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# Non-linear drag induced entropy generation analysis in a microporous channel: The effect of conjugate heat transfer

Harshad Sanjay Gaikwad [a,*], Pranab Kumar Mondal [a], Somchai Wongwises [b,*]

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

[b] Fluid Mechanics, Thermal Engineering and Multiphase Flow Research Lab (FUTURE), Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangmod, Bangkok 10140, Thailand

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ABSTRACT

The entropy generation analysis in a viscous dissipative flow of a Newtonian fluid through a hyper-porous microchannel formed between two heated parallel plates is conferred. Employing an analytical method, which is consistent with the perturbation analysis, the transport equations governing the thermo-hydrodynamics are studied. The effects of nonlinear Forchheimer drag and conjugate heat transfer on the thermal transport characteristics of heat are considered, while the thermal boundary conditions of third kind have been employed at the outer boundaries of channel for the conjugate heat transfer analysis. The explicit alterations are made in the thermal transport of heat in the system as attributable to the effect of dissipative heat generated due to the non-linear effect Forchheimer drag, Darcy frictional effect and the viscous shearing stress in the flow field. To account these effects, the explicit variation of Forchhiemer constant, Darcy number, porosity, thickness and conductivity of upper wall and Biot number of upper wall are carried out to shows the changes in the available energy of the system. Also, it is shown that the effect of non-linear drag mainly stemming from the presence of complex porous structure in the flow field and its interaction with the conjugate transport of heat alters the heat transfer rate in the system non-trivially, which, in turn, gives rise to the entropy generation in the system. The individual contribution of two different effects viz., the heat transfer and viscous dissipation on the system entropy generation rate for different cases are studied. It is believed that the implications of the present analysis may have direct bearing on the design of micro devices/systems typically used in electronic cooling, micro-heat pipes.



## 1. Introduction

With the growing demand of miniaturizations, the analysis of microscale thermo-fluidic transport has received emergent importance to the research community for the last few decades [1–4]. Microscale transport of heat turns out to be an important subject in many practical areas of engineering applications such as MEMS (Micro-Electro-Mechanical Systems), electronic cooling, micro-heat pipes and many others miniaturized structures, sensors, actuators [5–9]. The underlying physical issues involved with the thermo-fluidic transport in the application of these kinds are, indeed, complex, while researchers have attempted to explore those aspects from both the theoretical analysis [10–14] and experimental investigations [3,4,15,16]. The higher surface to volume ratio, which is inherent to the microsystems/devices, makes the microscale heat transfer to be fundamentally different from the macroscale transport of heat. Since downsizing leads to an enhancement in surface to volume ratio, the problem intrinsic to the microscale thermo-fluidic transport lies with the significant pressure drop which varies inversely to the cross-sectional length scale of the micro devices/systems [4,3]. It may be mentioned here that the insertion of porous structure inside the microsystems/devices increases the heat transfer rate without compromising the escalation in surface to volume ratio of these system/devices.

Being a novel design step for the narrow confinements, the microchannels with embedded porous structures are very often used for microscale thermo-fluidic transport [5–7,17]. The similar features of a microchannel and porous structure [8], like high surface to volume ratio, less weight and high heat transfer coefficients, indeed, vouch to embed the porous structure inside a microchannel without sacrificing the underlying dynamical behavior to a great extent. A major concern with the thermo-fluidic transport

* Corresponding authors.
*E-mail addresses:* mail2pranab@gmail.com (P.K. Mondal), somchai.won@kmutt.ac.th (S. Wongwises).

