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The prediction of radiation heat transfer in open cell metal foams by a model based on the Lord Kelvin representation

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ABSTRACT

A theoretical approach proposed in the literature has been used to develop a new radiative heat transfer model based on the tetrakaidecahedric representation of open cell metal foams proposed by Lord Kelvin. The analytical approach has been combined with numerical simulations based onto ray-tracing Monte Carlo method. An iterative matrix algebra implemented procedure has been used to consistently calculate the coefficients involved in view factors. The radiative conductivity of foams has been evaluated by means of the proposed model. Predictions are compared both with experimental results from the literature, obtained on several metallic foams, and with predictions given by an existing simpler model based on a cubic representation of the foam unit cell. The agreement of experimental results with predictions derived by means of the proposed model is good and far better than that with predictions by the simpler model.

1. Introduction

The analysis of radiative heat transfer in open-cell metal foams is of fundamental importance to many engineering applications, such as compact heat exchangers, fire barriers and volumetric absorbers in receivers of concentrator solar systems [1–3]. So far, the number of published studies interested in thermal radiation in metallic or ceramic foams is relatively weak and rather uncollected [2,3]. On the contrary, thermal radiation in packed beds, polymeric foams and fibrous insulation has been extensively investigated both experimentally and numerically [2,4,5]. However, results of most of studies on packed beds and granular porous media are not applicable to metal foams because of their distinctive features, such as high porosities and a unique open-celled cellular structure [2].

The major difficulties in predicting radiative heat transfer in foams arise from the complexity of their architecture and from the inherent complexity associated with the transport mechanism. Different methods to determine the radiative characteristics of foams are answered to the literature [6,7]. Some of them consider the material as a dispersion of opaque particles of given shapes and use the Mie theory or the geometric optics laws [8,9]. Glicksman et al. [10] modeled the radiative heat transfer in cellular foams insulation by representing their structure as random arrangements of opaque struts with constant thickness forming regular dodecahedron cells. Considering the independent scattering hypothesis, the authors proposed an expression of the mean extinction coefficient as a function of the mean cell diameter and of the porosity. Kuhn et al. [11] employed infinitely long cylinders to model the struts and used Mie scattering calculations to predict the radiative characteristics. The model proposed by Doermann and Sacadura [8] improved the previous ones. The authors considered a particle modeling, obtained from the microscopic analysis of carbon open-cell foams, that was more representative of the actual geometry. Kaemmerlen et al. [12] used morphological data and optical properties of a bulk medium to model radiative heat transfer in extruded polystyrene foams (XPS). The radiative properties of XPS foams were determined by adding the contributions of each particle (walls and struts) using the independent scattering hypothesis. The key difference with previous studies was related to the morphological parameters, in particular reference was made to a concave triangle strut rather than the most used cylindrical strut. Loretz et al. [13] reviewed analytical models for the computation of radiative characteristics of foams for a wide variety of cells shapes and struts cross sections. The authors determined

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Nomenclature

a	distance between opposite body centered cubic nodes
A	irradiated surface area of a sphere
A_{bcc}	body centered cubic surface area
A_{Π}, A_{Ω}	void surface area
A_s	strut surface area
C_0	coefficient in Eq. (26)
C_1	coefficient in Eq. (26)
C_2	coefficient in Eq. (26)
C_3	coefficient in Eq. (26)
d	strut diameter
d_p	cell diameter
d_s	sphere diameter
d_w	hexagonal equivalent circle diameter
F_{st}	strut–strut view factor
$F_{s\Pi}$	strut–void view factor
$F_{\Pi\Omega}$	void–void view factor
$F_{\Pi s}$	void–strut view factor
$F_{st,\ av}$	average strut–strut view factor
$F_{S(dS)dA}$	view factor in Eq. (17)
$F_{S(dS)A}$	view factor in Eq. (18)
h	spherical cap height
i	plane number
$JA^{(i)}$	A void radiosity
$JB^{(i)}$	B void radiosity
$JC^{(i)}$	C void radiosity
$JD^{(i)}$	D void radiosity
$JE^{(i)}$	E void radiosity
k_r	radiative conductivity
l_s	strut length
l	void side length
n_i	nodes
N_p	number of cells along z
PPI	nominal pore density
q_r	heat flux
r_s	sphere radius
s	sample thickness
S	irradiating surface area of a sphere
T	temperature
x, y, z	cartesian coordinates

Greek letters

α_i, β_i, γ_i	coefficients in Eqs. (4)–(6)
ε	emissivity
ΔT	temperature difference
ρ	reflectivity
σ	Stephan–Boltzmann constant
φ	porosity

Subscripts

c	cold plate
eff	effective
h	hot plate
+, −	refer to the direction of the heat flux

Superscripts

i	i-th plane

the model and the microstructure that best simulate the radiative behaviour of high porosity metallic foams comparing predictions by the model with experimental results. The above cited model was used by Coquard et al. [14] in the prediction of coupled conductive and radiative heat transfer in metallic foams at high temperature.

Other researches made use of inverse methods based upon direct measurements of the reflectance and transmittance [15,16]. Hendricks and Howell [17] measured spectral hemispherical reflectance and transmittance in reticulated porous ceramics at room temperatures. Absorption, scattering coefficient and phase function were obtained by means of an inverse analysis and a discrete ordinates model, using measured data. Mital et al. [18] evaluated experimentally the radiative characteristics of cellular ceramics at high temperatures, that turned out to be practically independent of the temperature in the 1200–1400 K tested temperature range.

Another approach consists in realizing a ray tracing Monte Carlo simulation at the local scale [19]. Tancrez and Taine [20] developed a general method for the direct determination of absorption and scattering coefficients and phase function of a porous medium by a Monte Carlo technique. Petrasch et al. [21] investigated theoretically the radiation heat transfer in reticulated porous ceramics using a Monte Carlo method applied to the real structure reconstruction of the foam microstructure by X-ray tomography technique. However, Monte Carlo simulations in tomographed samples require a huge computational effort and should be restricted to the study of the detailed effect of the architecture. Tomographic images were used also by Coquard et al. [22] to investigate the radiative characteristics of Al–NiP foams. Akolkar and Petrasch [23] employed a non-energy-partitioning Monte Carlo Ray Tracing 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.

Zhao et al. [24], instead, proposed a rather simple explicit analytical model, based on a discrete representation of foams, in order to establish functional relationships between the cellular structure and the radiative transfer characteristics in terms of radiative conductivity of metal foams. Radiation in open cell metal foams was described, with reference to cells with ideal morphologies. The model assumed a simple cubic cell consisting of slider cylinders as the basic unit cell. The predicted effective radiative conductivities were compared with those measured in vacuum for FeCrAlY foams by Zhao et al. [25]. Results showed that the model predicted the correct trend of the experimentally measured conductivity versus temperature, although the predicted conductivity was, in general, lower than that measured. In order to improve the predictive capability of the Zhao's et al. model [24], Contento et al. [26] proposed a numerical approach to calculate view factors and coefficients different from those in [24]. The predicted radiative conductivity was lower than the measured one, likely because of the strong simplification in the description of the foam geometrical structure. The Zhao's et al. model was used by Andreozzi et al. [27] to evaluate the local radiative conductivity and the effects of radiative heat transfer in a two-dimensional conductive–convective–radiative problem involving a forced fluid flow within a heated channel filled with a metal foam.

In the present study the theoretical approach proposed by Zhao et al. [24] has been used to develop a new radiative heat transfer model based on a more realistic representation of open cell metal foams. The currently used tetrakaidecahedric TD geometry proposed by Lord Kelvin [28] has been chosen as the basic unit cell of the model. It allows to represent the foam as a body centred cubic nodal structure and can be considered a good compromise between the accuracy of the predictions and the simplicity of the