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Numerical investigations on the effect of fin shape and surface roughness on hydrothermal characteristics of slip flows in microchannels with pin fins

Abdolali Khalili Sadaghiani, Ali Koşar*

Mechatronics Engineering, Center of Excellence for Functional Surfaces and Interfaces (EFSUN), Sabanci University Nanotechnology and Applications Center (SUNUM), Faculty of Engineering and Natural Sciences, Sabanci University, Tuzla, Istanbul 34956, Turkey

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ABSTRACT

Accurate modelling of convective heat transfer in micro/nano gas flows is critical for many applications such as temperature/mass flow micro-sensors and mixing/separation analysis of gases in micro-systems. This study numerically investigates the effect of pin fin shape and wall roughness on heat transfer and flow field of gas flows in rough microchannels in the presence of the second order slip boundary condition. The hydrothermal characteristics of flows were obtained for a smooth microchannel under slip boundary conditions for the constant wall temperature (330 K) and constant wall heat flux (10 kW/m^2) boundary conditions. Afterwards, four types of pin fin shapes (rectangular, diamond, oblong, and elliptic) and two types of surface roughness (regular and random rough elements) were taken into account. According to the obtained results, although velocity slip raises Nusselt number, temperature jump tends to reduce it. It was shown that the generated recirculating flows between the roughness elements reduce Nusselt number and increase friction factor. Furthermore; it was found that the effect of pin fin shape diminishes with surface roughness.

1. Introduction

A wide range of applications in nano-technology and micro-electro-mechanical systems (MEMS) involve gas flows in small scale, where the classical continuum approach is not applicable and different flow characteristics exist compared to those in conventional systems. One major difference lies in the presence of slip conditions in the solid-fluid interface. Classified by the non-dimensional number, Knudsen number (ratio of the molecular mean free path length to a representative physical length scale), gas flows are typically categorized in four regimes, namely continuum ($Kn < 10^{-3}$), slip flow ($10^{-3} < Kn < 10^{-1}$), transition ($10^{-1} < Kn < 1$), and free molecular ($1 < Kn$) regimes [1]. Gas flows in channels with dimensions less than 50 μm mostly correspond to the slip flow regime and to a Knudsen number in the order of 10^{-3} to 10^{-1}. In slip flows, thermodynamic disequilibrium occurs on the solid boundary due to less interaction among the gas molecules near the wall boundaries compared to those in the core of the flow. Previous investigations [2–8] confirmed that the continuum approach is not suitable for predicting flow characteristics and rarefaction effects, e.g. reduced momentum exchange between the microsystem and environment in slip flows [9,10]. Numerical modelling is an alternative to experiments [11], under such conditions, allowing an exhaustive description of surface modifications. Particularly when gas rarefaction is at high level, it is not so easy to experimentally detect the effects of surface conditions, since is often masked by several uncertainty sources [12,13].

Gas flows are modeled using the continuum or the molecular dynamics (MD) approaches [14,15]. With the use of modified velocity and temperature boundary conditions at fluid-solid boundaries, the Navier-Stokes equations are still acceptable for such slip flows [16]. As an example, Duan and Muzychka [17] investigated slip gas flows in non-circular microchannels. A simple model was suggested for predicting friction factor. In addition, it was demonstrated the developed model could be employed for the early transition regime using the second-order slip boundary condition. Colin et al. [8] studied second order slip flows in a rectangular microchannel and suggested a slip flow model with validity up to $Kn = 0.25$. They demonstrated that for flows with $Kn < 0.05$, differences between the flow rates predicted by the first-order slip flow model and their proposed second-order model were negligible, and the value of slip coefficient did not play any significant role. Sharipov [18] numerically solved the Shakhov model of the Boltzmann equation with the Cercignani–Lampis approach to define the interaction between gas flow and wall. The results showed that the Poiseuille flow rate significantly depended on accommodation coefficient, and it always decreased with accommodation coefficient. On the other hand, the dependence of mass flow rate in Poiseuille flows on

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* Corresponding author.
E-mail address: kosara@sabanciuniv.edu (A. Koşar).

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energy accommodation coefficient was very weak. Pan et al. [19] numerically studied Couette flows between two parallel plates for different gases, wall temperatures and channel hydraulic diameters using the Monte Carlo method and concluded that the choice of accommodation coefficient in slip flow modelling with the use of Navier–-Stokes equations directly affected the precision of numerical results.

The precision of first and second order slip flow models is investigated in the literature. It is well accepted that the first order slip flow model is not appropriate for high Knudsen numbers in the slip flow region. Aydin and Avci [20] analytically studied second-order slip flows between two parallel plates including viscous dissipation under constant wall temperature and constant heat flux conditions. For both conditions in the presence of temperature jump boundary conditions heat transfer deteriorated with Knudsen number. Beskok [21] numerically considered a backward-facing step channel for modelling separated rarefied gas flows and proposed a new slip condition. The results indicated that velocity and temperature profiles predicted by the first and higher-order models had deviations for flows with $Kn > 0.04$. Leontidis et al. [22] numerically analyzed a 2D model for a Knudsen pump using the first order slip flow model. Their results had a good agreement with other numerical methods such as DSMC (Direct Simulation Monte Carlo) or kinetic approaches. They showed that modified Navier-Stokes equations could be used with UDFs to analyze slip flows for Knudsen numbers up to 0.2.

