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A new prediction model for the effective thermal conductivity of high porosity open-cell metal foams

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ABSTRACT

In this paper, a new prediction model for the effective thermal conductivity (ETC) of high porosity open-cell metal foams is proposed by introducing the concave tri-prism foam ligament to the tetrakaidecahedron-based foam cell structure as well as considering the effects of ligament orientation and filling medium. The proposed model can avoid using the non-universal empirical parameter that has to be determined experimentally. For validation of the present model, the ETC measurements of copper foams saturated with air, water and paraffin, which are rarely reported in the literature, are also conducted in this work. These ETC data of copper foams, along with the ETC measurements of aluminum and nickel foams from the literature, are used to validate the present model. It shows that the present model, when compared with other ETC models reported in the literature, can better predict the ETC experimental results of high porosity metal foam, with the average prediction deviations for different metal foams (copper, aluminum and nickel foams) saturated with different mediums (air, water and paraffin) within 10%, which can be attributed to the adoption of relatively realistic foam structure and simultaneous consideration of the ligament orientation and filling medium effects in the present model.

1. Introduction

Open-cell metal foams with high porosity, having many prominent thermal properties such as high conductivity, high permeability, light weight and large area-to-volume ratio, are widely used in various actual devices including compact heat exchangers [1–6], fuel cells [7], solar collectors [8,9], thermal energy storage units [10,11], etc. The effective thermal conductivity (ETC) of open-cell metal foams is an important thermophysical parameter in the heat transfer analysis of metal foams [8,9,11]. The prediction of ETC of open-cell metal foams has attracted considerable attention in the past decades. A review of prediction models for ETC of open-cell metal foam has been made by Coquard and Baillis [12,13] and Randrianalisoa and Baillis [14].

Various prediction models based on 2D or 3D geometrical structures of foam have been proposed to predict the ETC of open-cell metal foams. Calmidi and Mahajan [15] and Bhattacharya et al. [16] proposed 2D structure-based ETC models, in which the metal foam was assumed to be in 2D hexagonal arrays with cylindrical ligaments joined by square [15] or circular [16] nodes, respectively. Inspired by Calmidi and Mahajan's work, Boomsma and Poulikakos [17] proposed a 3D structure-based ETC model by assuming the representative cell of metal foam to be the Kelvin tetrakaidecahedron which is constructed by cylindrical ligaments and cubic nodes. This 3D model could reflect a more realistic foam cell structure than the 2D model, however, there existed errors in this model [18], which was further confirmed and corrected by Boomsma and Poulikakos's later work [19]. By considering the effect of ligament orientation on the ETC, Dai et al. [18] modified the Boomsma and Poulikakos's model and thereby increased the model prediction accuracy. Note that all models mentioned above are in semi-analytical forms which include additional empirical parameters (establishing the geometrical relationship between foam ligament and node) that must be determined experimentally. Considering that most empirical parameters are determined from the experimental data of aluminum foam samples [15–19], their applicability to other metal foams such as nickel and copper foams remains questionable. Recently, Yang et al. [20] proposed a simplified 3D structure-based model to predict the ETC of high porosity metal foams. This model does not need any additional empirical parameter, however, it ignores the heat conduction via the filling medium. Also note that in all above-mentioned models, the foam ligament

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Nomenclature

a_1	geometrical parameter controlling cross-sectional shape of ligament [−]
a_2	geometrical parameter controlling cross-sectional size of ligament [m]
a_3	geometrical parameter controlling longitudinal curvature of ligament [−]
H	height [m]
k	thermal conductivity [W m^{-1} K^{-1}]
L	distance between centers of neighboring nodes [m]
l	ligament length [m]
M	mass of metal foam sample [kg]
S	area [m^2]
T	temperature [K]
V	volume [m^3]
x, y, z	coordinates [m]

Greek symbols

ε	porosity [−]
θ	angle [°]
λ	dimensionless parameter, $\lambda = a_2/L$ [−]
ρ	density of metal foam material [kg m^{-3}]

