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Entropy generation of viscous dissipative nanofluid flow in thermal non-equilibrium porous media embedded in microchannels

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ABSTRACT

Based on the first-law and second-law of thermodynamics, we investigate thermal performance and entropy generation of water–alumina nanofluid flows in porous media embedded in a microchannel under local thermal non-equilibrium condition. Analytical closed-form solutions of two-dimensional temperature distributions are obtained for the cases with and without the viscous dissipation term in the energy equation. The thermal non-equilibrium entropy generation function is derived using the differential method. Due to the embedment of the porous medium in the microchannel and the suspension of the nanoparticle in the working fluid, the viscous dissipation effect is magnified significantly, altering thermal characteristics and entropy generation of the system. For the case where the viscous dissipation effect is neglected, total entropy generation and fluid friction irreversibility are overrated while heat transfer irreversibility is remarkably underestimated. In a low-aspect-ratio microchannel, the suspension of nanoparticles in the fluid decreases the thermodynamic efficiency from the second-law point of view. Utilization of nanofluids in a high-aspect-ratio microchannel enhances exergetic effectiveness in low-Reynolds-number flow regime. By reducing the nanoparticle size, entropy generation can be decreased by as much as 73%. The optimum Reynolds number associated with minimum entropy generation for nanofluid flow in a porous microchannel is identified. The optimum range of porous medium permeability is characterized by $\mathrm{Da} \geqslant 10^{-1}$. It is observed that effectiveness of the interstitial heat transfer between the solid and fluid phases of the porous medium induces a pronounced effect on the entropy generation, signifying the importance to consider the thermal non-equilibrium condition in the second-law performance analysis of porous-medium flow.

1. Introduction

The miniaturization of electronic devices has led to an appreciable hike in the local temperature ascribable to the high density power dissipation rate. The thermal management in such devices has become a challenging issue. Micro-scale heat transfer becomes a topical subject and innovative methods have been devised to improve the thermal performance of heat sinks. Microchannel heat sink manifests itself as an efficient and robust device to increase the thermal performance in a confined space [1]. By embedding porous media into the microchannels, the surface contact area-to-volume ratio of the flow can be increased. It is reported that the thermal performance of a microporous heat exchanger is higher than that of a conventional microchannel [2]. In the presence of porous media, the local velocity mixing of working fluid is enhanced, leading to a high heat transfer coefficient [3]. Therefore, the embedment of porous media in a microchannel appears to be a promising high-heat-flux removal method in miniaturized devices [4]. However, the choice of working fluid is also of great importance. The low thermal conductivity of the fluid poses a primary limitation to the performance of the thermal heat sink. By suspending nano-scale solid particles in conventional fluid, the effective thermal conductivity can be augmented significantly, leading to enhancement of heat transfer performance. This kind of fluid was coined “nanofluid” [5]. Numerous studies show the great potential of nanofluids in enhancing heat transfer performance of the flow [1,6,7]. Besides, various studies have been performed to investigate hydrodynamic and thermal characteristics of nanofluids [8–12].

By combining the second-law of thermodynamics with the principles of fluid mechanics and heat transfer, the irreversibility or the degree of thermodynamic non-ideality of the system which affects energy efficiency of a system can be scrutinized. Based on the Gouy-Stodola theorem, loss of available work is directly proportional to entropy generation, which is a measure of irreversibility in a system

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Nomenclature

a_i	specific surface area ($\mathrm{m^{-1}}$)
Be	Bejan number
Bi	Biot number
Br'	modified Brinkman number
c_p	specific heat ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
D	hydraulic diameter of microchannel (m)
Da	Darcy number
d_p	diameter of nanoparticle (m)
h	heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
h_i	interstitial heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
H	half-height of the microchannel (m)
k	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
K	permeability ($\mathrm{m^2}$)
Kn	Knudsen number
L	length of the microchannel (m)
M	viscosity ratio as defined in Eq. (8)
N_S	dimensionless entropy generation
N_HT	dimensionless heat transfer irreversibility
N_FF	dimensionless fluid friction irreversibility
Nu	Nusselt number
Pr	Prandtl number
q	heat flux ($\mathrm{W\,m^{-2}}$)
Re	Reynolds number
S	shape factor of the porous medium
$\dot{S}'''_\mathrm{gen}$	volumetric rate of entropy generation ($\mathrm{W\,m^{-3}\,K^{-1}}$)
$\dot{S}'''_\mathrm{HT}$	volumetric rate of heat transfer irreversibility ($\mathrm{W\,m^{-3}\,K^{-1}}$)
$\dot{S}'''_\mathrm{FF}$	volumetric rate of fluid friction irreversibility ($\mathrm{W\,m^{-3}\,K^{-1}}$)
T	temperature (K)
$\overline{T}$	bulk mean temperature (K)
u	nanofluid velocity ($\mathrm{m\,s^{-1}}$)
$\bar{u}$	cross-sectional averaged nanofluid velocity ($\mathrm{m\,s^{-1}}$)
U	dimensionless nanofluid velocity
$\bar{U}$	cross-sectional averaged dimensionless nanofluid velocity
x	longitudinal coordinate (m)
X	dimensionless longitudinal coordinate
y	transverse coordinate (m)
Y	dimensionless transverse coordinate

