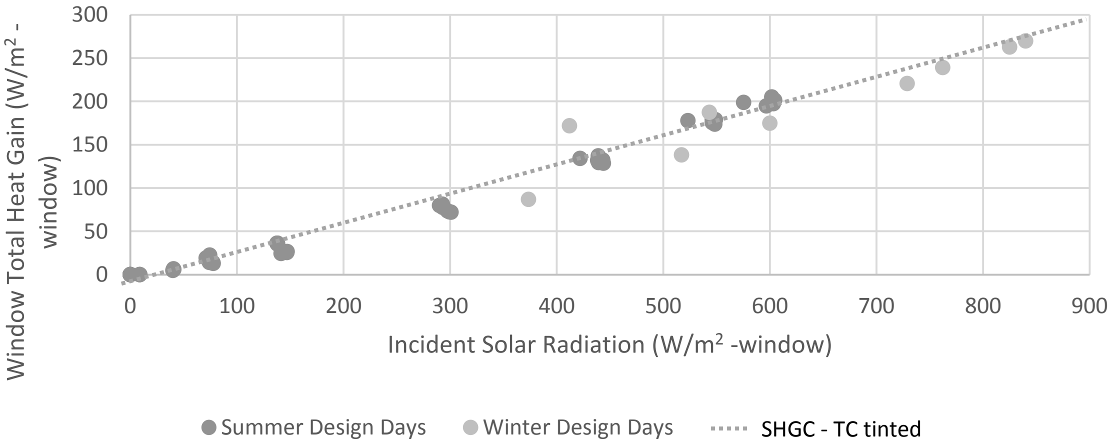
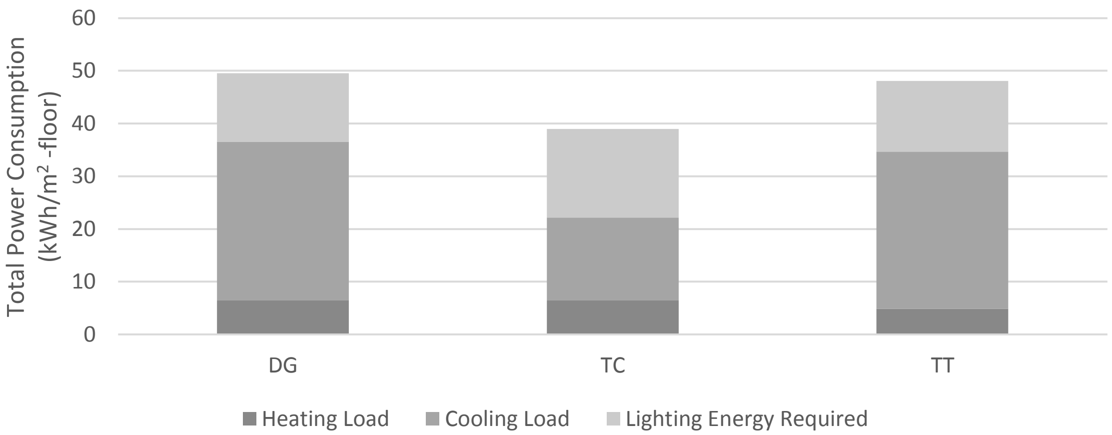


Figure 7 – Sets of window total heat gains and incident radiation resulting in tinting

Figure 8 shows the resulting power consumption of the reference DG and the TC and TT windows. Although the TC and TT sometimes act in a negative way, e.g. preventing passive heating on sunny winter days and decreasing natural illuminance, the overall combined effect of both windows is positive. The TC provides a saving of 10.53 kWh/m^2 –floor per year, 21% while the TT provides a saving of 1.41 kWh/m^2 –floor per year, 3%.



5. CONCLUSIONS

In this paper, a thermotropic layer made of HPC and NaCl was synthesized and tested at the University of Nottingham. The developed thermotropic layer has a transmission temperature of 32-33˚C. Below the Transition T_{vis} = 65-95%, T_{IR} = 40-90% above the transition T_{vis} = 5-35 %, T_{IR} = 10-50%.

