International Journal of Heat and Mass Transfer 92 (2016) 539–549

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Thermal conductivity correlations of open-cell foams: Extension of Hashin–Shtrikman model and introduction of effective solid phase tortuosity

Prashant Kumar *, Frédéric Topin

IUSTI, CNRS UMR 7343, Aix-Marseille Université, Marseille, France

ARTICLE INFO

Article history:
Received 2 March 2015
Received in revised form 20 July 2015
Accepted 25 August 2015

Keywords:
Hashin–Shtrikman model
Effective solid phase tortuosity
Intrinsic solid phase thermal conductivity
Strut morphology

ABSTRACT

Open-cell foams have emerged as promising materials for use in heat sink and heat exchanger applications. The thermal behavior of open-cell foams depends on their microscopic structure. The effective thermal conductivity of open-cell porous foams can be measured using experimental techniques, predicted from the 3-D direct numerical simulations on reconstructed foam structures obtained from micro-computed tomography images or derived from idealized structure thermal analysis. Based on the tetrakaidecahedron unit cell and different strut morphologies, three dependent and interdependent empirical correlations for effective thermal conductivity were derived. They encompass all morphological parameters and ratios of constituent phases of foams of different materials.

In this process, the Hashin–Shtrikman (HS) bounds model was first extended and applied to the resistor model. A correlation term, Ω was introduced to take into account the thermal conductivities of constituent phases and the morphological parameters of the foam structure. Secondly, a more complex effective model that is a combination of series and parallel models was derived by introducing effective solid phase tortuosity. Lastly, a simple model (KT-model) was derived that can be used to predict either effective thermal conductivity or intrinsic solid phase conductivity depending upon which one of these quantities is known. The present study clearly demonstrates that the proposed empirical correlations yield extremely accurate estimates of the effective thermal conductivity for all the experimental and numerical data of different foam materials reported in the literature.

1. Introduction

In recent years, high porosity foam materials have attracted attention due to their low density and peculiar transport properties, which make them attractive for enhancing the thermal performances of heat transfer devices, while allowing the use of smaller and lighter equipment [1,2].

Accurate knowledge of thermal transport properties of open-cell foams is required in order to effectively utilize them in heat transfer applications. From a practical point of view, it is common to assimilate the foam to a homogeneous medium having an effective thermal conductivity (λ_{eff}), thereby effectively neglecting the detailed micro-scale effects of the porous structure [3].

The effective thermal conductivity of open-cell foams can be obtained either by measuring it directly with experimental techniques (e.g. [4–9]) or numerically calculating the value from simulations, considering the detailed morphology of porous media. With the development of 3-D image processing that can reconstruct the same structure as the original foam sample, many researchers nowadays have performed numerical simulations using the Lattice Boltzmann method (e.g. [10]), on commercial software or in-house code based on finite volume and finite element methods (e.g. [11–23]).

However, experiments or numerical approaches can be time consuming and depend on various factors like the intrinsic solid and fluid phase conductivities, morphology of foam structures, verification of local thermal equilibrium condition, boundary conditions, etc. Therefore, an alternative approach in the form of empirical correlations provides fairly straightforward expressions for quick and reasonably accurate estimations of the effective thermal conductivity thus presenting a wide range of applicability.

---

* Corresponding author at: 5, Rue Enrico Fermi, Technopole de Château Gombert, 13453 Marseille Cedex 13, France. Tel.: +33 (0) 04 91 10 68 36.

E-mail addresses: prashant.kumar@etu.univ-amu.fr (P. Kumar), frederic.topin@univ-amu.fr (F. Topin).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.08.085
0017-9310/

Nomenclature

Latin symbols

A/R	side length of strut shape/radius of strut shape (mm)
L_c	node-to-node length (mm)
L_s	strut length (mm)
M	adjustable parameter (Eq. (10), –)
N	adjustable parameter (Eq. (10), –)
R_{eq}	equivalent circular strut radius, mm
S	constant (Eq. (8), –)
S'	constant (Eq. (14), –)
S_T	effective solid tortuosity (Eq. (12), –)

Greek symbols

λ_s	intrinsic solid phase conductivity, W m^{-1} K^{-1}
λ_s^B	parent or bulk material conductivity, W m^{-1} K^{-1}
λ_f	fluid phase conductivity, W m^{-1} K^{-1}
λ_{eff}	effective thermal conductivity, W m^{-1} K^{-1}
$\lambda_{\text{parallel}}$	parallel thermal conductivity, W m^{-1} K^{-1}
λ_{series}	series thermal conductivity, W m^{-1} K^{-1}
$\lambda_{\text{HS,Upper}}$	HS upper bound thermal conductivity, W m^{-1} K^{-1} (Eq. (1))
$\lambda_{\text{HS,Lower}}$	HS lower bound thermal conductivity, W m^{-1} K^{-1} (Eq. (2))
ψ	dimensionless morphological parameter (Eq. (4), –)
ε_o	open porosity (–)
ε_n	nominal porosity (–)
Ω	correlation factor (Eq. (3), –)
α_{eq}	ratio of equivalent circular strut radius to node-to-node length (–)
β	ratio of strut length to node-to-node length (–)

