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Determination of radiative properties of representative and real open cell foam structures using the finite volume method

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ABSTRACT

In the present work, a numerical model is developed to determine radiative properties of a few idealized open cell structures, namely, Dul'nev's unit cell, Viskanta's unit cell and cubic unit cell. A parametric study is carried out to investigate the effect of porosity, pore density and surface reflectivity on radiative properties of the porous structures. The developed 3-D numerical model is also applied to estimate radiative properties of actual foam structures that are obtained using CT scan. The proposed model is based on the information of solid and fluid voxels and a Cartesian coordinate based blocked-off region approach integrated with the finite volume method is used to solve the radiative transfer equation. It is shown that the periodic boundary condition with a specular reflection approach applied to an unit cell can mimic a complete porous structure with multiple cells. The ranges of extinction coefficient and scattering albedo predicted using present numerical model fall within the expected limits.

1. Introduction

The attractive properties of open cell foams like high porosity, high surface area to volume ratio and high tortuosity enhance the heat transfer as well as flow mixing capability. The metallic and ceramic foams are versatile media for high-temperature applications such as volumetric solar absorber [1], porous media combustion [2], porous radiant burners [3] and fire barriers [4]. Radiative heat transfer is inevitable at such high-temperature applications. Efficiency and effectiveness of the systems that incorporate porous media for heat transfer enhancement can be improved if thermal properties of the porous media such as extinction coefficient (β), scattering albedo (ω), and scattering phase function (Φ) are known beforehand. A lot of work has been done in the past few decades to estimate the radiative properties of the porous structures.

Kuhn et al. [5] considered pentagonal dodecahedrons to represent morphology of the expanded polystyrene and polyurethane foams. The struts of the foams were described as infinitely long cylinder, and the randomly oriented platelets were considered to represent the cell walls. The radiative properties of the foams were determined using Mie scattering theory and geometric optics. Doermann and Sacadura [6] used a combination of geometric optics and diffraction theory to determine spectral absorption and scattering coefficients as well as phase function of the open cell carbon foam. The radiative properties determined are function of porosity, morphology of the foam, dimensions of the struts, thermal properties of the involved phases, and spectral hemispherical reflectivity of the struts. The geometric data required in the above study can be obtained from microscopic analyses, but the spectral hemispherical reflectivity ρ_λ is very problematic to get directly. Baillis et al. [7] proposed an identification model to predict $\rho_{\lambda,}$ along with the spectral radiative properties of the carbon foams by integrating an identification method with the experimentally measured bidirectional spectral transmittance data. A few other identification methods which are based on integration of reference measurements with the radiation transfer model are presented by Hale and Bohn [8], Hendricks and Howell [9,10], and Baillis and Sacadura [11].

Tancrez and Taine [12] developed a Monte Carlo based model to predict continuum-scale radiative properties of sets of overlapping spheres. The extinction, absorption, and scattering coefficients of the continuous medium are determined by identifying the corresponding probabilities from the local treatment of the porous medium. The model is subsequently applied to actual structure of mullite foam [13] and experimental validation of the same is reported in Ref. [14]. Coquard et al. [15] used an alternate Monte Carlo ray tracing method where absorption, scattering, and extinction coefficients are defined as inverse of mean free path lengths. The model is validated by comparing predicted values of hemispherical transmittance and reflectance with the experimentally measured values. Cunsolo et al. [16] highlighted that for Beerian media, both Monte Carlo formulations, proposed by Taine and co-workers [12–14] and Coquard et al. [15], are equivalent. The

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model based on mean extinction path length [15] was later extended to determine radiative properties of irregular cell solid foams, represented by Voronoi structure [16], actual structure of Al-NiP foams [17] and Nickel foams [18].

Loretz et al. [19] proposed a novel approach where extinction coefficient of the foam is determined directly from its CT scan images. According to this incremental projection approach, slice-by-slice CT scan images are placed on top of each other to find the area covered by the fluid pixels of all these stacked slices while seeing from the top. The transmissivity ττ is calculated from the ratio of area covered by these fluid pixels to the total cross-sectional area. This is then used in the Beer's law to predict extinction coefficient of the porous medium. Mendes et al. [21] later used this approach to predict extinction coefficient of Al_2O_3 ceramic foams.

Fu et al. [21] proposed a zonal method based unit cell model to estimate extinction coefficient and scattering albedo of spherical voided cubic cell porous media. The analytically obtained effective reflectance and transmittance were used in the inverse algorithm to determine radiative properties of the considered structure. The scattering effect present in this model depends on the reflectivity of the material interface. With isotrpic scattering assumption, the estimated extinction coefficient and scattering albedo inherently take care the directionality of the scattering and hence these coefficients are termed as scaled extinction coefficient β^* and scaled scattering albedo ω^*. Following the work of Fu et al. [21], Patel and Talukdar [22] developed a unit cell model where an analytical approach to determine effective reflectance $\rho_{e,c}$ and transmittance $\tau_{e,c}$ of the unit cell using zonal method [21] was completely replaced by a 3-D numerical model. Compared to complete porous structure simulations, such unit cell models are computationally economical. In the numerical model of Patel and Talukdar [22], transverse windows which are parallel to direction of heat transfer were considered to be symmetric and a symmetry boundary condition was implemented by considering diffuse reflection of the incident radiation heat flux. It is expected that the unit cell with proper symmetry boundary condition is able to replicate the behavior of a porous structure with multiple unit cells in the transverse directions. However, it is noticed recently that the model does not completely mimic the results of a complete porous structure, although the results from this model compare quite well with the results of Fu et al. [21]. More issues with the model are discussed in section 2.2.1 and 3.1.3.

