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Research Paper

Interface entropy generation in micro porous channels with velocity slip and temperature jump

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HIGHLIGHTS

- Total entropy generation rate in porous microchannels is investigated.
- Velocity slip and temperature jump are incorporated into the boundary conditions.
- Effects of interface entropy generation are considered in total entropy generation rate.
- Upper and lower walls are included into the entropy generation analyses.
- Interface entropy generation has great impact on the entropic behavior of microchannel.

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ABSTRACT

In a certain size micro thermofluid systems, the temperature of the cooling fluid at the vicinity of the solid hot wall differs from the temperature of the wall. This temperature difference can be modelled by using a temperature jump parameter, which relates the temperatures of the fluid and solid at the interface, and the gradient of the temperature in the solid wall. In this investigation, two micro porous channels with asymmetric thick walls have been considered; one with constant, but different, temperature boundary conditions and the other one with heat flux and convection boundary conditions at each of the walls, in order to determine the impact of the interface entropy generation rates on the total entropy generation calculation, particularly when the solid-fluid interface temperature jump has been assumed in a micro channel. The effects of the magnetic field have been addressed in both the momentum and energy equations of the porous section of the system. The slip velocity and temperature jump interface boundary conditions for both the upper and lower fluid-wall interfaces are considered. The results indicate that when the temperature jump parameter is weak, the interfaces entropy generation rates may be neglected in the calculation of the total entropy generation rate. However, if the temperature jump parameter is strong enough, the total entropy generation rate should be calculated by considering the interfaces entropy generation rate. It is interesting to note that depending on the micro porous channel outer boundary conditions, the total entropy generation rate may increase or decrease in accordance with the temperature jump parameter.

1. Introduction

Miniaturized thermofluid systems have gained considerable attention from both a theoretical and experimental perspective due to the importance in the area of micro manufactured devices [1–3]. Recently, micro heat sink thermal systems, such as microchannels, and microtubes, have been used to reduce the temperature of these micro electronic systems [4]. Microchannels have also been utilized in a number of other applications including heat removal in microelectronics, drug delivery, etc. [5,6]. Among these, microchannels filled with porous media have gained considerable attention [7,8] as they show interesting applications for cooling purposes [9] and pumping technology for biomedical engineering [10]. All these practical applications have led many scholars to concentrate on various transport phenomena in microchannels totally or partially filled with porous media [11,12].

In the evaluation of micro scale heat and mass transport systems, it is important that special attention be paid to the influence of the length scale of the fundamental equations and boundary

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Nomenclature

a_1	slope of the thermal conductivity versus temperature for lower solid material, K^{-1}
a_2	slope of the thermal conductivity versus temperature for upper solid material, K^{-1}
B_0	magnetic field, T
Br	Brinkman number (Pr · Ec)
Da	Darcy number
Ec	Eckert number
h	convection heat transfer (case two), $W\,m^{-2}\,K^{-1}$
h_3	height of the channel, m
k_1	reference thermal conductivity for lower solid material, $W\,m^{-1}\,K^{-1}$
k_2	reference thermal conductivity for upper solid material, $W\,m^{-1}\,K^{-1}$
k_{eff}	effective thermal conductivity of porous medium, $W\,m^{-1}\,K^{-1}$
k_{e1}	ratio of porous medium thermal conductivity to lower solid material thermal conductivity
k_{e2}	ratio of porous medium thermal conductivity to upper solid material thermal conductivity
M	Hartmann number
N_L	dimensionless lower wall-fluid interface entropy generation rate
N_s	dimensionless local entropy generation rate
N_t	dimensionless total entropy generation rate
N_U	dimensionless upper wall-fluid interface entropy generation rate
Nc	dimensionless convection heat transfer (case two)
Pr	Prandtl number
Q_H	dimensionless heat flux boundary condition (case two)
q_H	heat flux boundary condition (case two), $W\,m^{-2}$
S'''	local entropy generation rate, $W\,m^{-3}\,K^{-1}$
S_L	lower wall-fluid interface entropy generation rate, $W\,m^{-2}\,K^{-1}$
S_U	upper wall-fluid interface entropy generation rate, $W\,m^{-2}\,K^{-1}$
T	temperature, K
T_1	temperature of the lower solid material, K
T_2	temperature of the upper solid material, K
T_C	outer temperature of the upper solid material, K
T_H	inner temperature of the lower solid material, K
T_p	temperature of the porous medium, K
U	dimensionless velocity
u_p	velocity of the fluid in porous medium, $m\,s^{-1}$

