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On the thermally developing forced convection through a porous material under the local thermal non-equilibrium condition: An analytical study

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ABSTRACT

The aim of the present analytical study is to investigate a thermally developing forced convective heat transfer inside a channel filled with a porous medium whose walls are imposed to a constant heat flux (i.e. the iso-flux thermal boundary condition). The Darcy's law of motion and the two-energy equation (i.e. local thermal non-equilibrium, LTNE) model are considered. A perturbation analysis is conducted to avoid using any model for the iso-flux thermal boundary condition. Thermally developing forced convection inside a porous-filled channel has previously not been analyzed without implementing a heuristic model for the iso-flux thermal boundary condition. The temperature difference between the fluid and solid phases (called the LTNE intensity) is analytically obtained. Results concerning the LTNE intensity is compared with the available models of the iso-flux thermal boundary condition. In addition, the Nusselt number of a thermally developing convection through a porous material is obtained for the LTNE condition. Also, an expression representing the developing length, i.e. the dimensionless axial location at which the flow becomes fully developed, for a porous-filled channel is proposed for the first time.

1. Introduction

Local thermal non-equilibrium (LTNE) may be observed in various engineering applications including microchannel heat sinks, heat pipes, fluidized beds, dryers, and catalytic reactors, thus, motivating numerous researchers to study the LTNE condition with an aim of accurately predicting the thermal behavior of porous media [1–10]. Amiri et al. [11] numerically focused on the inertial as well as viscous effects of the equation of motion of a fluid saturated porous medium. For the first time, they discussed on the iso-flux thermal boundary condition modeling. Kuznetsov [12] used the Brinkman–Forchheimer-extended Darcy equation to analytically study the LTNE condition for the first time. Kuznetsov [12] discussed the thermal non-equilibrium effects in a channel filled with a fluid saturated porous medium based on a perturbation analysis. Kuznetsov used the results of the previous studies (Vafai and Kim [13,14], and Nield et al. [15]) for the flow field and a two-equation energy model [16,17] for the temperature field and proposed a simplified relation for measuring the LTNE. Using the Darcy's law of motion, Nield and Kuznetsov [16] analytically investigated the conjugate heat transfer problem of a saturated porous channel. Lee and Vafai [17] analytically characterized the forced convective flow through a channel filled with a porous material and obtained the dimensionless temperature for the fluid and solid phases as well as the Nusselt number. Alazmi and Vafai [18] investigated four important categories in modeling the fluid flow and heat transfer through porous media, namely constant and variable porosity, thermal dispersion, and local thermal non-equilibrium phenomena. They numerical experiments showed that the above-mentioned variants have stronger influences on the flow field than the heat transfer. Alazmi and Vafai [19] numerically studied two primary assumptions for the iso-flux thermal boundary condition with seven different sub-models. They found the Nusselt number obtained by each model.

Nield et al. [20] applied a modified Graetz methodology to investigate the thermal development of forced convection in a parallel plate channel filled by a saturated porous medium, with walls held at uniform temperature, and with the effects of axial

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Nomenclature

a_{sf}	specific surface area (m^{-1})
b	a constant value
Bi	Biot number
c_p	specific heat at constant pressure ($J\ kg^{-1}\ K^{-1}$)
d_0, d_n	constant values
d_i, i = 1–4	constant values
d_p	pore diameter (m)
f	an intermediate function
g	an intermediate function
H	half of the channel gap (m)
h_{sf}	fluid–solid heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
k	conductivity ratio ($k_{f,eff}/k_{s,eff}$)
k_f	conductivity of fluid phase ($W\ m^{-1}\ K^{-1}$)
$k_{f,eff}$	effective conductivity of fluid phase ($W\ m^{-1}\ K^{-1}$)
k_m	effective conductivity of the medium ($k_{f,eff} + k_{s,eff}$) ($W\ m^{-1}\ K^{-1}$)
k_s	conductivity of solid phase ($W\ m^{-1}\ K^{-1}$)
$k_{s,eff}$	effective conductivity of solid phase ($W\ m^{-1}\ K^{-1}$)
MA	Model A
MB	Model B
MC	Model C
n	counter
Nu	Nusselt number
O	order of magnitude
Pe	Peclet number
Pr	Prandtl number
q''_w	heat flux at the wall ($W\ m^{-2}$)
Re	Reynolds number
T	temperature (K)
T_i	inlet temperature (K)
u	Darcian velocity ($m\ s^{-1}$)
x^*, y^*	dimensional coordinates (m)
x, y	dimensionless coordinates

