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Numerical investigation of heat transfer in a micro-porous-channel under variable wall heat flux and variable wall temperature boundary conditions using local thermal non-equilibrium model with internal heat generation

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ABSTRACT

The phenomenon of forced convective heat transfer with internal heat generation in a micro-channel filled with a porous material saturated with a rarefied gas is studied using finite element method by varying wall heat flux and wall temperature ratio under local thermal non-equilibrium (LTNE) conditions. The Darcy–Brinkman model is used to describe the flow inside the porous material. Numerical solutions are obtained for both the fluid and solid temperature distributions by considering the case A for variable wall heat fluxes, case B for variable wall temperature ratio and case C for temperature jump coefficient. The Nusselt number for the fluid at the channel walls is calculated. The effect of significant parameters such as Biot number, wall temperature ratio, fluid and solid internal heat generation, fluid to solid effective thermal conductivity ratio are discussed. Comparative study on Nusselt number is carried out in case A with constant wall heat flux as well as variable wall heat flux. The Nusselt numbers obtained for case B indicate a strong dependency on the variation of internal heat generation for Bi = 0.5. The velocity slip coefficient is found to have negligible effect on the Nusselt numbers for all the three cases.

1. Introduction

Forced convective heat transfer in porous media is encountered in a wide variety of industrial applications such as thermal energy storage, nuclear waste repository, electronic cooling, and geothermal energy utilization and in petroleum industry. Problems in which the temperatures and heat fluxes are changing periodically with time are encountered in many engineering applications. Examples of the physical situations are: (i) heat removal of nuclear fuel debris buried in the deep sea-bed and (ii) heat recovery from geothermal systems. Periodic variation of earth temperature, periodic heating and cooling of buildings, solar heating systems, thermostatically controlled resistance heating systems, nuclear fuel rods, cooling of electronic devices and heat exchangers with variable mass flow rate are some examples which involve internal heat generation [1]. In recent years, research activity in heat transfer in micro and nano scale geometries are rapidly developing due to the incredible growth of micro-electro-mechanical systems (MEMS). Several engineering and biomedical applications have also determined an increasing research interest in micro and nano flows [2–12]. A general introduction on the importance of micro-systems and slip conditions at the boundary of the flow domain is reported in the papers [13–22]. Analysis of heat transfer and fluid flow in micro-channels filled with a porous material under local thermal equilibrium condition has been studied extensively [19,23,24].

Two primary models can be applied for studying heat transfer in a porous medium. They are local thermal equilibrium (LTE) and local thermal non-equilibrium (LTNE) models [16,25–27]. Amiri et al. [28] presented two primary approaches for the constant wall heat flux boundary conditions under the local thermal nonequilibrium condition in porous media. The first is to assume that the total wall heat flux is divided between the two phases based on their effective conductivities and the corresponding temperature gradients with additional boundary conditions that the two phases are in local thermal equilibrium at the wall ($T_{fw} = T_{sw}$). In the second approach, each of the two phases receive an equal

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Nomenclature

a_{sf}	interfacial area per unit volume of porous media (m^1)
Bi	Biot number is defined by Eq. (22)
c_p	specific heat of the fluid, ($J \cdot kg^{-1} \cdot K^{-1}$)
Da	Darcy number, K/H^2
D_H	hydraulic diameter of the channel (2H)
G	negative of the applied pressure gradient ($Pa \cdot m^{-1}$)
h_{sf}	fluid to solid heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
H	height of the micro-channel (m)
K	permeability of the porous medium (m^2)
k	the ratio of fluid effective thermal conductivity to that of the solid is defined by Eq. (22)
k_f	thermal conductivity of the fluid ($W \cdot m^{-1} \cdot K^{-1}$)
$k_{f,eff}$	effective thermal conductivity of the fluid, εk_f
k_s	thermal conductivity of the solid ($W \cdot m^{-1} \cdot K^{-1}$)
$k_{s,eff}$	effective thermal conductivity of the solid, $(1-\varepsilon)k_s$
Kn	Knudsen number based on permeability, $\lambda/\sqrt{K}$
M	viscosity ratio μ_{eff}/μ
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
q_{w1}	bottom wall heat flux ($W \cdot m^{-2}$)
q_{w2}	top wall heat flux ($W \cdot m^{-2}$)
q_{wi}	q_{w1}, q_{w2}
q_{wr}	wall heat flux ratio q_{w1}/q_{w2}
S_f	internal heat generation within the fluid phase $W \cdot m^{-3}$
S_s	internal heat generation within the solid phase $W \cdot m^{-3}$
T	temperature (K)
T_{w1}	bottom wall temperature
T_{w2}	top wall temperature
$T_{f,m}$	average temperature (K)
u	longitudinal velocity (m/s)
$\bar{u}$	average velocity
$\hat{u}$	characteristic velocity
U	dimensionless velocity, u/u_r
$\bar{U}$	dimensionless average velocity
w	$=w_f + w_s$
w_f	parameter defined by Eq. (22)
w_s	parameter defined by Eq. (22)
x	longitudinal coordinate (m)
y	transverse coordinate (m)
Y	dimensionless y coordinate, y/H

