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Effects of shear work on non-equilibrium heat transfer characteristics of rarefied gas flows through micro/nanochannels

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ABSTRACT

In the current work, the effect of shear work due to the velocity slip on the non-equilibrium heat transfer in a pressure driven micro/nanochannel is evaluated under the constant wall heat flux boundary condition. As our simulation tool, the DSMC method is employed. Implementation of the wall heat flux in the DSMC method is performed using the “modified Iterative” technique. We investigate the effects of rarefaction, property variations and compressibility. The numerical results show that shear stress on the walls significantly affects all aspects of the flow behavior and heat transfer through micro/nanochannels such as heat flux rates. We also analyze the counter-gradient heat flow (cold to hot heat transfer) phenomenon appearing at the cooling conditions. It is observed that viscous dissipation affects the heat flux applied to the walls and may overcome the wall heat flux, i.e., in the case of low cooling wall heat flux condition, shear work may completely heat the flow field. Nusselt number singularity is also discussed.

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1. Introduction

With today’s rapid development of micro/nano devices, optimum design and prediction of fluid and heat transfer characteristics of rarefied gas flow through micro/nano-devices are crucial. As the size of systems falls in the order of mean free path of gas molecules (λ), the effects of properties variation, viscous dissipation and flow rarefaction influence the fluid flow and heat transfer behaviors. The viscous dissipation and flow rarefaction are characterized by Brinkman number ($\mathrm{Br} = \mu u_b^2/2Hq_w$) and Knudsen number ($\mathrm{Kn} = \lambda/H$), respectively. Compared to the macro-devises, the viscous dissipation due to a large surface to volume ratio causes a measurable increase in the heat transfer rate at solid boundaries.

An essential characteristic of the heat transfer behavior of any system is the Nusselt number (Nu), defined as the ratio of the convective heat transfer coefficient to the conductive heat transfer coefficient across the boundary. For a parallel plate channel subject to constant wall heat flux (CWH) boundary condition, the Nusselt number could be written as follows:

$$\mathrm{Nu} = \frac{2q_w H}{k_t(T_w - T_b)} \tag{1}$$

where q_w, H, k_t and T_w are the wall heat flux, the channel height, gas thermal conductivity and wall temperature, respectively. Moreover, the bulk temperature (T_b) is defined as

$$T_b = \frac{\int_A \rho u_x T dA}{\int_A \rho u_x dA} \tag{2}$$

There are theoretical and numerical investigations around the topic of heat transfer in micro/nano rectangular channels in low to moderate Knudsen number ranges, i.e., slip flow regime. Inman [1] has performed the first investigation of slip flow heat transfer. Inman studied a parallel plate channel with constant wall heat flux analytically. He studied the velocity slip and temperature jump in his investigation and proposed an expression for the Nusselt number as a function of rarefaction (Kn) parameter. Hooman [2] suggested a correlation using the superposition approach for straight microchannels of uniform, but with an arbitrary cross section in the slip region. He showed that applying an average slip velocity and temperature jump definition; one can still use the no-slip/no-jump results with some minor modifications. Miyamoto et al. [3] studied heat transfer characteristics of the choked gas flows through a narrow parallel-plate channel. They found that due to the developing flow effects, the Nusselt number abruptly changes near the inlet and exit. In addition to viscous dissipation and rarefaction effects, the influence of streamwise conduction was investigated by Jeong and Jeong [4] on the Graetz problem in a flat plate microchannel. This investigation revealed that the Nusselt number decreases as the Peclet number decreases. They also showed that if the streamwise conduction is included, the Nusselt number becomes greater compared with the solution where streamwise conduction is neglected. The interactive effects of the Brinkman and Knudsen numbers on the Nusselt number are analytically

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determined by Aydin and Avci [5]. They showed that an increase in the Knudsen number decreases the Nusselt number due to the increased temperature jump over the wall. They indicated that in the absence of viscous dissipation, the solution is independent of whether there is wall heating or cooling. The effects of viscous dissipation and rarefaction on hydrodynamically and thermally developed laminar forced convection of constant wall heat flux (CWH) microchannel was considered by Sadeghi and Saidi [6]. They showed that the effect of viscous heating on the Nusselt number at greater values of the Knudsen number becomes insignificant and in the absence of viscous heating, increasing values of Knudsen number lead to smaller values of the Nusselt number. Furthermore, they observed that viscous heating causes singularities in the Nusselt number values. These singularities have been discussed by Miyamoto et al. [3], Aydin and Avci [5] and Sheela-Francisca and Tso [7] as well. Hadjiconstantinou [8] considered the effect of shear work at solid boundaries on the convective heat transfer and obtained the solution of the constant-wall-heat-flux problem in small scale gaseous flows where slip effects are present. Colin [9] provided a detailed review of the convective heat transfer in microchannels with different geometrical shape and wall boundary conditions. His study was focused on flows with $\mathrm{Kn} < 0.2$. A comparison of different models for Nusselt number showed that there is a considerable difference between different analytical Nusselt expressions.

