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Forced convection in porous microchannels with viscous dissipation in local thermal non-equilibrium conditions☆

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ABSTRACT

Fully developed, steady-state forced convection, in parallel-plate microchannels, filled with a porous medium saturated with rarefied gases at high temperatures, in local thermal non-equilibrium (LTNE) condition, is investigated for the first-order slip-flow regime ($0 \leq Kn \leq 0.1$). Both velocity and temperature jumps at the walls are accounted for. An analytic solution is proposed for the Darcy–extended Brinkman flow model with assigned uniform heat flux at the microchannel walls and viscous heat dissipation in the fluid phase. The solution for NTLE includes the shear work done by the slipping effects. A closed-form expression of the Nusselt number is derived. A validation analysis with respect to the case of channels filled with saturated porous medium is accomplished. The results show that the internal dissipation increases as the velocity slip increases. In addition, the heat dissipation strongly affects the fluid temperature profiles. The increases in velocity slip and temperature jump lead to decreases of temperature gradients in the fluid and solid along the sections. The heat transfer at channel walls is enhanced due to an increase in the bulk heat transfer.

1. Introduction

The continuous micro-devices growth in several applications such as biomedical instrumentations, electronic packaging, micro-mechanics and avionics has determined an intense research activity in fluid flow and heat transfer at micro and nanoscales. In gas flows at microscale, the Knudsen number, Kn, defined as the ratio of the fluid mean free path to the macroscopic length scale of the physical system, λ/L_{ref}, is generally used to classify the flow into four regimes [1,2]: continuum no-slip-flow regime ($Kn < 0.001$), continuum slip-flow regime ($0.001 < Kn < 0.1$), transitional flow regime ($0.1 < Kn < 10$) and free molecular flow regime ($Kn > 10$). Many investigations have been conducted on forced convection in single phase flow in channels, tubes and ducts at microscale as reviewed in [3,4], for example.

The effects of viscous dissipation determine an important condition on fluid and thermal behavior in the analysis of forced convection in micro flows and in porous media. Their contribution should be taken into account also at moderate velocity, as indicated, for example, in [5–9]. Moreover, research interest has been recently focused on microchannels and microtubes filled with porous medium due to their applications in micro filtration, fractionation, catalysis and microbiology, as underlined in [10–12]. However, forced convection in porous media embedded in microchannels and microtubes does not seem widely studied. In fact, analytical and/or numerical solutions for different geometrical and thermal conditions should mainly be examined in local thermal non-equilibrium (LTNE), which has received much less attention, as recently emphasized in [11,12]. In what follows, a short review of the studies dealing with microchannels and microtubes filled with porous media is presented.

Haddad et al. [13] studied numerically the developing hydrodynamic and thermal behaviors of free convection gas flow in a vertically open-ended, parallel-plate microchannel filled with porous media in LTNE. Nield and Kuznetsov [14] proposed analytical solutions for forced convection with slip flows in parallel-plate channels and circular ducts saturated by a rarefied gas in LTE. Haddad et al. [15,16] presented numerical investigations on forced convection slip flow in parallel-plate channels, at uniform wall temperature, filled with porous media assuming LTE condition in [15] and considering LTNE in [16]. Haddad et al. [17] accomplished the analysis on forced convection slip flow in a circular microchannel filled with porous media with the wall at uniform temperature. Hooman [18,19] carried out a numerical analysis for two and three-dimensional disturbances on fully developed forced convection in a rectangular microchannel, filled with or without a porous medium using a collocation method. Kuznetsov and Nield [20] derived analytical solutions for forced convection in a parallel-plate channel or in a circular tube filled with a hyperporous medium saturated by a rarefied gas and in LTE condition, with walls held at constant

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Nomenclature

Bi	Biot number, Eq. (15)
Br	Brinkman number, Eq. (15)
c_p	specific heat, kJ/kg K
Da	Darcy number, $Da = K/H^2$
G	negative of the applied pressure gradient, Pa/m
h_v	volumetric heat transfer coefficient, W/(m^3 °C)
$2H$	channel height, m
K	permeability, m^2
k	thermal conductivity, W/(mK)
Kn	Knudsen number, $Kn = \lambda/H$
l	channel length, m
M	viscosity ratio, $M = \mu_e/\mu$
Nu	average Nusselt number, Eq. (28)
p	pressure, Pa
Pr	Prandtl number
$\dot{q}_w$	heat flux, W/m^2
$\dot{q}_{w,m}$	modified wall heat flux, Eq. (5b), W/m^2
T	temperature, K
T_m	bulk mean temperature, Eq. (6), K
u	velocity, m/s
U	dimensionless velocity, Eq. (10)
u_m	mean velocity, Eq. (6), m/s
$\hat{u}$	dimensionless velocity, $\hat{u} = u/u_m$
x,y	coordinates, m
Y	dimensionless coordinate, $Y = y/H$

