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Entropy generation of viscous dissipative flow in thermal non-equilibrium porous media with thermal asymmetries

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ABSTRACT

The effect of thermal asymmetrical boundaries on entropy generation of viscous dissipative flow of forced convection in thermal non-equilibrium porous media is analytically studied. The two-dimensional temperature, Nusselt number and entropy generation contours are analysed comprehensively to provide insights into the underlying physical significance of the effect on entropy generation. By incorporating the effects of viscous dissipation and thermal non-equilibrium, the first-law and second-law characteristics of porous-medium flow are investigated *via* various pertinent parameters, i.e. heat flux ratio, effective thermal conductivity ratio, Darcy number, Biot number and averaged fluid velocity. For the case of symmetrical wall heat flux, an optimum condition with a high Nusselt number and a low entropy generation is identified at a Darcy number of 10^{-4}, providing an ideal operating condition from the second-law aspect. This type of heat and fluid transport in porous media covers a wide range of engineering applications, involving porous insulation, packed-bed catalytic process in nuclear reactors, filtration transpiration cooling, and modelling of transport phenomena of microchannel heat sinks.

1. Introduction

Forced convective heat transfer in porous media prevails in versatile engineering applications such as electronics cooling, porous insulation, catalytic reactors and flow of liquid in biological and physiological processes. Due to the presence of frictional heating arising from increasing contact of fluid and solid phases and the wall as well as internal heating associated with the mechanical power needed to extrude the fluid through a porous medium, the effect of viscous dissipation is essentially significant as compared to that of clear-fluid flow [1–5]. Viscous dissipation which manifests itself as a source term in the fluid flow induces appreciable rise in fluid temperature due to the conversion of kinetic motion of fluid to thermal energy. Most of the related studies involving viscous dissipation effect in porous-medium flow employed the one-equation model which assumes both the solid and fluid phases to be in locally thermal equilibrium [6–10]. However, the distinctive thermophysical properties of solid phase and fluid phase in a porous medium instigate considerable thermal resistance at the interface between the two phases and induce significant temperature difference between the two phases, invalidating the assumption of local thermal equilibrium [11]. By considering viscous dissipation effect of force convection in porous medium subjected to uniform wall heat fluxes, the one-equation-model deviates significantly from the two-equation model and the Nusselt number is strongly affected by viscous dissipation [5,12]. On the other hand, studies of asymmetrical thermal boundaries on forced convection heat transfer in porous channel are relatively scarce. By employing the local thermal equilibrium model, Mondal [13] investigated asymmetrical heating and cooling of a porous medium in a parallel plate channel subjected to constant wall temperatures with internal heat generation. Therefore, the issue of coupled effects of thermal asymmetries and local thermal non-equilibrium on forced convection in porous media poses an interesting subject to be addressed and investigated.

Apart from the analysis based on the basic conservation laws, the second-law analysis dealing with entropy generation attributed to thermodynamic irreversibilities is crucial for optimum operating conditions in designing a system with less entropy and exergy destruction. In accordance to the Gouy–Stodola theorem, the loss of the available work of the system is directly proportional to the entropy generation [14]. This type of engineering approach which is known as EGM (Entropy Generation Minimization) is a robust design tool in applied thermal engineering applications [15–19].