Even tough previous researchers have studied the effects of viscous dissipation, but some simplifications made in analytical/numerical solutions caused that the physics behind the heat transfer was not predicted correctly in particular cases. For example, in some occasions, it was assumed that the wall temperature gradient is constant and equal to the bulk temperature gradient along the channel, i.e., $\partial T_w/\partial x = \partial T_b/\partial x = const.$, i.e., see Ref. [8]. This assumption makes prediction of the Nusselt number singularity impossible. Moreover, if the flow properties variation and compressibility effects are neglected [2,5,8], it is expected that the derived expressions for any flow properties such as Nusselt number and temperature profile become valid only for low dissipation rates, i.e., small Brinkman numbers. The objective of the present work is to numerically investigate the effects of rarefaction and viscous dissipation on the convective heat transfer behaviour of parallel plate micro/nanochannels in the slip flow regime, subject to constant wall heat flux thermal boundary condition. In this study, the order of magnitude of the shear stresses, slip velocity and viscous dissipation have been investigated numerically for specific cases. In this way, improvement of analytical solutions with the help of numerical analysis would be possible. A detailed discussion of the contrast between cooling heat flux and viscous dissipation, which eventually leads to the singularity in Nusselt number, is presented. Numerical results are obtained using a two-dimensional direct simulation Monte Carlo (DSMC) solver. To verify the simulations, numerical results for thermally and hydrodynamically fully developed parallel plate under constant wall heat flux for Nusselt numbers are compared with different analytical solutions which account viscous dissipation. We study the effect of shear work at the wall boundaries and consider how viscous dissipation affects convective heat transfer.

3. Numerical method

The present research uses the DSMC method that follows the scheme proposed by Bird [10]. It is a particle base method which utilizes random sampling for obtaining numerical solutions of rarefied gas flows. The method simulates the gas flow using many independent simulator particles which are representatives of a large number of real gas molecules. In order to implement DSMC, the flow field must be divided into computational cells. Provided that an adequately large number of particles are used, and the cell size and time step are suitably small, the DSMC method converges to the solution of the Boltzmann equation. DSMC time step should be chosen small enough such that the positional changes of particles and their collisions could be decoupled for each time step. The cells provide geometric boundaries required to sample macroscopic properties. Each cell is typically divided into subcells utilized to increase the accuracy of the selection of collision pairs. In the current work, the previous code of Akhlaghi and co-workers [11–16] is extended to simulate rarefied flow in the micro/nano channel geometry. The GHS collision model, introduced by Hassan and Hash [17], is utilized to consider accurate variation of the viscosity with the temperature over a wide range of temperature variations. This model is an extension of the variable hard sphere (VHS) model to include terms that allow modeling of molecules with both repulsive and attractive potentials. For the GHS model, the total collision cross section could be written as follows:

$$\sigma = \sigma_0\left(\phi(g_0/g)^{2\nu_1} + (1-\phi)(g_0/g)^{2\nu_2}\right) \tag{3}$$

where $\sigma_0 = \pi d_0^2$ is the reference cross section, $g = \sqrt{4RT}$ and the parameters with subscript zero are calculated at the reference temperature (T_0), for more details, see Ref. [17]. The choice of the collision pair is done based on the no time counter (NTC) method. Monatomic argon, $m = 6.63 \times 10^{-26}$ kg and $d = 4.17 \times 10^{-10}$ m, is considered as the working fluid. In order to ensure the satisfaction of the limits on the cell size, the cell dimensions are considered as 0.1λ and are much smaller than that for most cases. 30 particles are initially set in each cell to minimize the scattering noise. All walls are treated as diffuse reflectors using the full thermal accommodation coefficient. Half-range Maxwellian distribution is used to determine the velocity of the wall-reflected particles. After achieving steady flow condition, sampling of flow properties within each cell is fulfilled during a sufficient time period to suppress the statistical scatters of the solution. All thermodynamic parameters such as velocity, density, and temperature are then determined from this time-averaged data. The wall heat flux is imposed in the DSMC solver using the "modified iterative" technique developed. To impose a desired wall heat flux (q_{des}) in the iterative technique previously suggested by Akhlaghi et al. [11], the wall temperature is corrected from the previous time step magnitude, $T_w(x)^{old}$ according to the following formula:

$$T_w(x)^{new} = T_w(x)^{old}\left(1 + RF\frac{q_w(x) - q_{des}(x)}{|q_{des}(x)| + \varepsilon_0}\right) \tag{4}$$

Adjusting the relaxation factor (RF) in a manner which ensures the convergence behavior depends on the desired wall heat flux magnitude, flow rarefaction (Kn), wall sampling period (Δt) and number of DSMC particles impinging the wall. Therefore, it is difficult to determine an efficient value for RF in each case. The parameter ε_0 which is defined only in the case of adiabatic condition is a non-zero positive value which is negligible compared to the incident energy

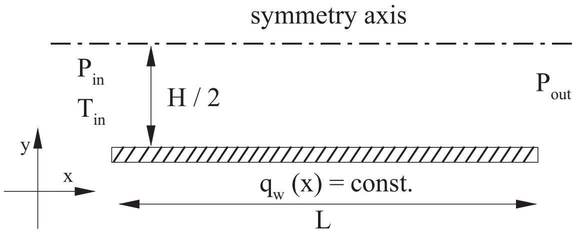

Fig. 1. 2D plane micro/nanochannel geometry and imposed boundary conditions.

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