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Microchannels enhanced by porous materials: Heat transfer enhancement or pressure drop increment?

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ABSTRACT

The analytical heat transfer performance study (i.e. HTP, introduced as the ratio of the heat transfer rate enhancement to the pressure drop increment) for microchannels enhanced by a porous material is performed. The Darcy–Brinkman equation of motion and the two-energy equation model for heat transfer within the porous material (i.e. the local thermal non-equilibrium condition, LTNE) are used to find the Poiseuille (Po) and Nusselt (Nu) numbers in the slip-flow regime (i.e. when the Knudsen number, Kn, < 0.1). To cover a wide range of heat exchangers, effects of hydrodynamical characteristics of the porous material (i.e. porosity, ϕ, and Darcy number, Da), the effective thermal conductivity ratio (k), the interphase convective heat exchange between the two phases (Bi), the velocity-slip and temperature-jump coefficients (α and β), the dimensionless thermal resistance of the walls (R_w), and the internal heat generations within the solid and fluid phases of the porous material (ω_f and ω_s) are considered. HTP maps are presented for a wide variation range of all pertinent parameters to design or to select a micro-heat exchanger according to the heat transfer enhancement with respect to the pressure drop cost. Results reveal that the HTP may effectively be increased by inserting rarefied porous inserts. The present analysis suggests the implementation of porous inserts within flow passages especially when $0.001 < Kn < 0.1$ (the slip-flow regime).

1. Introduction

Besides decreasing the dimension of flow passage to improve the heat transfer ability per unit area of conventional heat exchangers [1–7], other novel techniques are used to enhance the thermal performance of such systems like using converging flow passages [8–10], geometrical optimizations [11–15], or filling the flow passages with porous materials [16–21]. Microchannels have been used in industries and researches from electronic cooling to biotechnology. To find the practical applications, the current status and the future needs of microchannels one can refer to Refs. [4,22–27].

A micro-scale channel filled with a porous material has been numerically and analytically investigated by Haddad et al. [28] and Nield and Kuznetsov [29], respectively, for the first time. Haddad et al. [28,30,31], Nield and Kuznetsov [29] and Al-Nimr and Haddad [32] discussed the flow behavior and the heat transfer rate of such porous filled micro-channels in the slip-flow regime as pioneering studies. Hooman [33,34] used Fourier series expansion method to find dimensionless velocity and temperature profiles for rectangular microchannels filled with porous media in the slip-flow regime. Developing convection heat transfer of porous-filled flow passages was studied by Kuznetsov and Nield [35] in the slip-flow regime, for the first time. Shokouhmand et al. [36] numerically investigated the heat and fluid flow through porous-filled micro-circular passages considering velocity-slip and temperature-jump at the wall. Hashemi et al. [37] used Bessel functions to study the flow and heat transfer in a porous annulus in the-slip flow regime. All above-mentioned articles assumed the local thermal equilibrium condition (i.e. the one equation energy model). For the first time under the local thermal non-equilibrium (LTNE) condition, Buonomo et al. [38] studied the fully developed heat transfer of a micro-channel filled with a porous material. Most recently, Dehghan et al. [39] analyzed the heat flux splitting (or the heat flux bifurcation phenomenon introduced by Yang and Vafai [40]) for a channel fully filled with a porous material under LTNE condition in the slip-flow regime. They also discussed the validity region of the local thermal equilibrium (LTE) condition in the no-slip and slip-flow regimes. Dehghan [41] recently analyzed the thermal response of partially porous-filled channels under the LTNE condition. He also introduced the heat flux bifurcation for channels partially filled with porous materials.

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Nomenclature

a_{sf} specific surface area (m^{-1})
Bi the interphase heat transfer parameter or Biot number (defined by Eq. (27))
c_p specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
D_h hydraulic diameter (m)
d_p particle diameter (m)
fr friction factor (used in Eq. (20))
G negative of the axial pressure gradient ($N\,m^{-3}$, $-dP/dx^*$)
HTP heat transfer performance (defined by Eq. (1))
H half of the channel height (m)
h_{sf} fluid–solid heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k effective conductivity ratio ($k_{f,eff}/k_{s,eff}$)
k_f thermal conductivity of fluid phase ($W\,m^{-1}\,K^{-1}$)
$k_{f,eff}$ effective thermal conductivity of fluid phase ($W\,m^{-1}\,K^{-1}$)
k_m effective thermal conductivity of the medium ($W\,m^{-1}\,K^{-1}$, $k_{f,eff} + k_{s,eff}$)
k_{rw} ratio of wall conductivity to the effective conductivity of solid phase ($k_w/k_{s,eff}$)
k_s thermal conductivity of solid phase ($W\,m^{-1}\,K^{-1}$)
$k_{s,eff}$ effective thermal conductivity of solid phase ($W\,m^{-1}\,K^{-1}$)
k_w thermal conductivity of wall ($W\,m^{-1}\,K^{-1}$)
Kn Knudsen number (l/D_h)
l molecular mean-free-path of the fluid
Nu Nusselt number
P intrinsic pressure of the fluid phase ($N\,m^{-2}$)
Pe Peclet number ($Pe = Re^*Pr$).
Po Poiseuille number (defined by Eq. (20))
Pr Prandtl number
q''_w heat flux at the wall ($W\,m^{-2}$)
R_w dimensionless thermal resistance of the wall (τ/k_{rw})
Re Reynolds number ($\rho \times u_m^* \times 4H/\mu$)
S porous medium shape parameter (defined by Eq. (19))
S_f internal heat generation within the fluid phase ($W\,m^{-3}$)
S_s internal heat generation within the solid phase ($W\,m^{-3}$)
T temperature (K)
t wall thickness (m)
u^* velocity ($m\,s^{-1}$)
$\hat{u}$ normalized velocity
u dimensionless velocity
$x^*,\ y^*$ dimensional coordinates (m)
$x,\ y$ dimensionless coordinates

