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Radiative properties modeling of open cell solid foam: Review and new analytical law

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A B S T R A C T

In recent years, a number of analytical and numerical models have been dedicated to characterization of radiative properties of open-cell foams. In the current study, a review of different numerical and analytical methods is proposed, explaining the methodologies and evidencing the common points, limits and assumptions. Numerical methodologies are firstly applied to sets of spherical particles and compared with benchmark exact analytical solution. In a second step 3D Voronoi open cell foams are generated, the various methods analyzed are tested and compared. Some attention is dedicated to the evaluation of effects due to varying degrees of irregularity in the structure and ligament. Finally, a new analytical law is proposed to determine radiative extinction coefficient of 3D Voronoi open cell foam without significant additional computational effort. This relation is expected to be useful for preliminary optimization/design purposes.

1. Introduction

Cellular foams are a key material for many energy-engineering applications. Their high porosity (or low relative density) and large specific area play an important role from the thermal point of view. For example, high porosity closed cell polymer foams are used as efficient insulating materials [1–7]. Open-cell solid foams can be designed to have very low up to high values of thermal conductivity, depending on the conductivity of the solid [8–11]. Thus, they are employed in a variety of energy related applications, such as volumetric solar energy receivers for CSP plants [12], compact heat exchangers [13], porous radiant burners [14,15] and fire barriers [16,17]. Accurate modeling of thermal properties is obviously highly desirable for the optimization of the performance in these applications. Considering the high porosity (typically in a range from 85% up to 98%), radiative heat transfer contribution can be significant, and in some cases even prevalent over other heat transfer modes. For this reason, a large number of analytical and numerical models have been dedicated to characterization of radiative heat transfer in open-cell solid foams. Most studies focus on determining appropriate equivalent continuous medium properties.

General lines on the use of the Radiative Transfer Equation (RTE) can be found for example in textbooks [18–21]. Various authors have developed specific adaptations of RTE for dispersed media, such as the Multi Phase Approach (MPA) [22–24] and the Dependence Included Discrete Ordinates Method (DIDOM) [25]. However, RTE is usually considered sufficiently accurate for most practical cases, if the relevant coefficients (radiative properties) are correctly determined [23,26,27].

As such, most of the literature has been focused on finding efficient and reliable ways to determine radiative properties. An overview of radiative properties determination for porous media can be found in the monograph by Dombrovsky and Baillis [21]. Reviews dealing with radiative properties of highly porous foams can be found in Refs. [28] and [29].

The radiative properties may be theoretically predicted and/or identified from directional/hemispherical transmittance/reflectance measurements [30–34], often employing the Fourier Transform Infrared (FTIR) method.

The large number of analytical models available in literature mostly refers to independent scattering in randomly dispersed media [35]. High porosity foams are modeled as a random dispersion of particles, whose contributions are summed up to obtain the effective radiative properties. This approach, originally proposed by

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Nomenclature

Latin symbols

$f_c(\varepsilon)$	extinction coefficient correction function
g	phase function asymmetry factor
$G(s)$	cumulative free path distribution function
G	area projected by a single scatterer
$I_\lambda(r,\theta)$	spectral radiation intensity (W/m sr)
$I_\lambda^b(T)$	spectral blackbody radiation intensity (W/m sr)
$I^b(T)$	global blackbody radiation intensity (W/sr)
k_r	radiative conductivity (W/m K)
n	refractive index
M	grid resolution of projection
N	total number of rays cast
N_v	number of scatterers per unit volume (m^{-3})
r	position vector (m)
R^2	coefficient of determination
s	path length (m)
s_{avg}	average path length (m)
s_n	path length of the n-th realization (m)
S_r	extinction coefficient correction factor
S_v	specific surface area (m^{-1})
$S_{v,f}$	specific surface area per unit volume fluid (m^{-1})
$W(\mu)$	distribution function of scattering angle cosines
$f_c(\varepsilon)$	extinction coefficient correction function

