International Journal of Heat and Mass Transfer 80 (2015) 688–697

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Review

A novel numerical cubic filament model and method for the two-energy equation in porous media

Yang Pan [a,*], Guoliang Xu [b], Wenhao Li [b,c], Chun Zhong [a]

[a] *School of Civil Engineering and Architecture, East China Jiaotong University, Nanchang, Jiangxi 330013, China*
[b] *School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China*
[c] *Department of Mechanical Engineering, Shizuoka University, 3-5-1 Johoku, Hamamatsu 432-8561, Japan*

ARTICLE INFO

Article history:
Received 25 April 2014
Received in revised form 14 September 2014
Accepted 25 September 2014
Available online 19 October 2014

Keywords:
Two-energy equation
Porous media
Consistent rule
Cubic filament model (CFM)
Control volume

ABSTRACT

A consistent rule, which requires the flow and heat transfer of both a numerical model and real porous media should simultaneously satisfy the same governing equations as well as the same or consistent transport properties, is proposed for establishing a numerical model by which the flow and heat transfer of real porous media can be simulated. A cubic filament model (CFM) with regular geometry solid matrix is modeled. In the procedure of modeling, transport properties of both the cubic filament model (CFM) and real porous media, including porosity, permeability, tortuosity, specific surface, inertial coefficient, surface heat transfer coefficient and thermal conductivity of both fluid and solid, are analyzed and developed. According to analysis of transport properties and the consistent rule, structure parameters of the cubic filament model (CFM) are determined. To avoid complexity of determining the effective conductivity, it is proposed that solid matrix and fluid are divided into two independent control volumes for the cubic filament model (CFM). Meanwhile, equivalent conductivity of solid matrix and average temperature differences of the source terms are derived for the cubic filament model (CFM).

Contents

1. Introduction . . . 689
2. Analysis and numerical model . . . 690
    2.1. Consistent rule of numerical model and real porous media in flow and heat transfer . . . 690
    2.2. Cubic filament model and structure parameters and porosity . . . 691
    2.3. Permeability . . . 691
    2.4. Tortuosity χ and specific surface a_{sf} . . . 692
    2.5. Surface heat transfer coefficient h_{sf} (or Nu) and inertial resistant coefficient C_F . . . 694
3. Control volume partition and numerical methods . . . 695
    3.1. Partition of control volume in the cubic filament model (CFM) . . . 695
    3.2. Thermal conductivities and thermal properties . . . 696
    3.3. Treatment of temperature difference in convective heat transfer term . . . 696
4. Concluding remarks . . . 697
Conflict of interest . . . 697
Acknowledgment . . . 697
References . . . 697

---

* Corresponding author. Tel.: +86 791 87046075.
E-mail address: hdjdpan@sina.com (Y. Pan).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.09.065
0017-9310/© 2014 Published by Elsevier Ltd.

Nomenclature

a_{sf}	specific surface
A	surface area
C_k	dispersion coefficient
C_F	inertial coefficient
c, c_p	specific heat
Da	Darcy number
d, d_p, d_s	filament space, pore distance and square side length
D_f, D_T	fractal dimension
h_{sf}	interfacial heat transfer coefficient
k	thermal conductivity
k_d	permeability
k_{dis}	thermal dispersion
L	length
L_0	characteristic length
Nu	Nusselt number
p	pressure
Pr	Prandtl number
Re	Reynolds number
T	temperature
$\langle T\rangle^{f,s}$	intrinsic average temperature
u	velocity
$\langle u\rangle$	phase average velocity
V	volume
x_j	Cartesian coordinate
Greek symbols	
λ	pore diameter
ε	porosity
μ	dynamic viscosity
ρ	density
χ	tortuosity
Subscripts and superscripts	
eff	effective value
f	fluid
s	solid

1. Introduction

Large porosity porous media with high conductivity solid matrix (porosity of porous media larger than 0.90), such as metal foams and metal meshes, with the high conductivity and large surface area structure of the matrix, have strong enhancement of surface heat transfer between solid matrix and fluid. Therefore, this kind of porous media are widely applied in high efficient heat exchangers, thermal management of electronic components, and energy storage systems with phase change.

