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Experimental study on the radiative properties of open-cell porous ceramics

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ABSTRACT

Open-cell porous ceramic is an ideal volumetric heat absorbing material, and understanding in detail the thermal properties of the material, particularly its radiative properties, is of primary importance for the design and improvement of volumetric solar receivers. This work investigates the radiative properties of open-cell porous ceramic through experiment. Fourier transform infrared spectroscopy (FTIR) was applied to measure the spectral transmittance of open-cell porous ceramic samples with different porosities and cell densities in infrared wavelengths between 2.5 and 25 μm. The results were analyzed to determine the spectral extinction coefficient and Rosseland extinction coefficient, which showed that the radiative properties of porous ceramic are strongly dependent on its microstructure parameters, while the type of material has little influence. The spectral extinction coefficient and Rosseland extinction coefficient both increased with increasing cell density and decreasing porosity. Based on the experimental results, two empirical correlations related to the window diameter and porosity were proposed to predict the Rosseland extinction coefficient of open-cell porous ceramics. Finally, the radiative thermal conductivities of different porous ceramics were studied.

1. Introduction

Concentrated solar power (CSP) technology is an effective way to solve environmental pollution problems over the coming decades. With the help of a thermal energy storage system, a CSP plant has the ability to provide constantly dispatched electricity and grid services in the same way as conventional fossil fuel power plants, although at present generating costs are two or three times higher (Behar et al., 2013; Pitz-Paal et al., 2013). However, the technology holds great promise, and it is important to promote and support the innovation and development of CSP systems. A typical CSP plant consists of three main subsystems: solar collector field, solar receiver and power conversion system. By increasing the receiver operating temperature, the operating efficiency of the tower concentrating solar system (CRS) can be increased by 40–60% (Ávila-Marín, 2011). Volumetric receivers are able to produce higher outlet temperatures than tube receivers, and the receiver thermal efficiency of volumetric receivers can be over 75% more than tube receivers due to the volumetric effect (Ávila-Marín, 2011). Therefore, volumetric receivers are the most promising solar receiver (Fend et al., 2004; Bai, 2010; Mey et al., 2014).

The volumetric absorbing materials can be metal or ceramic. Ceramic materials have many advantages compared to metals: they are more resistant to abrasion, can operate at higher temperatures and do not suffer from corrosion. Open ceramic materials are the most suitable option for volumetric receiver temperatures above 800 °C (Behar et al., 2013; Dietrich et al., 2010, 2014). Open-cell porous ceramics are a highly porous material, with porosities typically in the range of 75–90% and possessing solid network structures (Dietrich et al., 2010, 2014; Fischedick et al., 2015). These ceramics have a uniform cell distribution, high specific surface area, low relative density, low pressure drop and good radial mixing (Regulski et al., 2015; Dietrich et al., 2009). Given these characteristics, open-cell porous ceramics are an ideal material to serve as the absorbing material of a volumetric receiver. Therefore, in order to optimize the thermal efficiency of a volumetric receiver and improve its design, a thorough study of the radiative characteristics of porous ceramics is an important first step.

Currently, there are three main methods for investigating the radiation characteristics of porous ceramics: classical independent scattering theory prediction, Monte Carlo simulation and spectrometric measurements. Classical independent scattering theory assumes that all particles (struts and strut junctures) are randomly distributed and oriented within the porous ceramic volume, allowing the radiative properties to be calculated by adding the

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individual contributions of all particles in a volume (Baillis et al., 1999, 2000; Doermann and Sacadura, 1996; Randrianalisoa and Baillis, 2014). Hsu and Howell (1992) considered the porous ceramic as randomly distributed, independently scattered spherical particles with cell diameter (D), where a correlation only depended on cell diameter and porosity to describe the Rosseland extinction coefficient. Baillis et al. (1999, 2000), Doermann and Sacadura (1996) assumed that porous ceramic cells are composed of randomly oriented struts and strut junctures, and computed the radiative properties by using a combination of geometric optics and diffraction theory. Loretz et al. (2008) calculated the radiative properties using different assumptions of the structure (e.g., different cell shapes and strut cross-sections), then compared the results of each assumption with experimental results from spectrometric measurements.

The Monte Carlo method is very suitable for calculating the attenuation of thermal radiation in complex structures, and the radiative properties can be calculated using the actual structure of the material. Parthasarathy et al. (2012) applied the RTMC method to the porous structure obtained from μ-CT images to calculate the equivalent extinction coefficient and scattering phase function. With this method, the influence of structure and surface reflectivity on the scattering phase function is also important. Cunsolo et al. (2015) applied the RTMC method to calculate the extinction coefficient of metal foam using the material's real microstructure and a computer-generated foam structure, and found good agreement when they compared the results from the different foam structures.

