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# Evaluation of radiative properties of a representative foam structure using blocked-off region approach integrated with finite volume method

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ABSTRACT

A Finite Volume Method (FVM) based numerical model is developed to determine radiative properties of unit cell porous structure that represents a ceramic/metallic foam. Blocked-off region approach is used to model an idealized unit cell structure. Effective reflectance and transmittance of a unit cell are obtained numerically using FVM. Recurrence relationship is then used to determine effective reflectance and effective transmittance between layers of porous cells. Based on these values of reflectance and transmittance, the radiative properties, i.e. the extinction coefficient and the scattering albedo are calculated for an equivalent homogeneous porous media. Genetic algorithm is used to predict these properties using an inverse analysis. Developed model is validated using the previously published results and its accuracy is found satisfactory. Effect of solid reflectivity, porosity and pore density on radiative properties of open cell porous structure are also studied. It is observed that extinction coefficient increases with increase in solid reflectivity and decrease in porosity. Similarly, scattering albedo also increases with increase in solid reflectivity. No significant variation of scattering albedo is observed with porosity.



## 1. Introduction

Porous media e.g., metallic foams and ceramic foams (Fig. 1) plays vital role in various industrial applications such as light-weight structures [1], impact/blast energy absorption systems [2], sound absorbers [3], compact heat exchangers [4], electromagnetic wave shields, porous radiant burners [5] and fire barriers [6]. This multi functionality of foams is attributed to their attractive thermo-mechanical properties like light weight and high strength, high surface area to volume ratio, high porosity, ability to mix passing fluid, low apparent thermal conductivity and many more.

Among the various applications of foams, its usefulness and utility for high temperature applications is seen to be promising and versatile. The three main areas of interests in this direction are porous media combustion [7], fire barriers [8] and enhancement of heat transfer with porous insert [9–11]. Other important application of the foam as a convection to radiation converted (C-R-C) is in designing of compact and efficient heat exchangers. The heat absorbed by absorbing channel walls can be utilized in other industrial processes. As seen, a wide variety of engineering systems involve semi-transparent media, like porous materials and notably foams. Radiative heat transfer is inevitable at such high temperature applications. Heat transfer modelling becomes inaccurate without the proper knowledge of the material radiative property data. The modelling of radiative transfer is of primary importance for the prediction and optimization of the performance of porous media. Accurate modelling of radiative heat transfer in a porous medium requires the knowledge of their radiative properties, extinction coefficient ($\beta$), scattering albedo ($\omega$) and scattering phase function ($\Phi$) appearing in the radiative transfer equation (RTE). The directional dependency of the scattered radiation depends upon the nature of the scattering phase function. If radiation is equally scattered in all the directions, then the scattering phase function of the participating media can considered as unity. It is important to estimate these properties ($\beta$, $\omega$ and $\Phi$) accurately in order to perform numerical modelling with better reliability and accuracy and a lot of work has been done in the past few decades.

In order to develop an accurate model to study transport phenomena through porous media, a more precise approach is to generate actual foam structure. The effective radiative properties of foam greatly depend on its morphology [12]. Based on structural

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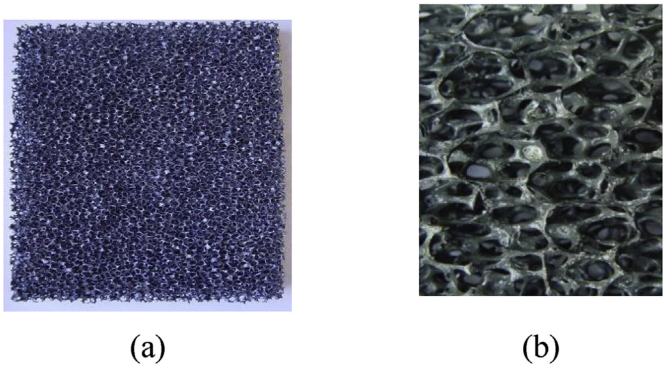


**Fig. 1.** **(a)** Ceramics foam **(b)** magnified view.

configuration, foams can be broadly categorized as open cell and closed cell structures. Accuracy of determined radiative properties, based on detailed model, relies upon accurate modelling of the foam structures. For this, X-ray tomography technique enjoys popularity [13–18], as it is capable to produce actual foam structure. However, detailed simulation on such complex structures requires important computational resources and time. Another relatively simple and less time consuming approach is to first determine the thermo-physical and radiative properties of the porous media from the simulations performed at the pore level. Then, subsequently, the obtained radiative properties of porous media are used in volume averaged equations which are derived based on homogeneous porous media assumption. Further, computational time and complexities involved can be reduced by assuming porous medium as an idealized simple structure [8,14,19–29] instead of considering actual porous structure [13–18]. A good compromise between the computational resources and accuracy of results can be achieved in this way [28]. Talukdar et al. [28] used blocked-off region approach [30–32] to model porous structure as cubic unit cell composed of rectangular struts and cubic lump as shown in Fig. 2. However, their study was limited to determination of effective thermal conductivity considering coupled conduction-radiation modes of heat transfer. No effort was made previously to determine the radiative properties for such regular porous structure.

