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Wall temperature effect on mass flux in a short micro-tube

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ABSTRACT

Effects of wall temperature on mass flux and flow field structure in a circular micro-channel are investigated in this paper. It is revealed that the wall temperature affects the mass flux of pressure-driven flow by the viscosity. The simplified relationship between the wall temperature and the micro-tube mass flux is proposed for pressure-driven low-speed flow. However, for high-speed incoming flow, the wall temperature affects the micro-tube mass flux by changing the half-region viscosity. Overall, the effect of wall temperature on the mass flux for low-speed pressure-driven flow is greater than that for high-speed incoming flow.

Micro-Electro-Mechanical System (MEMS) has experienced a great prosperity in recent years with great research achievements. It has been applied in many areas, such as micro-channel gas transport ([1–3]), computer chip cooling ([4,5]) and micro-sensor measurement ([6,7]). Micro-tubes are introduced to conduct micro-flows in some MEMS. They can perform as the cooling devices to transfer the high heat flux in electronic components ([8,9]), act as flow channels in micro pumps, valves, chamber, ejectors and mixers ([10–12]) and work as micro Pitot tubes to measure the flow field ([13–15]).

According to literature [3,16,17] on microfluidics, the wall conditions show great influence on the flow field in micro-tubes, because of the large surface-volume ratio. Some researchers investigated the effect of non-uniform wall temperature distribution in temperature-driven flows, in which micro-tubes were either infinitely long or with non-circular cross sections [18–20]. Few literature focus on the effect of wall temperature on the flow field in pressure-driven flows or high-speed incoming flows, especially in a short tube. Zhang et al. [21] investigated the wall temperature effect on the flow field in a short tube for the pressure-driven flow. It demonstrated that the wall temperature showed great influence on the mass flux. Unfortunately, it did not explain the reason for the great effect, which is an important topic in this paper. Moreover, Zhang et al. [21] focused on the pressure-driven flow, over 80% of which belonged to the non-compression region. For the high-speed incoming flow, the flow experiences great compression effect in the short micro-tube. The other topic focuses on the effect of wall temperature on the flow field in this case. The achievements in this paper will help the engineers to evaluate the effect of wall temperature in slip regime on the flow field, especially on the mass flux. Besides, it will also help improve the understanding of flow field to design a prospective micro-channel.

The Variable Hard Sphere (VHS) model is chosen as the molecular collision model while the Larsen-Borgnakke model acts as the internal energy model. The time step is 2×10^{-11} s. The computational grids are structured with a division of 500×50 for the reference simulation case and the size of the largest grid for other simulation cases is less than the local mean free path. Darbandi and Roohi [22] found that the pressure distribution would not change if the mean particle number in a cell reaches 17 and it is over 40 for all the simulation cases in this paper.

The DSMC soft, Plume Work Station (PWS), has been developed and widely used by Cai's group ([3,16,23–27]). The PWS software is validated to be feasible and accurate in rarefied gas simulation. We simulated the standard case with PWS, in which the computational conditions are the same with that from Refs. [28–31]. Fig. 1 (a) shows the comparisons of velocity profile at $X = 0.4$ with reference results. The term U/U_∞ refers to the normalized axial velocity by the incoming flow speed. The term Y/D refers to the radial distance normalized by the micro-tube diameter. It shows a great agreement with those from references. Besides, the heat transfer coefficient along the wall is shown in Fig. 1 (b). The term X/L refers to the axial distance normalized by the micro-tube length. The heat transfer coefficient stands for the normalized heat flux between the wall and the flow field. It shows that the heat transfer coefficient

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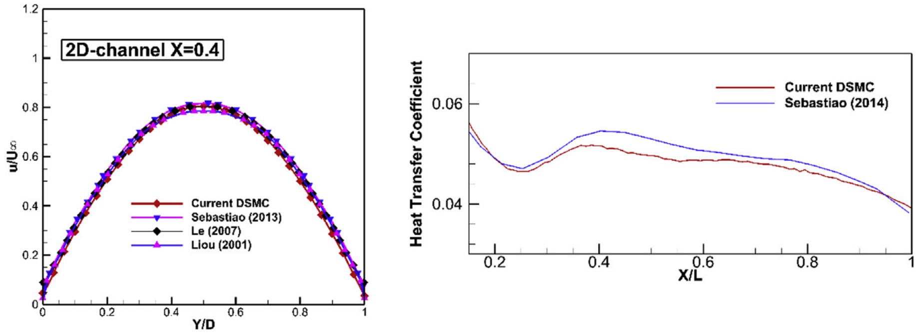

(a) (b)

Fig. 1. Comparisons of (a) velocity profile at X = 0.4 and (b) heat transfer coefficient with reference results.

obtained from PWS shows an agreement with that by Sebastiao, with the maximum deviation of 7%. It validates the well performance of PWS in micro-channel simulation.

