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Non-linear drag induced irreversibility minimization in a viscous dissipative flow through a micro-porous channel

Harshad Sanjay Gaikwad, Dipankar Narayan Basu, Pranab Kumar Mondal*

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, 781039, Assam, India

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ABSTRACT

We focus on the entropy generation minimization analysis associated with the thermo-fluidic transport of a Newtonian fluid through a hyper-porous channel formed between two asymmetrically heated parallel plates. Employing an analytical method, which is consistent with the perturbation analysis, we solve the governing transport equations taking the effects of nonlinear Forchheimer drag and conjugate heat transfer into account. We also invoke to the thermal boundary conditions of third kind at the outer boundaries of channel for the conjugate analysis of heat transfer. We bring out the alterations in the entropy generation rate in the system as attributable to the nonlinear interactions between the heat transfer rate as modulated by the fluid temperature, temperature gradient, the dissipative heat originating from the non-linear Forchheimer drag, Darcy frictional effect and the viscous shearing stress in the flow field. Also, we unveil optimum values of wall thickness, wall to fluid conductivity ratio and other thermophysical parameters, leading to a minimum entropy generation rate in the system for a given set of the other different parameters considered. We believe that the inferences obtained from this analysis may improve the design and optimization of thermodynamic systems/devices typically used in different engineering applications.

1. Introduction

Thermo-fluidic transport through microchannel finds many applications such as electronic cooling, aerospace, MEMS and biomedical devices [1–3]. Since downsizing leads to an increment in surface to volume ratio, the underlying flow dynamics at microscale is crucially affected by the significant pressure drop which varies inversely to the length scale, to be precise the cross-sectional length scale of the micro devices/systems [4,5]. To circumvent this problem, a remedy could be of an enhancement in the channels cross-sectional size without compromising the augmentation in surface to volume ratio of the channel. A suggestive way of accomplishing this effect is to embed the porous matrix in the microchannel, which, in essence, keeps the pressure drop to a manageable limit without conceding the escalation in surface to volume ratio. In fact, the insertion of porous matrix in a microfluidic channel increases the heat transfer rate, thus leads to a novel design step for the narrow confinements which are very often used for thermo-fluidic transport in microfluidic systems/devices [6–9]. Actually, a few important features of porous structures *viz.*, high surface to volume ratio, low weight and high heat transfer coefficients, which too bear a resemblance to the features of a microchannel [10], indeed, supported to combine the porous material in a microfluidic channel without sacrificing the underlying dynamical behavior to a great extent. Accounting these characteristics features of the porous structures, microchannels with embedded porous matrix, to be precise, the micro-porous channels bear thermal properties similar to that of the normal microchannels, essentially by negotiating the significant pressure drop and find many industrial applications as well. For instance, microporous channels are largely used in filtration, detection of particles, and tissue engineering, porous insulation, micro heat pipe wicking structure and microelectronic heat transfer equipments [11].

On the other hand, the understanding of pore scale thermofluidic transport is an important scientific challenge from different perspectives: first to maintain flow through a microporous fluidic system having complicated porous network without sacrificing the efficiency of processes. Second, the nonlinear effect of the viscous dissipation, originating from the

* Corresponding author.
E-mail address: pranabm@iitg.ernet.in (P.K. Mondal).

