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Research Paper

Effects of wall conditions on flow field in a circular micro-channel

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HIGHLIGHTS

- TMAC rather than NMAC has great influence on the flow field in circular microchannel.
- The flow field is greatly influenced by the velocity stages in vicinity of the wall.
- Effect of wall roughness on flow field is much greater than that of wall material.

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ABSTRACT

Effects of a gas-surface interaction model, the Cercignani-Lampise-Lord model, on primary fluid properties in a circular micro-channel are investigated in this paper. The tangential momentum accommodation coefficient (TMAC) has a significant influence on the flow field in the micro-channel. However, the variation of the flow field with the normal momentum accommodation coefficient is not as significant as that with the TMAC. The fundamental mechanism behind the change of flow field is revealed. Moreover, it is found that the effect of the wall roughness on the flow field is much greater than that of the wall material. When the wall roughness varies, the mass flux of the ring section region between the half radius and the radius changes a lot while the rest remains unchanged. However, the heat flux over the cross section remains almost unchanged with the variation of the wall material when the wall is rough.

1. Introduction

Micro-Electro-Mechanical System (MEMS) has been regarded as a potential area with great growth prospect, especially when manufacturing technologies, such as silicon micro machining, Lithographies Gal-vanoformung Abformung and Electrical Discharge Machining, have made great progress [1–4]. Many products, such as the micro nozzle, micro sensor and micro pump, have played an important role in corresponding areas [5]. Despite the MEMS achievements, the understanding of its fluid dynamics is far from satisfactory. Additionally, the requirements for a high precision simulation model propel the research on gas flows in MEMS. The MEMS contains many micro-channels with different construct types, such as the rectangular and circular types. In most cases, the micro-channel height D_c is comparable to the mean free path λ in the micro-channel. Based on the definition of the Knudsen number (a dimensionless number indicating the flow rarefied degree), $Kn = \lambda/D_c$, the flow in the micro-channel is in the transition regime [4]. As a result, the continuum hypothesis breaks down and is not justifiable any more.

According to the current literature, most researchers have focused on the flow field simulation in the micro-channels. Some researchers simulated the flow with analytic methods. Taheri and Struchtrup [6] investigated the flow field structure in a parallel plate micro-channel with temperature gradient by solving the regularized 13-moment equations. Kanki and Iuchi [7] researched the Poiseuille flow by solving the Boltzmann equation with the Bhatnagar-Gross-Krook model. Other researchers simulated the high speed flow with Direct Simulation Monte Carlo (DSMC) method. Liou and Fang [8] investigated the velocity in a 2-D micro-channel with Variable Hard Sphere (VHS) model, revealing that the temperature jump and convection heat transfer near the wall would be enhanced by increasing the Knudsen number of the incoming flow. Mavriplis et al. [9] found that the bow shock wave near the boundary wall would expand with an increase of Knudsen number. In addition, for the transition flow, the convection heat flux showed a monotonic decrease with the increase of the incoming flow pressure. Le et al. [10] found the pressure boundary condition applicable to the case in a 2-D micro-channel when the pressure at the outlet was equal to the background pressure. The background pressure only influenced the second half flow field of the 2-D micro-channel and the wall heat flux rose with the increase of the background pressure. Most of the DSMC

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Nomenclature

Abbreviations

MEMS	Micro-Electro-Mechanical System
DSMC	Direct Simulation Monte Carlo
VHS	Variable Hard Sphere
CLL	Cercignani-Lampise-Lord
TMAC	tangential momentum accommodation coefficient
NTAC	normal thermal accommodation coefficient
PWS	Plume Work Station
NMAC	normal momentum accommodation coefficient