Subscripts

A	layer A of unit cell
a	air
B	layer B of unit cell
C	layer C of unit cell
c	cold
eff	effective
exp	experiment
f	filling medium
h	hot
i	index representing A, B, C
lig	foam ligament
mf	metal foam
nod	foam node
p	paraffin
pre	prediction
pyb	pyramid base
s	skeleton
st	steel
stl	lower steel plate
stu	upper steel plate
w	water

structures are simplified to be circular or square cylinders. According to the Plateau's rules, the concave tri-prism ligament structure with a Plateau border and a node joined by four ligaments would very likely form during the natural foaming process, and thus is a relatively more realistic foam ligament structure [21,22]. Kanaun and Tkachenko [23] developed a mathematical model to describe this concave tri-prism foam ligament structure with the Plateau border. With this structure, they numerically calculated the effective conductive properties of open-cell foam materials using the finite element method. To our knowledge, however, no prediction model for the ETC of open-cell metal foams has been established on the basis of relatively realistic foam model by introducing the concave tri-prism ligament structure to the Kelvin tetrakaidecahedron foam cell. Thus it is necessary to develop a new model for the ETC of high porosity open-cell metal foams, which can comprehensively consider the effects of relatively realistic foam structure, ligament orientation and filling medium, and also avoid using additional empirical parameters to be determined experimentally.

The applicability of the ETC model depends on the validation of a great number of experimental data. Nevertheless, most of the existing experimental data on ETCs of metal foams are for aluminum foams. Using steady state method, Calmidi and Mahajan [15,24] and Phanikumar and Mahajan [25] measured the ETCs of aluminum foams (with porosity of 0.9–0.98) saturated with air and water, respectively. Their experimental data indicated that the ETC increased significantly with the decrease of porosity, while no systematic influence of pore density on ETC was observed. Fetoui et al. [26] measured the ETCs of highly porous aluminum foams saturated with air using a transient photo-thermal method, and obtained the same results as Calmidi and Mahajan [15]. Sadeghi et al. [27] studied the ETCs of aluminum foams with different porosities and pore densities under various compressive loads. It was found that the ETC was sensitive to foam porosity but was relatively insensitive to compressive load below 2 MPa. Dyga and Witczak [28] tested the ETCs of aluminum foams saturated with air, oil and water, respectively. They found the effect of heat transfer via filling fluid on ETC was much more evident for liquid-saturated foams than for gas-saturated foams. Note that all the above works are for aluminum foams, and very limited experimental endeavor were conducted for other metal foams. Recently, Xiao et al. [29,30] conducted experimental investigations on the ETCs of nickel and copper foams, respectively. However, the medium filling the foam in their study is only limited to solid paraffin. To better validate the ETC model, experimental data of the ETCs for different high porosity metal foams, especially for the copper foams of important applications in many areas [1,3,11] and saturated with different mediums should be enriched.

This study intends to develop a new prediction model for the ETC of high porosity open-cell metal foams. The model adopts a relatively realistic metal foam structure represented by Kelvin tetrakaidecahedron cell with concave tri-prism ligaments, and simultaneously considers the effects of ligament orientation and filling medium on the ETC. The proposed model is anticipated to avoid using the additional experimentally-determined empirical parameter as applied by most previous studies. To better validate the present model, experiments on the ETCs of copper foams saturated with air, water and paraffin that are rarely reported in the literature are also carried out. The present model is validated by the experimental data from the present study and the open literature. Finally, comparisons of the applicability for different high porosity open-cell metal foams saturated with different filling mediums between the present model and other models in the literature are made.

2. Mathematical model for the ETC of open-cell metal foams

2.1. Geometrical model of open-cell metal foams

An accurate description of foam geometrical structure is important for developing the reliable model for ETC of open-cell metal foams, especially when the metal foams are saturated with relatively low thermal conductivity mediums [31]. Fig. 1(a) shows a SEM image of copper foam structure. As can be seen, the realistic