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**Nomenclature**

*Symbols*

| | |
|---|---|
| $Be$ | Bejan number (–) |
| $Bi_{i=1,2}$ | Biot number for lower wall ($i=1$) and upper wall ($i=2$) (–) |
| $C_f$ | Forchhiemer drag coefficient (–) |
| $C_p$ | specific heat at constant pressure (kJ/kg K) |
| $C_1 - C_6$ | integration constants (–) |
| $Da$ | Darcy number (–) |
| $d_{i=1,2}$ | Wall thickness for lower wall and upper wall (m) |
| $F$ | Forchhiemer constant (–) |
| $G$ | non-dimensional pressure gradient (–) |
| $H$ | half Height of the channel (m) |
| $(h_e)_{i=1,2}$ | convective heat transfer coefficient for lower and upper wall (W/m$^2$ K) |
| $(h_{eff})_{i=1,2}$ | effective heat transfer coefficient for lower and upper wall (W/m$^2$ K) |
| $I_1 - I_{10}$ | coefficients in temperature distribution equations (–) |
| $K$ | permeability of the medium (m$^2$) |
| $k_f$ | thermal conductivity of the fluid (W/m K) |
| $k_{wi=1,2}$ | thermal conductivity of the lower and upper wall (W/m K) |
| $k_{i=1,2}$ | thermal conductivity ratio of lower and upper wall to the fluid (W/m K) |
| $N_s$ | non-dimensional local entropy generation rate (–) |
| $p$ | pressure (N/m$^2$) |
| $T$ | fluid temperature (K) |
| $T_a$ | ambient temperature (K) |
| $T_{wi=1,2}$ | temperature of the lower and upper wall (K) |
| $u$ | one dimensional fluid seepage velocity (m/s) |
| $u_m$ | mean velocity of the fluid (m/s) |
| $\hat{u}$ | non-dimensional fluid velocity (m/s) |
| $\mathbf{v}$ | three dimensional fluid seepage velocity (m/s) |
| $x$ | X-direction (–) |
| $y$ | Y-direction (–) |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | porous media shape factor (–) |
| $\delta_{wi=1,2}$ | non-dimensional wall thickness of lower and upper wall (–) |
| $\varepsilon$ | porosity (–) |
| $\mu_f$ | fluid viscosity (Pa s) |
| $\mu_{eff}$ | effective fluid viscosity (Pa s) |
| $\theta$ | non-dimensional temperature of fluid (–) |
| $\theta_{wi=1,2}$ | non-dimensional temperature of lower and upper wall (–) |
| $\theta_a$ | non-dimensional ambient temperature (–) |
| $\phi$ | irreversibility ratio (–) |
| $\Phi$ | viscous dissipation (W/m$^3$) |
| $\rho_f$ | fluid density (kg/m$^3$) |

*Subscripts*

| | |
|---|---|
| $a$ | ambient |
| $eff$ | effective |
| $f$ | fluid |
| $m$ | mean in the conduction limit |

through microporous channel is the effect of viscous dissipation. The dissipative heat generation in channel acts as a distributed heat source and stimulates the fluid temperature and the internal energy of the system as well [7,10,18]. More practically, the conduction heat transfer through the microchannel walls i.e. conjugate heat transfer at the walls could bear a significant impact on the thermo-fluidic transport and entropy generation of the system as reported in the literature [19–23]. Mondal et al. [20,21,23] performed several studies of conjugate heat transfer analysis along with the viscous dissipation considering different aspects of the micro-fluidic devices. The effect of viscous dissipation due to non-linear drag in harmony with the thermo-fluidic transport through microporous channel, invites the thermodynamic irreversibility and degrades the second law efficiency of the thermodynamic system/devices [24–26]. Considering this aspect, entropy generation analysis has been made with an effect of asymmetric convective cooling and viscous dissipation for different microfluidics applications [19,27–29]. However, Abbassi et al. [26] studied the irreversibility analysis considering porous structure in microchannel heat sinks and Ting et al. [30] studied the viscous dissipative effects of Nano fluids in microchannel. However, the effect of conjugate heat transfer and viscous dissipative effects of non-linear Forchhiemer drag in porous media with dominant conductive heat transfer paradigm in fluid is overlooked in entropy generation analysis by these literatures.

Motivated by the above issue, an attempt has been made to investigate the entropy generation rate for a viscous dissipative flow through a microporous channel under the influence of conjugate transport of heat in the system. The flow of Newtonian fluid is considered through a hyper-porous microchannel formed between two parallel plates having finite thickness. In this analysis, the non-linear quadratic Forchheimer drag, Darcy friction factor as well as the viscous shear stresses have been considered while modeling the viscous dissipation function in the thermal energy equation [22,31–33]. It shown that the non-linear interactions between the dissipative effect generated due to non-linear drag and the effect of conjugate transport of heat lead to the alteration in fluid temperature and temperature gradient across to the walls of the channel, which, in turn, invites the irreversibility in the system.

## 2. Mathematical formulation of the problem

### 2.1. Governing transport equations

The thermo-fluidic transport of a Newtonian fluid through an asymmetrically heated porous microchannel is considered under the influence of an external pressure gradient as schematically shown in Fig. 1. The channel is formed between two parallel plates having finite thickness. Since the channel walls are considered here to have a finite thickness, the heat conduction across the walls is taken into consideration in the present analysis. The conduction of heat through the solid matrix of the porous channel is not considered in this analysis. Also, the thermo-physical properties of the fluid are assumed to be constant in this study, while the effect of viscous dissipation is taken into account in the analysis. Moreover, the channels walls are kept at constant heat flux thermal boundary condition, while for the momentum equation, the no-slip boundary condition is considered at the walls as well as in the solid porous structures.

The continuity and Brinkman-Forchheimer extended Darcy equations have been considered to resolve the physics of interest involved with the flow dynamics through the micro porous