Greek letters
α^* velocity-slip coefficient (defined by Eq. (14))
α dimensionless velocity-slip coefficient (defined by Eq. (18))
β^* temperature-jump coefficient (m, defined by Eq. (15))
β dimensionless temperature-jump coefficient (defined by Eq. (27))
ε_h pressure drop increment (defined by Eq. (3))
ε_{th} heat transfer increment (defined by Eq. (2))
θ dimensionless temperature (defined by Eq. (18))
λ heat transfer parameter ($\lambda = \sqrt{Bi(k+1)/k}$, defined by Eq. (27))
μ fluid viscosity ($kg\,m^{-1}\,s^{-1}$, used in Eq. (1))
μ_{eff} fluid viscosity ($\mu_{eff} = \mu/\phi$, $kg\,m^{-1}\,s^{-1}$, used in Eq. (4))
ρ fluid density ($kg\,m^{-3}$)
τ dimensionless thickness of wall (defined by Eq. (27))
ϕ porosity of the medium
ω heat generation parameter (defined by Eq. (27))

Subscripts
1–3 identifiers
c clear-fluid flow (without porous materials)
f fluid phase
m mean value
p filled with porous materials
s solid phase
w wall

Besides using the theory of porous media to analyze the micro-scale flow passages filled with a porous material, a practical approach to model the microchannel heat sinks (MCHS) was introduced by Koh and Colony [42] based on the Darcy's law of motion and the theory of porous media (i.e. an averaging procedure over the cross-sectional area) to find the temperature distribution. The theory of porous media for analyzing the MCHS has been improved by Kim and Kim [43], Kim [44], and Deng et al. [45] by incorporating the wall effects on the velocity profile (i.e. the Darcy–Brinkman equation of motion), by considering different temperatures for solid walls and fluid flowing through the walls (i.e. LTNE condition), and by considering the conjugate heat transfer (i.e. combining the conduction in the walls of a microchannel heat sink and the forced convection through channels). Later, Chen and Ding [46] numerically investigated a microchannel heat sink (MCHS) enhanced by nanoparticles in the no-slip flow regime. Using the porous media approach for their system, Chen and Ding [46] discussed the total thermal resistance of a MCHS.

To find a measure to the heat transfer enhancement versus the pressure drop increment by porous inserts, Cekmer et al. [47] introduced the heat transfer performance (HTP) definition. Cekmer et al. [47] discussed the HTP (i.e. the heat transfer and pressure drop increment ratios) of a channel partially filled with porous media under LTE condition. Recently, Mahmoudi et al. [48] extended the HTP study of Cekmer et al. [47] based on the LTNE condition. They assumed different porous-fluid interface models. Meanwhile, Wang et al. [49] numerically investigated the heat transfer enhancement and the friction factor reduction by implementing gradient porous materials (GPM). No analytical, numerical, or experimental study has been presented on the HTP of channels filled with a porous material for the slip-flow regime and for the conjugate heat transfer. Consequently, the present study has been conducted to discuss the HTP of porous-filled microchannels to find their performance maps in the slip-flow regime under the LTNE condition. It is tried to answer whether the heat transfer enhancement obtained by porous inserts is comparable with its pressure drop increment, especially in the slip-flow regime? To conclude a fundamental and comprehensive study, effects of the conduction heat transfer of the channel walls (i.e. the conjugate heat transfer) as well as the presence of heat source/sink within the fluid and solid phases of the porous medium have been considered. Effects of pertinent parameters (S, k, Bi, ω, α, and β) on the HTP are discussed.

2. Mathematical modeling

2.1. HTP definition

The HTP shows the heat transfer enhancement (arising from inserting a porous material inside the channel) divided by pressure