International Journal of Thermal Sciences 104 (2016) 135–145

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Effect of pore to throat size ratio on thermal dispersion in porous media

Turkuler Ozgumus, Moghtada Mobedi*

Department of Mechanical Engineering, Izmir Institute of Technology, Urla, Izmir 35430, Turkey

ARTICLE INFO

Article history:
Received 13 January 2015
Received in revised form
23 November 2015
Accepted 8 January 2016
Available online xxx

Keywords:
Porous media
Thermal dispersion
Volume averaging method
Throat effect

ABSTRACT

In this study, the effects of pore to throat size ratio on thermal dispersion of periodic porous media consisting of inline array of rectangular rods are investigated, numerically. The continuity, momentum and energy equations are solved for representative elementary volumes (REVs) of the porous media to obtain microscopic velocities in the voids between the rods and temperature distribution for entire of the REVs. Volume averaging method is employed to compute the macroscopic velocity and temperature values. There are velocity and temperature deviations between the macroscopic and microscopic values. These deviations are computed numerically and thermal dispersion coefficients of the porous media are determined. The aim of this study is to analyze the effects of pore to throat size ratio on the longitudinal and transverse thermal dispersion in the porous media. The study is performed for pore to throat size ratios between 1.63 and 7.46, porosities from 0.7 to 0.9, and pore level Reynolds numbers between 1 and 100. It is found that in addition to the porosity and Reynolds number, the parameter of pore to throat size ratio plays an important role on thermal dispersion in a porous medium. It is found that there is an optimum value of pore to throat size ratio for maximum longitudinal thermal dispersion coefficient; however, the transverse thermal dispersion increases with the increasing of values of pore to throat size ratio.

1. Introduction

A fluid can flow through the open pores that exist in a solid phase or between the solid particles. Flow in a porous medium is complex due to the discontinuity in flow field. The pore-level analysis of fluid flow and heat transfer for entire porous medium to determine velocity, pressure and temperature distributions is a difficult approach. To simplify the analysis, the macroscopic approach based on volume averaging technique was developed [1]. In the macroscopic approach, a porous medium consisting of different phases is considered as an imaginary continuum domain and the macroscopic governing equations are employed to determine the macroscopic velocity, pressure and temperature distributions for the entire porous medium. The macroscopic governing equations can be obtained by applying the volume averaging technique on the corresponding microscopic governing equation. As a consequence of application, some extra terms (involving coefficients such as permeability, interfacial convective heat transfer coefficient and thermal dispersion coefficient) appear in the macroscopic momentum and energy equations. Thermal dispersion term in the macroscopic energy equation indicates the non-uniformities of the pore level velocity and temperature and as well the effect of hydrodynamic mixing. The effect of thermal dispersion on convection heat transfer in a porous medium becomes stronger as Reynolds number increases. Thermal dispersion also depends on other parameters such as Prandtl number, porosity, solid-to-fluid thermal conductivity ratio. Additionally, the shape of particles strongly influences thermal dispersion [2].

Thermal dispersion coefficient can be calculated experimentally or theoretically. The reported experimental studies on determination of thermal dispersion for packed beds filled with different particles were extensively reviewed and classified in Ref. [3]. Recent developments in computational technology lead researchers to determine thermal dispersion coefficient by using numerical methods. For instance, Sahraoui and Kaviany [4] considered two-dimensional periodic arrangement of cylinders

* Corresponding author. Current address: Faculty of Engineering, Shizuoka University Hamamatsu Campus, 3-5-1 Johoku, Naka-ku, Hamamatsu, Japan.
E-mail addresses: turkulerozgumus@iyte.edu.tr (T. Ozgumus), moghtadamobedi@iyte.edu.tr, moghtada.mobedi@shizuoka.ac.jp (M. Mobedi).

