International Journal of Thermal Sciences 76 (2014) 147–154

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Prediction of radiative heat transfer in metallic foams

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ARTICLE INFO

Article history:
Received 1 August 2012
Received in revised form
30 July 2013
Accepted 2 September 2013
Available online 10 October 2013

Keywords:
Radiative heat transfer
Metallic foams
Modelling
Radiative conductivity
Porosity

ABSTRACT

A simplified analytical–numerical method to model radiation heat transfer in metallic foams is proposed. It modifies a model taken from the literature and allows to predict the radiative conductivity for high and low porosity foams. A simplified cubic representative elementary volume of the foam is assumed and radiative heat flux is evaluated by computing radiosities and view factors. The analytical approach proposed in this paper slightly modifies some coefficients of the original model. Test ray-tracing and numerical simulations based onto Monte Carlo method are carried out in order to consistently calculate some view factors. The comparison with experimental results shows that predictions of the proposed model are more accurate than those of the original one.

1. Introduction

Open-cell metallic foams are, now, being widely used in many industrial applications where heat transfer is important, such as compact heat exchangers [1], fire barriers [2] and volumetric absorbers in receivers of concentrator solar systems [3], because of their low density, high surface area per unit volume, high solid conductivity, and good flow-mixing capability [4]. In the mentioned applications an accurate knowledge of the thermal behaviour of the foam is essential. Moreover, these applications generally imply high temperatures and, thus, radiation heat transfer plays a significant role. Radiation heat transfer is complex because of absorption, emission and scattering of radiative energy by the solid phase, that closely depend not only on the porous structure of the material but also on the optical properties of the solid phase, which are hardly available at high temperature [5]. The radiative characteristics of porous media can be evaluated by analytical modelling and experimental approaches. The former seems to allow a better comprehension of the complex radiation heat transfer in a foam. Two are the most used modelling approaches: i) analytical models, that link the pore level geometry to the radiative continuum properties of an equivalent medium and, subsequently, solve the radiative transfer equation (RTE) at the continuum level; ii) direct pore level simulation of radiation heat transfer. The former involves either the use of theoretically determined radiative characteristics of porous media [6] or the use of experimental results available in the literature [7–9]. The latter implements porous media geometry either via analytical approximations [10,11] or using geometrical data from computer tomography [12–14]. Radiation in porous media can be approached, also, by the less used multilayer method [15]. In this method the material is assumed to behave like a multilayer system. The number, the thickness and the relevant physical properties of the subdivided layers could be chosen arbitrarily.

The most part of the analytical studies, dealing with radiation propagation in open-cell foams, are based on the Homogeneous Phase Approach (HPA). This approach implies that the radiative behaviour of a foam can be matched faithfully by an equivalent homogeneous semi-transparent emitting, absorbing and scattering medium. Baillis et al. [16] used the HPA to model radiative heat transfer in carbon foams for aeronautics and spatial thermal insulation. The authors used a combination of the geometric optics laws and of the diffraction theory to study foams constituted of randomly arranged struts with triangular cross-sections. The reflectivity of the material was identified by means of bi-directional transmittance measurements. Placido et al. [17] developed a geometrical cell model to predict the radiative and conductive properties of various types of insulation foams, such as expanded polystyrene, extruded polystyrene and polyurethane foams with different morphologic structures. Coquard et al. [18] proposed a

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http://dx.doi.org/10.1016/j.ijthermalsci.2013.09.001

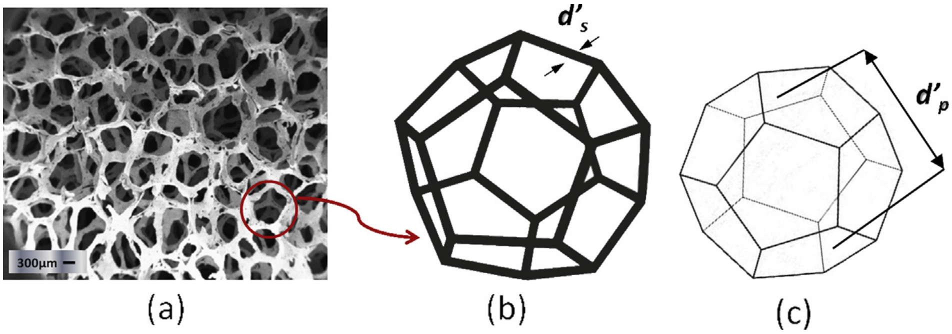

Fig. 1. Microstructure of a metal foam: a) SEM morphology; b) cell unit; c) corresponding pentagonal dodecahedric geometry.

new model to predict conductive and radiative coupled heat transfer in low-density EPS foams. The models used for the prediction of conductive and radiative properties tried to take into account as faithfully as possible the real morphology of EPS foams. Loretz et al. [19] reviewed analytical models of computation of radiative characteristics of foams for a wide variety of cells shapes and struts cross sections. The authors determined the model and the microstructure that best simulate the radiative behaviour of high porosity metal foams comparing predictions by the model to results of spectrometric measurements. The above cited model was used by Coquard et al. [20] for the prediction of coupled conductive and radiative heat transfer in metallic foams at fire temperature.

