International Journal of Heat and Mass Transfer 66 (2013) 868–878

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effective thermal conductivity of sintered porous media: Model and experimental validation

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ARTICLE INFO

Article history:
Received 4 March 2013
Received in revised form 17 July 2013
Accepted 28 July 2013
Available online 23 August 2013

Keywords:
Porous media
Effective thermal conductivity
Heat pipes
Sinterization

ABSTRACT

A model to estimate the effective thermal conductivity of sintered porous media for heat pipes is proposed in this paper. An elementary cell of a porous media is physically modeled as two metallic hemispheres in contact with a fluid film around them. The electrical circuit analogy is employed to determine the heat leaving the top and reaching the bottom of the cell. The thermal circuit consists of two parallel resistance paths, one for the solid spheres in contact and the other for the heat transfer in the fluid. A literature model is employed to calculate the thermal resistance within the hemispherical particles. Also, literature models are used for the determination of the geometry of the neck produced between particles during the sintering process. The neck dimensions are used to estimate the neck thermal resistance, which is in series with the hemisphere resistances. Effective thermal conductivity experimental data were obtained for porous materials produced with atomized copper powder, with particle diameters ranging from 20 to 50 μm. The comparison between present model and data is good. Statistics of the particle size distribution is employed to determine average particle dimensions. The porosity and permeability of the material tested was characterized in the laboratory. The samples were tested in three conditions: vacuum and saturated with distilled water or methanol. Literature models for the effective thermal conductivity for bed packed (not sintered) porous media were also compared with the present model and data results.

1. Introduction

Effective properties are usually used to define the physical characteristics of the porous materials. The effective thermal conductivity, for instance, is determined considering the thermal conductivity of the constituent phases of the material, i.e. the solid phase (matrix) and the fluid phase (liquid or gas).

Much of the heat transfer work in the literature treats all porous media equally, independently of the technology employed for their fabrication. Actually, there is a large difference among porous media produced by different technologies, as observed in sintered and bed packed metal powder. Usually, a distinction is made between the thermal conductivity of densified (or sintered) and not densified porous media. Carson et al. [1] and Atabaki and Baliga [2] verified that the thermal conductivity of a non-sintered material is much smaller than that of sintered materials. The models proposed by Chi [3], Faghri [4] and Peterson [5], are simple arrangements in series or parallel of the porous media phases, using the analogy with electrical circuits. The values estimated by the series and parallel models are used as upper and lower limits of the effective thermal conductivity. Among his works conducted for non-sintered materials, Handley [6] presented a theoretical and experimental study concerning the effective thermal conductivity of a bed packed particulate material. This researcher proposed a theoretical model based on energy balance equations averaged in the volume, following the hypothesis adopted by Whitaker [7]. In this model, an experimental factor for the evaluation of the consolidation degree of particles during sinterization is adopted. Recently, Bahrami et al. [8] studied the effective thermal conductivity of two rough steel packed spheres in contact, surrounded by air, using the thermal circuit analogy. In this work, an expression for the determination of the constriction and spreading thermal resistances for solid and hollow spheres in contact were obtained, based on an exact solution previously developed by Yovanovich et al. [9].

Sintered porous media can be considered as sphere particles connected by necks, which are created by heating process and diffusion mass phenomena. Therefore, its effective thermal conductivity depends on the number of created necks. Birboim et al. [10] considered the influence of necks for modeling the effective thermal conductivity of porous media made of sinterization of zinc oxide (ZnO). They predicted the effective thermal conductivity