Greek symbols

α	velocity slip coefficient
α_1	dimensionless slope of the thermal conductivity versus temperature for lower solid material
α_2	dimensionless slope of the thermal conductivity versus temperature for upper solid material
β	temperature jump coefficient
κ	permeability, m^2
μ_f	dynamic viscosity of the base fluid, $kg\,s^{-1}\,m^{-1}$
θ	dimensionless temperature
θ_1	dimensionless temperature of the lower solid material
θ_2	dimensionless temperature of the upper solid material
θ_p	dimensionless temperature of the porous medium
θ_H	dimensionless temperature at outer side of the lower wall
γ	specific heat transfer ratio
λ	mean free path, m
σ	electrical conductivity of fluid, $S\,m^{-1}$
σ_V	momentum accommodation coefficient
σ_T	thermal accommodation coefficient

conditions as they differ from the macro to micro scale [13]. This approach has been practiced by many scholars, in the investigations of fluid flow and heat transfer in microchannels and microtubes [14–16]. In these situations, two important modifications should be considered. These include about the slip velocity and the temperature jump. In a certain size micro thermofluid systems which can be characterized by the Knudsen number (Kn), the temperature of the coolant at the vicinity of the heated wall differs from the temperature of the wall. This temperature difference can be modelled by using a temperature jump parameter, which relates the temperatures of the fluid and solid at the interface, and the gradient of the temperature in the solid wall. A higher value for the temperature jump parameter means that these two temperatures differs highly from each other, and the size effect is more pronounced. When Kn, which describes the ratio of the mean free path of the flowing fluid to the thermofluid system size, is large enough, the slip velocity and temperature jump must be considered in the formulation of the problem. To be more precise, it has been stated in the literature that for Kn is higher than 0.01, the continuum assumption used in the derivation of the Navier-Stokes equations breaks down [17,18], and hence the temperature jump and slip velocity boundary conditions should be assumed. When the Kn is below 0.01, the non-slip boundary condition assumptions are valid and the continuum perspective can be applied [19]. Realizing this, a number of investigators have attempted to consider the slip velocity and temperature jump boundary conditions in the analysis of the fluid flow and heat transfer of small scale fluid and/or thermal systems [15,16,20–22]. For example, Malvandi and Ganji [15] considered slip velocity for nanofluid flow in a microchannel, and Zhang et al. [16] investigated a temperature distribution in a microchannel assuming both velocity slip and temperature jump boundary conditions. Aziz and Niedbalski [20] considered both first-order and second-order velocity slip models for a microtube, and developed the temperature distribution formulation based on the first-order temperature jump model. Shamshiri et al. [21] considered the first-order velocity slip and temperature jump boundary conditions to simulate the first and second law analyses for concentric rotating shafts. The first-order temperature jump boundary condition has been also considered for visualization of the temperature distribution in solid media by Dai et al. [22]. It may be useful to note that, if the temperature jump occurs in a channel, it means that a thermal resistance exists at the fluid-solid interface, which decreases the cooling characteristic of the system and increases the overall temperature of the structure, and consequently may cause structural failure.

The utilization of an entropy generation analysis approach for thermal systems has recently gained considerable attention [23–25]. This is particularly true when the effects of the above-mentioned systems scale on the entropy generation rate formulations and calculations and the temperature jump boundary condition have been observed at the interface of two different materials in micro systems. In this case, only a very few studies have been reported. A pioneer investigation about the effects of temperature jump and velocity slip in microchannels was performed by Hooman [26,27]. Homan [26] provided an analytical