Abbreviations

LTE	local thermal equilibrium
HS	Hashin–Shtrikman
KT	Kumar–Topin
µCT	micro-computed tomography
CFD	computational fluid dynamics

Subscript

eq	equivalent
c	circular
s	square
det	diamond (double equilateral triangle)
h	hexagon
st	star (regular hexagram)
rs	rotated square
rh	rotated hexagon

Various correlations have also been proposed in the literature based on the experimental and numerical results/values for effective thermal conductivity. Their advantage lies in the fact that empirical correlations are comparatively easy, fast, and inexpensive to use in comparison with individual studies of particular working fluids on a case to case basis on a 3-D reconstructed foam (by X-ray tomography, Voronoi tessellation method, etc.), numerical solutions of transport equations, or computational time. Various simplified models for predicting the effective thermal conductivity of open-cell foams can be found in the literature, and recent reviews have been presented by several researchers (e.g. [24–27]). Empirical correlations are very useful to investigate the influence of the morphological parameters of foams on their apparent thermal conductivity and give insight on how to optimise the thermal performances of various industrial components. The derivation of correlations reported in the literature can be classified in three ways: (1) from experiments [6–9]; (2) from numerical simulations (e.g. [26,18–21]; (3) from congregate data of the literature (e.g. [28–33])).

Effective thermal conductivity correlations described in the literature are based either on the asymptotic bound approach (e.g. [29,9,20]) or on the micro-structural approach (e.g. [5,28,7,30,31,18,19,21]). In this context, this work highlights a few critical issues in determining effective thermal conductivity and answers the following questions: (1) What is the physical meaning of intrinsic solid phase thermal conductivity (λ_s)? (2) Is intrinsic solid phase thermal conductivity (λ_s) different than the bulk solid phase conductivity of the parent material (λ_s^B)? (3) Is porosity the only parameter to relate with effective thermal conductivity? (4) Is the combination of series and parallel bounds (also known as Wiener bounds; [34] sufficient to characterize effective thermal conductivity? (5) How should the effective solid phase tortuosity (S_T) be introduced in the correlation?

Kumar et al. [18] and Kumar and Topin [19] showed that the ratio of conductivity between phases impacts the effective thermal conductivity under the condition of local thermal equilibrium (LTE). When the fluid phase conductivity has the same order as the solid phase, then the fluid phase starts to play an important role in determining effective thermal conductivity. In this situation, the correlations derived by several authors [5,6,28,7,29,11,8,30] do not hold and introduce high error, as also shown in the works of Dietrich et al. [9]. The correlations derived by these authors contain parent material or bulk phase solid thermal conductivity (λ_s^B) and porosity. Kumar et al. [18] and Kumar and Topin [19] highlighted that since different commercially available foams employ different manufacturing techniques, there are significant changes in intrinsic solid phase thermal conductivity of foams compared to the same parent material one where $\lambda_s < \lambda_s^B$ (a reduction of about 25% in λ_s^B). Similar observations were demonstrated by Dietrich et al. [9] and Randrianalisoa et al. [17] where these authors measured intrinsic solid phase thermal conductivity of their open-cell foams.

Dietrich et al. [9] proposed a parameter $b = 0.51$ in their correlation that was estimated by an empirical approach based on the conductive heat transfer occurring through the parallel layout without any restriction imposed by the serial part and is related with porosity as the only structural parameter of foam samples. In principle, the parameter should depend on the foam structure under consideration. Edouard [31] used morphological parameters of a foam matrix to derive an effective thermal conductivity correlation based on the cubic lattice unit cell, which does not correspond to the real foam structure and thus, could not be used as periodic unit cell.

Kumar and Topin [19] showed that the shape and size of the cells as well as the shape of struts have negligible effects on modeled predictions in the case of isotropic foams. However, in the case of anisotropic foams, the size of the cells as well as the strut shapes strongly impact the effective thermal conductivity over porosity [35]. Nevertheless, porosity was the only structural parameter considered by most of the correlations. Therefore, the direct influence of the morphology of foam structures on the magnitude of the effective thermal conductivity was neglected by numerous correlations, although its influence on the conductive heat transfer is already known to be relevant.

Mendes et al. [20] presented an analysis for the determination of effective thermal conductivity of open-cell foam-like