Flow characteristics and channel geometry (surface roughness and surface structure) are inherently interrelated. Morini et al. [23] investigated rarefaction effects on pressure drop for incompressible flows through microchannels having different cross sections. Rarefaction effects on the Poiseuille number were much stronger for lower aspect ratios (that means for larger wetted perimeter). The same observation was made by Duan and Muzychka [24] with a development of a model for Poiseuille number prediction in elliptic microchannels. They concluded that the cross-section geometry had a considerable effect on the Poiseuille number. Zhu et al. [25] theoretically investigated the virtual effect of aspect ratio on drag coefficient in slip flow regime in microchannels with arbitrary shapes. They reported higher friction coefficient for the second-order slip boundary condition (in comparison to the first order). Sadeghi et al. [26] theoretically studied longitudinal forced convection for gaseous slip flows across a periodic sector of micro-cylinders. Their results showed that both Poiseuille number and Nusselt number decreased with Knudsen number.

Surface structure and roughness are important parameters affecting forced convection heat transfer in microchannels [27–32]. Rovenskaya and Croce [27] numerically investigated the flow field in a rough microchannel using a hybrid solver, dynamically coupling kinetic and Navier–Stokes solutions, and a full Navier–Stokes solver. It was found that the roughness had a remarkable effect on flow characteristics. Furthermore, the authors concluded that Navier–Stokes equations coupled with the slip boundary condition offered reasonably good results for a smooth surface up to Knudsen number equal to 0.1. Zhang et al. [30] modeled gas slip flows in rough microchannels using the Lattice Boltzmann method and obtained larger Poiseuille number for the microchannel with rough surfaces in comparison to smooth ones. The same observation was reported by Deng et al. [32]. Furthermore, the authors reported that gas flow characteristics in the transition flow regime were more sensitive to the roughness height than that in the slip flow regime. Cao et al. [31] investigated the effect of surface roughness on slip flows in submicron size platinum channels using triangular, rectangular, sinusoidal and randomly triangular structures. The friction coefficient increased not only as the Knudsen number decreased but also as the surface roughness increased. Furthermore, the authors concluded that the effects of roughness and rarefaction on friction coefficient of gas micro-flows were strongly coupled.

The effect of surface structure on hydrothermal characteristics of single phase flows (gas/liquid) was extensively covered in the literature [33–40]. Zhao et al. [35] experimentally investigated pressure drop in a channel with circular, diamond, elliptical, square, and triangular shape mini pin fins. According to their obtained results, at low Reynolds numbers, the elliptical shape had the largest friction factor, followed by the circular, square, rectangular, and triangular ones, respectively. Guo et al. [37] performed an experimental study on friction factor (non-slip condition) for rough circular pin fin arrays and concluded that the geometrical characteristics of the pin fin channel such as aspect ratio and spacing had a significant effect on friction factor. Shafeie et al. [39] investigated convective heat transfer of laminar flows in heat sinks (pin finned) with alternating heights and oblique and staggered arrangements. The configuration with the oblique orientation of short pins offered the highest heat removal for a given pumping power.

The abovementioned studies mostly reported a decrease in pressure drop and heat transfer in slip flows. This is due to the lower velocity gradients near the wall boundaries for the former, and the presence of temperature jump for the later. For structured channels, such as channels with pin fins, the effects of slip conditions are more dominant due to more wall-fluid interactions. Heat transfer augmentation comes with pressure losses in a structured channel. Under slip conditions, heat transfer could be increased in structured channels with rather lower pressure losses, which constitutes the motivation of this study. In this study, Navier-Stokes equations were solved for slip and transition regimes in a microchannel with pin fins using the ANSYS Fluent 16.0 commercial software [41,42]. In the literature, gas flows in plain channels have been mostly investigated, while studies on gas flows on surfaces with pin fins are rather scarce [43–49]. Thus, it was aimed to provide insight into heat transfer and flow characteristics in microchannels with pin fins for Knudsen numbers ranging from 10^{-3} to 10^{-1}. Nusselt numbers under slip conditions were compared to those under non-slip condition in a micro channel with pin fins so that the effect of structured surfaces on could be assessed for slip conditions. Furthermore, the effect of surface roughness and pin fin shape was studied. It is worthwhile to note that although several studies have attempted to improve second-order slip models to determine the slip coefficient (which can be used for the transition regime), an accepted second-order slip model still does not exist [50]. In order to modify the velocity and temperature boundary conditions, UDF's (user defined functions) were implemented to the CFD (Computational Fluid Dynamics) software to analyze slip flows.

2. Formulation

2.1. Conservation equations

It is assumed that the flow is laminar and steady, and radiative heat transfer is neglected. Inlet and outlet boundary conditions are constant inlet velocity and outlet pressure, respectively. The transport equations are as follows:

$$\text{Mass:}\nabla\cdot(\rho\vec{\mathrm{v}}) = 0 \tag{1}$$

$$\text{Momentum:}\nabla\cdot(\rho\vec{\mathrm{v}}\vec{\mathrm{v}}) = -\nabla p + \nabla\cdot\underline{\underline{\tau}} \tag{2}$$

$$\text{Energy: }\nabla\cdot(\rho\vec{\mathrm{v}}C_pT) = -\underline{\underline{\tau}}\colon\nabla\vec{\mathrm{v}} - \nabla\cdot\vec{q} \tag{3}$$

Here, the stress tensor is presented as:

$$\underline{\underline{\tau}} = \mu(\nabla\vec{\mathrm{v}} + \nabla\vec{\mathrm{v}}^{\mathrm{T}}) \tag{4}$$

The second-order model refers to the approximation of Boltzmann equation up to $O(Kn^2)$ in the Navier-Stokes equations. At small Knudsen numbers, slip flow results converge to the non-slip condition, where the velocity on the solid-fluid interface is zero. Nevertheless, slip flow effects become dominant, when Knudsen number is in the range of 10^{-3}- 10^{-1}. Slip flow theory has been validated by the asymptotic solution of Boltzmann equations [51,52]. Using the slip flow model, Navier-Stokes equations are applicable to analyze a system with characteristic lengths almost equal to the mean free path of the working