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Smart or not? A theoretical discussion on the smart regulation capacity of vanadium dioxide glazing

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ABSTRACT

As a typical thermochromic material, vanadium dioxide (VO_2) has the potential to serve as a smart regulator of building energy consumption. However, a selection of currently used VO_2 glazing types were found to lack such smart regulation capacity due to their increased solar absorptivity after entering the metallic state, and the cooling energy consumption of a room containing such VO_2 glazing increased as the transition temperature decreased. This study presents a comprehensive discussion of this glazing's smart regulation capacity. It is observed that the VO_2 glazing's smart regulation capacity is influenced by property variations in its solar absorptivity and transmittance after the transition process. Smart Index (*SI*) is proposed to evaluate the "smart level" of VO_2 glazing, and a contour map of *SI* is plotted to provide a concise method of determining how "smart" VO_2 glazing can be.

1. Introduction

As one of the main sources of carbon dioxide emissions, China's buildings sector was responsible for approximately 25% of the country's primary energy consumption in 2010 [1]. It is estimated that the worldwide building sector's energy-saving potential will be approximately 20 exajoules (EJ) per year from 2009 to 2030. This value is equal to the current annual electricity consumption of the United States and Japan [2]. One route to achieving building energy efficiency would be to improve window performance because the energy losses through windows account for approximately 20% to 40% of total building energy consumption [3]. Chromogenic windows, as one of the most widely investigated advanced windows, can smartly change their spectral properties when triggered by an external stimulus and is thus called a "smart" window [4]. Such chromogenic technology involves electrochromic [5], photochromic [6], thermochromic [7] and gasochromic technologies [8].

Vanadium dioxide (VO_2) was first reported as a typical thermochromic material in 1959 [9], and can undergo a reversible transition at a certain transition temperature (τ_c). When in its semiconductor state at low temperatures, the VO_2 has relatively high solar transmittance, but when in its metallic state at high temperatures, it has relatively low solar transmittance. Due to these characteristics, VO_2 glazing, generally manufactured by plating VO_2 on a glass substrate, has potential for smart regulation applications in building energy efficiency. When the ambient temperature or the solar irradiance on the VO_2 glazing is low, it will have a low temperature and transfer into its semiconductor state with high transmittance to increase the solar radiation transmitted into the room, which is the room's main heat gain. When the ambient temperature or the solar irradiance on the glazing is high, it will have a high temperature and transfer into its metallic state with low transmittance to solar radiation. In theory, with an appropriate τ_c, the adoption of VO_2 glazing can reduce both cooling and heating energy consumption by regulating the room's heat gain.

There are currently some problems associated with the application of VO_2 in buildings [10]. Studies were performed to enhance the VO_2 glazing's visible light transmittance in both states and its solar transmittance in the semiconductor state [11,12]. However, these transmittances were still much lower than that of ordinary glazing. The lower solar transmittance led to a decrease in the building's heat gain from solar radiation, which made the VO_2 glazing a poor choice in winter. In other words, the current VO_2 glazing could reduce only cooling energy consumption, not heating energy consumption. As a result, the VO_2 glazing's transition temperature (τ_c) was anticipated to be as low as possible to maintain the glazing in its metallic state with low transmittance for a longer time, which would theoretically lead to lower heat gain and cooling energy consumption. Tungsten (W) doping was identified as an effective method of decreasing τ_c [11], which could be brought to a comfortable temperature of $\sim 25\ ^{\circ}C$ [10]. However, in our previous work [12], we found that a lower τ_c led to higher cooling energy consumption in some types of VO_2 glazing.

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That work calculated the energy consumption of a room using a VO_2 glazing sample with different τ_c values, and indicated that a lower τ_c value led to higher energy consumption in the summer. Such a phenomenon meant that the longer the VO_2 remained in its semiconductor state, the less cooling consumption was needed in the summer. This decrease was also caused by markedly increased absorptivity after the VO_2 transferred into its metallic state. When in its semiconductor state, the glazing's solar absorptivity, reflectivity, transmittance and thermal emissivity were 0.30, 0.33, 0.37 and 0.84, respectively; but when in its metallic state, the corresponding values were 0.48, 0.21, 0.31 and 0.57, respectively. After changing from the semiconductor to the metallic state, the solar transmittance and absorptivity of the glazing decreased and increased, respectively. A lower solar transmittance led to a decrease in the solar radiation transmitted into the room, which decreased the cooling consumption, while a higher solar absorptivity led to a higher glazing temperature, increasing both the heat flux from the glazing to the indoor air and the cooling consumption. If the decrease in the cooling consumption caused by the reduction of the directly transmitted solar radiation was less than the increase in the cooling consumption caused by the increase in heat flux from the glazing to the indoor air, the cooling consumption rose when the glazing transferred into its metallic state. This phenomenon indicated that the glazing had no smart regulation capacity, and lowering its τ_c value did not improve its performance.

It was known that the VO_2 glazing under study achieved a lower transmittance by increasing its absorptivity, rather than increasing its reflectance after changing into its metallic state, which means the phenomenon identified in [12] could occur in applications involving other types of VO_2 glazing. The future of VO_2 glazing applications would be poor in the absence of any smart regulation capacity. In this study, we analyze the relationships between the energy consumption levels and τ_c values of other VO_2 glazing samples, and their smart regulation capacities are discussed based on these results. A concise method of distinguishing whether a certain VO_2 glazing has smart regulation capacity, and how "smart" it might be, is also presented.

