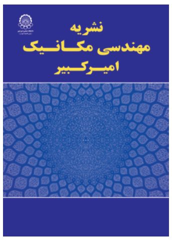

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Sensitivity Analysis of Fluid Flow to Slip Coefficient Using the Lattice Boltzmann Method

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ABSTRACT: In this paper effect of slip coefficient on incompressible gas slip flow as well as a sensitivity analysis of flow behavior to this coefficient in a rough microchannel are investigated. Local slip velocity and average Poiseuille number in hydrodynamically developed region are presented. The lattice Boltzmann method with combination of bounce back-specular reflection velocity slip boundary condition has been utilized as the numerical method. In this boundary condition, the slip coefficient is proportional to momentum accommodation coefficient. Sensitivity analysis is done in different relative roughness heights and densities of surface roughness and in different Knudsen numbers. It is shown that as the relative roughness height increases, the sensitivity of Poiseuille number to this coefficient is enhanced, while negligible sensitivity difference is seen for different roughness densities. In near continuum flow, slopes of the Poiseuille number curve in rough and smooth surface are different, and this trend becomes more similar as the Knudsen number increases.

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1- Introduction

For a gas flow in small dimension, if the Knudsen number (Kn) ranges between 0.01 and 0.1, slip flow regime occurs. The Lattice Boltzmann Method (LBM) is capable of modeling slip flow regime with low computational cost. One of the slip boundary condition in LBM is the combination of bounce back and mirror reflection [1]. Slip coefficient in this boundary condition is proportional to tangential momentum accommodation coefficient [2]. Surface roughness is one of the parameters that affect the value of tangential momentum accommodation coefficient [3].

In this paper, the effect of slip coefficient on gas flow behavior, and sensitivity of Poiseuille number to the slip coefficient are studied. The flow is assumed to be incompressible and roughness is modeled by regular rectangular elements.

2- Problem Statement

Incompressible, steady state gas flow in slip regime between two parallel plates is modeled. Surface roughness is considered to be symmetric on the upper and lower wall so that the flow is symmetric. Figure 1 shows the geometry of the microchannel.

Reynolds number and roughness height are defined as $Re=D_H u_{in}/v$ and $e=h/D_H$, respectively. Poiseuille number is also calculated based on Equation 1.

$$f\cdot Re_i=-\frac{(P_i-P_{out})D_H^2}{0.5\Delta L\,\mu\,\bar{u}_i} \tag{1}$$

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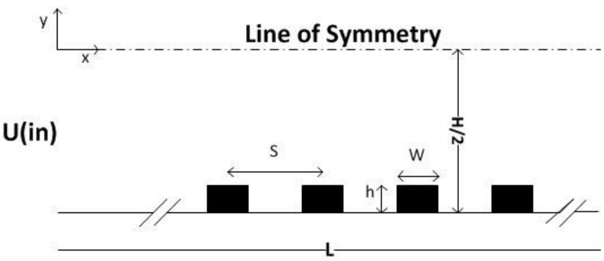

Figure 1. Geometry of the channel

3- Lattice Boltzmann Equations

Density distribution function in LBM is shown by $f(\mathbf{x},t)$, which obeys Equation 2 [4]:

$$f_i(\vec{x}+\vec{e}_i\Delta t, t+\Delta t)=f_i(\vec{x},t)-\frac{f-f^{eq.}}{\tau}. \tag{2}$$

Density and velocity are calculated using Equation 3:

$$\rho=\sum_{i=1}^{9}f_i,\quad \rho\vec{u}=\sum_{i=1}^{9}\vec{e}_i f_i \tag{3}$$

The relationship between Knudsen number and dimensionless relaxation time is defined as Equation 4 [5]:

$$\tau_f=\sqrt{\frac{6}{\pi}}\frac{Kn}{\Delta}+\frac{1}{2} \tag{4}$$

For the slip boundary condition, combination of bounce back and mirror reflection is applied using Equation 10 [1]:

$$\begin{aligned} f_2&=f_4\\ f_5&=r\tilde{f}_7+(1-r)\tilde{f}_8 \end{aligned} \tag{5}$$

$$f_6 = r\tilde{f}_8 + (1-r)\tilde{f}_7$$

where r is the slip coefficient.

4- Results

In order to validate the code, results obtained from current study are compared to the analytical results in Table 1. Slip coefficient is calculated based on proposed formula in Guo et al [1] study, which adjusts the lattice Boltzmann results to the analytical solution results.

