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Direct simulation of roughness effects on rarefied and compressible flow at slip flow regime ☆

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ABSTRACT

A two dimensional numerical simulation is performed for incompressible and compressible fluid flows through microchannels in slip flow regime with consideration of slip and temperature jump boundary conditions. The wall roughness is simulated in two cases with triangular microelements and random shaped micro peaks distributed on wall surfaces to study the effects of roughness shape and distribution on the flow field. Various Mach and Knudsen numbers have been used to investigate the effects of rarefaction as well as compressibility. It is found that rarefaction has a more significant effect on the flow field in microchannels with higher relative roughness. It is also found that the effect of compressibility will be more noticeable when relative roughness increases. In addition a high influence of roughness distribution and shape can be seen for both compressible and incompressible flows. The numerical results have also been checked with available theoretical and experimental relations and a good agreement has been achieved.

1. Introduction

In order to design microdevices properly, it is necessary to establish the physical laws governing fluid flow and heat transfer in microgeometry. However, it has been reported that phenomena in microgeometry may differ from those in macroscopic counterparts. Several factors that are dominant in micro scale have been identified through a number of experimental, analytical and numerical works. Among them, noncontinuum effect, compressibility effect, and various surface effects have been under vigorous investigation.

At the microscale level, it is impossible to obtain a completely smooth wall surface. According to the traditional knowledge for macrosystems, when the relative roughness is less than 5%, its effect on the friction factor is negligible. But for microscale channels, previously reported experimental and computational results have drawn a conclusion that surface roughness has a significant influence on flow and heat transfer [1,2]. For example, the experiment by Kandlikar et al. [2] indicated that for a 0.62 mm tube with relative roughness of 0.355%, the effect of roughness on the friction factor and heat transfer was significant. Mala and Li [3] observed that for rough channels with diameters ranging from 50 to 254 lm (relative roughness height 0.7–3.5%), the pressure gradient was higher than that predicted by the classical theory and the friction factor increased when the Re number was increased. In addition, an early transition from laminar to turbulent flow occurred at a Reynolds number less than 2300. They concluded that these phenomena can be well explained due to the surface roughness effects.

In some experimental works such as Wu and Little [4,5], friction factors have been measured for both laminar and turbulent flows in miniaturized channels etched in silicon and glass. The hydraulic diameter of trapezoidal-cross-section microchannels ranged from 45.46 to 83.08 mm. The measured values of the friction factor were much larger (e.g., 10–30% in silicon channels and 3–5 times in glass channels) than those predicted by the conventional correlation for a smooth circular tube. They attributed their anomalous results to the large relative (and asymmetric) roughness of test channels (actually, the equivalent relative roughness was estimated to be in the range of 0.2 to 0.3 through indirect measurement). Choi et al. [6] measured friction factors of nitrogen flow in microtubes with diameters ranging from 3 to 81 mm. The measured friction factors for laminar and turbulent flows were found to be consistently smaller than those predicted by the macro scale correlation in macro tubes. For laminar flow ($Re<2300$), the friction constant, C, was 19–27% smaller than the conventional one, with an average friction constant of 53, instead of 64.

In the modeling of roughness effect on rarefied flows, Usami et al. [7] studied rarefied gas flow through a 2D channel using a DSMC method by varying the surface roughness distribution and the Kn number. The reduction of flow conductivity caused by surface roughness was obtained in the transition regime. Sun's study [8] by using a DSMC method found that the roughness element size had a significant effect on the friction factor of rarefied flows when $0.01<Kn<0.1$. Karniadakis et al. [9] applied a more accurate gas flow

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Nomenclature

c_p	specific heat (J/kg k)
D_h	hydraulic diameter
e	relative roughness
f	friction factor
H	channel height
K	thermal conductivity
L	channel length
n	unit inward normal vector
P	static pressure (Pa)
r	roughness height
R	gas constant
T	temperature
u	stream velocity
v	normal velocity
Pd	peak density
fRe	Poiseuille number
Kn	Knudsen number
Ma	Mach number
Nu	Nusselt number
Pe	Peclet number
Pr	Prandtl number
Re	Reynolds number
U, V	dimensionless velocity
X, Y	dimensionless coordinate variables
Greek symbols	
α	thermal diffusion coefficient (m^2/s)
μ	viscosity(m^2/s)
θ	dimensionless temperature
ρ	density (kg/m^3)
σ_T	energy accommodation coefficient
σ_v	momentum accommodation coefficient
Subscript and superscript	
i	inlet
w	wall
*	dimensionless variables

model and found that the roughness effect becomes more significant on rarefied flows when the Kn number was increased.