2. Methodology and materials

Modeling software called BuildingEnergy was developed and used to simulate the cooling/heating load of a room [12,13]. This modeling software was compiled based on a non-steady state heat transfer model, and the building envelope, indoor air and outdoor air were divided into hundreds of nodes. The energy conservation equation for each node was listed based on the implicit difference method, and the equations of all the nodes in the temperature field formed a matrix. The temperature field could be determined by solving the matrix via the Gauss-Seidel iteration method.

BuildingEnergy was validated by the ANSI/ASHRAE Standard 140-2004 (*Standard Method of Testing for the Evaluation of Building Energy Analysis Computer Programs*) [12]. Its simulated results were also compared with the results from an experiment conducted in the *Testing and Demonstration Platform for Building Energy Research*, which contains two identical testing rooms with internal dimensions of $2.9 \times 1.8 \times 1.8\ m^3$ (length × width × height). During the experiment, one testing room contained VO_2 glazing and the other contained ordinary float glazing. The experiment began on July 7th, 2012 in Hefei, China and lasted for 7 days. The comparisons between the simulated and measured results are shown in Fig. 1, which indicates little difference between the simulated and measured results.

A mid-floor room in a multi-story residential building is used to discuss the VO_2 glazing's application performance for a typical residential room. This room has internal dimensions of 4 m × 3.3 m × 2.8 m (length × width × height) and contains only one exterior wall, with a 1.5 m × 1.5 m single window in the middle of the exterior wall. The inner heat gain from the occupants and equipments is taken to be 4.3 W per unit floor area, and that from lighting is 3.5 W per unit floor area when the lights are on from 18:00 until 22:00 every day. The ventilation rate is set as 1.0 air changes per hour (ACH) when the space cooling is operating and 10.0 ACH at all other times. During the cooling period, the indoor temperature is maintained at the recommended 26 °C by the space cooling [14]. The application's performance is considered in Guangzhou, China, which is located at latitude 23N and longitude 113E and has a cooling period from May 13th to October 17th. The climate data used to simulate the room's performance in BuildingEnergy are the typical meteorological yearly data offered by the Chinese Architecture-specific Meteorological Data Sets for Thermal Environment Analysis.

Three typical types of VO_2 glazing are chosen for study, the properties of which are listed in Table 1. VO_2 glazing A is the sample adopted in Fig. 1 and the VO_2 glazing B is the sample discussed in [12]. VO_2 glazing A is produced as follows. The VO_2 particles are pretreated in a poly vinylpyrrolidone aqueous solution and then transferred to an ethanol solution to form SiO_2

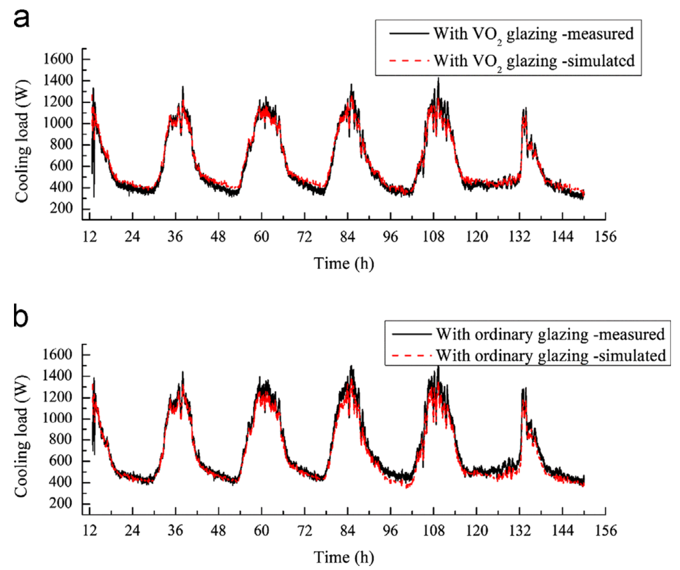

Fig. 1. Comparison between the simulated and measured results.

Table 1
Spectral data for the VO_2 glazing samples.

Properties	VO_2 glazingA[1]		VO_2 glazingB[2]		VO_2 glazingC[3]	
	S-state[a]	M-state[b]	S-state[a]	M-state[b]	S-state[a]	M-state[b]
Transition temperature	41.3 °C		30.0 °C		38.5 °C	
Solar absorptivity	0.482	0.590	0.300	0.480	0.310	0.410
Solar reflectance	0.078	0.055	0.330	0.210	0.230	0.210
Solar transmittance	0.440	0.355	0.370	0.310	0.460	0.380
Emissivity	0.880	0.880	0.840	0.570	0.830	0.790

[a] Semiconductor state at low temperature.
[b] metallic state at high temperature.
[1] Manufactured by the State Key Laboratory of High Performance Ceramics and Superfine Microstructure, Shanghai Institute of Ceramicss (SIC), Chinese Academy of Sciences (CAS).
[2] reported in [16].
[3] reported in [18].