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# Thermal radiation in subwavelength aluminum foam structures by finite-difference time-domain method

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ABSTRACT

We investigated the thermal radiation properties of subwavelength aluminum foam structures in this work. A Maxwell's equation solution (Finite-Difference Time-Domain) method was used to numerically calculate spectral thermal radiation in subwavelength foam structures. Due to the complexity of the real foam structures, we started our researches by investigating two periodic structures (linear and staggered foam structures) with cubic representative elementary volume. Different number of layers from 1 to 5 has been studied. The cavity resonances that enhanced the absorption coefficient of the incident wave energy were clearly observed. The results also showed that the radiation properties of staggered foam structures can be affected by the polarization angle at normal incidence. Additionally, the absorption ratio of every layer of the foam structures has been studied. Finally, cavity resonance also can be clearly seen at oblique incidence. This work will provide an accurate validation result for the study of radiative transfer in subwavelength foam structures using the methods based on radiative transfer equation or geometrical optics in future.



## 1. Introduction

The advantages of foams lie on their low-density, high strength structure and large surface area in a limited volume [1]. There has been an increased interest on the investigation of thermal transport in metal foams due to its potential applications in many of the heat transfer research areas, such as firewalls [2], light-weight structures [3], impact/blast energy absorption systems [4], and compact heat exchangers [5]. These applications usually involve high temperatures. Hence, the radiative heat transfer becomes one of the essential thermal energy transport mechanisms of foams. The thermal radiation in cellular metallic foams which has been studied by many researchers in recent years [6–18], is a complex phenomenon. Zhao et al. [7] developed an analytical model to characterize the radiative transport process in highly porous, open-cell metal foams with idealized cellular morphologies. The contribution of reflectance to radiation can be as high as 50% and cannot be neglected. Zhao et al. [8] also measured the radiative transfer in FeCrAlY foams having high porosity (95%) and various cell sizes, produced via the sintering route. Hsu and Howell [9] measured the thermal conductivity and optical properties of highly porous partially stabilized zirconia and found that the extinction coefficient agrees well with the geometric optics limit prediction for pore size greater than 0.6 mm. Loretz et al. [10] developed a new method of scattering phase function determination, combining specular and diffuse phase functions, in order to take into account the real scattering behavior of the foam. Contento et al. [11] proposed a simplified analytical numerical method based

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**Nomenclature**

| | |
|---|---|
| $a$ | area of the monitor plane |
| $A$ | absorptance |
| $\mathbf{E}$ | electric field vector |
| $\mathbf{H}$ | magnetic field vector |
| $\mathbf{k}$ | wave vector |
| $L$ | outer side length of the elementary cell |
| $l$ | inner side length of the elementary cell |
| $\hat{n}$ | complex refractive index, $\hat{n}=n+i\kappa$ |
| $p$ | power |
| P-polarization | parallel polarization |
| $R$ | reflectance |
| S-polarization | vertical polarization |
| $\mathbf{S}$ | Poynting vector |
| $T$ | transmittance |
| $X$, $Y$, or $Z$ | $X$, $Y$, or $Z$ axis in the Cartesian coordinate system |

*Greek Symbols*

| | |
|---|---|
| $\alpha$ | absorption ratio |
| $\varepsilon$ | relative (electric) permittivity or dielectric function |
| $\varepsilon_0$ | permittivity of vacuum |
| $\kappa$ | imaginary part of $\hat{n}$ |
| $\lambda$ | wavelength |
| $\mu$ | relative (magnetic) permeability |
| $\mu_0$ | permeability of vacuum |
| $\theta$ | incidence angle |
| $\psi$ | polarization angle |
| $\phi$ | azimuthal angle |

*Superscripts*

| | |
|---|---|
| \widehat | complex variable |
| $*$ | complex conjugate |

*Subscripts*

| | |
|---|---|
| $i$ | the $i$th layer |
| inc | incidence |
| $r$ | the reflective monitor plane |
| $t$ | the transmitted monitor plane |

on ray-tracing Monte Carlo method model radiation heat transfer in metallic foams. Coquard et al. [12,13] computed the spectral extinction coefficient, scattering albedo and scattering phase function for varying cell shapes and porosities of extruded and expanded foams. They [14] also proposed a rather comprehensive modeling of the radiative properties of Al–NiP foam samples using both X-ray tomographies to depict the porous architecture and stereoscopic micrographs.

So far, previous works mainly depend on two methods of investigation of the radiative properties of foam structures. The former is the experimental measurement [8,9]. The latter is the geometric optics (GO) approximation [9,11,14]. Considering the experiments of subwavelength structures require high cost and the GO approximation can only be applied as foam cell sizes are much greater than incident wavelength, a more accurate numerical method for subwavelength foam structures should be developed. However, to the best of our knowledge, no research based on rigorous solution of electromagnetic wave movement using Maxwell's equations has been published, due to the complicated foam microstructures and consuming computation time.

This work is the first ever to investigate the special thermal radiation in subwavelength foam structures by a Maxwell's equation solution method: Finite-Difference Time-Domain (FDTD). Due to the complexity of the real foam structures, we started our researches by investigating two periodic structures (linear and staggered foam structures) with cubic representative elementary volume. Different number of layers from 1 to 5 has been numerically researched. Furthermore, the effect of the polarization of the incident wave (parallel ($P$) and vertical ($S$) polarizations) has also been considered in detail. Finally, the absorption ratio $\alpha_i$ of the $i$th layer of foam structures has been studied. This work can provide an accurate validation result for the study of radiative transfer in subwavelength foam structures using the methods based on radiative transfer equation or geometrical optics in future.

## 2. Geometry description and theoretical formulation

### 2.1. Geometry

The main purpose of this work is to investigate the thermal radiation in subwavelength aluminum foam structures in detail. Indeed, the foam structures are almost always complex with randomly oriented- cells. However, the cells in one foam structure are mostly homogeneous in size and shape, which can be assumed as a periodic structure with simplified cubic representative elementary volume as mentioned in Ref. [7]. Hence, we assumed the elementary cell as shown in Fig. 1(a). $L$ ($=1$ μm) and $l$ ($=0.7$ μm) represents the outer and inner side length, respectively. This 3D elementary cell has the same geometric parameters (i.e., $L$ and $l$) in the $X$, $Y$, and $Z$ directions. Due to the complexity of the real foam structures, two different simplified models were considered: one is the linear foam structure as shown in Fig. 1(b), while the other is the staggered foam structure as shown in Fig. 1(c). In the present study, the whole structures are made of aluminum, and the optical constants are adopted from Ref. [19]. Fig. 1(d) shows the the plane of incidence and polarization. A wavevector $\mathbf{k}_{\mathbf{inc}}$ represents the electromagnetic wave with a free-space wavelength $\lambda$ incident onto the foam structure at an incidence angle $\theta$, polarization angle $\psi$, and azimuthal angle $\phi$. The incidence angle $\theta$ denotes the angle between $\mathbf{k}_{\mathbf{inc}}$ and the surface normal of the structure (i.e., –$X$ direction). The angle $\psi$ between electric field