In study of flow and heat transfer for porous media, there are two assumptions, local thermal equilibrium (LTE) assumption and local thermal non-equilibrium (LTNE) assumption. More researchers pay attention to the latter. Amiri and Vafai [1], Alazmi and Vafai [2] have respectively investigated multi-factor effect, such as dispersion effect, local thermal non-equilibrium effect, non-Darcian effect and variable porosity, on forced convection flow and free surface flow through porous media, in which they found that local thermal non-equilibrium effect is more pronounced in the presence of thermal dispersion. Viskanta [3] has adopted two-energy equation model to analyze and model transport phenomena in porous media. Nakayama and his research team [4–8] have made extensive investigations for two-energy equation model, including exact solutions, tortuosity and dispersion effects, local thermal non-equilibrium analysis and so on. Mahajan and his co-workers have investigated high porosity metal foams based on two-energy equation model. In study of forced convection in metal foams [9], their results indicate that thermal dispersion effect is very low for foam–air combinations and very high for foam–water. In study of natural convection in metal foams [10], they found that effect of local thermal non-equilibrium is significant at high Rayleigh and Darcy numbers. They have made comprehensive analytical and experimental investigations for transport properties of high porosity metal foams [11,12], and obtained calculating models of effective thermal conductivity, permeability and inertial coefficient respectively. Although different expressions exist for two-energy equation, almost all of researchers have a consistent conclusion that a local thermal non-equilibrium (LTNE) assumption should be adopted, and two energy equations for the solid matrix and fluid should be respectively set up due to existent temperature difference between the matrix and fluid for porous media, especially for large porosity porous media. LTNE assumption or two-energy equation model is more perfect physical description for the flow and heat transfer of porous media. But, it is very difficult to calculate numerically two-energy equation model because of disorder structure of the matrix in porous media, e.g. difficulties in partitioning the grids and determining the space location for both the solid matrix and fluid, which results in incapable of obtaining fluid flow field and temperature distributions of both fluid and solid phases. Furthermore it has seriously restricted and influenced development of numerical calculation of two-energy equation for porous media.

In recent year, some studies have focused on exact solutions for two-energy equation model. Kuwahara et al. [5] proposed a thermal nonequilibrium model for fluid saturated porous media based on an effective porosity which accounts for the effects of tortuosity and thermal dispersion on effective thermal conductivities of both solid and fluid phases. Their exact solutions of metal foam–air combination indicate that LTE assumption is available for isothermal hot and cold walls, but fail for constant heat flux walls. Yang et al. [7] have considered a LTNE model for thermally fully developed flow within a constant heat flux tube filled with metal foam, and obtained exact temperature profiles of both solid and fluid phases. They have also found that Nuseelt number, as a function of Peclet number, is a significant increase due to both high stagnant conductivity and thermal dispersion. Yang and Vafai [13] have found and analyzed a phenomenon of heat flux bifurcation inside a porous medium for the first time. They obtained exact temperature profiles of both the fluid and solid phases for convection heat transfer within a channel filled with a porous medium under a constant wall heat flux boundary condition. In their other literature [14], a transient thermal response of a packed bed has been investigated by using a LTNE model and heat flux bifurcation phenomenon. And exact solutions have been derived for both fluid and solid temperature distributions under the constant wall temperature boundary condition. In addition, by analyzing the heat flux bifurcation phenomenon, they [15] have investigated convective heat transfer within a channel partially filled with a porous medium under LTNE model, with consideration of both thermal dispersion and inertial effects. Exact solutions have been obtained for fluid and solid temperature profiles and Nusselt number. All of these studies of exact solutions for LTNE model have great significance in mechanism research of flow and heat transfer for porous media. However, we notice that the scope of application should be limited for any exact solution due to some assumptions, e.g.