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Effect of foam properties on radiative properties of open-cell silicon carbide foams

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ABSTRACT

Low density and small-cell size foams can be used in thermal protection and/or thermal insulation systems. At high temperature (> 1000 K) thermal radiation may be important or dominate heat transfer in the foam; however, studies based on more detailed thermal radiation analysis are limited due to the lack of detailed information on radiative properties of foams. Of particular interest of this study is to understand how the properties of foam material such as its density and mean cell size affect the radiative properties of silicon carbide (SiC) foams. In this paper, the dimensionless strut diameter is considered as an important parameter of foams, and the radiative properties of foams are analyzed using the Mie scattering theory. Also, the spectral extinction coefficients of SiC foams are measured experimentally in the laboratory at room temperature. The mean radiative properties are calculated at 1000 K and compared with theoretical calculations, and the data are found to agree well with the predictions. The attenuation/extinction behavior of SiC foams can be characterized by the approach presented in this study. The results should be useful for applications of foams at high temperature.

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1. Introduction

Ceramic, silicon carbide, and other open foams have been used in high temperature thermal protection systems owing to their high melting points, low effective thermal conductivities and low densities. The surface temperatures of a space shuttle orbiter, for example, can reach as high as 1922 K (3000 °F) due to aerothermal heating [1]. Ceramic matrix composites (CMC, C/SiC, ACC, and SiC/SiC) can provide good specific strength to meet the requirements of thermal insulation/protection systems. Heat transfer through foams is by conduction through the foam solid skeletons and across gas-filled voids, and thermal radiation. The morphological properties of foams affect significantly radiative heat transfer in the foams.

Experimental and theoretical studies of extinction coefficient (absorption + scattering) and scattering albedo, which affect the radiant energy transport in the media, have been performed and can be found in the literature [2–5]. A common approach that is widely employed by researchers is to use Fourier Transform Infrared Spectrometer (FTIR) to measure the transmittance of foam samples and then to determine the extinction coefficient via Beer's law [2–4]. The radiative thermal conductivity is calculated based on the Rosseland approximation. Lu et al. [2] used a FTIR spectrometer to measure silica

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Nomenclature

a,b	Mie coefficients (dimensionless)
D_p	mean cell diameter (m)
D_{str}	mean strut diameter (m)
k	index of absorption (dimensionless)
n	index of reflection (dimensionless)
N	number particles per unit volume (#/m^3)
PPI	pores per inch
Q	efficiency (dimensionless)
w	dimensionless width of strut

Greek

β	extinction (absorption+scattering) coefficient (1/m)
λ	wavelength (μm)
ϕ	porosity (dimensionless)
χ	size parameter (dimensionless)
ω	scattering albedo (dimensionless)

Subscripts

a	absorption
s	scattering
ext	extinction
λ	spectral dependence

aerogels, which are considered nano-porous open-cell foams, in the spectral range from 2.5 μm to 40 μm. Tseng and Chu [3] and Tseng and Kuo [4] examined the extinction coefficients of high porosity closed-cell polystyrene (PS) foams with cell sizes ranging from 0.08 to 0.37 mm [3] and from 0.2 to 0.4 mm [4], respectively. Tseng and Chu [3] indicated that radiation heat transfer increases as the broken cell ratio (cell size) increases. Spectral extinction coefficients for different porosity PS foams were reported; however, there is a question about the extinction data reported by them, because the measured thickness of the foam sample was smaller than the mean cell size of the foam. Tseng and Kuo [4] reported that the average cell size was a function of foam density. But, the authors [3,4] did not discuss in their papers how the foam density and the mean cell size of the samples affect the mean extinction coefficient. Coquard et al. [5] experimentally studied the thermal and radiative properties of metal and ceramic foams via laser-flash measurements. The authors indicated that the radiative behavior depended significantly on the wavelength considered, and the behavior was mostly influenced by the cell size and the density of the foam. Also, they noted that global/scaled radiative properties are to be used for the entire wavelength range of interest instead of numerous spectral values for the simplification of calculations. A scaled extinction coefficient, scattering albedo, and scattering phase function are sufficient to characterize the interaction of the material with thermal radiation [5].

Most theoretical studies of the thermal and radiative properties of foams are based on a polyhedron cell model to create a simple geometrical shape of a cell to simulate the real foam cell. Doermann and Sacadura [6] employed a unit cell (dodecahedron model) for theoretical study of the radiative properties of carbon foams. The authors noted that heat transfer occurs by conduction through solid and gas phases, and radiation through the gas phase. Attenuation of thermal radiation occurs via scattering and absorption at the junction of the foam cells. In the model, two types of particles are used to make up the foams: strut and strut junctures [6]. However, they did not show a comparison of the model predictions with experimental data. A cubic unit cell model for evaluating the effective thermal conductivity and mean extinction coefficient of open-cell foams was provided by Dulnev as cited by Kamiuto [7]. Predictions of the extinction coefficients of foams based on Dulnev's model do not appear to agree well with our experimental data. Thus, a better model for the prediction of the extinction coefficient of foams is needed to characterize the attenuation behavior in different densities and cell size foams.

The purpose of this paper is to understand radiative properties of SiC foams in order to assess the selection of foams to be used for high temperature applications. The focus of the study is to determine how the foam properties, such as density, PPI (number of pores per inch), and material, affect the radiative properties based on electromagnetic (EM) theory approach. This information is important for effectively controlling radiative heat flux through foams for thermal protection or insulation purposes.

2. Analysis

Foams contain solid skeletons and voids and are considered as porous media. Since we only consider low density ($<20\%$) and small mean cell size (>40 PPI) SiC foams, we assume that the foam is homogeneous and isotropic. Some authors [3,4] expressed the extinction coefficient of foams as a function of mean cell size, but we believe that the extinction coefficient of foams cannot be a function only of the mean cell size alone. The ligaments of the foam absorb and scatter radiation and provide the pathways for heat to be conducted. This is consistent with the statement of Doermann and Sacadura [6]. Thus, the dimensionless strut diameter D_{str}/D_p of foams is considered to be a major parameter in the analysis, and it is estimated based on the polyhedron cell model. The average cell size is smaller than 0.6 mm for a foam having PPI larger than 40. Thus, we assume that the cell shape has little influence on the radiative properties for low density small-cell foams. In addition, the cubic cell is the simplest shape of cell for analyzing the problem. The dimensionless

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