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.07.088

Nomenclature

A	area
a	inner sphere radius
b	outer sphere radius
c	radius of the chord subtended by contact area
$\bar{d}$	particle mean diameter
d_f	driving force
Ds	surface diffusion coefficient
k	thermal conductivity
k_B	Boltzmann's constant
k_e	effective thermal conductivity
k_r	reference thermal conductivity
l	sample length
L	cell length
m_d	dry mass
m_w	wet mass
Q	quartile
q_z	heat flux rate
$\bar{Q}$	average heat flux rate
Q_s	activation energy for surface diffusion
R	thermal resistance
R_L	constriction/spreading resistance
R_p	thermal resistance of neck
R_1,R_2	thermal resistance of sample case
$\boldsymbol{R}^*$	dimensionless resistance $\boldsymbol{R}^* = k_s \times R_L$
r	particle radius
r_m	radius of curvature of the neck
r_p	radius of the neck
T	temperature
T_M	melting temperature
x	radius of neck in the plane of contact of two particles
$\dot{x}$	rate of neck growth
x	position of temperature sensors

Greek symbols

α	contact half-angle
γ_s	Surface energy
δ_s	effective surface thickness
D_{os}	coefficient of the surface diffusion
ξ	radii ratio b/α
ρ	theoretical density
ρ_a	apparent density
ρ_{air}	air density
ρ_l	liquid density
ρ_s	solid density
ϕ	polar angle
Ω	atomic volume

Subscripts

c	hot
h	cool
s	solid
l	liquid
r	reference
t	total

using a numerical solution of the Fourier Equation proposed by Atabaki and Baliga [2], which take into account a factor of consolidation degree of sintered powder wick.

An interesting model for the effective thermal conductivity based on experimental data was proposed in the PhD thesis of Alexander (apud Atabaki and Baliga [2]) for metal felts, sintered powders, layers of wire cloth and unconsolidated beads. Sintering is also used in screens to produce heat pipe capillary structures.

From this literature review, it is possible to observe that the effective thermal conductivity of sintered porous media has not yet been fully modeled. Therefore, the main goal of this work is to propose an effective thermal conductivity model for sintered porous media made from metal powders, based on two literature models: the phenomenological analyses of Birnboin et al. [10], which uses the fabrication process and the geometry of the metal powder spheres, including particle size, as input parameters, and the thermal conduction between spheres in contact model, presented by Bahrami et al. [8] and Yovanovich et al. [9]. The analogy between thermal and electrical circuits is employed.

2. Model

This section presents the model developed in this work for the effective thermal conductivity for sintered porous media. The conduction in the solid phase (matrix) is modeled using a literature conduction heat transfer model between two solid hemispheres in contact. The model for the liquid phase is based on a conduction heat transfer within hollow spherical shells model, available in the literature. The analogy between electrical and thermal circuits is employed to link these models. Following, details of the modeling are shown.

2.1. Contacting sphere physical model

The physical model adopted for determining the theoretical effective thermal conductivity of a sintered porous media is displayed in Fig. 1. The model is based on the thermal analyses of a unit cell, which thermally represents the whole porous media. The actual porous media can be reproduced by stacking several of these cells in a vertical arrangement and replicating this pile in a horizontal array, forming a three dimensional structure. The cell is formed by two metal hemispheres of radius r_1 and r_2, which represent the powder from which the porous media is made. These radius are considered equal and equivalent to the powder mean radius. The hemispheres are joined by means of a neck formed during the sintering process. A stationary liquid film, in a hollow hemi-

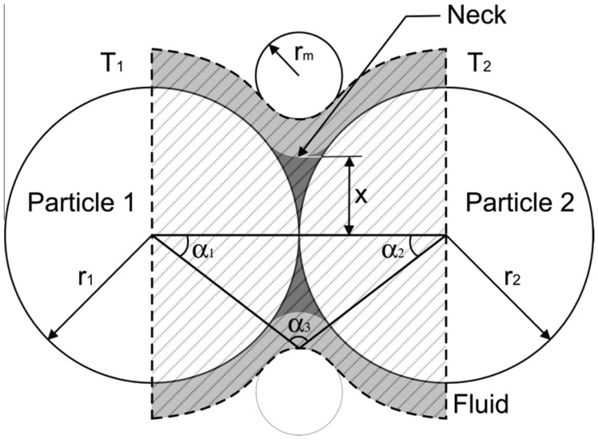

Fig. 1. Elementary cell physical model.