Methods to determine radiative properties of porous media are thoroughly reviewed in literature [33–35]. Most of the published work on the determination of radiative properties of porous media can be classified into four major categories. (i) Porous media are assumed as a random distribution of particles of idealized shape. Radiative properties of media are determined using Mie scattering theory or geometric optics laws [14,20–22]. (ii) Monte Carlo simulation is carried out at microscopic level of given porous structure [13,16,36,37]. While using this approach, care must be taken to consider sufficient number of rays, so that the results are not affected by ray effect. However, application of Monte-Carlo method to actual porous geometry obtained using tomography, demands huge computational resources [15]. (iii) Methods based on identification of parameters where experimentally measured or numerically calculated data are used as a reference value to estimate radiative properties of porous media using some kind of inverse method. This approach is used by many researchers [14,22,24,38–49]. (iv) Recently, a new approach to determine extinction coefficient of actual porous media using tomographic image technique is proposed [15–17]. It calculates transmissivity from the area covered by fluid pixels out of the total cross sectional area. From the calculated transmissivity, extinction coefficient can be calculated using Beer's law. This approach to determine extinction coefficient fails when porous media are assumed to be an idealized structure as aforementioned approach will give porosity in that case. Moreover, scattering albedo with anisotropy effect of the porous media cannot be calculated using the image processing technique.

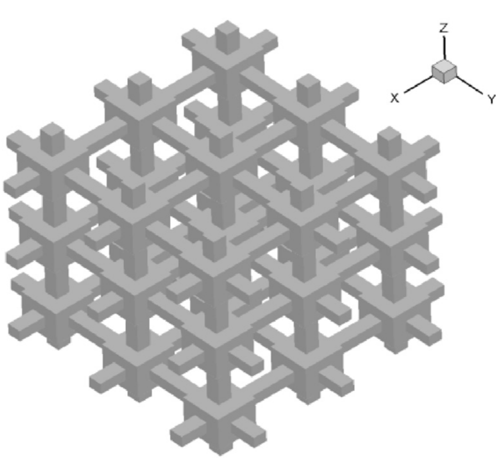


**Fig. 2.** Schematic of representative cubic unit cell with lump.

In the present study, two different kinds of cubic unit cell structures, with and without lump, are considered. The porosities of both unit cells are maintained identical to compare the effect of presence of the lump. Although the present study focuses on a regular unit cell structure, the developed model can be applied for complex foam structures too. The Finite Volume Method (FVM) proposed by Chai and Patankar [50] is applied to solve the standard RTE in a 3D cubic unit cell. As the solid phase is assumed to be opaque, the transmissivity of the struts is zero. Hence, depending on the absorptivity of the solid matrix, some portion of the thermal radiation is absorbed and the remainder is reflected equally in all directions. From the converged solution, effective reflectance and transmittance of a cubic unit cell are determined. These data are then used to predict the absorption and scattering coefficient of an equivalent homogeneous porous media. Genetic algorithm (GA) is used to optimize the parameters, absorption and scattering coefficient. The RTE for the homogeneous media too is solved with a 1D code based on FVM. The variation of effective radiative properties of open cell foam with solid material reflectivity, porosity and pore density in terms of pores per centimetre (PPC) are identified.

This work makes an effort to predict the radiative properties of a cubic unit cell using a new methodology. In it, the blocked-off region approach is integrated with FVM to calculate transmissivity and reflectivity of a porous medium. Radiative properties of a 1D homogeneous porous medium are then estimated by coupling FVM radiation code with GA using inverse method.

## 2. Problem formulation and solution methodology

### 2.1. Unit cells

The internal morphology of an open cell porous structure revealed that it consists of struts and lump at the junction of struts. Depending on manufacturing process, size of the lump can be neglected. In present work, two simplified representative cubic unit cells are considered. They only differ by presence of lump at the junction of struts. Schematic diagrams of these unit cell with and without lump are shown in Fig. 3(a) and (b), respectively. The Porosity of both the unit cells are maintained identical so that effect of presence of lump on radiative properties is possible to check. As a result, struts dimension of unit cell with lump is lesser than that of