Table 1. Comparison of Poiseuille number

Analytical	Current study	Kn
90.93	90.94	0.008
84.04	84.08	0.02
74.19	74.23	0.04
65.98	66.05	0.06
59.07	60.02	0.08
53.19	53.80	0.1

Figure 2 shows the slip velocity for different slip coefficients. As the slip coefficient increases, portion of diffuse reflection increases and portion of mirror reflection decreases, and as a result, slip velocity decreases. In valleys due to formation of sedentary flows, the slip velocity is almost zero.

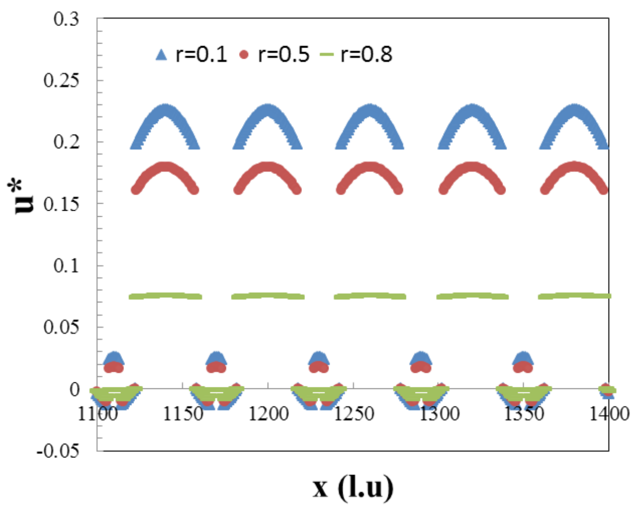

Figure 2. Slip velocity for different slip coefficients

Figure 3 shows Poiseuille number for different roughness heights in different slip coefficients. As roughness height increases, sensitivity of the Poiseuille number to the slip coefficient increases.

Figure 4 compares Poiseuille number in different Knudsen numbers, for rough and smooth surface. In lower Knudsen numbers the change trend for smooth and rough surface is different. As the Knudsen number increases, Poiseuille number behavior follows the same trend in smooth and rough surface. This is because in higher Knudsen numbers the effect of roughness is less captured by the fluid.

5- Conclusions

It is shown as the surface roughness height increases, sensitivity of the Poiseuille number to the slip coefficient

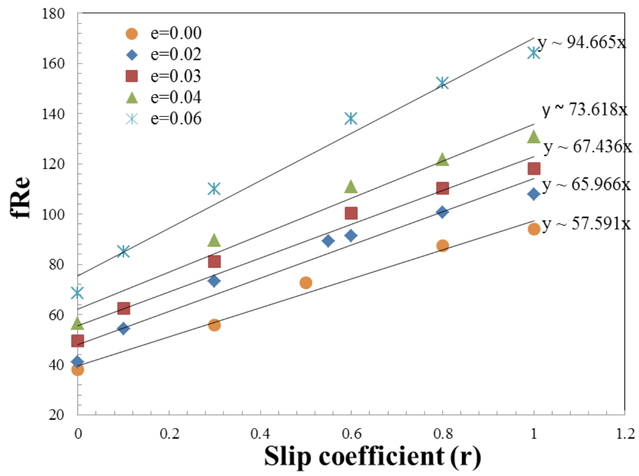

Figure 3. Poiseuille number vs. slip coefficients for different roughness heights

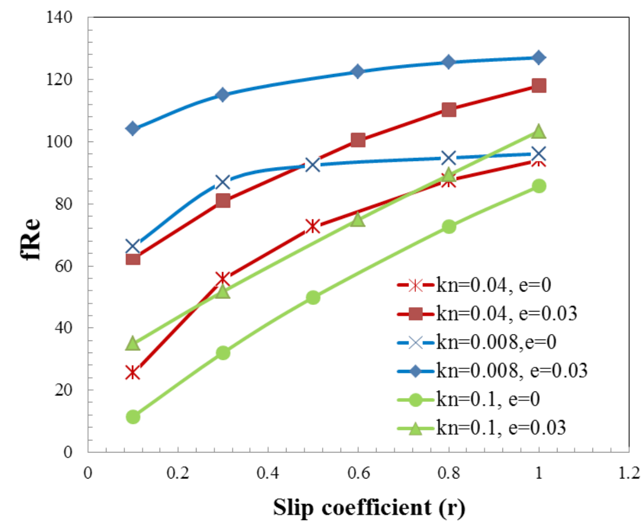

Figure 4. Comparison of Poiseuille number vs. slip coefficients for rough and smooth surface

increases. In addition, as the Knudsen number increases, Poiseuille number versus slip coefficient change trend for rough and smooth surface follows the same trend. This is because in higher Knudsen numbers, effect of surface roughness is less captured by the gas.

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