However, for a rarefied gas flowing in a microchannel, the roughness effect is more complex and difficult to measure [10]. Experimental investigation by Sugiyama [11,12] demonstrated that the conductance of an unsteady rarified flow between two flat, rough plates decreased significantly with decrease in Kn when Kn>1. It reached the minimum value around Kn=0.5, and with further decrease in Kn, the conductance increased rapidly. Their calculation also showed that pronounced effect of the wave angle on the flow conductance, when Kn=1 and Kn=0.1. They did not investigate the roughness effect on rarefied flow in the slip regime (0.001<Kn<0.1).

There are also some studies on direct simulation of roughness. Valdes et al. [13] have numerically investigated the roughness effect on laminar incompressible flow through microchannels. In their work the roughness is simulated by the superimposition of randomly generated triangular peaks on the inner wall of a smooth microchannel. In one of recent researches Ji et al. [14] studied the influence of roughness in slip flow regime with second order slip boundary conditions. They simulated the roughness with rectangular elements on two parallel plates with different spacings and heights to investigate the effect of wall roughness on friction factor and Nusselt number. They showed that the effect of wall roughness is reduced with increasing Knudsen number.

In this study we will focus on slip flow regime (0.001<Kn<0.1) that requires the use of slip boundary conditions. Although there are several models for slip boundary conditions, we will use the Maxwell model for slip and Smoluchowski for temperature jump conditions [15] that will be discussed later. Compressibility and rarefaction effect on fluid flow will be taken into consideration.

2. Problem definition and CFD model

2.1. Model development

We consider a pressure-driven gas flow between two long parallel flat plates. Fig. 1a shows a schematic of the *2D* flow through a rough channel with length *L* and height *H*. To simulate roughness on channel surfaces we considered triangular peaks with height *r* and width *w* for all of the models associated with case 1. These elements are uniformly and symmetrically distributed on the top and bottom surfaces. Although, this geometry is not exactly the same as the actual rough surface, it is considered as a close approximation to investigate the roughness effect on the flow field and pressure distribution. This was also used by Ji et al. [1] with a different simulation of roughness shape (they assumed roughness as rectangular elements). We can also simulate roughness with randomly distributed peaks with various heights. Although this seems to be the best approximation, through our knowledge there has been no study on accommodation coefficients in such geometries, so in this study we will also search for differences between friction factors associated with change in roughness shapes. Hence there is also case 2, which contains models where roughness elements are randomly distributed on their surfaces (Fig. 2b).

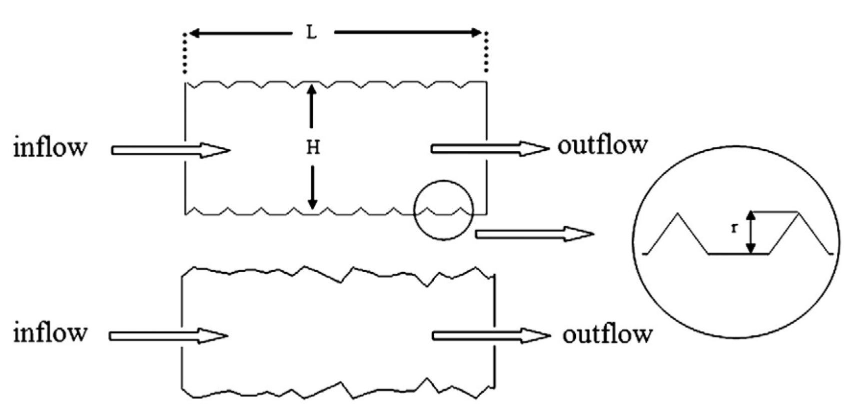

Fig. 1. Microchannels with triangular and random roughness elements (both have 5% relative roughness).