Greek symbols

β	extinction coefficient (m^{-1})
β_I	extinction coefficient – least squares fitting (m^{-1})
β_{II}	extinction coefficient – inverse average length (m^{-1})
β_c	corrected extinction coefficient ($units^{-1}$)
β_{an}	extinction coefficient – analytical ($units^{-1}$)
β_{num}	extinction coefficient – numerical ($units^{-1}$)
β_λ^*	spectral extinction coefficient adjusted for anisotropic scattering (m^{-1})
β_R^*	Rosseland mean extinction coefficient (m^{-1})
δ	Dirac delta function
ε	porosity
κ	absorption coefficient (m^{-1})
λ	wavelength (m)
σ	scattering coefficient (m^{-1})
μ	scattering angle cosine
μ_n	scattering angle cosine of the n-th realization
$\Phi(\mu)$	scattering phase function
ρ_s	solid surface reflectivity
ω	scattering albedo

Glicksman et al. [30], who modeled the foam as a set of dodecahedral cells, was also followed by Placido et al. [2] for polymer closed foam, and Baillis et al. [36,37] for open cell carbon foams. Coquard et al. [38] and Loretz et al. [39] extended these results by considering models with different cells and strut shapes.

Independent scattering approaches remain largely prevalent in literature, probably thanks to their comparative simplicity. A typical limitation of these studies is the difficulty to account for shadowing effects. Independent scattering approaches also typically require the knowledge of a number of geometrical parameters of the foam, such as the strut diameter or cell size, which are difficult to determine univocally, because of the intrinsically random quality of the real foam structures.

To overcome these limitations, alternative numerical methods have been developed and, thanks to increasing computational power, have lately gained large popularity. In particular, numerical methods based on Monte Carlo techniques for the determination of radiative properties are becoming very popular in order to study either real structures obtained from tomographic imaging or computer generated structures that closely mimic the microstructure of the real foams.

Tancrez and Taine [40] proposed to use the Radiative Distribution Function Identification (RDFI) model and determined radiative properties of spherical packed beds. Zeghondy et al. [34,41] and Petrasch et al. [42] applied the RDFI approach to tomographic data. Coquard et al. [43–45] proposed to use an alternative Monte Carlo approach based on mean free path calculation.

In addition to Monte Carlo methods, some alternative numerical methods have been presented in literature. Most notably, Loretz et al. [46] presented a geometric approach to rapidly calculate extinction coefficient from open cell foam tomographic data.

Techniques based on tomographic data provide satisfactory agreement with experimental data, but their dependence on high quality scans of existing foam samples makes them of limited utility for design purposes. Some recent studies have sought to overcome these limitations by digitally reproducing the foam structures using different approaches, including mathematical morphology operations applied on existing tomography data [47,48], simulation of the bubbling process [49], regular [50,51] and irregular [52,53] Voronoi partitions. By computer generating a number of structures and running numerical simulations [47,48,53] it is possible to obtain useful results for the optimization of energy transfer. Irregular 3D Voronoi structures seem to be particularly promising for this purpose as they replicate the structures of real foam pretty well [54].

In the current paper, a special emphasis is put on the predictive models of radiative properties of cellular foams with open cells and high porosities ($\varepsilon > 85\%$). In the light of the state of the art, a representative selection of numerical and analytical methods is presented in a comparative fashion, focusing on their similarities and differences, their strong points, limits and assumptions.

Subsequently, the methods are numerically compared. First, sets of spherical geometries are generated. For such geometries, an exact analytical solution exists [40] that can be used as a benchmark to evaluate the numerical methodologies. 3D Voronoi open cell structures are also considered, to provide a more realistic representation of the foam. Structures with two different degrees of irregularity and two different ligament shapes (circular and triangular) are considered. The various methods analyzed are tested and compared. Based on the results obtained, guidelines are proposed to allow optimal choice of the numerical method. Additionally, some corrections to commonly used analytical relations are proposed, that should improve their accuracy without significant additional computational effort. This new relation should provide useful guidance for preliminary optimization/design tasks.

2. Radiative properties modeling

Porous media such as foams are usually considered as equivalent continuum media and the Radiative Transfer Equation (RTE) can be used [18–20]: