International Journal of Heat and Mass Transfer 127 (2018) 843–856

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Development of correlations for effective thermal conductivity of a tetrakaidecahedra structure in presence of combined conduction and radiation heat transfer

Vipul M. Patel [a], Miguel A.A. Mendes [b], Prabal Talukdar [a,*], Subhashis Ray [c,*]

[a] Department of Mechanical Engineering, Indian Institute of Technology Delhi, New Delhi 110016, India
[b] LAETA, IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
[c] Institute of Thermal Engineering, Technische Universität Bergakademie Freiberg, Germany

ARTICLE INFO

Article history:
Received 12 April 2018
Received in revised form 21 June 2018
Accepted 8 July 2018

Keywords:
Effective thermal conductivity
Radiative properties
Correlations
Porous media
Tetrakaidecahedra structure

ABSTRACT

The variations in the total effective thermal conductivity ($k_{eff,t}$) of a tetrakaidecahedra unit cell structure as functions of porosity (ϕ), thermal conductivity of the solid phase (k_s) and the average temperature of the medium (T_{avg}), in the presence of combined conduction and radiation heat transfer, are presented in this article. For this purpose, the governing energy conservation equation is numerically solved using the blocked-off region approach based on the finite volume method. In addition, the variations in the radiative properties of the structure as functions of surface reflectivity (ρ_s), pore density (PPC) and ϕ are investigated, for which, a pure radiation heat transfer based numerical model is developed and used. From the detailed numerical simulations, three different correlations for $k_{eff,t}$ are proposed. Correlation 1 is developed by fitting the raw simulated data, although its form does not respect some of the limiting conditions. Particularly for $k_s < 5$ W/mK and in the absence of thermal radiation, it under-predicts the effective thermal conductivity due to pure heat conduction ($k_{eff,PC}$). Correlation 2, on the other hand, satisfies all possible limiting conditions, although it requires one additional simulation or correlation for $k_{eff,PC}$. Finally, correlation 3 is obtained by superposing the effective thermal conductivities due to pure radiation ($k_{eff,R}$) and $k_{eff,PC}$, while introducing an adjustable coefficient in order to account for the coupling between them. From the investigation on radiative properties, it is observed that the extinction coefficient increases with the decrease in ϕ and with the increase in PPC as well as ρ_s and hence $k_{eff,t}$ as well as $k_{eff,R}$ is expected to decrease for these conditions.

1. Introduction

The improved thermal-hydraulic properties of open cell foams, such as low overall density, high specific surface area, moderately high effective thermal conductivity (ETC, or k_{eff}), considerably high tortuous flow path, allowing flow with comparatively lower pressure drop, attracts researchers to investigate their performance for various applications. Beforehand knowledge of the effective thermos-mechanical properties of porous foams allows the designer to improve the performance of systems that use them for different purposes. Some of the important applications of open cell porous foams may be identified as compact heat exchanger [1], fire retardants [2], radiant burner [3], convection to radiation converter (C-R-C) [4,5], porous media combustion [6], solar radiation absorber [7], etc. The study of fluid flow and heat transfer in porous media may be carried out using the simplified homogeneous medium approach (HMA), see e.g., [8,9,10]. However, the accuracy of the HMA extensively depends on the specified effective properties that appear in the considered averaged equations. For example, while analysing the convective heat transfer through porous media with the assumption of local thermal non equilibrium condition, an adequate knowledge of the interfacial/volumetric heat transfer coefficient is essential and the temperature distribution within the fluid-saturated porous media can be predicted with reasonable accuracy if the ETC is accurately known. For the high-temperature applications, the ETC of the porous media mainly depends on (i) thermal conductivity of the solid and the fluid phases, (ii) porosity, (iii) morphology of the porous structure, (iv) optical property of the solid surface, and (v) radiative properties of the involved phases.

The existing theoretical and empirical models for predicting the ETC of porous foams with various degrees of complexity have been

* Corresponding authors.
E-mail addresses: prabal@mech.iitd.ac.in, prabal.talukdar@gmail.com (P. Talukdar), ray@iwtt.tu-freiberg.de, juhp_sray@yahoo.co.in (S. Ray).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.048
0017-9310/

Nomenclature

a	parameters used for fitting A
A	coefficients in Eqs. (10) and (20); exponent in Eq. (16)
b	parameters used for fitting B
B	exponent in Eq. (10)
c	parameters used for fitting β
$\hat{e}$	unit vector
G	incident radiation (W/m^2)
I	radiation intensity (W/m^{2}sr)
k	thermal conductivity (W/mK)
L	length of the computational domain (m)
$\vec{q}$, q	heat flux (W/m^2)
$\vec{r}$	position vector (m)
$\hat{s}$	direction vector for radiation intensity
T	temperature (K)
x, y, z	Cartesian coordinates (m)

Greek symbols

α	absorptivity
β	extinction coefficient (m^{-1})
ΔT	temperature difference (K)
ε	emissivity
κ	absorption coefficient, (m^{-1})
ρ	reflectance; reflectivity
σ	Stefan Boltzmann constant ($= 5.67 \times 10^{-8}$W/m^{2}K^4); scattering coefficient, (m^{-1})
τ	transmittance
ϕ	porosity
Φ	scattering phase function
ω	scattering albedo
Ω	solid angle, (sr)

Subscripts

avg	average
b	blackbody
B, T	pertaining to 'Bottom' and 'Top' boundary
c	unit cell
e, eff	effective
E, W	pertaining to 'East' and 'West' boundary
f	fluid
$face$	solid-fluid interface
i	incident
n	number of layers
PC	due to pure conduction
R	due to pure radiation
s	solid; surface
t	total

Abbreviations

CV	control volume
GA	genetic algorithm
HPM	homogeneous participating medium
FVM	finite volume method
PPC	pores per centimetre
RTE	radiative transfer equation

thoroughly reviewed by Coquard and Baillis [11], Coquard et al. [12] and Ranut [13] and hence they are briefly summarised here for the sake of completeness. Based on these reviews, the available models may be categorised into three groups, namely, (i) asymptotic solutions, (ii) empirical correlations and (iii) unit cell approach [13].

Asymptotic solutions: In this approach, all models, forming two limiting bounds for the ETC, can be put together in the asymptotic expressions. For any pure heat conduction case, the solutions, based on the parallel and the series resistance models, most often form the upper and the lower bounds of the ETC, respectively. These bounds are also referred to as the Weiner bounds [14]. Quite obviously, the actual k_{eff} lies within these two limiting values. In comparison to these bounds, slightly restrictive bounds were proposed by Hashin and Shtrikman [15]. The expressions of these bounds may be mathematically shown to be equivalent to the Maxwell-Eucken models [16] which were derived in order to estimate the effective electrical conductivity of spheres, dispersed in a continuous phase. However, for the case of two-phase system, as considered by Maxwell [16], the dispersed phase never forms any continuous pathways and hence the estimated effective properties were found to be more biased towards the property of the continuous phase [17]. Carson et al. [17] used the effective medium theory (EMT) in order to calculate k_{eff} of the two-phase system, where the involved phases are randomly dispersed. The calculated k_{eff} was found to be 'unbiased' towards the thermal conductivities of the involved phases.

Empirical correlations: The simplified models, whose coefficients are determined by fitting the experimental data, are placed under the category of empirical correlations. For example, Calmidi and Mahajan [18] proposed a modified form of the parallel arrangement model in order to express k_{eff} of the metal foam. From the experimental data fit, the constant 'A' was found to be 0.181 and 0.195 for air and water as the working fluid, respectively. Bhattacharya et al. [19] used a combination of the series and the parallel arrangement models in order to estimate k_{eff} of the metal foam. The constant $A = 0.35$, obtained by fitting the experimental data, satisfied all data points for both air and water as the fluid medium. Singh and Kasana [20] used the experimental data of Bhattacharya et al. [19] and proposed a separate correlation by combining the series and the parallel arrangement models. The exponent 'F', appeared in the resultant expression, highlights the fraction of material oriented in the direction of heat flow. 'F' was further expressed as functions of the porosity ϕ and the ratio of thermal conductivities of the solid and the fluid phases (k_s/k_f). Dietrich et al. [21] proposed a serial combination of the parallel and the series bounds of k_{eff}. For this purpose, an empirical constant was evaluated by fitting the experimental measurements, carried out for alumina, Mullite, and OBSiC foams. They observed that for the same solid material, k_{eff} of the foam could be approximately five times higher than that observed for the packed bed. The experimental approaches, used in order to determine k_{eff} of the open cell porous foams, may appear to be simple, but they are definitely not straightforward, as discussed in some of the previous studies [22,23,24]. For example, the contact area between the sensor and the foam sample, selection of the sensor diameter and the contact pressures are some of the key parameters which significantly affect the measurements of k_{eff}.

Unit cell models: The representative unit cell based geometric or numerical models can be placed in this category. In the first category, i.e., in the *unit cell based geometric models*, in order to express the ETC of the porous foams as functions of the material properties and the porosity, different unit cell based geometric models were developed. For example, Calmidi and Mahajan [18]