List of symbols

D_c	micro-channel height (m)
Kn	Knudsen number
$\overline{v_{t,r}}$	average tangential reflected velocity (m/s)
γ_t	random tangential reflected velocity (m/s)
$v_{t,r}$	tangential reflected velocity parallel component (m/s)
$\omega_{t,r}$	tangential reflected velocity vertical component (m/s)
v_m	most probable molecular thermal speed (m/s)
ran$f$	random number between 0 and 1
D	micro-channel diameter (m)
R	micro-channel radius (m)
L	micro-channel length (m)
U_∞	freestream incoming velocity (m/s)
D_p	parallel plate spacing (m)
T_r	reference temperature (K)
D_e	potential parameter in the Langmuir slip model
k_B	Boltzmann constant
T_w	wall temperature (K)
h	the wall roughness element height (m)
Q	mass flux per unit radial width (kg/(m·s))
u	axial velocity (m/s)

Greek symbols

λ	mean free path (m)
α	thermal accommodation coefficient
e	energy flux to the surface (W/m^2)
σ	momentum accommodation coefficient
τ	tangential momentum flux
ν	exponent of the inverse power laws
ρ	density (kg/m^3)
μ	viscosity coefficient (m^2/s)

Subscripts

n	normal component
t	tangential component
i	incident component
r	reflected component
w	wall

simulations focused on the effects of the primary fluid properties (the pressure and Knudsen number of the incoming flow, background pressure and fluid viscosity) on the flow field structure and heat flux in 2-D micro-channels. The gas-surface interaction effects on primary fluid properties were less reported [11]. Additionally, the Maxwell and diffuse reflection models were widely employed as the gas-surface interaction model in DSMC simulations.

According to the experimental results [4,12–15], molecules reflected from the solid surface present lobular distributions under high vacuum conditions, which is poorly described by both the Maxwell and diffuse reflection models. The Cercignani-Lampise-Lord (CLL) model can describe the lobular distributions and the gas-surface interaction better. However, the effects of the two accommodation coefficients in the CLL model on the fluid primary properties were not investigated deeply. As far as we learned, only Sebastião and Santos [4,11] studied the problem in a 2-D micro-channel and found that the normal and tangential accommodation coefficients represent an opposite influence on the primary field properties. Moreover, the primary field properties showed a greater sensitivity to tangential momentum accommodation coefficient changes than to the normal one. They also investigated the influence of different accommodation coefficients on the heat transfer, pressure and friction, revealing that the heat flux to the lower surface was influenced by the accommodation coefficients of the upper surface [4]. However, the reasons for the flow field variations caused by different accommodation coefficients were not demonstrated yet. Besides, Sebastião's study focused on the 2-D micro-channel with two parallel plates. Nowadays, circular micro-channels are applied in many areas as well. They can perform as the cooling devices to transfer the high heat flux in electronic components [16,17], and also can work as the flow channels in micro pumps, valves, ejectors and mixers [18,19]. Furthermore, the Pitot micro-tube with circular cross section plays an important role in high-speed and rarefied plume measurements [20–22]. The flow in the micro-channel with circular cross section is different from that with two parallel plates. Therefore, our research investigates the effects of the two accommodation coefficients in the CLL model on primary fluid properties in the circular micro-channel. Furthermore, the fundamental mechanism behind the influence is also revealed. This study can help understand the effects of the wall conditions on the flow field in circular micro-channel and the fundamental mechanism behind the effects, which may help improve the design and manufactory of circular micro-channels in MEMS.

Although many researchers demonstrated that the accommodation coefficients were sensitive to gas-solid interface conditions, the significant effects of the surface material and roughness are not well understood [23]. Therefore, the surface material and roughness are decoupled and investigated respectively in this paper.

2. Gas-surface interaction model

Common gas-surface interaction models contain the specular reflection, diffuse reflection, Maxwell and CLL models. The specular reflection model assumes that molecules are reflected like perfectly elastic spheres with a reversal of the normal velocity component. The diffuse reflection model assumes that particles, reflected equally in all directions, completely adapt to the wall temperature. Both assumptions are far from reality. The Maxwell model assumes that some particles are specularly reflected and the rest are diffusely reflected. It does not deviate far from the experimental results but there exists a certain deviation.

The CLL model satisfies the principle of reciprocity. Different from the Maxwell model, it decomposes the spatial distribution of particles into two orthogonal directions, i.e. the normal direction of the tangential plane and the velocity projection direction on the tangential plane. Along the normal direction, this model