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Thermal and visual performance of real and theoretical thermochromic glazing solutions for office buildings

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ABSTRACT

Thermochromic windows are able to modulate their transmittance in both the visible and the near-infrared field as a function of their temperature. As a consequence, they allow to control the solar gains in summer, thus reducing the energy needs for space cooling. However, they may also yield a reduction in the daylight availability, which results in the energy consumption for indoor artificial lighting being increased.

This paper investigates, by means of dynamic simulations, the application of thermochromic windows to an existing office building in terms of energy savings on an annual basis, while also focusing on the effects in terms of daylighting and thermal comfort. In particular, due attention is paid to daylight availability, described through illuminance maps and by the calculation of the daylight factor, which in several countries is subject thresholds.

The study considers both a commercially available thermochromic pane and a series of theoretical thermochromic glazing. The expected performance is compared to static clear and reflective insulating glass units. The simulations are repeated in different climatic conditions, showing that the overall energy savings compared to clear glazing can range from around 5% for cold climates to around 20% in warm climates, while not compromising daylight availability.

Moreover the role played by the transition temperature of the pane is examined, pointing out an optimal transition temperatures that is irrespective of the climatic conditions.

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1. Introduction

The solar radiation admitted through the glazed envelope of a building plays an important role on its energy and visual performance. In fact, solar gains contribute to heat the indoor spaces, thus inducing a cooling load in summer; on the other hand, they have a positive effect in winter. Moreover, one should not forget the importance of the glazed surfaces for daylighting purposes. Hence, the correct management of solar gains is essential, especially in passive buildings.

In order to control dynamically the behaviour of a glazed surface according to the needs of the building, chromogenic windows are available, also known as “smart glasses” [1]. The term “smart” is used to indicate a glass that can switch its optical properties when subject to an appropriate input, such as voltage, light or heat. This allows to create a building shell that is adaptive to climate, i.e. able to admit solar energy if there is a heating demand, or to reject solar energy when there is a cooling demand [2]. Smart glasses can provide improved indoor comfort by being able to prevent glare and thermal discomfort, and simultaneously they can provide large energy savings for air cooling [3].

Amongst smart glasses, electrochromic glazing (EC) is the most popular typology, and its performance has been widely investigated by researchers [4]. When a voltage pulse is applied between two transparent electrodes, ions move between the EC glazing and ion storage films, and the overall transparency is changed. A voltage pulse with opposite polarity makes the device restore its original properties [5]. Electric power is only needed for switching, i.e. no power is needed to maintain the windows in their clear or dark state, but only to change them from one state to the other. More details can be found in Refs. [6,7].

However, when speaking of *smart passive window solutions*, one mostly refers to other kinds of dynamic glazing, such as the *thermochromic* ones (TC).

Thermochromic materials can change their optical properties according to their temperature. In particular, at low temperatures a TC material is monoclinic, semiconducting and rather transparent to visible and infrared radiations (clear state); on the other hand, above a specific *transition temperature* (T_c) the TC material shows a transition into a metallic state (tinted state), and becomes

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Nomenclature

Variables

DF	daylight factor [−]
E	illuminance [lux]
I	solar irradiance [W m^{-2}]
k	thermal conductivity [W m^{-1} K^{-1}]
r	reflectance [−]
s	thickness [mm]
T	temperature [°C]
U	thermal transmittance [W m^{-2} K^{-1}]

Greek letters

ε	thermal emissivity [−]
λ	wavelength [nm]
τ	transmittance [−]

Subscripts

c	transition of the thermochromic material
min	minimum
op	operative
sol	solar
vis	visible

relatively reflecting towards infrared radiations, while varying also its visual appearance [8].

Obviously, when using TC materials in buildings as a passive system, their performance is highly dependent on the interaction between the material and the climatic conditions. In this sense, it is essential that the transition temperature T_c is compatible with the temperature usually achieved on a window exposed to solar radiation, otherwise the TC glazing would remain in the clear state for most of the time, thus scarcely exploiting its potential [9]. Moreover, an ideal TC window should keep a high visible transmittance also in its tinted state, in order not to penalise daylighting [10].

