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Developing fluid flow and heat transfer in a channel partially filled with porous medium

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Abstract

A three-dimensional computational model is developed to analyze fluid flow in a channel partially filled with porous medium. In order to understand the developing fluid flow and heat transfer mechanisms inside the channel partially filled with porous medium, the conventional Navier–Stokes equations for gas channel, and volume-averaged Navier–Stokes equations for porous medium layer are adopted individually in this study. Conservation of mass, momentum and energy equations are solved numerically in a coupled gas and porous media domain along a channel using the vorticity–velocity method with power law scheme. Detailed development of axial velocity, secondary flow and temperature field at various axial positions in the entrance region are presented. The friction factor and Nusselt number are presented as a function of axial position, and the effects of the size of porous media inside the channel partially filled with porous medium are also analyzed in the present study.

Keywords: Porous medium; Numerical analysis

1. Introduction

Fluid flow and heat transfer in a channel partially filled with porous medium are important in many engineering applications such as thermal insulation, water movement geothermal reservoirs, grain storage, solar collector, food processing, fuel cells and many other electrochemical systems. In order to optimize the design considerations for various specific applications, it is necessary to better understand fundamental mechanisms in the fluid flow and thermal transport. The influence of velocity, temperature, and pressure distributions in a channel partially filled with porous medium must be mapped into enabling the selection of specific operation parameters for any applications. One of the important applications, for example, is for the heat transfer, fluid flow and mass transport analyses on the membrane electrode assembly (MEA) and gas flow channels in the fuel cell. It is worth noting that fuel cells offer the potential of ultra-low emissions combined with high efficiency power output. Recent rapid advances in fuel cell technology have resulted in a vast increase in fuel cell research and development directed towards wide spread applications, such as electric powered vehicle, wireless communications [1] and stationary power supply [2]. A typical proton exchange membrane (PEM) fuel cell consists of a gas channel; porous media gas diffuser, porous catalyst layer and membrane. It is therefore necessary to analyze

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Nomenclature

A	cross-section area, cm^2
Da	Darcy number, κ/D_e^2
D_e	hydraulic diameter, $4A/S'$, cm
Pr	Prandtl number
R	gas constant, J/mol K
Re	Reynolds number
S	porous layer thickness ratio
S'	perimeter
T	temperature, K
T_m	mean temperature, K
a	channel width, cm
b	porous media thickness, cm
k_{gr}	porous media conductivity
k_{gas}	fluid gas conductivity
u, v, w	velocity in x, y, z-direction, cm/s
p	pressure, Pa

Greek symbols

ε	porosity, 0.5
ρ	density, g/cm^3
κ	permeability, cm^2
ν	kinematic viscosity, cm^2/s
μ	dynamic viscosity, g/cm s
ζ	vorticity

Superscript

$-$	non-dimensional variable

Subscripts

i	inlet
eff	effective

the fluid flow, heat transfer and mass transport inside of the fuel cell to further improve the performance of the fuel cell [3,4].

A general theory and numerical techniques for flow field and heat transfer were developed and simulated in a rectangular duct without porous media have been studied by Clark and Kays [5]. They used numerical method to evaluate Nu for $\alpha^* = 0$, 0.25, 1/3, 0.5, 1/1.4, and using a $10 \times 10\alpha^*$ grid. Here α^* denotes aspect ratio. Miles and Shih [6] refined the calculations by employing a denser grid of $40 \times 40\alpha^*$. Schmidt and Newell [7] used finite difference method to calculate the flow and temperature fields, and compute the Nusselt number. For a porous media channel, most existing related studies on convection heat transfer in composite system were focused on the problem of natural convection [8–17]. There have been very few investigations on the interaction of forced convection on fluid layer and porous layer in a composite system. This type of problem was first investigated by Beavers and Joseph [18]. They presented an empirically based correlation for the velocity gradient at the interface in terms of the velocity in the fluid layer and porous media region. Later, this problem was studied by Vafai and Thiyagaraja [19]. They analytically studied the fluid flow and heat transfer for three types of interfaces: interface between two different porous media, the interface separating a porous medium from a fluid region and the interface between a porous medium and impermeable medium. They obtained an analytical solution based on matched asymptotic expansions for velocity and temperature distribution. Vafai and Kim [20] revisited the same problem and presented an exact solution for the fluid flow without any approximation. In their study, the shear stress in the fluid and the porous medium were taken to be equal at the interface region. The exact solution for the temperature distribution is solved by matched asymptotic double expansion perturbation solution of Vafai and Kim [20].

More recently, Ochoa-Tapia and Whitaker [21] presented a hybrid interface condition. They assumed a jump, which is proportional to the permeability of the porous medium, on the shear stress at the interface region. Ochoa-Tapia and Whitaker [22] also proposed a hybrid interface condition for the heat transfer process, in which they introduce a jump condition to account for possible excess in the heat flux at the interface. Very recently, Alazmi and Vafai [23] critically examined the differences in the fluid flow and heat transfer characteristics due to different interface conditions. In their study, five primary categories for interface conditions for the fluid flow and four primary forms of interface conditions for the heat transfer between a porous medium and a fluid layer were considered.

To date, however, most of these existing related studies on convection in composite systems of porous media were focused on the interface boundaries and/or natural convection in an enclosure [24–30]. To the best of the authors' knowledge, there have not been any investigations on the forced convection in a composite channel with porous medium in the open literature.

The present work constitutes the development of a three-dimensional (3-D) model and the simulation using a novel numerical technique to analyze the general heat convection and fluid flow in a channel partially filled with porous medium. In this study, instead of multiple domains, in which requires the specification of the interface conditions [23], we used a single-domain CFD formulation for porous medium and fluid layer. Using this