In the present work, the numerical model presented earlier [22] is modified by changing the symmetry boundary conditions of the transverse windows with periodic boundary conditions using specular reflection. The modified unit cell model is checked against the complete porous structure simulation of Dul'nev unit cell. The radiative properties of three representative unit cell structures, namely Dul'nev unit cell, Viskanta's unit cell and cubic unit cell, shown in Fig. 1, are determined. Such a comparison of radiative properties for different unit cells are not seen in the literature. To highlight the significance of modification incorporated in the present model, the radiative properties of the Viskanta's unit cell structure obtained using the present numerical model are compared with the unit cell model of Fu et al. [21]. Likewise, the present results for a cubic cell porous structure are compared with the work presented earlier [22]. The effect of porosity, pore density and surface reflectivity on radiative properties of the considered porous structures are investigated. The radiative property results of the unit cells is expected to serve as a bench mark data for future work. To show the versatility of the present numerical model, it is further extended to determine effective radiative properties of Al_2O_3 – ceramic foam structures obtained using CT-scan images.

2. Numerical model to determine radiative properties of porous structures

2.1. Representative unit cells and Al_2O_3 –ceramics foams

The unit cell based numerical model is developed to determine radiative properties of representative porous structures, namely Dul'nev unit cell, Viskanta's unit cell and cubic unit cell. Schematic diagrams of the unit cells mentioned above are shown in Fig. 1. The porosity of the unit cell structure varied in the range of 0.72–0.944. The pore density for the representative porous structure is defined in terms of pores per centimeter (PPC). In the present work, PPC of the idealized porous structure ranges from 1 to 8. The effects of porosity (ε), pore density (PPC), and surface reflectivity (ρ_s) on β^* and ω^* of the porous structure are investigated. In the present study, the surface reflectivity ρ_s ranges from 0.50 to 0.99.

The 3-D numerical model, developed in the present work, is extended to determine radiative properties of the Al_2O_3–ceramic foams obtained using CT scan images. The representative domain size chosen for these two ceramic foam samples is $L_r \approx 18$ mm which is several times larger than the pore diameter d_p. The foam sample 1 shown in Fig. 2(a) has been obtained from the foam having a porosity of 0.74, pore density of 10 pores per inch (PPI), and characteristic pore size d_p of 4 mm. The foam sample 2, shown in Fig. 2 (b), has a porosity of 0.79, PPI of 30, and pore dimension d_p of 2.8 mm. The CT-scan images have been obtained with a resolution of 65 μm. It was observed that some of the CT scan images are not containing proper voxel information. Such images are discarded for the radiative property calculation. The final dimension of both foam samples in X and Y direction is 18 mm whereas the size of the foam in the Z direction is 12 mm.

2.2. Methodology and numerical modelling

Fu et al. [21] proposed a unit cell based combined analytical-numerical model to predict radiative properties of the idealized porous structure. This model was divided into three essential steps. In the first step, effective reflectance ($\rho_{e,c}$) and transmittance ($\tau_{e,c}$) of an idealized

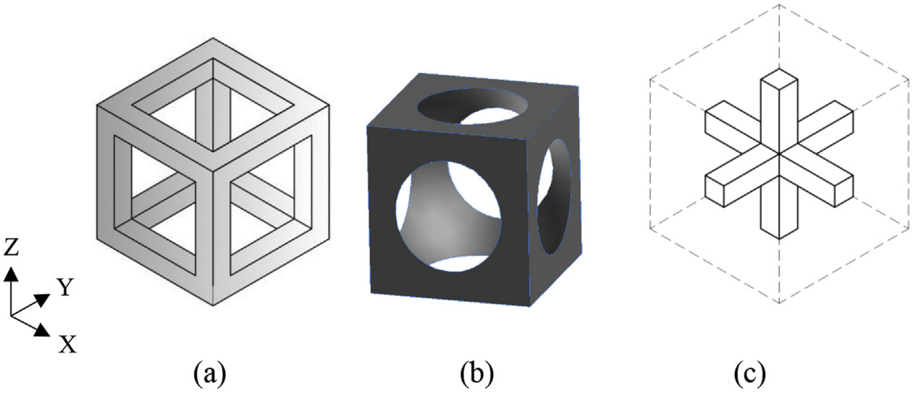

Fig. 1. (a) Dulnev's unit cell (b) Viskanta's unit cell and (c) cubic unit cell.