Greek symbols

α	velocity slip coefficient, Eq. (10)
β	temperature jump coefficient, Eq. (15)
ε	porosity
γ	specific heat capacity ratio, $\gamma = c_p/c_v$
κ	effective thermal conductive ratio, Eq. (15)
λ	mean free path, m
μ	dynamic viscosity, Pa s
μ_e	effective dynamic viscosity, Pa s
θ	dimensionless temperature
$\theta_{f,m}$	dimensionless bulk fluid temperature, Eq. (24)
ρ	density, kg/m^3
σ_T, σ_v	accommodation coefficients
ω	porous medium shape parameter, $\omega = (M\,Da)^{-1/2}$
eff	effective
eq	equivalent
f	fluid
s	solid

heat flux. Chauhan and Kumar [21] studied also, under the LTE condition, the fully developed forced convection in a circular channel filled with a highly porous medium, saturated with a rarefied gas in the slip-flow regime, for imposed uniform heat flux at the tube wall. Shokouhmand et al. [10] carried out numerical solutions of a fully developed flow for thermally developing forced convection in a circular micro/nanochannel filled with porous media by assuming LTE. Hashemi et al. [22] investigated analytically the fully developed forced convection of a dilute gas in a porous annular microduct under LTE assumption. Numerical investigations on microchannel heat sinks with porous media have been presented in [23,24].

More recently, several analytical and numerical investigations on convective heat transfer in micro-passages filled with porous media, in slip-flow regime for $Kn < 0.1$, have been accomplished in [25–35] under the LTNE assumption. A microchannel filled with a porous medium was studied by Dehghan et al. [25] for assigned wall heat fluxes. Analytical solutions for both the fluid and solid temperature distributions within a microtube and a micro-annulus filled with porous media were proposed by Wang et al. [26,27] for prescribed wall heat flux. An investigation on forced convection heat transfer in rarefied gas in microchannels filled with porous media and internal generation was conducted analytically by Mahmoudi [28]. Thermal boundary conditions for constant wall heat flux were examined. An analytical investigation of heat transfer performances for microchannels filled with porous media was performed by Dehghan et al. [29], who have presented performance maps for prescribed wall heat flux and internal heat generation. The configuration studied in [29] was anew considered by Dehghan et al. [30] for thermally developing forced convection. An analytic study on forced convection in microchannels filled with microfoams, asymmetrically heated at uniform heat fluxes, was presented by Xu et al. [31]. The combined convection–radiation heat transfer inside a microchannel filled with a porous medium was numerically investigated by Dehghan et al. [32]. The effect of viscous dissipation on the thermal characteristics of nanofluid flows through porous media embedded in microchannels subjected to uniform wall heat flux was investigated by Ting et al. [12,33–35] by assuming LTNE. The effective viscosity of the water–Al_2O_3 nanofluid was modeled using a modified Einstein model, and the viscous dissipation term in the energy equation for the fluid phase was based on the formulation suggested by Al-Hadhrami et al. [36]. Analytical solutions of the two-dimensional temperature distributions were obtained for the models with and without the viscous dissipation term in the energy equation. It was found that the use of porous medium may lead to enhance the thermal performance, especially when increasing the channel aspect ratio or the thermal conductivity of the porous matrix.

It should be noted that the viscous dissipation effect in gaseous forced convection in microchannels and microducts filled with porous media does not seem to have been fully investigated. Therefore, there is a lack of knowledge on this topic though the use of micro systems filled with porous media is growing in applications. In the present study, an analytical solution for fully developed forced convection in microchannels filled with an air-saturated porous medium is derived with the viscous dissipation accounted for. The solution is given for prescribed and uniform wall heat fluxes and first-order slip velocity and temperature jump conditions.

2. Analysis and mathematical model

2.1. Governing equations

The steady, laminar forced convection of air through parallel-plate microchannels filled with a porous medium is considered in the present study. The geometry, along with the coordinate system, is shown in Fig. 1. The two parallel walls are distant from $2H$, and uniform wall heat fluxes are applied on both the channel walls. The fluid flow through the porous matrix is assumed incompressible, hydrodynamically and thermally developed (constant thermo-physical properties). Moreover, the buoyancy force, dispersion and radiative heat transfer are considered negligible, whereas the viscous dissipation is taken into account. The Darcy-extended Brinkman model and LTNE conditions with a rigid solid matrix are considered. The porous solid matrix is assumed isotropic and homogeneous. In the present investigation, the Knudsen number is defined as the ratio of the fluid mean free path to the half-channel gap ($Kn = \lambda/H$) and is assumed to be less than $Kn = 0.1$.

The conservation equations related to momentum and energy are [11]:

Darcy–Brinkman momentum equation

$$G = \frac{\mu}{K}u - \mu_e\frac{d^2u}{dy^2} \tag{1}$$

where $G = \Delta p/l$ is the negative of the pressure gradient applied between the inlet and the outlet sections of the channel of length l. K