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Size dependences of hydraulic resistance and heat transfer of fluid flow in elliptical microchannel heat sinks with boundary slip

Dalei Jing [a],*, Shiyu Song [a], Yunlu Pan [b],*, Xiaoming Wang [c]

[a] School of Mechanical Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China
[b] School of Mechanical Engineering, Harbin Institute of Technology, Harbin 150001, China
[c] School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin 150001, China

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ABSTRACT

As a well-accepted interfacial property, boundary slip condition is believed to affect hydraulic and thermal performances of various micro/nanofluidic applications. By considering the boundary slip for water flow through a microchannel heat sink, size dependences of hydraulic resistance and heat transfer of the water flow in a group of elliptical microchannel heat sinks with the same channel cross-sectional area but different length ratios of semi-major and minor axes are re-examined. The present work finds that hydraulic resistance and heat transfer of water flow in a microchannel are strongly dependent on the geometric parameters of the channel and the boundary slip condition. Both the hydraulic resistance and the convective heat transfer coefficient of the water flow in the elliptical shaped microchannel decrease with the increasing hydraulic diameter of the channel. An elliptical shaped microchannel having the largest hydraulic diameter, namely a microtube with the minimum length ratio of semi-major and minor axes being equal to one, has the smallest hydraulic resistance and the smallest heat transfer coefficient. Boundary slip at the solid-liquid interface can attenuate the hydraulic resistance and enhance the heat transfer capacity of the water flow in a microchannel, and these effects of slip on the mass and heat transfer are size-dependent. For the microchannel with a smaller hydraulic diameter, slip has a more significant attenuation effect on the hydraulic resistance and a more significant enhancement effect on the heat transfer. Geometric size optimization combined with the effective regulation of boundary slip can be a potential method to improve the mass and heat transfer of fluid flow over the micro/nanoscale.

1. Introduction

With the aid of rapid developments of advanced manufacturing techniques, fluidic systems incorporating microchannels have gradually spread their applications in various fields, for example Lab-on-a-Chip for biomedical detection or microchannel heat sink for the cooling of a single microelectronic chip integrating millions of transistors [1–3]. For these microfluidic applications, precise manipulation of small amounts of fluid and effective improvement of heat and mass transfer performance are highly desired. Thus, optimization design of a microfluidic system or a microchannel heat sink to achieve good hydraulic and thermal performances has inspired wide scientific attentions.

Among the relevant studies of hydraulic and thermal performance of fluid flow in a microchannel heat sink, the cross-sectional shapes and the geometric parameters of the microchannel were found to have a great influence on the hydraulic resistance and heat transfer of fluid flow [4–13]. For example, Mortensen et al. [6] reexamined the Hagen-Poiseuille flow in straight microchannels with different cross-sectional shapes of elliptic, rectangular, triangular and harmonic-perturbed circles and investigated the shape dependence of the hydraulic resistance of fluid flow in a microchannel. They found that for microchannels with a given cross-sectional shape, the hydraulic resistance of fluid flow in the microchannel depends linearly on a dimensionless compactness C ($C = P^2/A$, where P and A are the perimeter and cross-sectional area of the channel, respectively). Gunnasegaran et al. [7] studied the effects of geometrical parameters on water flow and heat transfer characteristics in microchannels with cross-sectional shapes of rectangular, trapezoidal and triangular. They found that for a given cross-sectional shape, a channel having a smaller hydraulic diameter has greater values of heat transfer coefficient and pressure drop.

Although the effects of cross-sectional shapes and geometric parameters of the microchannel on the hydraulic resistance and

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* Corresponding authors.
E-mail addresses: jingdalei_hit@126.com (D. Jing), yunlupan@hit.edu.cn (Y. Pan).

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heat transfer of fluid flow in the microchannel heat sinks have been widely studied, a hydrodynamic boundary condition named no-slip boundary condition at the solid-liquid interface was widely assumed [4–13]. In practical, the no-slip condition is not always valid for the micro/nanofluidic flow. Another hydrodynamic boundary condition named boundary slip condition has been well-accepted and validated with the development of advanced experimental and theoretical techniques including atomic force microscope and particle image velocimetry [14–19]. Fig. 1 gives the simplified schematic of no-slip condition and boundary slip condition. From Fig. 1, it can be found that a significant difference between the no-slip condition and the slip condition is the relative velocity between the channel wall and a layer of liquid adjacent to the wall. The no-slip condition refers that there is no relative motion between the channel wall and the layer of liquid adjacent to the wall, however, the slip condition means there exists a certain relative motion between the wall and the adjacent liquid and their relative velocity is not zero. Normally, a parameter named slip length defined in the following equation has been introduced to manifest the boundary slip condition [14,16].

$$v_{lw} = l_s \frac{\partial v_l}{\partial z}\bigg|_{\text{wall}} \tag{1}$$

where v_{lw} is the relative velocity between the liquid at the wall and the wall, l_s is the slip length, and $\frac{\partial v_l}{\partial z}\big|_{\text{wall}}$ is the liquid velocity gradient in the direction perpendicular to the wall. The typical value of slip length ranges from several nanometer to tens of micrometers, which means the boundary slip can make a remarkable effect on the flow over the micro/nanoscale [18–24]. Thus, consideration of boundary slip is necessary during the analysis of hydraulic and thermal performances of fluid flow in microchannels and the optimization design of a microchannel heat sink. However, most of the previous studies assumed the no-slip condition at the solid-liquid interface [4–13], which is not always reasonable.