Another way for treating radiative transfer problems is the Multi-Phase Approach (MPA). Gusarov [21,22], Consalvi et al. [23] and Lipinski et al. [24,25] employed the MPA to investigate the radiative transfer in dispersed media of opaque and semi-transparent particles in a transparent or absorbing fluid substance. The principle of the MPA is to model the radiation transfer in the material using two different coupled transport equations, related to the fluid or solid phases. Gusarov also analyzed the radiative contribution to the thermal conductivity of composite media by the Chapman-Enskog expansion of a multiphase radiation transfer model [26]. Tancrez and Taine [27] developed a general method of direct identification of absorption and scattering coefficients and phase function of a porous medium by a Monte Carlo technique. Petrasch et al. [12] investigated theoretically the radiation heat transfer in reticulated porous ceramics using a Monte Carlo method applied to 3-D tomographic representations of the foam microstructure. Tomographic images were used also by Coquard et al. [28] to investigate the radiative properties of Al–NiP foams. Akolkar and Petrasch [29] employed a non-energy-partitioning Monte Carlo Ray Tracing (MCRT) model to optimize radiative transfer in porous media. Results were determined via a two-flux model of radiative transfer for an opaque, diffusely or specularly reflecting solid-phase within a non-participating void phase. Zeghondy et al. [30] proposed a Radiative Distribution Function Identification (RDFI) to obtain the extinction and absorption coefficients and bi-directional phase function of porous materials. Zhao et al. [31], instead, proposed a rather simple explicit analytical model, based on a discrete representation of foams and on the evaluation of radiosities. Radiation in open-cell metallic foams, in terms of emissivity, reflectivity and view factors, was described, using cells with ideal morphologies. The model assumed a simple cubic cell as Representative Elementary Volume (REV) and predicted the correct trend of the experimentally measured conductivity versus temperature curve, although the predicted conductivity was, in general, lower than that measured.

The model of Zhao et al. [31] was used by Andreozzi et al. [32] to evaluate the local radiative conductivity and the effects of radiation heat transfer in a two-dimensional conductive-convective-radiative problem involving a forced fluid flow within a heated channel filled with a metallic foam.

In the present paper, an analytical approach, based on a simplified version of the foam microstructure, has been chosen rather than numerical models requiring long and expensive X-ray tomography. In particular, with reference to open-cell metallic foams the present study improves the capability of the model proposed by Zhao et al. [31] to predict the values of the radiative conductivity for high and low porosity samples. Coefficients in the iteration model are recalculated and different assumptions are made to evaluate the involved view factors. When it is necessary, they are calculated numerically by methods based onto ray-tracing Monte Carlo method, more accurate than the Zhao et al.'s analytical approach. An iterative procedure is implemented by means of the software *Mathematica*, used to consistently calculate the view factors and coefficients. The radiative conductivity of foams is evaluated. Predictions are compared to both experimental results obtained on several metal foams by Zhao et al. [33] and computed results obtained using the model proposed by Zhao et al. [31].

The recalculated coefficients in the proposed model work better than those in the Zhao et al.'s model [31]. A more accurate evaluation of configurations factors between voids, by means of a numerical approach, was needed for foams with a porosity lower than 95%.

2. Radiation heat transfer model

2.1. Assumptions

The microstructure of a typical open cell metallic foam is currently assumed to be made up of ligaments that form a network of interconnected dodecahedric cells of characteristic size d'_p with roughly 12–14 pentagonal or hexagonal faces, as shown in Fig. 1. The cells are randomly orientated and mostly homogeneous in size and shape. The ligaments are composed by metal struts and lumps of solid material in their intersection points. The porous medium is characterized by the porosity, ϕ, and by the pore density that is referred to in Pores Per Inch, *PPI*, units. The geometry of the cross section of metal struts varies from a circular to a triangular shape in the $0.85 \div 0.94$ porosity range and from a triangular to an inner concave triangular shape in the $0.94 \div 0.98$ porosity range [34]. In the following, the effect of different cross section strut geometries on radiative conductivity is neglected, a circular section is assumed in all cases and reference is made to a d'_s diameter of cylindrical struts.

In order to simplify the modelling of the radiation heat transfer in this complex geometry, an open cell foam made up of uniformly distributed, equal-sized, cubic cells is assumed. In particular, reference is made to the s thick foam sample, sandwiched between