http://dx.doi.org/10.1016/j.ijthermalsci.2016.01.003
1290-0729/

and determined the longitudinal and transverse total thermal diffusivities, including both molecular diffusion and dispersion coefficients, by considering slip and no-slip temperature boundary conditions. It was shown that the ratio of total thermal diffusivity to thermal conductivity of the fluid changes with the square of Peclet number for inline arrangement while for the staggered arrangement the ratio increases linearly with Peclet number. It was also observed that for low Peclet numbers, the total thermal diffusivity is almost equal to the stagnant thermal conductivity of the porous medium and the thermal dispersion is negligible. Kuwahara et al. [5] studied periodical square rods in inline arrangement to determine transverse thermal dispersion and tortuosity. Two correlations for the determination of thermal dispersion, for high and low Peclet numbers, in terms of porosity, Peclet number and fluid thermal conductivity were suggested. Kuwahara and Nakayama [6] considered the same porous structure to find the longitudinal thermal dispersion and they found that the transverse thermal dispersion is substantially lower than longitudinal one. Correlations for the longitudinal thermal dispersion with porosity and Peclet number were proposed for the considered porous structure. Saada et al. [7] studied heat and fluid flow in porous media with the square rods and plus-shaped rods in inline and staggered arrangements. It was found that for the identical shape of rods, the longitudinal thermal dispersion is higher for the inline arrangement while the transverse one is higher for the staggered arrangement. Pedras and de Lemos [8] studied a periodic infinite porous medium consisting of elliptic rods. It was claimed that the type of thermal boundary condition has negligible effect on the longitudinal thermal dispersion value and only a slight effect on the transverse thermal dispersion could be observed. Xu et al. [9] studied periodic array of parallel plates and determined thermal dispersion analytically. It was shown that thermal dispersion can be influenced by the type of thermal conditions imposed on the medium since the imposed heat source condition affects the temperature non-uniformity in the channel. Alshare et al. [10] investigated the change of thermal dispersion in an array of square rods with inline arrangement by changing the representative elementary volume (REV) aspect ratio. Both transverse and longitudinal thermal dispersion conductivities were studied. It was found that the thermal dispersion depends on both Peclet number and flow angle, and the thermal dispersion coefficient in the flow direction is much larger than the thermal dispersion in the transverse direction to the flow. Jeong and Choi [11] investigated the longitudinal thermal dispersion in 2-D arrays of uniformly distributed circular and square cylinders, spheres and cubes by using lattice Boltzmann method. It was indicated that the inline arrangement causes higher longitudinal dispersion compared to the staggered arrangement and the dispersion depends on the arrangement rather than the shape of particles.

As seen from the above literature review, many studies on the determination of longitudinal and transverse thermal dispersion coefficients were reported. The effects of various parameters such as porosity, Reynolds and Prandtl numbers and fluid-to-solid thermal conductivity ratio on the thermal dispersion coefficient were investigated. However, to the best of our knowledge, no study on the effect of pore to throat size ratio on thermal dispersion has been reported. A porous medium can be described by different geometrical indicators such as porosity, nominal pore size and pore size distribution. Pore to throat size ratio is an important geometrical indicator of a porous medium and widely used to specify the structure of a porous medium. This indicator shows the degree of heterogeneity of the pores. As can be seen from Fig. 1, there are many types of porous media in which the effect of pore to throat size ratio should be taken into account. The contraction and expansion of fluid in a cell of metal foam (Fig. 1(a)) or cross cut pin fin array (Fig. 1(b)) for enhancing heat transfer are two examples for which the effect of pore to throat size ratio on heat and fluid flow should be taken into account. The effects of pore to throat size ratio on the pressure drop through the porous media and permeability are investigated prior to the present study [13]. The aim of the present study is to investigate the effect of pore to throat size ratio on the longitudinal and transverse thermal dispersion coefficients of porous media consisting of array of rectangular rods in inline arrangement, numerically. The velocity and temperature fields are obtained for the REV of the porous media and then the longitudinal and transverse thermal dispersion coefficients are calculated. The study shows that the thermal dispersion coefficients of two porous media with identical porosity, equivalent particle and hydraulic pore diameters but different pore to throat size ratios can be considerably different and the pore to throat size ratio plays an important role on the dispersion of heat in porous media. Hence, the involving of pore to throat size ratio as a structural indicator will provide more general correlations for macroscopic transport properties, which can be valid for various porous media.

2. The considered porous media and computational domain

The schematic of the considered porous media is shown in Fig. 2. The porous media is an infinite media consisting of rectangular rods in inline arrangement. Considering the periodicity of the porous structure, representative elementary volumes with the dimensions of $H \times H$ is chosen to investigate the pore to throat size ratio effect on the thermal dispersion coefficients of the porous media. The dimensions of REVs are constant for all studied cases in the present study. The rectangular particles have dimensions of D_x and D_y along x and y directions. The pore to throat size ratio is defined as $\beta = H/(H - D_y)$. The pore to throat size ratio and porosity are changed from 1.63 to 7.46 and from 0.7 to 0.9, respectively. For instance,

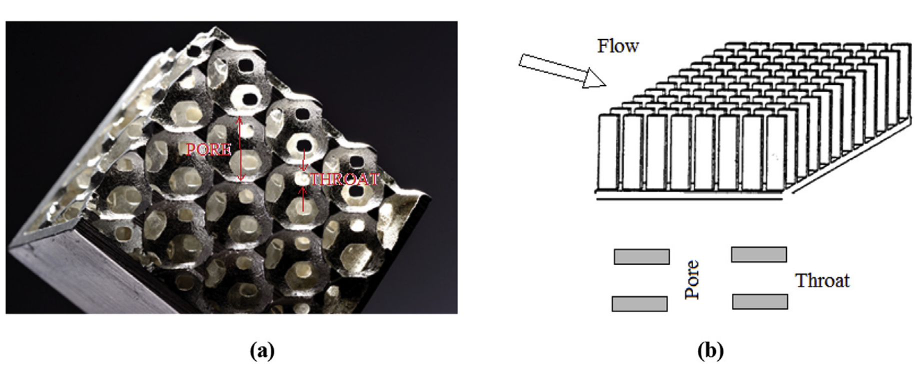

Fig. 1. Two periodic porous media in which the effect of pore to throat size ratio is significant, (a) Metal foam [12], (b) Cross Cut Pin Fins.