Greek symbols

ϕ	nanoparticle volume fraction
θ	dimensionless temperature
κ	effective thermal conductivity ratio as defined in Eq. (23)
μ	dynamic viscosity ($\mathrm{N\,s\,m^{-2}}$)
ρ	density ($\mathrm{kg\,m^{-3}}$)
λ	molecular mean free path (m)
ξ	aspect ratio of the microchannel
ε	porosity of the porous medium
ϖ	dimensionless heat flux

Subscripts

eff	of porous medium effective properties
f	of base fluid
fh	of frictional heat generation
ih	of internal heat generation
in	value at the channel entrance
nf	of nanofluid
p	of nanoparticle
s	of porous medium solid phase
vd	of viscous dissipation
w	of channel wall
1	of Model 1
2	of Model 2

[13]. Optimization may therefore be carried out to minimize entropy generation in the system, leading to optimal engineering design which makes the thermodynamics and heat transfer process more "applicable" [13]. This engineering research approach has been known as Entropy Generation Minimization (EGM) [13]. EGM appears as a powerful tool to optimize efficiency of various heat transfer and fluids engineering devices [14–17]. A review on entropy generation of nanofluid flow shows that suspension of nanoparticle in a conventional fluid can be very beneficial in decreasing entropy generation [18]. By incorporating the viscous dissipation effect, entropy generation of nanofluid flow in a microchannel increases with nanoparticle volume fraction which reduces exergetic effectiveness of the flow [14,18]. The viscous dissipation effect is particularly significant in a microchannel due to its large length-to-diameter ratio, and is further enhanced in fluids of low specific heat and high viscosity, such as nanofluids of which the specific heat is reduced and the viscosity is increased due to the suspension of solid nanoparticles in the fluid [19].

For forced convection in porous media, the effect of viscous dissipation is essentially indispensable due to the presence of the frictional heating arising from increasing contact of the fluid with the solid phase and the wall, as well as internal heating associated with the mechanical power needed to extrude the fluid through a porous medium [20–23]. Most of the entropy generation studies on viscous dissipative fluid flow in porous media utilize the volume-averaged entropy generation function which assumes the condition of local thermal equilibrium between solid and fluid phases [24–27]. Under certain circumstances, significant differences in thermophysical properties between fluid and solid phases in a porous medium induce a substantially large thermal resistance at the interface between the two phases. This would lead to pronounced difference in the temperature between the solid and the fluid phases and thus invalidates the assumption of local thermal equilibrium [28]. In the up-to-date literature, there are only three studies on the entropy generation of porous medium flow which consider the thermal non-equilibrium condition between the two phases [29–31]. A numerical study employed the thermal non-equilibrium model to investigate the entropy generation of the laminar natural convection in a saturated porous cavity [29]. By using a similar model, the entropy generation analysis was performed on the rarefied gaseous slip flows in microchannels filled with porous medium [31]. Besides, the volume-averaged form of entropy generation function was derived for non-equilibrium heat transfer in high conductivity porous foams and concluded that bulk of the entropy generation occured within the fluid constituent [30]. Although these studies analysed different geometry and heat transfer mechanism, they drew the same conclusion which states that significant deviation could occur between the results obtained from thermal equilibrium and non-equilibrium models. Therefore it is important to consider the thermal non-equilibrium between the two phases in the entropy generation analysis of porous medium flow.

In the existing literature, studies on entropy generation of thermal non-equilibrium porous medium flow are extremely scarce and none of these studies deals explicitly with viscous dissipation effect on nanofluid flow in a microchannel filled with a porous medium. To bridge this information gap, the present study investigates the