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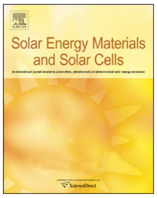

Multi-Angle method to retrieve infrared spectral properties of a high-transparency material at high temperatures

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ABSTRACT

A Multi-Angle (MA) method was proposed to determine the high-temperature spectral properties of high-transparency and low-absorption materials. This method overcomes the experimental difficulties of temperature gradient and low recognition. Through just rotating the sample to tune the incident/transmitted angle, this method can provide multiple distinctly different and independent transmittances, and there is barely any influence on the temperature field of the sample. Measurements are performed on an ultraviolet fused silica between 0.8 and 5 μm for several high temperatures, using a modified FTIR system coupling with a heating cell. Based on the transmittance data, a genetic-algorithm-based least-square method was used to extract the refractive index and the absorption index. In this identifying process, a Monte-Carlo ray-tracing (MCRT) method was adopted to predict the experimental value. The genetic algorithm was used to search and optimize the association of the indexes of refraction and absorption. Using this experimental identifying method, temperature and frequency dependence of transmission properties of the UV fused silica up to 1800 K were obtained. The spectral refractive index gradually decreases with wavelength and slightly rise with increasing temperature. The spectral absorption index is also dependent on wavelength as well as temperature. As the absorption bands broadening with the increasing temperature, three absorption peaks all shift toward longer wavelengths and vary differently from 1200 to 1800 K. The indexes of refraction and absorption can be used for predicting the transmitting rates of fused silica windows based on different entrance angles at high temperatures.

1. Introduction

Based on the utility of spectral selectivity, various energy-efficient windows are used in the photo-thermal solar energy conversion in which most of them encounter high temperature surroundings. For example, fused silica is one kind of highly transparent materials in the near-infrared region and widely used to manufacture energy-efficient windows in different shapes for high-temperature Volumetric Solar Receiver (VSR) [1,2]. The window transmits concentrated solar flux into the receiver and prevents the most infrared energy converted from escaping [3–5]. As a critical part of the whole assembly, the energy-efficient window could reduce the heat loss of convection and radiation, and raise the thermal efficiency of the receiver [6,7]. Some numerical results of transmission onto an elliptic shape window had been obtained, the transport direction and solar energy absorbed by the quartz window were assumed unchanged [8,9]. However, the features of absorption, reflection and transmission are dependent on wavelength and temperature. The infrared spectral properties are fundamental parameters for prediction and evaluation on the performance of a window. Knowledge of the spectral radiative properties at high-temperature is important so as to ensure the desired effect of an energy-efficient window. All energy-efficient windows are made of high-transparency materials with low-absorption. The acquisition of spectral properties of this material confronts a series of experimental and identifying difficulties.

The spectral properties of fused silica have been the subject of numerous studies [10–14], especially at room temperature [15]. Since the weak emitting capacity, optical properties of semitransparent solids are usually determined by measurements of either the transmittance or the reflectance [16,17]. Each of these methods has advantages and disadvantages, depending upon the spectral region and the general feature of the material being studied. In a traditional reflection method [18–22], external radiation is reflected from the surface. It must be modulated to distinguish it from the emitted or reflected furnace radiation, which is very limited in applies for high transparent materials. Moreover, if the reflected radiation must be measured over all angles of reflection, and this limits the degree to which the sample can be surrounded by the heating element to gain multiple optical outlets. This

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may also result in an unpredicted temperature gradient in the sample. Compared to reflection methods, the transmittance method is even excellent when the tested material has high transmitting rates. In this case, the measure system has high Signal-to-Noise Ratio (SNR), which is of primary importance in practices especially at high temperatures when the stray radiation is very strong. The transmittance-based [23–28] method also suffers the problem of decreasing the temperature precise as the number of optical outlets on the furnace increases. In addition, the diversity of transmittance data which is very necessary in a retrieval procedure would be very slightly for a high transparent material when the incident angle is single and the thickness varies in an acceptable range. The combination method of radiance, reflectance and transmittance measurements [29–32] can provide a variety of surface properties, and has no limit on the researched materials. However, the measure scheme may be changing with the tested parameter, which would cause different random errors. This would result in artificial error when the residual in a retrieval model is calculated by the root-sum-square of the experimental data and the relevant predicted values. A robust methodology allowing the radiative properties of a high-transparency material to be determined is even in great demand, especially at an elevated temperature.

This article presented an experimental identification method based on MA measurements. This method overcomes the difficulties of temperature gradient and low recognition. And this method can be used for determining the spectral properties of various solar photo-thermal windows with high-transparency and low absorption characteristics. Rotating the sample to tune the incident/transmitted angle, the MA measurements on a single sample can provide multiple distinctly different and independent transmittances. There is barely any influence on the temperature field of the sample. The measurements on an ultraviolet (UV) fused silica are performed between 0.8 and 5 μm for room temperature and from 1200 to 1800 K. Based on the transmittance data, a genetic-algorithm-based least-square method was used to extract the refractive index and the absorption index. In this identifying process, a Monte-Carlo ray-tracing (MCRT) method was adopted to predict the experimental value using the initial or iterative spectral properties. The genetic algorithm was used to search and optimize the association of the indexes of refraction and absorption. Using this experimental identifying method, temperature and frequency dependence of transmission properties of the UV fused silica were obtained. The spectral refractive index gradually decreases with wavelength and slightly rise with increasing temperature. The spectral absorption index is also dependent on wavelength as well as temperature. As the absorption bands broadening with the increasing temperature, three absorption peaks all shift toward longer wavelengths and vary differently from 1200 to 1800 K. The derived indexes of refraction and absorption can be used for predicting the transmitting rates of fused silica windows in Volumetric Solar Receivers based on different entrance angles.

