International Journal of Thermal Sciences 118 (2017) 374–385

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Investigation of turbulence effects within porous layer on the thermal performance of a partially filled pipe

Majid Eshagh Nimvari [a], [*], Nima Fallah Jouybari [b]

[a] Faculty of Engineering, Amol University of Special Modern Technologies, Amol, Iran
[b] Department of Mechanical Engineering, Tarbiat Modares University, P.O. Box 14115-143, Tehran, Iran

ARTICLE INFO

Article history:
Received 1 May 2016
Received in revised form
7 May 2017
Accepted 9 May 2017

Keywords:
Partially porous media
Turbulence
Thermal performance
Turbulent kinetic energy
Dissipation rate
Darcy number

ABSTRACT

Turbulent flow in a composite porous/fluid domain is usually addressed in the literature assuming laminar flow inside the porous region. However, some of the recent studies revealed the high level of turbulent quantities inside the porous region of composite porous/fluid domains. Therefore, a comparison is made between the results of turbulent and laminar simulations in the present study in order to get more insight on the effects of turbulence inside the porous region on fluid flow and heat transfer in a pipe partially filled with a porous media. The effects of turbulence inside the porous layer on velocity, turbulence parameters, temperature distribution and Nusselt number are analysed for different Darcy numbers and several porous layer thicknesses. It is shown that the turbulence effects inside the porous layer are important even for pore base Reynolds numbers lower than the critical Reynolds number in porous media.

1. Introduction

The study of flow over layers of permeable media has many applications in several environmental and engineering analyses. Relevant examples include, but not limited to solid matrix heat exchangers, microelectronic cooling, heat pipes, atmospheric boundary layer over forests under fire, canopy flow, flow over vegetation, heterogeneous reactors, cooling and heating processes, geothermal energy management and currents at the bottom of rivers [1–3]. Therefore, the number of studies that deal with flow and heat transfer in composite porous/fluid domains has risen steadily in the last years [4]. In most of them, the flow regime within the porous layer is considered to be laminar. However, the flow regime is observed to be turbulent in many practical applications such as heat exchangers, reactors or canopy flows [5]. This fact prompted researchers to investigate the effects of turbulence on fluid flow and heat transfer in conduits partially filled with porous media.

In order to investigate the effects of turbulence on forced convection in a composite porous/fluid domain, Kuznetsov and coworkers [6–8] studied the interaction between the turbulent flow in the clear region of a conduit filled with a homogeneous fluid and laminar flow in the porous layer adjacent to the wall. They have validated their assumption by estimating the Reynolds numbers in the clear fluid and porous regions of the channel. In this way, the penetration depth of turbulent eddies coming from the interface into porous media is considered to be very small. It is observed that the laminar velocity in the clear region is much larger than that predicted by turbulent simulation, and the laminar flow assumption significantly under-predicts the Nusselt number values in composite channel. Later, Saati and Mohamad [9] and Yang and Hwang [5] used similar model to investigate turbulent flow and heat transfer in a channel and pipe partially filled with porous media.

In the studies mentioned above, the flow regime inside the porous media is considered to be laminar since the calculated pore based Reynolds number in porous media, Re_p, was lower than critical Re_p reported in the literature [10,11]. However, the results of Direct Numerical Simulation (DNS) performed by Stalio et al. [12] for fully developed turbulent heat transfer in a channel partially filled with aluminum foam contradicts this assumption. While, the Re_p in their study was lower than critical Re_p inside the porous region, it is shown that Nusselt number computed over the permeable wall is higher than that over impermeable wall due to presence of normal turbulent heat flux. Chandesris et al. [13] also

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[*] Corresponding author.
E-mail address: m.eshagh@ausmt.ac.ir (M.E. Nimvari).

http://dx.doi.org/10.1016/j.ijthermalsci.2017.05.006
1290-0729/

carried out DNS study of turbulent flow and heat transfer over an inline arrangement of cubic particles. They observed that large vortical structures form and evolve at the permeable wall. Their observation was in agreement with that of Breugem and Boersma [14] in the similar geometry. These structures penetrate inside the porous layer even in the case of $\mathrm{Re_p} < \mathrm{Re_{p,critical}}$ resulting in an enhanced turbulent heat transfer just above the porous layer compared to the solid wall.

Researchers such as Allouache and Chikh [15] and Nimvari et al. [16] also investigated turbulent flow and heat transfer in a composite porous/fluid domain. Unlike Stalio et al. [12] and Chandesris et al. [13], they used macroscopic turbulence models to take into account the turbulence effects within the solid matrix. Allouache and Chikh [15] performed numerical simulation of turbulent flow in an annular heat exchanger partially filled with porous media. A modified k-epsilon model is used to simulate turbulent flow inside porous media by time averaging the general macroscopic transport equations. It is showed that the turbulent intensity is significantly affected by the permeability of porous media and has a maximum at a certain Darcy number. Nimvari et al. [16] used the macroscopic turbulence model proposed in Pedras and de Lemos [17] to study turbulent heat transfer inside a channel partially filled with porous media in central and boundary arrangements. It is found that the maximum in TKE profile occurs at the porous-fluid interface and turbulent kinetic energy significantly penetrates into the porous layer. These results support the previous observation on the importance of turbulence effects inside the porous media. They observed that the maximum heat transfer rate is obtained in non-dimensional porous layer of 0.8 and 0.6 for central and boundary arrangements, respectively.

