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Detailed and simplified models for evaluation of effective thermal conductivity of open-cell porous foams at high temperatures in presence of thermal radiation

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A B S T R A C T

Simulations of coupled conduction–radiation heat transfer through open-cell porous foams have been performed in this article in order to evaluate the effective thermal conductivity (ETC) at high temperatures due to combined effects. For this purpose, the complex structure of foams has been generated using the knowledge obtained from 3D Computer Tomography (CT)-scan images and both detailed and simplified homogeneous modes have been employed during the present investigation. For detailed models, in addition to the energy conservation equation, the radiative transfer equation has been solved in order to obtain the distribution of radiation intensity using the blocked-off region approach, which can handle the voxel information acquired from the CT-scan data. Proposed simplified models, on the other hand, are based on homogenization approach and the performance of these simplified models has been compared with the reference model in terms of their accuracy. Simplified models mainly require information about the ETC due to pure conduction calculated from detailed 3D simulation and the extinction coefficient estimated from the CT-scan data using the image processing technique. Extensive parametric study has been conducted and the analysis of results show that ETCs estimated from the simplified models reasonably agree with those obtained from the most accurate model, depending upon the chosen value of extinction coefficient.

1. Introduction

Developmental efforts on producing varieties of ceramic foams have increased significantly in the recent years due to their ever-increasing applications in numerous technological fields. The unique structural properties, such as large surface area to volume ratio of metal/ceramic foams (porous media), makes it very useful for many industrial applications, especially where heat transfer is of primary concern. In this respect, the evaluation of effective thermal conductivity (henceforth will be referred to as the ETC, throughout the paper) of porous foams has become a major requirement for accurate prediction of heat transfer behaviour of many systems, such as heat exchangers, thermal insulators or combustion systems, to name a few. The complex morphology of foam structures plays an important role in the heat transfer characteristics and consequently, the ETC can be quite different for different foams, even with same porosity. If the heat transfer takes place at a high temperature, the ETC has a larger contribution from thermal radiation and hence an accurate modelling of radiation heat transfer becomes inevitable.

Unfortunately, however, the morphology of porous media is generally quite complex and resolving these structures with a numerical model has always been a challenging task. Available literature on modelling of heat transfer through porous foams can be divided broadly into two categories, (i) a detailed model, considering the complex structure of the foam up to a certain resolution and (ii) use of a homogeneous model with effective thermo-physical and optical properties, calculated using some form of correlations or directly measured from experiments. Nowadays, a wide variety of approaches can be found under these two main classifications, which are discussed in the following paragraphs.

As far as detailed models are concerned, since actual foam structures are quite complex in nature, several researchers attempted to synthetically generate some equivalent regular structures that can reasonably approximate real foams for the purpose of heat transfer simulations. As reported in the literature, ceramic and metallic foam structures can be represented, for example, with cubic [1,2], dodecahedral or tetrakaidecahedral structures. It was

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Nomenclature

G	incident radiation, W/m^2
I	radiation intensity, W/m^2 sr
k	thermal conductivity, W/m K
L	length, m
$q, \vec{q}$	heat flux, heat flux vector, W/m^2
$\vec{r}$	position vector, m
s	distance along the direction of radiation intensity, m
$\hat{s}$	direction vector for radiation intensity
S	source function, W/m^3
T	temperature, K
x, y, z	cartesian coordinates, m

Greek symbols

β	extinction coefficient, 1/m
ΔT	temperature difference between hot and cold boundaries
ε	emissivity
ϕ	azimuthal angle, rad
Φ	scattering phase function
κ	absorption coefficient, 1/m
θ	polar angle, rad
Θ	scattering angle, rad
ρ	reflectivity
σ	Stefan–Boltzmann constant = 5.67×10^{-8} W/m^2 K^4
σ_s	scattering coefficient, 1/m
τ	transmissivity
ω	scattering albedo
Ω	solid angle, sr

Subscripts

av	average
b	blackbody
c	cold
C	conductive
eff	effective
f	fluid
h	hot
max	maximum
min	minimum
r	representative
R	radiative
s	solid

Abbreviations

ETC	effective thermal conductivity
FVM	finite volume method

observed that dodecahedral and tetrakaidecahedral structures [1] could reasonably represent ceramic or metallic foams if some of the global properties, like porosity, pore density (pores per inch, in short, ppi), etc., are maintained. Kuhn et al. [3] used infinitely long and randomly oriented cylinders in order to describe struts of polyurethane foams. The unit cell was assumed as a pentagonal dodecahedron and triangular strut cross-sections were converted into their circular counterparts with the same geometric mean cross-sectional area. However, it was later realised on from the Computer Tomography (CT)-scan images that cells are not only made of pentagonal dodecahedron shapes but also tetrakaidecahedral cells do exist. Subsequently, it was confirmed by Dillard et al. [4] who showed that the most representative cells in polyurethane foams contain 12 faces. Most of the faces of their foams were pentagonal (57%) with the presence of considerable fractions of quadrilateral (17.6%) as well as hexagonal (21.6%) faces. Nevertheless, in terms of modelling effort, the construction of grid for these idealised structures, although not simple, is relatively easier than that for the actual foam structures.

In recent days, however, owing mainly to the availability of three-dimensional (3D) CT-scan imaging, researchers have started developing models using the real structural data of foams in digitised form. Although these geometric models are more accurate and hence realistic than modelled representative regular structures, they suffer from the requirement of significantly larger computational efforts. For example, regarding radiation heat transfer, Monte Carlo simulations [5] with these 3D CT-scan data could be computationally quite expensive for simulating these foams in practical applications. On the other hand, in order to simulate conduction heat transfer, although detailed simulations can be performed for small foam samples [6–8], in general, its modelling for significantly larger practical applications is also prohibitive and, to some extent, unjustified owing to the requirement of excessive computational time.

Homogeneous models, those use effective properties of porous media, can prove to be good alternatives for saving computational effort. However, the main limitation with these models is to obtain the required properties in an accurate manner; in particular, the ETC due to conduction–radiation and other optical properties, like, extinction coefficient, scattering albedo and scattering phase function. Experiments are the common practice for the evaluation of these properties. Substantial amount of investigations regarding radiative properties [9–14] and the ETC due to pure conduction [15,16] have been reported in the literature along with their measured values. Monte-Carlo ray-tracings simulation is an attractive alternative for numerical evaluation of radiative properties and has been used by several researchers using the 3D CT-scan data for generating the true geometry of foam [17–20]. For example, in the work of Parthasarathy et al. [20], a ray-tracing Monte-Carlo simulation was presented. In their study, the computational grid was reconstructed from 3D CT-scan images and Magnetic Resonance Image (MRI)-scans of different reticulated porous media. A ray-tracing algorithm was adopted in order to track rays inside the grid structure. Statistically large number of rays was traced for their path-lengths and incident angles those were subsequently used for the determination of probability-based equivalent extinction coefficient and scattering phase function for various porous media with different porosities and pore densities.

Loretz et al. [21] discussed numerical methods for the determination of extinction coefficient along with its experimental measurements and reported reasonably good agreement between modelled predictions and the experimental data. Based on certain combination of pentagonal dodecahedral and/or tetrakaidecahedral cells, they subsequently proposed a relation for the extinction coefficient as a function of porosity and average cell diameter. Another new method was also proposed in their study, where extinction coefficients were determined based on the slice-by-slice superposition of 3D CT-scan images. They finally concluded that this new method, being quite easy to implement and computationally far less time consuming, also provides reasonable results since the method uses actual structure of foams in the form of 3D digitised data.