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Radiative properties of irregular open cell solid foams

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ABSTRACT

In recent years, Monte Carlo numerical methods have increased utilization to characterize the radiative properties of open cell solid foams. A great interest has been also observed in recent literature in methodologies to digitally generate foam-like structures to be used in Monte Carlo simulations. These approaches enable researchers to overcome the limitations of studies based on tomographic data. In this work, a novel methodology for generation of foam-like structures is presented. The method is based upon Voronoi partitions with random seeding points, combined with Surface Evolver to obtain a more realistic cell structure. The detailed geometrical characteristics of the struts are taken into account. The generated structures can be created to compare well to real tomographic samples. A number of characteristics of the resulting structure can be controlled. The application of Monte Carlo simulations to the generated structures allows the precise evaluation of each parameter' influence on the extinction coefficient. This in turn makes it possible to propose some simplified analytical correlations. The correlations are validated against Monte Carlo simulations on tomographic data and compared with existing reference relations from literature. Finally, simplified forms of the relations are proposed.

1. Introduction

Cellular foams are a key material for many technological applications. Their high porosity (or low relative density) and large specific surface 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 [1–4]. Metal or ceramic foams are being employed in a variety of high temperature applications, such as volumetric solar energy receivers for CSP plants [5], compact heat exchangers [6], porous radiant burners [7,8] and fire barriers [9]. 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 [10]. For this reason, a large number of analytical and numerical approaches have been dedicated to the characterization of radiative heat transfer in cellular solid foams. Most studies focus on determining appropriate equivalent continuous medium properties.

Specifically focusing on radiation, the current baseline state-of-the-art approach is based on the utilization of the Radiative Transfer Equation (RTE). General lines on the usage of RTE for radiative transfer can be found for example in textbooks [11–14]. While alternative approaches exist, the RTE approach is usually considered sufficiently accurate for most practical cases, if the relevant coefficients (radiative properties) are correctly determined [15–17].

As such, most of the literature has been focused on finding efficient and reliable ways to determine radiative properties [18–20]. In recent years, numerical methods based on Monte Carlo techniques for the determination of radiative properties are becoming established in order to study either real structures obtained from tomographic imaging [47,48] or computer generated structures that closely mimic the microstructure of the real foams.

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Nomenclature

Latin symbols

CV	Coefficient of variation of cell diameter
d	Local strut diameter, m
d_c	Cell diameter (equivalent sphere), m
$d_{c,G}$	Cell diameter (equivalent dodecahedron), m
d_i	Strut cross section incircle diameter
$d_{j,max}$	Strut junction maximum diameter, m
d_{max}	Maximum strut diameter, m
d_{min}	Minimum strut diameter, m
d_o	Strut cross section circumcircle diameter, m
g	Phase function asymmetry factor
I/I_0	Unextincted fraction of radiation
k	Normalized curvature
l	Strut length, local abscissa, m
L	Total strut length, m
N	Number of rays
p_{avg}	Mean free path, m
p_n	Free path of the n-th ray, m
S_s	Strut cross section surface, m^2
S_v	Specific surface area, m^{-1}
t	Diameter ratio

Greek symbols

β	Extinction coefficient, m^{-1}
β^+	Nondimensional extinction coefficient
ε	Porosity
$\Phi(\mu)$	Scattering phase function
ρ_s	Solid surface reflectivity
σ_{d_c}	Standard deviation of cell diameter, m
ω	Scattering albedo

Tancrez and Taine [21] proposed to use the Radiative Distribution Function Identification (RDFI) model and determined radiative properties of spherical packed beds. Zeghondy et al. [22,23] and Petrasch et al. [24] applied the RDFI approach to tomographic data of cellular foam samples. Coquard et al. [25–27] proposed to use an alternative Monte Carlo approach based on mean free path calculation. Cunsolo et al. [28] recently presented a review including an extensive discussion of numerical methods, including Monte Carlo techniques.

Techniques fully 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. To overcome these limitations, a number of recent studies have sought to digitally reproduce the foam structures using different approaches, including mathematical morphology operations applied on existing tomography data [29,30], simulation of the bubbling process [31], regular [32,33] and irregular [34,35] Voronoi partitions. By computer generating a number of structures and running numerical simulations [29,30,35] 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 can be described with a limited amount of parameters, are based on well-known generation methods and approximate the structures of real foam reasonably well [36].

In the current paper, a novel methodology is presented that allows the generation of polygonal mesh to represent high porosity open cell foams with high control of a number of geometrical parameters. The methodology is subsequently applied systematically with individually varying parameters to generate a number of structures. The generated structures are introduced into a Monte Carlo algorithm for the calculation of radiative properties, and especially of the extinction coefficient, β. For each structure, the specific surface area S_v and porosity ε are also calculated, and the normalized extinction coefficient $\beta^+ = 4\beta{\cdot}\varepsilon/S_v$ [21] is deduced. This procedure makes it possible to determine which parameters have a significant effect on the extinction coefficient and which parameters have a negligible effect, thus defining the inputs required to calculate the extinction coefficient with a given accuracy. Based on this assessment, new analytical relations are given that fit the numerical results with a minimum number of parameters and with more accuracy than those usually used in the literature. These relations are expected to be useful for material design purposes.

2. Methodology

2.1. Digital generation methodology

2.1.1. Digital generation methodology - presentation

In the present work, a methodology is proposed that makes it possible to generate realistic foam structures. The methodology involves the generation of a pseudo-random lattice of seeding points, the generation of a Voronoi diagram of these points, the stabilization of the resulting cell structure in Surface Evolver [37], the addition of polygonal struts along the resulting skeleton, and finally the virtual welding of the polygonal struts at their intersections through a shrink-wrapping [38] process. While similar generation methods based on Voronoi diagrams have already been presented in literature [28,34,35], the current approach does present some distinct features, specifically the use of Surface Evolver and the capability to directly generate intersection-free triangular meshes.

The process requires initially generating a number of seeding points. The corresponding final structure will be a periodic structure containing as many cells as initial seeding points. For this study, a number of 128 initial seeding points, corresponding to a 128 cell final structure has been used. This number of cells ensures convergence of Monte Carlo algorithms [28] and allows for the creation of a cubic Kelvin foam (see section 3) with a whole number of Kelvin periodic units (made up by 2 cells). The points are generated with a Random Sequential Absorption algorithm [39] that drops equal-sized spheres into space, enforcing non-overlapping condition, with a final packing density around 30%, the centers of the spheres being used as the seeding point. This serves to insure a minimum distance between any two seeding points (Fig. 1).

The periodic 3D Voronoi diagram of the seeding points is then generated. The Voronoi diagram partitions the space in polyhedral regions, one for each seeding point. Every point of a given region is closer to that region's seed than to any other seed. The resulting data structure is adapted into a Surface Evolver input file. Treating the structure with Surface Evolver makes it possible to achieve two results:

- The resulting structure is an energetically stable structure rather than just a random structure, that which should make it more realistic.