Solar Energy Materials and Solar Cells 169 (2017) 145–150

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Dual-intelligent windows regulating both solar and long-wave radiations dynamically

Linshuang Long, Hong Ye*

Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230027, PR China

ARTICLE INFO

Keywords:
Dual-intelligent
Dynamic regulation
Long-wave thermal radiation
Solar radiation

ABSTRACT

Advanced energy-efficient windows have been widely investigated due to the special role of windows among building envelopes. Here, we propose an idea of dynamic management of both solar radiation and long-wave thermal radiation. A window based on this idea can be named as a dual-intelligent window, which blocks the solar radiation as well as emits little long-wave thermal radiation to the indoor side during hot daytime and cools the room by dissipating heat from the indoor side to the outdoor side through radiative heat transfer at cool nights. Based on the properties of thermochromic vanadium dioxide (VO_2), it was found that a dual-intelligent window can be accomplished by pasting the VO_2 film onto the indoor side of the window. The energy performance of this conceptual dual-intelligent window was numerically simulated and compared with low-emissivity window and traditional VO_2 window where the VO_2 film is on the outdoor side. The results show that the window with low emissivity cannot reduce the energy consumption for cooling due to the lack of the ability of regulating the long-wave thermal radiation. The dual-intelligent window surpasses the traditional intelligent VO_2 windows due to the fact that the application of the dual-intelligent window can reduce cooling energy by 21.7% compared with the traditional intelligent window. This improvement of dual-intelligent window emphases the advantages of dynamically regulating solar and long-wave radiations simultaneously.

1. Introduction

The building sector is responsible for 30–40% of the primary energy used in developed countries and is also one of the main sources of carbon dioxide emissions, which produces a widespread public concern about global warming. Therefore, developing energy-efficient buildings is an urgent requirement for a sustainable and environmentally friendly society. For a building, the development of building envelopes should be the prerequisite and foundation. As a significant part of a building envelope, windows contain great potential for energy-saving development because up to 60% of the total energy losses from buildings may be attributed to them [1]. Apart from conducting heat between the indoor and outdoor environments like any other part of envelopes, a unique feature of the window resides in the fact that it transmits solar radiation as well as emits/absorbs long-wave thermal radiation.

Many efforts have been made to enhance the energy performance of windows from the perspective of radiations, especially the solar radiation. Due to the fact that the solar radiation varies over time, the response properties of the window to the solar radiation should be changeable to realize dynamic control of daylight and solar energy in buildings. The so-called smart or intelligent windows can adjust their radiation properties in response to the demands of inhabitants [2,3]. The most comprehensively investigated smart windows may be the thermochromic and electrochromic windows, for which the regulations of the solar radiation properties are triggered by temperature and electrons, respectively [4–7].

Vanadium dioxide (VO_2) is a representative thermochromic material. First reported by Morin [8], VO_2 is able to undergo a reversible transition at a phase transition temperature (T_τ): when the temperature of the material is lower than T_τ, it is monoclinic, semiconducting and rather infrared transparent, and when the temperature is higher than T_τ, it is tetragonal, metallic and near-infrared reflecting. These features make VO_2 windows appropriate for building energy efficiency [9,10]. In addition to these smart thermochromic windows, a smarter window was also introduced, which can separately regulate the near-infrared and visible parts of the solar radiation [11,12]. The above-mentioned windows are associated with the solar radiation, which is within a wavelength range of 0.3–2.5 μm, and the other type of radiation, i.e., the long-wave thermal radiation, is also concerned by researchers.

Regarding to the long-wave radiation, due to the high absorptivity of silicon dioxide, which is the main material of glass, to the radiation with a wavelength longer than 2.5 μm, the window is almost opaque to

* Corresponding author.
E-mail address: hye@ustc.edu.cn (H. Ye).

http://dx.doi.org/10.1016/j.solmat.2017.05.022
Received 10 March 2017; Received in revised form 4 May 2017; Accepted 13 May 2017
0927-0248/

the long-wave radiation. The windows with low emissivity (low-e) coatings were considered energy-efficient as they can, theoretically, hinder the long-wave thermal radiation entering a room in summer as well as block the radiation leaving the room in winter. Therefore, decreasing the emissivity of windows is the target of some researchers [13–15]. However, Ye et al. have found that the emissivity should not always be low, but should accommodate to the changing circumstance as the solar radiation properties should [16]. They further indicated that the regulations of both long-wave and solar radiations are equally important to improve the energy performance of windows [17].

Although combinations of thermochromic materials and low-e coatings have already been investigated [18,19], only one type of radiation, i.e., the solar radiation, was intelligently regulated, raising the demand of smart control of both types of radiations. In this study, we introduce a conceptual dual-intelligent window based on VO_2. Unlike traditional VO_2 windows that work only for solar radiation, the dual-intelligent window is able to dynamically regulate solar and long-wave radiations simultaneously, leading to a much better energy performance compared with the traditional counterpart. The performance of the dual-intelligent window was numerically demonstrated and compared with other types of windows.

2. Properties

2.1. Optical constants of VO_2

As mentioned in the introduction, vanadium dioxide is a phase change material whose properties change with temperature. In this study, the properties of interest are the optical constants, i.e., refractive index and extinction coefficient, because the radiation properties of a component are mainly determined by the structure and optical constants of the materials. The optical constants of VO_2 among the waveband of solar radiation (0.25–2.5 μm) were investigated by Kakiuchida et al. [20], where the optical constants were extracted from the measurement of a VO_2 film prepared by magnetron sputtering. With the optical constants, the radiation properties of a VO_2 film can be numerically calculated using the finite-difference time-domain (FDTD) method. The calculated spectral transmittance of VO_2 films with different thicknesses are compared with the measured data provided by Kang et al. [21] in Fig. 1(a). As Fig. 1(a) shows, the calculated results are close to the measured data, indicating that the employed method of simulations and optical constants of materials are reasonable. For a film with a certain thickness, the transmittance at low temperature is higher than that at high temperature due to the phase transition of VO_2. The film thickness also influences the transmittance. A thinner film has a higher transmittance than a thicker film in the same state. For the waveband of long-wave radiations, i.e., wavelengths longer than 2.5 μm, Barker et al. measured the reflectance of bulk VO_2 at low and high temperatures and studied the optical constants [22]. Using these properties, the reflectance of bulk VO_2 was obtained via FDTD and compared with the measured data, seen in Fig. 1(b). The incomplete data of wavelength shorter than 25 μm at high temperature in Fig. 1(b) were caused by the sample cracking during the measurement [22]. The metallic VO_2 at high temperature, from Fig. 1(b), has a higher reflectance than the insulating VO_2 at low temperature.

2.2. Radiative properties of VO_2 window

In building applications, VO_2 films need to be attached onto glass, which is made of silica (SiO_2) generally, to form VO_2 windows. The VO_2 window can be perceived as a combination of two layers: a layer of silica glass with a typical thickness of 6 mm and a layer of VO_2 film with a typical thickness of 100 nm. The tremendous difference in thickness between these two layers makes the FDTD method inefficient for the case of VO_2 window. Therefore, ray tracing method was employed. In the ray tracing method [23], considering the normally incident light

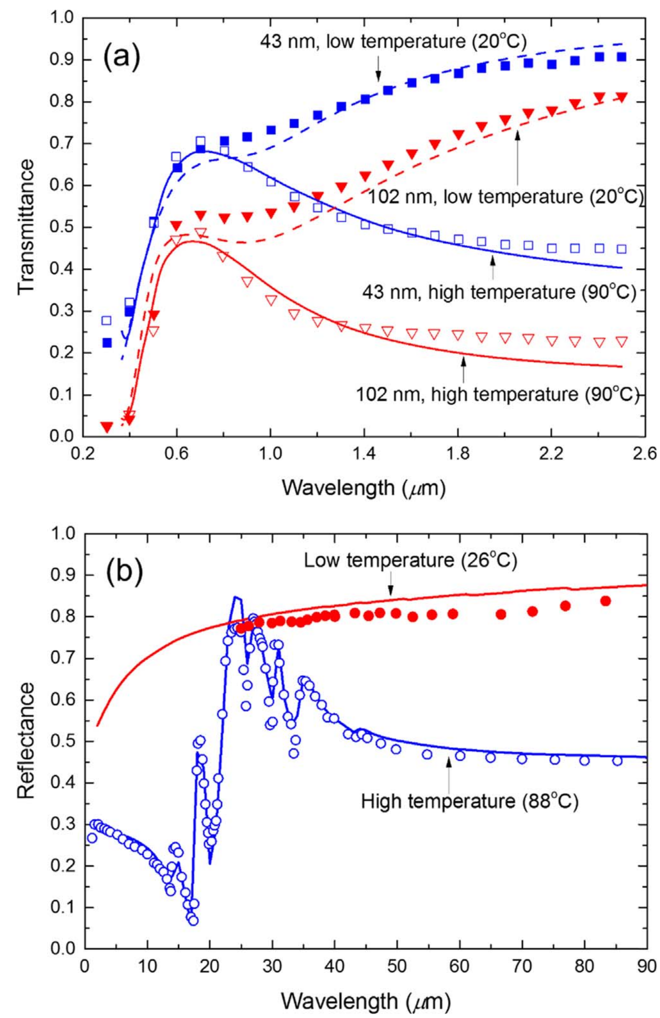

Fig. 1. Comparisons between data from measurement and results from calculation for (a) solar radiation, i.e., wavelengths between 0.25 and 2.5 μm, with different thicknesses of films and (b) long-wave thermal radiation, i.e., wavelengths longer than 2.5 μm. The calculated data were obtained via FDTD method using the optical constants provided in [20,22], and are plotted in lines in the figures. The measured data were extracted from references [21,22], and are represented by scatters in the figures.

from air to the VO_2 side of the window, the total transmittance T and reflectance R of the VO_2 window are given as

$$\begin{cases} T = \frac{\tau_1\tau_2}{1 - \tau_1^2\rho_1\rho_2} \\ R = \rho_1 + \frac{\tau_1^2\rho_2}{1 - \rho_1\rho_2\tau_1^2} \end{cases} \tag{1}$$

where τ_1 and τ_2 refer to the transmittance of VO_2 layer and SiO_2 layer, respectively; ρ_1 and ρ_2 represent the reflectance at the interface between air and VO_2 layer and the interface between VO_2 layer and SiO_2 layer, respectively. τ_1 and ρ_1 related to the VO_2 layer were still calculated using the FDTD method. ρ_2 can be obtained through Fresnel equations, and τ_2 follows [23].

$$\tau_2 = \exp\left(-\frac{4\pi\kappa_2 d_2}{\lambda\cos\theta_2}\right) \tag{2}$$

where d_2 corresponds to the thickness of the SiO_2 layer, and κ_2 is the extinction coefficient of SiO_2 at the wavelength of λ. The incident angle θ_2 is 0 when a normal incidence is considered. The absorptance A of the VO_2 window is obtained through $A = 1\text{-}T\text{-}R$. The spectral radiation properties of the VO_2 window are plotted in Fig. 2, where the emissivity equals to the absorptance according to Kirchhoff's law.

The integral properties of the spectral counterparts are listed in