In addition, simulations of a typical office with the developed TT and a TC installed were carried out using simulation software Energy Plus. The chosen TC window has a transition temperature of 20-21°C, T_{vis} = 65%, below transition T_{ir} = 80%, and above T_{ir} = 15%. From an annual energy prediction, exploring how the ambient environmental conditions affected the state of the TC, it was found that the incident solar radiation plays a large role in the tinting of the window, as heat gain within the film was predominately due to radiation and is less reliant on convection. The performance of the TC was compared to a standard double glazing unit; the use of the TC in comparison to the DG resulted in a 14.4 kWh/m^2 –floor, 32%, reduction in HVAC energy annually but a 3.87 kWh/m^2 –floor, 30% increase in lighting energy. Overall the TC saved 21% of combined energy annually; a significant reduction in energy use. The SHGC of the TC when tinted was 0.31 almost half that of the DG at 0.56, as the majority energy demand comes from cooling loads this reduction in transmitted radiation at peak temperatures greatly reduces this load. The results indicate that the TC technology would work best in areas with high levels of incident solar radiation and hot climates.

In addition simulation of typical hot days and cold days has also been carried out to evaluate fully the climatic impact on the window temperature and their capability to moderate solar heat gain. This can be seen through the results of the TT layer; the TT layer was only capable of tinting during the hottest days for very few hours, 5/72hr, 7% during the three day summer simulation, stunting the benefits of reducing the window heat gains, however this did allow for passive solar heating in the winter. The illuminance within the space was reduced, requiring extra lighting energy. However, when considering the whole system, the TT layer also provided a small energy saving of 1.41 kWh/m^2 –floor per year, 3%.

REFERENCES

[1] UK Green Building Council, “Key Statistics,” 2012. [Online]. Available: http://www.ukgbc.org/content/key-statistics-0. [Accessed 17 November 2014].

[2] National Insulation Association, “Did You Know Facts,” 2014. [Online]. Available: http://www.nia-uk.org/householder/index.php?page=did-you-know-facts. [Accessed 20 August 2014].

[3] M. Kamalisarvestani, R. Saidur, S. Mekhilef and F. Javadi, “Performance Materials and Coating Technologies of Thermochromic Thin Films on Smart Windows,” *Renewable and Sustainable Energy Reviews,* vol. 26, pp. 353-364, 2013.

[4] L. Long and H. Ye, “How to be Samrt and Energy Efficient: A General Disscussion on Thermochromic Windows,” *Scientific Reports,* no. 4, p. Article 6427, 2014.

[5] K. W. G. M. Resch, “Thermotropic Layers for Flat-Plate Collectors: A Review pf Various Concepts for Overheating Protection with Polymeric Materials,” *Solar Energy Materials and Solar Cells ,* vol. 93, no. 1, pp. 119-128, 2008.

[6] S. Hoffmann, E. S. Lee and C. Calvero, “Examination of the Technical Potential of Near-Infrared Switchin Thermochromic Windows for Commercial Building Applications,” *Solar Energy Materials and Solar Cells,* vol. 123, pp. 65-80, 2014.

[7] R. Baetens, B. P. Jelle and A. Gustavsen, “Properties, Requirements and Possibilities of Smart Windows for Dynamic Daylight and Solar Energy Control in Buildings: A State-of-the-art Review,” *Solar Energy Materials and Solar Cells,* vol. 94, no. 2, pp. 87-105, 2009.

[8] H. Ye, L. Long, H. Zhang and Y. Gao, “The Energy Saving Index and the Performance Evaluation of Thermochromic Windows in Passive Buildings,” *Renewable Energy ,* vol. 66, pp. 215-221, 2013.

[9] M. Saeli, C. Piccirillo, I. P. Parkin, R. Binions and I. Ridley, “Energy Modelling Studies of Thermochromic Glazing,” *Energy and Buildings,* vol. 42, no. 10, pp. 1666-1673, 2010.

[10] M. E. A. Warwick, R. Binions and R. Ridley, “The Effect of Transition Gradient in Thermochromic Glazing Systems,” *Energy and Buildings,* vol. 77, pp. 80-90, 2014.

[11] J. Schneider and A. Seeboth, “Natural Thermotropic Materials for Solar Switching Glazing,” *Materialwissenschaft und Werkstofftechnik,* vol. 32, no. 3, pp. 231-237, 2001.

[12] H. Watanabe, “Intelligent Window using a Hydrogel Layer for Energy Efficiency,” *Solar Energy and Solar Cells,* vol. 54, pp. 203-211, 1998.

[13] J. Schneider, A. Seeboth and A. Patzak, “Materials for Intelligent Sun Protecting Glazing,” *Solar Energy and Solar Cells,* vol. 60, no. 3, pp. 263-277, 1999.