Compared with the above two methods, spectrometric measurement is simpler and faster, and does not require significant computational effort. Dietrich et al. (2014) used Fourier transform infrared spectroscopy (FTIR) to investigate the spectral transmittance of porous ceramics with different cell densities and porosities, then calculated the spectral extinction coefficient of a foam ceramic using Beer's law. The group also proposed a correlation for calculating the Rosseland extinction coefficient related to the window diameter and porosity. Zhao et al. (2004) used FTIR to investigate the spectral transmittance of the porous metal FeCrAlY, which has a porosity of 95% but with different cell densities. Loretz et al. (2008) put forward a fast and simplified method to estimate the extinction coefficient of metal foams by processing 3D computerized tomography (CT-scan) images. The advantage of this method is that the extinction coefficient can be determined without any assumptions of the microstructure. The method is also applicable for determining the extinction coefficient of other porous materials.

The purpose of this paper is to investigate the radiative heat transfer mechanism of open-cell porous ceramic through physical experiments. Porous ceramics are considered a semi-transparent medium capable of absorbing, emitting and scattering thermal radiation. In order to determine the extinction coefficient of such materials, we use FTIR to measure the spectral transmittance at different infrared wavelengths ranging from 2.5 to 25 μm. The geometric parameters (window diameter) of the ceramic foam are measured by microscopy. We also analyze the effect of material geometry on the radiation characteristics of the materials and propose two reliable correlations to calculate the extinction coefficient using geometry parameters.

2. Radiative heat transfer theory

To describe radiative heat transfer inside an opaque medium, we must solve the radiative heat transfer equation in conjunction with the energy conservation equation. However, the strict form of the radiative heat transfer equation is seldom used due to its complexity. Instead, the so-called Rosseland equation is often used to describe radiative heat transfer inside an opaque material by considering its optical thickness medium (Glicksman et al., 1987; Kuhn et al., 1992; Caps et al., 1997)

$$\lambda_{radiation} = \frac{16 \cdot \sigma \cdot T^3}{3 \cdot E_R} \tag{1}$$

where $\lambda_{radiation}$ is the radiative thermal conductivity, σ is the Stefan–Boltzmann constant and E_R is the Rosseland extinction coefficient, where E_R can be defined by

$$E_R^{-1} = \left[\int_0^\infty \frac{1}{E_\lambda} \cdot \frac{\mathrm{d}I_\lambda(T)}{\mathrm{d}T} \cdot \mathrm{d}\lambda\right] \cdot \left[\int_0^\infty \frac{\mathrm{d}I_\lambda(T)}{\mathrm{d}T} \cdot \mathrm{d}\lambda\right]^{-1} \tag{2}$$

Here, E_λ is the spectral extinction coefficient, which represents the decay rate of the radiation intensity passing through the material, I_λ is the spectral radiative intensity of a black body and λ is the wavelength of the radiation.

When a spectral radiative intensity I_λ is incident on a volume element of thickness dS, its intensity is reduced by absorption and scattering. By considering this reduction, we can instead define the spectral extinction coefficient E_λ using

$$\mathrm{d}I_\lambda = -E_\lambda(S) I_\lambda \mathrm{d}S \tag{3}$$

According to the Lambert-Bell law, the relationship between the spectral extinction coefficient and the radiative intensity can be expressed as

$$\int_{I_\lambda(0)}^{I_\lambda(S)} \frac{\mathrm{d}I_\lambda}{I_\lambda} = \int_0^S E_\lambda(s)\mathrm{d}s \tag{4}$$

If the material is homogeneous and isotropic, then E_λ is an intrinsic parameter of the material, and Eq. (4) can be simplified to

$$E_\lambda = -\ln(\tau_\lambda)/L \tag{5}$$

where L is the thickness of the sample and τ_λ the spectral transmittance defined as $\tau_\lambda = I_\lambda(L)/I_\lambda(0)$.

3. Experimental

Silicon carbide foam ceramics are used as volumetric absorbing materials in many research articles. Compared with silicon carbide foam ceramic, alumina foam ceramic has a higher melting point (Al_2O_3: 2000 °C, SiC: 1500 °C) (Behar et al., 2013), also with great application potential as volumetric absorbing material. An absorber using a porous ceramic material was designed by the University of Colorado, and later built by Sandia and tested on the test bed at the PSA. The porous ceramic absorber was made up of 92% alumina with 80% porosity and 20 ppi (Behar et al., 2013). In order to investigate the influence of different materials on extinction coefficient, we use zirconia foam ceramic for comparison. Alumina and zirconia porous ceramics with different cell densities (10, 20 and 30 ppi) and porosities (75–90%) were experimental investigated in this study. A total of 16 different porous ceramic samples were selected for transmittance experiments. The ceramic materials and cell densities are shown in Table 1.

3.1. Pore size

A photograph of a typical ceramic sponge made of alumina is shown in Fig. 1(a). From the image, we can see that the porous ceramic is composed of a number of open cells, the reason for the material having such a high porosity. Cell diameter is an important geometry parameter when predicting the extinction coefficient of a material, as it characterizes the free path of the thermal radiation inside the porous ceramic. However, the diameter of a cell is difficult to determine accurately. Instead, Dietrich et al. (2014) introduced a different parameter to characterize the