A wide variety of materials have been found to have thermochromic properties [11]. Some materials, such as polymers, organic and inorganic compounds, offer a good modulation of the visible optical properties [12], but not good enough in the near-infrared field of the solar spectrum (780–2500 nm), where almost half of the solar energy is concentrated [13].

For this reason, metal oxides are mostly being used. In particular, the most common TC material for windows is vanadium dioxide (VO_2). VO_2 films can be prepared through various techniques, including chemical vapor deposition (CVD), sputtering and sol–gel method [14]. CVD technique is generally considered the most attractive one, because of its compatibility with high volume glass manufacture [15]. More information about deposition techniques for VO_2 are available in Ref. [16].

The phase transition temperature of pure VO_2 is 68 °C, which is quite close to current glazing temperature in building applications; however, this value of T_c is still too high. Previous studies demonstrated that optimal performance would require T_c being around 25 °C [17]; lower values of T_c may lead to higher cooling energy consumption in some cases [18]. Another limit of TC films with pure VO_2 is that their visible transmittance hardly exceeds 40%, which is too low for most applications to windows in buildings [19].

To overcome these drawbacks, research is being developed. VO_2 doping with tungsten ions (W) leads to a drop in the transition temperature at a rate between 5 °C and 24 °C per atomic percent of W incorporated, depending on the deposition conditions [13]. In some cases, a reduction rate of 27 ± 1 °C/at% is reported [19]. However, the addition of W does not introduce significant improvement on the visible transmittance [20].

VO_2 doping with fluorine has shown to reduce the transition temperature to around 20 °C, but this also introduces a wide hysteresis width for the thermochromic transition, which makes the solution less interesting for building applications [16].

Mg doping has a positive effect on the visible transmittance, which is found to increase monotonically from around 40% to more than 50% when the Mg attains 7.2 at%. A slight erosion of the intensity of the thermochromic effect may also occur [19]. Mg doping is advantageous also because it influences T_c favorably, with a reduction rate as high as 6 °C/at% [21].

Furthermore, the deposition of VO_2 nanoparticles – instead of the application of VO_2 films – can increase the visible transmittance in the tinted state up to 60% [19]. The incorporation of gold nanoparticles also leads to significant changes in the optical and thermochromic properties of the film. The transition temperature becomes close to 45 °C, and the film color is altered from an undesirable yellow/brown towards green/blue hues [15]. Other studies report about techniques based on VO_2 deposition with a growth directing surfactant. In this case, T_c=38.5 °C is achieved, and the visible transmittance shifts from 61% in the clear state to 51% in the tinted state [15].

As concerns the energy saving potential of TC windows in building applications, some studies have been recently published. Most of them are based on dynamic thermal simulations performed on very simple test rooms, the only window being provided with a VO_2 film having real transmission spectra [8,15,18,23]. These studies agree that currently available TC glazing can reduce the energy needs for space cooling with respect to common high-performing static glazing, while slightly increasing the energy needs for space heating and for artificial lighting. On a yearly basis, up to 10% energy savings may be registered in warm climates, whereas in cold climates TC glazing may even lead to energy waste [18].

Other studies refer to simple test rooms with theoretical TC glazing, in order to investigate into the potential performance improvement attained with an ideal window, having suitable transition temperature and solar transmittance in the tinted state [14,24,25]. Just one study is based on dynamic simulations on a large real office building [13]. The current understanding is that the optimal transition temperature lies around 20 °C. Moreover, current TC windows produce very little modulation in near infrared solar spectrum. However, if the properties of a TC glazing can be properly tuned, the technology has the potential to significantly improve building energy efficiency.

Some researchers also highlighted that, if the low solar transmittance in the tinted state is achieved by providing high solar absorptance to the pane instead of high solar reflectance, the heat flux transferred from the glazing to the room by convection and irradiation may overcome the savings stemming from the reduction in the direct solar heat gains [18]. This is particularly relevant for large glazed surfaces.

In this context, this paper proposes a further contribution with the aim to provide a comprehensive view about the performance of TC glazing in buildings. The case study is an existing office building located in the university campus of Catania (Southern Italy), which might benefit from the application of this technology,

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