To solve this problem, by considering the boundary slip condition of water flow through a group of elliptical shaped microchannel heat sinks with the same channel cross-sectional area, effects of geometric parameters of the microchannels on the hydraulic resistance and convective heat transfer performance of the water flow are re-examined in this paper. Effects of boundary slip on the hydraulic resistance and convective heat transfer coefficient of the water flow in the microchannel heat sinks are also studied.

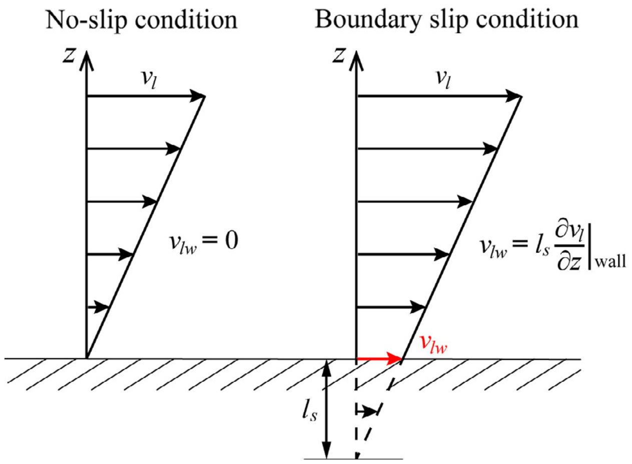

Fig. 1. Schematic diagram of no-slip condition and boundary slip condition. Where v_l is the velocity of the liquid, v_{lw} is the relative velocity between the liquid at the wall and the wall, l_s is the slip length, and $\frac{\partial v_l}{\partial z}\big|_{\text{wall}}$ is the liquid velocity gradient in the direction normal to the wall.

2. Problem descriptions

2.1. Description of the microchannel heat sinks

Considering the circular channel is the most common channel and the other channel with any cross-sectional shape can be an analogy of the circular microchannel by conversion of hydraulic diameter, thus, we choose the heat sink with circular microchannels. Furthermore, in order to analyze effects of geometric parameters of the microchannel on the hydraulic resistance and convective heat transfer of fluid flow in the heat sink, the circular microchannel is changed to a group of elliptical shaped microchannels with different dimensions under the constraint of constant channel cross-sectional area by adjusting the value of semi-major and minor axes. A typical schematic of the microchannel heat sink is illustrated in Fig. 2. Then, the heat sink exposes to a constant heat flux through the top plate, and the remaining surfaces of heat sink are assumed to be insulated. Cooling liquid of water is driven under the external pressure to remove the heat. The present work focuses on the effects of geometric parameters (the length values of major and minor axes) of the elliptical shaped microchannel on the hydraulic resistance and heat transfer, thus, only the computational domain with a single elliptical shaped microchannel is considered. The size of the computational domain is fixed at length $L = 1000\ \mu\text{m}$, width $W = 200\ \mu\text{m}$ and height $H = 200\ \mu\text{m}$. The geometric parameters of the elliptical shaped microchannel are adjusted under the constraint of constant channel cross-sectional area of $225\pi\ \mu\text{m} \times \mu\text{m}$.

2.2. Governing equations

The Continuity, Momentum and Energy equations are the basic equations to govern the fluid flow and heat transfer in a microchannel heat sink and to investigate effects of geometric parameters and boundary slip on the hydraulic resistance and heat transfer performance of water flow through the microchannel heat

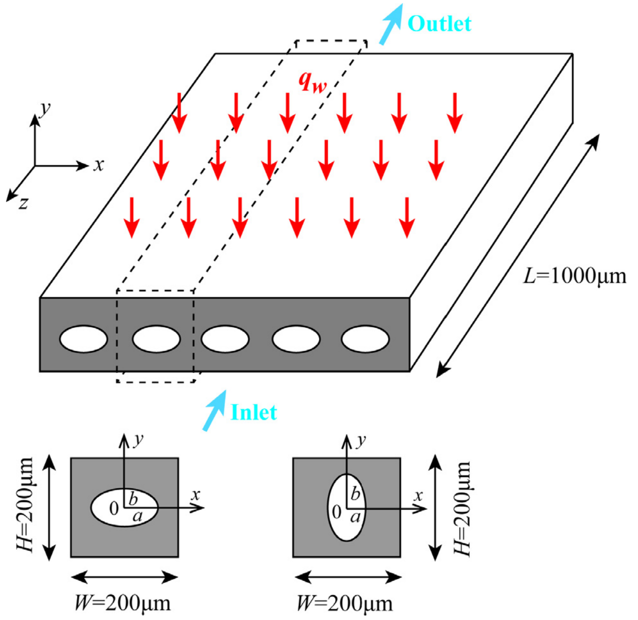

Fig. 2. Schematic of the elliptical shaped microchannel heat sink. Where q_w is the heat flux applied on the top plate of the heat sink, a and b are the semi-axes lengths of the ellipse at the x- and y- axis. The dashed line frame gives the computational domain with a fixed size of length $L = 1000\ \mu\text{m}$, width $W = 200\ \mu\text{m}$ and height $H = 200\ \mu\text{m}$.