C. R. Physique 15 (2014) 683–695

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Liquid and solid foams / Mousses liquides et solides

Thermal conductive and radiative properties of solid foams: Traditional and recent advanced modelling approaches

Propriétés thermiques conductives et radiatives des mousses solides : Approches de modélisation traditionnelles et avancées

Jaona Randrianalisoa [a,*], Dominique Baillis [b,**]

[a] *GRESPI, Université de Reims, EA 4694, Campus Moulin de la Housse, BP 1039, 51687 Reims cedex 2, France*
[b] *LaMCoS, INSA-Lyon, UMR CNRS 5259, 18-20, rue des Sciences, 69621 Villeurbanne cedex, France*

ARTICLE INFO

Article history:
Available online 6 October 2014

Keywords:
Metallic foams
Ceramic foams
Polymer foams
Cellular materials
Voronoi tessellation
Laguerre–Voronoi tessellation

Mots-clés :
Mousses métalliques
Mousses céramiques
Mousses polymères
Matériaux cellulaires
Mosaïque de Voronoï
Mosaïque de Voronoï–Laguerre

ABSTRACT

The current paper presents an overview of traditional and recent models for predicting the thermal properties of solid foams with open- and closed-cells. Their effective thermal conductivity has been determined analytically by empirical or thermal-resistance-network-based models. Radiative properties crucial to obtain the radiative conductivity have been determined analytically by models based on the independent scattering theory. Powerful models combine three-dimensional (3D) foam modelling (by X-ray tomography, Voronoi tessellation method, etc.) and numerical solution of transport equations. The finite-element method (FEM) has been used to compute thermal conductivity due to solid network for which the computation cost remains reasonable. The effective conductivity can be determined from FEM results combined with the conductivity due to the fluid, which can be accurately evaluated by a simple formula for air or weakly conducting gas. The finite volume method seems well appropriate for solving the thermal problem in both the solid and fluid phases. The ray-tracing Monte Carlo method constitutes the powerful model for radiative properties. Finally, 3D image analysis of foams is useful to determine topological information needed to feed analytical thermal and radiative properties models.

RÉSUMÉ

Cet article présente une vue globale des modèles traditionnels et récents de prédiction des propriétés thermiques et radiatives des mousses solides ayant des cellules ouvertes ou fermées. Leur conductivité thermique effective est déterminée par des modèles empiriques ou analytiques basés sur le réseau de résistances. Les propriétés radiatives nécessaires pour remonter à la conductivité radiative sont déterminées par des modèles analytiques basés sur la théorie de diffusion indépendante. Les approches robustes couplent la modélisation tridimensionnelle (3D) de mousses (par exemple, par la tomographie à rayons X, la mosaïque de Voronoï, etc.) et la résolution numérique des équations de transport. La conductivité thermique due à la phase solide est directement calculée par la méthode des éléments finis (EF), avec un coût de calcul raisonnable. La conductivité

* Corresponding author. Fax: +33 3 26 91 32 51.
** Corresponding author. Fax: +33 4 72 43 89 13.
E-mail addresses: jaona.randrianalisoa@univ-reims.fr (J. Randrianalisoa), dominique.baillis@insa-lyon.fr (D. Baillis).

http://dx.doi.org/10.1016/j.crhy.2014.09.002

thermique effective, quant à elle, peut être déterminée à partir des calculs EF combinés avec la conductivité thermique due à la phase fluide. Cette dernière peut être évaluée de façon précise par des formules simples dans le cas de l'air ou d'un gaz faiblement conducteur thermique. Cependant, la méthode des volumes finis apparaît la mieux appropriée pour résoudre le problème thermique, à la fois dans la phase solide et la phase fluide. La méthode de Monte Carlo et de tracé de rayons constitue une approche solide pour calculer les propriétés radiatives. Enfin, la reconstruction d'image 3D des mousses est essentielle pour déterminer les informations topologiques nécessaires pour alimenter les modèles analytiques de conductivité thermique et de propriétés radiatives.

1. Introduction

Cellular foams are a key material for many engineering applications. Their high porosity (or low relative density) and their large specific area play an important role from the thermal point of view [1]. For example, high porosity polymer foams allow realizing efficient insulating materials [2–5]. High-porosity open-cell metallic foams attracted much attention for designing compact heat exchangers and heat sinks [6–8]. Metallic foams filled with phase change materials offer a possibility for heat energy storage applications [9,10]. Thanks to the good resistance to high temperatures and strong chemical corrosion resistance of open-cell ceramic foams, they have been used as combustion support for porous burners [11–15], as catalyst support [16,17], and as volumetric absorbers in solar thermal and thermochemical reactors [18–20]. In all of these examples, the better knowledge of the foam thermal properties is of primary importance. They include thermal conductivity, radiative properties and convection exchange coefficient.

Heat transfer within highly porous cellular materials in the absence of forced fluid flow is essentially due to conductive and radiative heat transfers. Indeed, convective heat transfer within the fluid phase can be neglected since the usual size of the pores is sufficiently small, avoiding the natural convective flow to be significant. The conductive heat transfer may occur through the solid network, by lattice vibration and by charged particles, and through the fluid, by molecular interactions. The radiative heat transfer is by electromagnetic radiation exchanged between solid walls or struts. The combined conductive and radiative heat transfers in cellular materials for most of thermal applications can be characterized by an overall thermal conductivity, expressed as the sum of conduction and radiation contributions,

$$k^*_{\mathrm{tot}} = k^*_{\mathrm{rad}} + k^*_{\mathrm{cond}} \tag{1}$$

where k^*_{rad} and k^*_{cond} refer respectively to radiative conductivity and effective thermal conductivity. The later comes from heat conduction in solid and fluid phases of the foams.

In this paper, we present a survey of the literature describing the state-of-the-art on the modelling of thermal conductive and radiative properties of solid foam materials. Discussion about the thermal convection properties is out of the scope of this work and can be found elsewhere (e.g., in [21,22]). A special attention is paid to recent studies attempting to understand the impact of microstructure on thermal properties of foams.

The paper is divided into four parts. The Section 2 talks about the effective thermal conductivity. The Section 3 focuses on thermal radiative conductivity and especially on radiative properties. The Section 4 discusses the existing models and ongoing challenges. And the last Section 5 is devoted to the conclusion.

2. Effective thermal conductivity

Several approaches have assumed the conductive heat transfers within two-phase systems as a superposition of non-interacting heat flows within the two phases. In this manner, the effective thermal conductivity of a foam material, k^*_{eff}, has been expressed as [23]:

$$k^*_{\mathrm{eff}} = k^*_{\mathrm{s}} + k^*_{\mathrm{f}} \tag{2}$$

The subscripts "s" and "f" refer respectively to the solid- and fluid-phase thermal conductivities. For cellular materials for which the pore size is about a hundred of micrometres or greater, and for weakly thermally conducting gas as fluid, the confined fluid thermal conductivity, k^*_{f}, can be estimated as:

$$k^*_{\mathrm{f}} = (1 - \rho^*) k_{\mathrm{f}} \tag{3}$$

In Eq. (3), k_{f} refers to the bulk conductivity of the gas, i.e. not influenced by the presence of the solid walls. At given pressure and temperature, k_{f} can be calculated using the kinetic theory for gases or deduced from tabulated data (e.g., those given in [24]).

Application of Eq. (3) to foams was initially suggested by Glicksman and Schuetz [23]. As shown in [25], measurements and computation based on finite-volume method (FVM) applied in the solid and fluid phases confirm the suitability of Eq. (3) for highly porous closed- and open-cell foams (porosity greater than 80%) with gas such as air as the fluid substance.