2. Transmitting characteristics of a single absorbing slab

The consideration here is a single absorbing slab (with complex index of refraction $m_2 = n_2 - ik_2$) immersed in the nonabsorbing medium of argon (with complex refractive index $m_1 = n_1 - ik_1$, $n_1 = 1$ $k_1 = 0$). The infrared radiation travels through the argon and reaches the surface of absorbing medium at the angle of θ_1 with the surface normal (incident angle) as schematically shown in Fig. 1.

According to the electromagnetic wave theory, the Fresnel reflectivity can be expressed as [33]:

$$\rho = \left[\frac{(p - n_1 \sin\theta_1 \tan\theta_1)^2 + q^2}{(p + n_1 \sin\theta_1 \tan\theta_1)^2 + q^2} + 1\right]\cdot\frac{(\cos\theta_1 - p)^2 + q^2}{(\cos\theta_1 + p)^2 + q^2} \tag{1}$$

where,

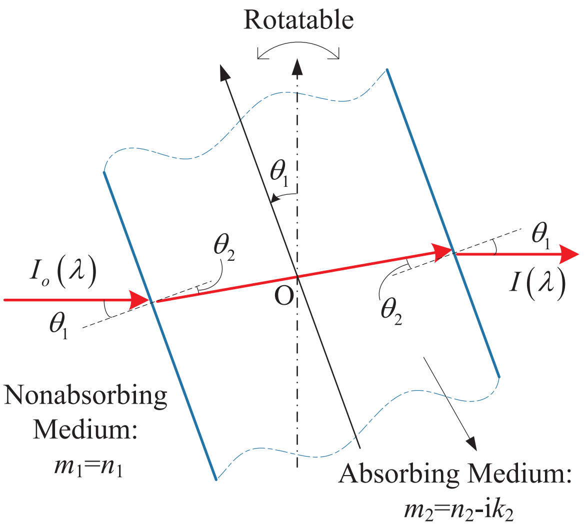

Fig. 1. Transmission mechanism of a single slab.

$$p^2 = \frac{1}{2}[\sqrt{(n_2^2 - k_2^2 - n_1^2 \sin^2\theta_1)^2 + 4n_2^2k_2^2} + (n_2^2 - k_2^2 - n_1^2 \sin^2\theta_1)] \tag{2}$$

$$q^2 = \frac{1}{2}[\sqrt{(n_2^2 - k_2^2 - n_1^2 \sin^2\theta_1)^2 + 4n_2^2k_2^2} - (n_2^2 - k_2^2 - n_1^2 \sin^2\theta_1)] \tag{3}$$

The refraction angle θ_2 may be calculated as [33],

$$p \tan\theta_2 = n_1 \sin\theta_1 \tag{4}$$

When the absorption index is negligibly small, the transmitted radiation may suffer multiple reflections and refractions on the two boundary interfaces as well as the inner absorptions. The apparent transmittance τ_{slab} of a single absorbing slab of thickness L accounting for multiple reflections, refractions and absorptions can be obtained by a ray-tracing method based on the geometric optics [33]:

$$\tau_{slab} = \frac{(1-\rho_{12})\cdot(1-\rho_{21})\exp[-4\pi k_2 L/(\lambda\cos\theta_2)]}{1-\rho_{12}\rho_{21}\{\exp[-4\pi k_2 L/(\lambda\cos\theta_2)]\}^2} \tag{5}$$

where, ρ_{12} denotes the reflectivity as the incident radiation illuminates on the end surface of sample; ρ_{21} represents the Fresnel reflectivity when the residual radiation hits the inner surface of the sample.

Strictly speaking, due to the absorption, slabs of different thicknesses should have definitely different transmittances. However, the difference may be hardly to be distinguished in actual measurements because of the presence of measure errors. The extreme situation of $k \to 0$, for normal incidence $\theta_1 = \theta_2 = 0$, results in $p = n_2 = n$, $q = k_2 = k$ and

$$\lim_{k\to 0}\tau = \lim_{k\to 0}[\exp(-4\pi kL/\lambda)] = 1 \tag{6}$$

$$\lim_{k\to 0}\rho_{12} = \lim_{k\to 0}\rho_{21} = \lim_{k\to 0}\frac{(n-1)^2 + k^2}{(n+1)^2 + k^2} = \frac{(n-1)^2}{(n+1)^2} \tag{7}$$

$$\lim_{k\to 0}\frac{\partial\tau_{slab}}{\partial L} = \lim_{k\to 0}\left[\frac{(1-\rho)^2(1+\rho^2\tau^2)\tau}{(1-\rho^2\tau^2)^2}\left(-\frac{4\pi k}{\lambda}\right)\right] = 0 \tag{8}$$

Eqs. (6) and (7) show the incident beam is only attenuated by surface reflection when absorption can be neglected. And for this case the changing rate of the transmittance with thickness approaches zero. So multiple slabs with different thicknesses would provide very approaching transmittance data. However, the parameter identification procedure must need at least two distinctly different transmittances to identify the refractive index n and the absorptive index k.

For this reason, a Multi-Angle (MA) method is proposed in this study to overcome the problem of low recognition. Consider a light of 0.5 μm