International Journal of Heat and Mass Transfer 86 (2015) 853–860

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A Lattice Monte Carlo analysis of the effective thermal conductivity of closed-cell aluminum foams and an experimental verification

Hong Ye *, Qing Ni, Mingyang Ma

Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230027, China

ARTICLE INFO

Article history:
Received 24 February 2014
Received in revised form 10 January 2015
Accepted 20 March 2015
Available online 9 April 2015

Keywords:
Closed-cell aluminum foam
Effective thermal conductivity
Lattice Monte Carlo method
Cubic unit model
Cell wall thermal conductivity
Plateau borders

ABSTRACT

A Lattice Monte Carlo (LMC) method was employed to predict the effective thermal conductivity (ETC) of closed-cell aluminum foams with porosities between 0.828 and 0.894 through a cubic unit model. The numerical results demonstrated a linear dependency on the relative density when the cell wall thermal conductivity (CWTC) was set as that of pure aluminum; the dependency had large deviations from the measured ETCs obtained via a steady-state comparative method. To characterize the actual CWTC, its relationship with the ETC was deduced, and its value was determined through the measured ETC. On the other hand, the cubic unit model was improved with consideration of the plateau borders characterized through Image-Pro software. With the corrected CWTC and the improved cubic unit model, the numerical results agreed well with the measured results. Hence, the LMC method can be used to predict the ETC of closed-cell aluminum foams accurately through a cubic unit model, provided that the relative density, the CWTC and the plateau borders are taken into account.

1. Introduction

Aluminum foams, characterized by a high porosity, are a type of lightweight, porous material with a base material such as aluminum or aluminum alloy. They can be classified with respect to their pore structures as closed-cell and open-cell foams. Closed-cell foams contain voids completely enclosed by the base materials, while open-cell foams exhibit interconnected voids. Due to their excellent performances of damping behavior, energy absorption, thermal insulation and sound absorption, aluminum foams have a great application potential in various fields such as aerospace, automobile, metallurgy, machinery, environmental protection, architecture and so on [1–4].

As one of the key parameters characterizing the thermal performance of aluminum foams, effective thermal conductivity (ETC) has recently been the subject of extensive research. The transient plane-source method [5–7] and the steady-state comparative method [8] are two common experimental methods used to measure the ETC. Another approach to determine the ETC is through analytical modeling. Existing empirical analytical models have been summarized [5,9]. Moreover, the ETC of aluminum foams can also be determined through numerical methods such as the Lattice Monte Carlo (LMC) method or the Finite Element (FE) method with models based on either simplified geometries [7,10] or real geometries obtained from micro-computed tomography images [11–14]. Fiedler et al. [7,10] employed the LMC method to investigate the ETC of closed-cell aluminum foams. Their results showed that the results from the simplified geometry model (the cubic inclusion model and the spherical inclusion model) are similar to those from the real geometry model (the CT model); furthermore, the results indicated that pore shape has little influence on the ETC. However, comparison between the numerical results and the measured ETCs yielded deviations, which were attributed by the authors to the unreasonable cell wall thermal conductivity (CWTC). In fact, in earlier researches, it was empirically assumed that the CWTC equaled the thermal conductivity of the base metal material [7,10,12,15]. However, the difference in the CWTC among different samples was not considered and could be caused by variations in the microstructure or the components of the cell walls. On the other hand, the cubic model can be further improved by considering the geometric imperfections of aluminum foams. Lu and Chen [16] employed analytical and FE methods to investigate the effect of the plateau borders on the heat conduction through a simplified honeycomb model, and they found that the plateau borders have effects on the ETC of aluminum foams. However, few works have been completed to characterize the plateau borders of aluminum foams to improve the cubic model for predicting the ETC.