Zhang et al. [21] has demonstrated that the mass flux is greatly influenced by the wall temperature (T_w), when the micro-channel length-radius ratio (L/R) is chosen as 10 and 20. When the wall temperature varies from 300 K to 900 K, the normalized mass flux (marked as W in Fig. 2) drops about 50% for both $L/R = 10$ and $L/R = 20$. It is important to reveal the physical mechanism behind the significant effect. The Mach number of over 80% region in the microchannel is less than 0.3 [21], which improves the heat and momentum transfer between the wall and the flow field. Besides, the great surface-volume ration in the micro-tube also help the gas particle to accommodate the wall. in fact, the difference between the centerline temperature and the wall temperature is less than 5% [21]. The heat transfer between the wall and the flow field is sufficient.

$$\mu = \frac{\frac{15}{8}(\pi mk)^{1/2}(4k/m)^{\xi}T^{1/2+\xi}}{\Gamma(4-\xi)\sigma_{T,ref}c_{r,ref}^{2\xi}} \tag{1}$$

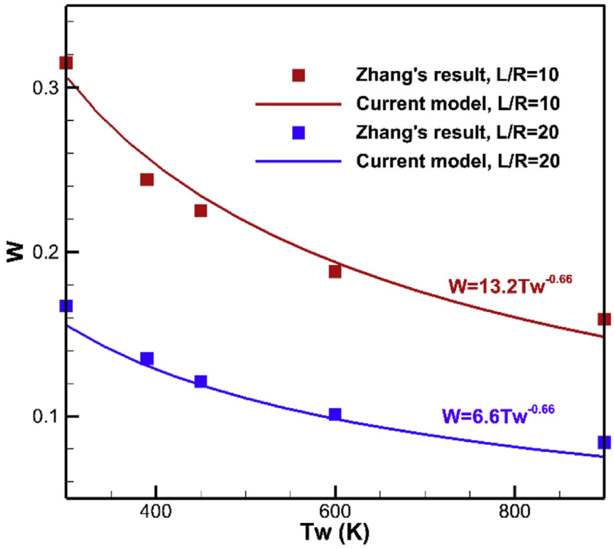

Fig. 2. Comparisons between current simplification model and the DSMC results from Zhang et al.

$$\dot{M} = \beta\frac{\pi R^4 P_0}{16\mu R T_0}\times\frac{\Delta P}{L}\left[\left(\prod+1\right)+2(4+\alpha)Kn_0 + \frac{8(\alpha+b)}{\prod-1}Kn_0^2\ln\left(\frac{\prod-bKn_0}{1-bKn_0}\right)\right] \tag{2}$$

Based on Eq. (2) [32], the mass flux is greatly influenced by the viscosity. According to Eq. (1) [33], the viscosity is supposed in proportion to $T_w^{1/2+\xi}$. So the mass flux is supposed in proportion to $T_w^{-(1/2+\xi)}$. The parameter ξ is 0.16 for He [33].

The simplified model results are shown in Fig. 2. The prediction shows an agreement with the DSMC results from Zhang et al. [21], with the maximum deviation of 8%. It validates the correction of the simplification relationship between the mass flux and the wall temperature. The wall temperature determines the whole flow viscosity in the micro-channel. Since the viscosity determines the flow friction in the micro-tube, the micro-tube mass flux is greatly influenced by the wall temperature. So it is well believed that the mass flux experiences a significant change with the variation of wall temperature. It is noted that the length-radius ratio of micro-tube is not smaller than 10, in which the flow can be heated or cooled by the wall sufficiently. Although there exists the temperature jump in the vicinity of the wall, the jumped temperature is very small compared with the wall temperature. Hence, the effect

Table 1
Freestream conditions of N_2.

Parameter	Value
Temperature (T_∞)	300 K
Pressure (P_∞)	7.248×10^4Pa
Density (ρ_∞)	0.8138 kg/m^3
Mach number	4.15
Knudsen number (Kn)	0.062

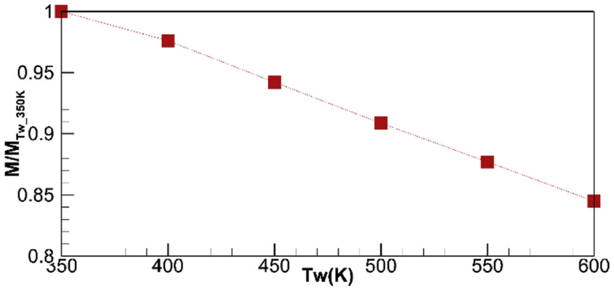

Fig. 3. Profile of normalized mass flux with wall temperature.