Greek symbols

α	velocity slip coefficient is defined by Eq. (2)
β	temperature jump coefficient defined in Eq. (39)
γ	specific heat transfer ratio
ε	porosity of the porous medium
$\Delta\theta$	dimensionless temperature difference $\theta_f - \theta_s$
θ	dimensionless temperature
$\theta_{f,m}$	dimensionless bulk fluid temperature
θ_{w1}, θ_{w2}	wall temperatures
θ_{wr}	wall temperature ratio θ_{w1}/θ_{w2}
λ	mean free path m
μ	viscosity ($kg \cdot m^{-1} \cdot s^1$)
μ_{eff}	effective viscosity of the porous medium ($kg \cdot m^{-1} \cdot s^1$)
ρ	density, (kg/m^3)
σ	accommodation coefficient

Subscripts

eff	effective property
f	fluid
m	mean
s	solid
T	thermal
v	momentum
w	wall

amount of the total heat flux at the pipe wall ($q_{fw} = q_{sw}$). Using one of the two primary approaches given in Amiri et al. [28] based on the two equation model Lee and Vafai [29] investigated the forced convective flow through a channel filled with a porous medium subjected to a constant heat flux, and derived exact solutions for both fluid and solid phase temperature fields. Marafie and Vafai [30] used the Brinkman-Forchhiemer analysis and obtained analytical solutions for the fluid and solid phase temperature distributions for the forced convective flow through a channel filled with a porous medium with a constant heat flux boundary conditions. Alazmi and Vafai [27] presented a comprehensive analysis of the effect of using different boundary conditions for the case of constant wall heat flux under the local thermal non-equilibrium condition.

Yang and Vafai [17] analyzed the phenomenon of temperature gradient bifurcation in a porous medium, with internal heat generation. A local thermal non-equilibrium (LTNE) model is used to represent the energy transport within the porous medium. Exact solutions are derived for both fluid and solid temperature distributions for the constant wall heat flux boundary conditions. Buonomo et al. [18] studied the forced convection heat transfer in a micro-channel filled with a porous material, whose channel walls were subjected to constant heat flux boundary conditions, by employing Darcy–Brinkman model under LTNE conditions. Exact solutions for the fluid and solid temperature fields as well as the Nusselt number were obtained as a function of various pertinent parameters. They have reported that the Nusselt number initially increases with the increase in Biot number and reached a constant asymptotic LTE Nusselt number later.

Yasser Mahmoudi [16] studied forced convection heat transfer in a micro-channel filled with a porous material saturated with rarefied gas with internal heat generation analytically. He used the boundary conditions of constant wall heat flux under local thermal non-equilibrium (LTNE) conditions. He studied the thermal behaviour of the porous-fluid system by considering thermally and hydrodynamically fully-developed conditions. The flow inside the porous material is modeled by the Darcy–Brinkman equation. Exact solutions were obtained for both fluid and solid temperature distributions using constant wall heat flux boundary conditions. The results indicate that the Nusselt number decreases with the increase of thermal conductivity ratio for both the models. This contrasts results from earlier studies [18] that the Nusselt number increases with the increase of thermal conductivity ratio when the solid temperature is equal to the fluid temperature at the boundary walls. The Biot number and thermal conductivity ratio are found to have substantial effects on the role of temperature jump coefficient in controlling the Nusselt number. It is shown that the Nusselt number varies drastically with the variation of solid internal heat generation when solid temperature is equal to the fluid temperature at the boundary walls [16].

Shokouhmand and Jomeh [31] studied slip-flow convection heat transfer in thermal entry region of a rectangular micro-channel. The wall heat flux is peripherally constant and varied exponentially with respect to the axis of the micro-channel. The three-dimensional energy conservation equation has been solved numerically for different aspect ratios. The fully-developed Nusselt numbers are obtained for different values of the parameter defined in the exponential function of heat flux. Results were also obtained