* Corresponding author. Tel./fax: +86 63607281.
E-mail address: hye@ustc.edu.cn (H. Ye).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.03.070
0017-9310/

Nomenclature

Mathematical symbols

A_{total}	area of the total section perpendicular to the global heat flow
A	sectional area of the cell wall perpendicular to the global heat flow
A'	sectional area of the cell wall perpendicular to the length direction
a	cell strut size
$a_1/b_1/b_2/c_1/c_2$	jump direction of the particle (in the calculation of tortuosity)
$c_{p,i}$	specific heat capacity
D	particle diffusivity
d	dimension
f_s	ratio of solid mass concentrating in the cell struts to the total mass
k	thermal conductivity
L_{cubic}	size length of the cubic unit model, cell size
l and l'	cell wall length and its projected length in the direction of the global heat flow
N	the number of particles (in the calculation of tortuosity)
P_j	jump probability
R	displacement vector
r	random number, $0 \leqslant r < 1$
s and s'	length of the practically curved cell walls and its projected length in the direction of the global heat flow
t	time
T	temperature
U	uncertainty
$x\ y\ z$	particle coordinate

Abbreviations

CWTC	cell wall thermal conductivity
ETC	effective thermal conductivity
FE	Finite Element
LMC	Lattice Monte Carlo

Greek symbols

Δ	difference
α	thermal diffusivity
ε	porosity
ζ	local tortuosity, l/l'
$\bar{\zeta}$	average tortuosity of sample section
θ	angle between the length direction and the global heat flow
ρ	density
ρ'	relative density
σ	thickness
ϕ	relative density of the section, A/A'

Subscripts

1, 2	phase 1 or phase 2
eff	effective
g	gas
m	base metal material
max	maximum
n	particle n
r	reference material
s	sample
wall	cell wall

In this work, the LMC method was employed through a cubic unit model to predict the ETCs of several closed-cell aluminum foams with porosities between 0.828 and 0.894. The numerical results were compared with the measured ETCs obtained via a steady-state comparative method. The actual CWTC and the plateau borders of aluminum foams were characterized and applied to improve the prediction.

2. Materials and methods

2.1. Material

The closed-cell aluminum foams studied in this work were manufactured in a similar way to that of Alporas (Shinko Wire) foams [17]. The cell size of the foam is approximately 2 mm. The relative density ρ' is defined as the ratio of the density of the foam to that of the base metal material. In this study, the density of the base metal material was conventionally set as that of pure aluminum, 2.7 g/cm^3. Five samples with a relative density between 0.106 and 0.172, machined via a wire-electrode cutting facility, were investigated in this work. The size of every sample is $230 \times 230 \times 40$ mm.

2.2. Lattice Monte Carlo simulation based on a cubic unit model

The ETC of closed-cell aluminum foam (k_{eff}) has four contributions: conduction along the cell walls, conduction through the gas phase, and convection and thermal radiation within the cells. Among them, the conduction through the gas phase could be neglected due to a relatively low thermal conductivity [18], and both the convection and the thermal radiation could also be ignored because the cell sizes are smaller than 10 mm [19] and the temperatures are below 700 K [16,20], respectively. Therefore, the ETC of closed-cell aluminum foam is dominated by the conduction along the cell walls.

The ETC of homogeneous closed-cell aluminum foam can be studied through a simple cubic unit model (Fig. 1), with porosity ε, size length L_{cubic} and a uniform cell wall thickness σ_{wall}. The porosity ε is defined as the ratio of the gas phase volume to that of the whole model and can be obtained by $\varepsilon = 1 - \rho'$ [21]. L_{cubic} is fixed as 2 mm. The size length L_{cubic} and the porosity ε can determine the cell wall thickness σ_{wall} according to $\varepsilon = (L_{cubic} - 2\sigma_{wall})^3/L_{cubic}^3$.

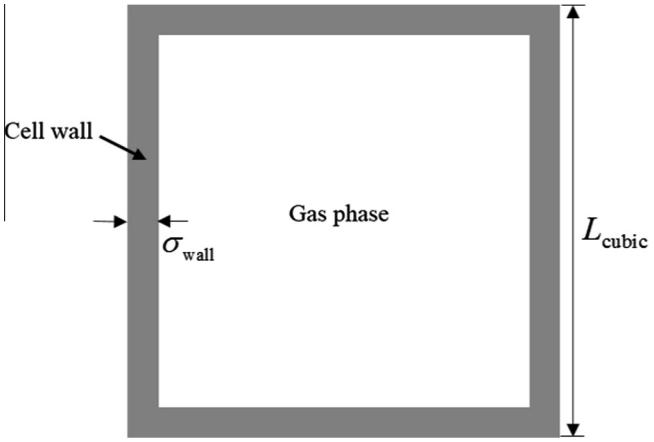

Fig. 1. The cross-section of the cubic unit model.