Greek letters

ΔNE	LTNE intensity ($\theta_s - \theta_f$)
ε	small parameter ($1/h_{sf}a_{sf}$, $W^{-1}\ m^3\ K$)
θ	dimensionless temperature
ρ	fluid density ($kg\ m^{-3}$)
σ_n	parameter in the obtained dimensionless temperature profile
ϕ	porosity of the medium

Subscripts

dev	developing
f	fluid phase
fd	fully developed component
i	inlet
m	bulk-mean value
n	counter
s	solid phase
w	wall

conduction and viscous dissipation included. Their analysis based on the LTNE assumption led to expressions for the local Nusselt number. Kuznetsov et al. [21] followed a similar methodology to the one used in Nield et al. [20] to investigate the thermally developing forced convection inside a fluid saturated pipe with an isothermal wall. Later, Nield and Kuznetsov [22] applied the classical Graetz methodology to study the thermal development of forced convection in a parallel plate channel filled by a saturated porous medium, with walls held at constant temperature, for the case of a non-Newtonian fluid of power-law type. Nield and Kuznetsov [22] obtained the Nusselt number at LTNE condition. Based on a pore-scale numerical simulation, Jiang and Lu [23] explored effects of the thermal contact resistance between a porous medium and an impermeable wall. They showed that the first approach of the iso-flux thermal boundary condition models (i.e. Model A of Ouyang et al. [7]) gives the closest results to the experiments when the thermal contact resistance is negligible and the wall has a finite thickness. Yang and Vafai [4] analytically investigated the effects of internal heat generations within the fluid and solid phases on the thermal behavior of a channel filled with a porous material. Later on, Yang and Vafai [5] analytically solved the problem of transient forced convection inside a saturated porous medium incorporating the LTNE model. Ouyang et al. [7] derived analytical solutions for thermally developing flows in porous media under LTNE condition for the constant wall heat flux boundary condition. They used three different models to obtain the local Nusselt number and to predict the dimensionless thermal entry length.

Recently based on a perturbation analysis, Dehghan et al. [24,25] investigated the LTNE situation in a fluid saturated channel or pipe filled with a saturated porous material. They proposed a dimensionless number representing the LTNE intensity in terms of pertinent parameters. Following the work of Dehghan et al. [26] who analyzed the heat transfer rate in a solar heat exchanger filled with porous media for the case of combined conduction–convection–radiation heat transfer, Dehghan et al. [27] investigated effects of the slip-flow regime on the combined convective–radiative heat transfer rate. Dehghan et al. [27] showed that the heat transfer rate is mainly controlled by the temperature jump phenomenon. Nield and Kuznetsov [28] analytically obtained the Nusselt number for forced convection heat transfer of nanofluids flow through a clear or porous-filled channel at LTE condition. Dehghan et al. [29] solved the non-linear problem of forced convection inside a porous-filled channel with a temperature-dependent conductivity using the perturbation technique. They found that the Nusselt number increases with a variable conductivity approach.

In the present study, thermally developing forced convection in a fluid saturated porous medium bounded by two infinite parallel-plates held at a constant heat flux is analytically investigated allowing the temperature of fluid and solid phases to be different (LTNE). It is assumed that the Darcy's law governs the fluid motion in the porous medium. The energy equation has been solved by the method of Fourier series. The temperature difference between the solid and fluid phases, called the 'LTNE intensity', is found without the need for implementing any model for the iso-flux thermal boundary condition. In addition, the Nusselt number and thermally developing length are also obtained. To the best of authors' knowledge, no other study has investigated the thermally developing forced convection heat transfer in a porous-filled channel without implementing a model for the iso-flux thermal boundary condition.

2. Mathematical modeling

The schematic diagram of the problem considered in this study is shown in Fig. 1. The following assumptions are invoked in the formulation of the model:

- The flow in the porous medium is incompressible and uniform along the cross-sectional area (Darcy's law).