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Nomenclature

B	Constant axial temperature gradient (K/m)
$Bi_{i=1,2}$	Biot number for both lower and upper wall (−)
C_p	Specific heat at constant pressure(KJ/(Kg.K))
C_f	Forchheimer Drag Coefficient (−)
C_1-C_6	Integration constants (−)
$d_{i=1,2}$	Wall thickness for lower and upper wall (m)
Da	Darcy Number (−)
F	Forchheimer Constant (−)
G	Negative of the Pressure Gradient (N/m^3)
H	Height of the half of the channel (m)
$(h_{eff})_{i=1,2}$	Effective heat transfer coefficient of both lower and upper wall (W/m^{2}K)
$(h_e)_{i=1,2}$	Convective Heat transfer coefficient (W/m^{2}K)
I_1-I_{10}	Coefficients for temperature distribution in fluid domain(−)
K	Permeability of the porous structure (m^2)
k_f	Thermal conductivity of the Fluid (W/mK)
$k_{wi=1,2}$	Thermal conductivity of the lower and upper wall (W/mK)
$K_{i=1,2}$	Thermal conductivity ratio for lower and upper wall (−)
M,N	Integration Coefficients in C_1-C_6 (−)
p	Pressure (N/m^2)
p_f	Pressure of fluid (N/m^2)
Pe	Peclet Number (−)
$\dot{S}$	Dimensionless Local Entropy generation rate (−)
T	Temperature (K)
$T_{wi=1,2}$	Temperature of lower and upper wall (K)
T_a	Ambient temperature (K)
u	x-direction axial velocity (m/s)
u_m	Mean Velocity(m/s)
$\overline{u}$	Dimensionless velocity (−)
v	y-direction velocity(m/s)
$\mathbf{v}$	Darcy Seepage velocity (m/s)
w	z-direction velocity (m/s)
x	x-direction
y	y-direction
Greek Symbols	
α	Porosity Shape Factor
$\delta_{i=1,2}$	Dimensionless wall thickness for lower and upper walls
ε	Porosity of the porous structure
μ_f	Fluid dynamic viscosity (Pa.s)
ρ_f	Fluid Density (Kg/m^3)
μ_{eff}	Effective fluid viscosity (Pa.s)
Φ	Viscous Dissipation
θ	Dimensionless Temperature Distribution in y direction
Θ	Dimensionless Temperature distribution both in x and y direction
Θ_a	Dimensionless Ambient temperature
$\Theta_{wi=1,2}$	Dimensionless Temperature of both walls
Subscripts	
f	Fluid
m	Mean
a	Ambient

Forchheimer drag, Darcy friction factor as well as the viscous shear stresses, drastically alters the thermal transport characteristics of heat and so is the exergetic efficiency of the system. Third, the conductive transport of heat through the walls of the channel as well as in the porous solid matrix plays a significant role in the alteration in underlying thermo-fluidic transport. From a theoretical point of view, the irreversibility losses, stems from the heat transfer due to finite temperature difference and adverse effect of viscous heating cannot be denied for the micro-devices/micro-systems involved with any engineering process [12–14]. Note that, for a given process, the concept of entropy generation function [14–19], which is proven as a useful tool for optimum design of thermodynamic devices, can be employed to characterize as well as to quantify the losses arising due to thermodynamic irreversibility. Related to this analysis, the effect of conjugate heat transfer can potentially have an influential role on entropy generation [20–28] as well, which has been overlooked in all the reported studies concentrating on the analysis of thermo-fluidic transport through micro-porous channel.

Our aim, in this paper, is to investigate the effect of conjugate heat transfer on the entropy generation rate associated with the thermo-fluidic transport though a micro-porous channel. Here, we have considered a flow of Newtonian fluid through a microchannel embedded with homogeneous hyper porous structure. We have taken the effects of several factors *viz*., the nonlinear quadratic Forchheimer drag, Darcy friction factor as well as the viscous shear stresses, while modeling the viscous dissipation function in the thermal energy equation [29–32]. Also, we have taken the effect of conjugate transport of heat, i.e., the transverse heat conduction in the channel walls as well as the convection heat transport from the wall to the ambience, into account in the present analysis. We bring out the alteration in the underlying thermal transport of heat as modulated by the fluid temperature and temperature gradient, largely attributed to the effect of nonlinear viscous heating in the fluid temperature. In particular, we have presented some results which impressively show that there exists an optimum value of wall thickness and different other thermo-physical parameters, leading to a minimum entropy generation in the present system.

2. Solution methodology

2.1. Governing transport equations

We schematically show, in Fig. 1, the problem considered in the

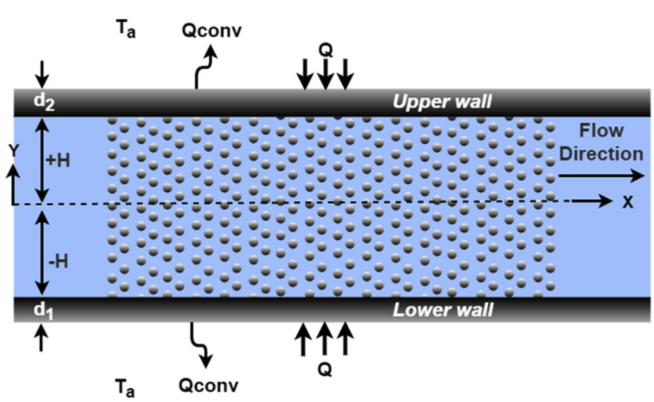

Fig. 1. Schematic showing the physical dimensions of the micro-porous channel formed between two parallel plates at $2H$ distance apart. Fluid is flowing along the x-direction of the channel.

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