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Nomenclature

A	temperature gradient along the channel (K)
a	specific surface area (m^{-1})
Be	local Bejan number
Bi	Biot number
Br	Brinkman number
Br'	clear-fluid Brinkman number
B_1	bottom wall inlet temperature (K)
B_2	top wall inlet temperature (K)
c_p	fluid specific heat capacity (J kg^{-1} K^{-1})
Da	Darcy number
FFI	dimensionless fluid friction irreversibility
H	half-height of the channel (m)
h	local interstitial heat transfer coefficient (W m^{-2} K^{-1})
h_{eff}	system effective convective heat transfer coefficient (W m^{-2} K^{-1})
$\bar{h}$	specific enthalpy (J kg^{-1})
HTI	dimensionless heat transfer irreversibility
K	porous medium permeability (m^2)
k_f	fluid thermal conductivity (W m^{-1} K^{-1})
k_{fe}	effective fluid thermal conductivity (W m^{-1} K^{-1})
k_r	effective thermal conductivity ratio
k_{se}	effective porous medium solid thermal conductivity (W m^{-1} K^{-1})
L	length of channel (m)
M	ratio of effective viscosity to fluid viscosity as defined in Eq. (2)
Nu	Nusselt number
P	fluid pressure (Pa)
q	heat flux (W m^{-2})
q_r	ratio of top wall heat flux to bottom wall heat flux
Re	reynolds number
S	porous medium shape factor as defined in Eq. (6)
s	specific entropy (J kg^{-1} K^{-1})
$\dot{S}'''_{gen}$	entropy generation rate per unit volume (W K^{-1} m^{-3})
S_{gen}	dimensionless entropy generation rate per unit volume
S_{genY}	channel-height averaged dimensionless entropy generation rate per unit volume
S_{genYX}	domain averaged dimensionless entropy generation rate per unit volume
T	temperature (K)
$\langle T \rangle$	bulk mean temperature (K)
V	dimensionless fluid velocity
$\langle V \rangle$	channel-height averaged dimensionless velocity (m s^{-1})
v	fluid velocity (m s^{-1})
x	longitudinal coordinates (m)
X	dimensionless longitudinal coordinates
y	transverse coordinate (m)
Y	dimensionless transverse coordinate

Greek symbols

ε	porosity of porous medium
μ	fluid viscosity (N s m^{-2})
μ_{eff}	effective viscosity (N s m^{-2})
ρ	fluid density (kg m^{-3})
θ	dimensionless temperature profile
$\langle \theta \rangle$	dimensionless bulk mean temperature

Subscripts

f	of fluid phase
s	of solid phase
$w1$	of bottom wall
$w2$	of top wall

Recently, a number of studies dealing with entropy analysis for internal forced convection have been reported [19–27]. However, there exist only limited studies on entropy generation of thermal non-equilibrium porous medium flow. The entropy generation of rarefied gaseous slip flow in micro-porous channel was studied under thermal non-equilibrium condition without considering viscous dissipation in the energy equation [28]. In another numerical modelling, the thermal non-equilibrium model was employed to investigate the entropy generation of natural convection in a saturated porous cavity [29]. On the other hand, the two-energy-equation model with viscous dissipation effect was used and the volume-averaged entropy generation function was developed and analysed numerically [30]. Ting et al. [31] pointed out that the entropy generation is intimately related to the effectiveness of the interstitial heat transfer between the solid and fluid phases of nanofluid flow in porous media, substantiating the significance of thermal non-equilibrium condition in the second-law analysis.

This study aims to analyse the forced convection of viscous dissipative flow in porous media subjected to thermal asymmetries from the first-law and the second-law thermodynamic aspects. Particularly, the second-law analysis associated with the effects of thermal asymmetry on forced convection in a thermal non-equilibrium porous media is still unavailable in the existing literature. By incorporating thermal asymmetric boundaries and utilizing thermal non-equilibrium model for forced convection in a porous medium, we obtain the two-dimensional closed-form solutions of temperature profiles of solid and fluid phases and derive the two-dimensional entropy generation analytically by considering the interstitial heat transfer between the solid and fluid phases. With the variations of various pertinent parameters such as Darcy number, Brinkman number and Biot number, the thermal non-equilibrium entropy generation is scrutinized under various cases of asymmetrical heat fluxes. We perform a comprehensive study to delineate the essential attributes of the underlying physical significance of the thermal asymmetries in the entropy generation of viscous dissipative flow in porous media.

2. Mathematical formulation

2.1. First-law formulation

The working fluid flows through a porous medium embedded in channel between two parallel plates subjected to asymmetrical thermal boundary conditions as illustrated in Fig. 1. For steady-state fully developed laminar flow in a porous medium between infinitely wide parallel plates, the Brinkman momentum equation is given by

$$-\frac{\mu}{K}v_x + \mu_{eff}\frac{d^2v_x}{dy^2} - \frac{dP}{dx} = 0, \quad (1)$$

where μ and μ_{eff} are the fluid viscosity and the effective viscosity of porous medium, respectively, K is the permeability, v_x is the fluid velocity and P is the pressure. The Forchheimer term is neglected in Eq. (1). This term is only dominant for high Reynolds number flow