The present study is aimed to investigate the effects of turbulence on fluid flow and heat transfer in a pipe partially filled with highly porous material for various porous layer thicknesses and Darcy numbers. To this end, two sets of simulations are conducted in the present study: (*i*) turbulent flow in both porous and clear fluid regions, (*ii*) turbulent flow in the clear fluid and laminar flow inside the porous layer. The turbulent flow in the clear fluid region is modeled using standard $k-\varepsilon$ model; while the Forchheimer's extended Darcy equation together with the macroscopic turbulence model proposed in Nakayama and Kuwahara [18] with the modifications of Jouybari et al. [19] is used to describe the flow field in the porous region. The importance of turbulence inside porous media is investigated through comparison of turbulent results with those predicted by the laminar model in different Darcy numbers and porous layer thicknesses. It is shown that turbulence effects in porous media significantly affect the heat transfer process in composite porous/fluid domains so that they cannot be neglected even for $\mathrm{Re_p} < \mathrm{Re_{p,critical}}$.

2. Geometry and numerical model

A schematic diagram of the flow under consideration and the coordinate system are shown in Fig. 1 where a pipe is partially filled with a layer of porous material at the core. The pipe diameter and length are $D = 2r_0$ and $200D$, respectively. The axisymmetric boundary condition is applied along the central axis at $r = 0$ in the present simulations. Also, r_p is the radius of the porous layer which is non-dimensionalized as $R_p = r_p/r_0$ in the present study. The local Nusselt number is defined as

$$Nu = \frac{2}{(\theta_w - \theta_m(Z))} \left.\frac{\partial\theta}{\partial R}\right|_{wall} \tag{1}$$

where $\theta_\mathrm{m}(z)$ is the average dimensionless temperature of the fluid in the cross section at z, defined as follows:

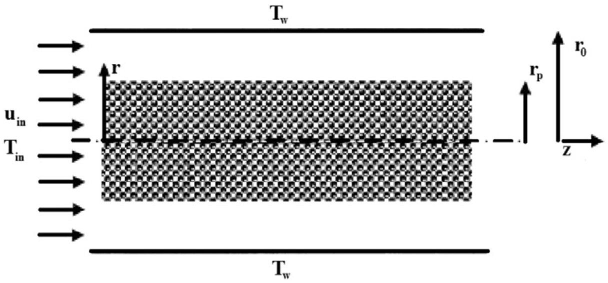

Fig. 1. Schematic diagram of the problem.

$$\theta = \frac{T_w - T}{T_w - T_{in}}, \quad \theta_m(Z) = \frac{\int_{R=0}^{R=1} U\theta R dR}{\int_{R=0}^{R=1} URdR} \tag{2}$$

where $R = r/r_0$ is the dimensionless radius and $U = u/u_{in}$ denote the dimensionless velocity in the z direction.

3. Microscopic and macroscopic models

Generally, there are two approaches to simulate turbulent flow inside porous medium, microscopic and macroscopic models. Although the microscopic approach seems highly interesting, accurate modelling of turbulence inside the pores is a very difficult task due to their complex geometry. As discussed in Teruel and Uddin [20], another difficulty arises from the modelling of turbulent flow close to the walls. Numerical simulation of turbulent flow inside the real geometry of porous media is computationally costly and impractical or even impossible in some cases [20]. Therefore, microscopic simulation of turbulent flow within the pores of porous media has been conducted for some simple geometries such as periodic arrangement of cylinders and cubes by solving the Reynolds-averaged Navier-Stokes equations or direct numerical simulation of Navier-Stokes equations within the solid matrix. The aim of these studies was usually to get more insight on turbulent structures inside the porous media [13,14,21] or to calculate the model parameters through averaging the equilibrium values [17,18,22,23]. In order to avoid the need for modelling the complex structure of pores, macroscopic turbulence models in porous media have been proposed by several researchers.

In an aim to present macroscopic turbulence models in porous media, most researchers follow a traditional approach which was originally developed for laminar flow through porous media. In this approach, the governing equations are obtained by volume averaging the Navier-Stokes equations over a Representative Elementary Volume (REV). In the case of turbulent flow within a porous material, most researchers applied the time and space averaging to the microscopic equations for handling turbulence and morphology, respectively. Masuoka and Takatsu [24] presented a zero equation macroscopic model for turbulent flow inside the porous media. The eddy viscosity in their study was modeled as the sum of eddy diffusivities from pseudo and void vortexes. A one-equation turbulence model for turbulent flow and heat transfer though stacked spheres was also proposed by Alvarez et al. [25]. The model constants were estimated through experimental measurements in their study. Therefore, the accuracy of the 1-equation model is limited to the conditions in which the model constants were calibrated. Macroscopic two-equation turbulence models are also reported in the literature. Most of two-equation models proposed in the literature are based on the clear fluid k–ε model that is modified to take into account the effect of solid matrix on TKE and