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Temperature jump at rough gas–solid interface in Couette flow with a rough surface described by Cantor fractal

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ABSTRACT

A lattice Boltzmann simulation of heat transfer for gas flowing in microchannels incorporating surface roughness as characterized by fractal Cantor structure is conducted to investigate the temperature jump at rough gas–solid interfaces in the slip flow regime. The gas temperature jump at rough interface as quantified by the temperature jump length is evaluated and compared with smooth interface. It is indicated that the temperature jump at a rough gas–solid interface is mainly dependent on Knudsen number, Prandtl number, and surface roughness. The presence of roughness is beneficial to the energy exchange at the gas–solid interface and introduces a smaller temperature jump when compared with a smooth surface. The local gas temperatures in the valley of rough surface are approximately equal to the corresponding surface temperatures while an obvious interfacial temperature jump is detected over the peaks of the rough surface. In addition, increase in Prandtl number, roughness height, surface fractal dimension as well as the decrease in Knudsen number can lead to the reduction of interface temperature jump for gas convection heat transfer in microchannels. Interestingly, in microchannels, the roughness height play a considerable role in the temperature jump at the gas–solid interface, however, the effect of fractal dimension on interfacial temperature jump is not so significant.

1. Introduction

Temperature jump at a gas–solid interface, a classical physical phenomenon, regains particular interest due to the rapid development of microfluidic devices [1–4]. In microfluidics, for gas flow, the mean free path of gas molecules is comparable with, or even larger than the system's characteristic length, so the significant rarefaction effect must be taken into account in gas dynamics [5,6]. And due to the rarefaction effect, a temperature jump arises at the gas–solid interface. In addition, shrinking down the characteristic size of a microscopic device leads to large surface-to-volume ratio, causing the surface plays a more significant role on the microfluidics flow behavior. The interfacial temperature jump is dependent on the nature and on the state of the solid wall, in relation to the nature of the gas [7]. In this context, it is critical to understand the role of surface topography on temperature jump at gas–solid interfaces with the existence of rarefaction effects.

After the pioneering work of explanation and estimate of temperature jump coefficient by Maxwell [2,8,9], the interfacial temperature jump was experimentally confirmed by Smoluchowski and theoretically studied by Knudsen as well as other researchers. Several classical formulae have been proposed to quantify the degree of temperature jump at the boundary [10]. During the past decade, with the development of computer technology, several efforts [2,7,11,12] have been recently devoted to investigate the temperature jump phenomenon by the use of computational fluid dynamics simulation, lattice Boltzmann simulation, and molecular dynamics simulation. The results indicate that heat transport across the boundary is mainly dominated by the gas–solid interaction, mean free path, and gas transport properties. Considering that the surface topography could highly affect gas dynamics and heat transfer in microgeometry, some attempts have been made to correlate the surface topography to the thermal behaviors at gas–solid interfaces via computational fluid dynamics simulation. Ji et al. [13] investigated the slip-flow heat transfer in rough microchannels. In the investigation, the geometric structures of rough surfaces are still modeled by regular patterns (rectangular roughness) with a focus on statistical roughness height. Zhang et al. [14] investigated the role of random surface roughness characterized by fractal geometry on slip flow and heat transfer in microbearings, and found that the effects of the gas rarefaction and surface roughness on flow behavior and heat transfer in the microbearing are strongly coupled. However, how the detailed nature of surface topography affects the interfacial temperature jump behavior is not well understood.

As stated earlier, the interfacial temperature jump is dependent on the nature and on the state of the solid wall. There has been a

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Nomenclature

D	fractal dimension
H	channel characteristic length
Kn	Knudsen number
L	length of rough surface profile
Pr	Prandtl number
T	temperature
f_x, f_y	proportionality coefficients
h	roughness height
h_v	first order slip coefficient
h_T	first order temperature jump coefficient
s	asperity number on a repeating segment
U	velocity of the upper solid wall, see Fig. 2
$\boldsymbol{u}$	velocity

Greek symbols

α	thermal diffusivity
γ	specific heat ratio
δ	root mean square height
ε_r	relative roughness
ζ	temperature jump length
θ	nondimensional temperature
ν	kinematic viscosity
ρ	density
σ_v	tangential momentum accommodation coefficient
σ_T	tangential energy accommodation coefficient
χ	model-dependent constant

Subscripts

w	solid wall
up	upper wall
low	lower wall

substantial body of literature describing and interpreting the detailed nature of surface topography. It is demonstrated that the actual surface roughness is a nonstationary process, and the surface parameters are strongly related to the scan length and the measurement technique and hence are not unique for a surface [15,16]. For such a structure, the multiscale and self-affine fractal behavior is always exhibited. Recognizing the multiscale and self-affine properties [17], we have introduced the fractal geometry to characterize the rough surfaces in microfluidics and investigated the heat transfer of liquid in rough micro/nanochannels [18–21]. It is indicated that the thermal behaviors at the liquid–solid interface are crucially affected by the interaction of the liquid with the confining solid surface, and the fractal dimension (i.e. topographical spectrum) plays a significant role in microscale convective heat transfer [19,20] and thermal slip at liquid–solid interface [21].

Unlike heat transport at liquid–solid interface, the thermal behavior at gas–solid interface involves the rarefaction effects of gas flow in the slip flow regime. More importantly, the gas is larger in mean molecular spacing when compared with the liquid. These factors are expected to induce different behavior of momentum and energy transfer at the gas–solid and liquid–solid interface. As an analogous physical phenomenon, whether the temperature jump at the gas–solid interface induced by the surface topography retains the same trend as that at liquid–solid interface is not completely known. In addition, how the nature of surface topography affect the gas heat transport across the boundary is less understood, especially the role of surface fractal dimension on temperature jump at gas–solid interfaces. Therefore, in this paper, a lattice Boltzmann model of heat transfer for gas flowing in microchannel with rough surface characterized by fractal Cantor structure is developed and numerically analyzed to investigate the role of surface topography on microscale heat transfer in the slip flow regime, in an effort to elucidate the temperature jump at rough gas–solid interfaces.

2. Fractal characterization of rough surface

To investigate the role of surface roughness on temperature jump at rough gas–solid interfaces, the characterization of rough surface profile is a necessary step. It has been shown that the surface roughness at all magnification is quite qualitatively similar in structure and exhibits a self-affine property [16]. The characterization of surface topography using fractal Cantor structure has been applied and examined in the investigation of contact problems [17]. As a consequence, the fractal Cantor structure is utilized to describe the rough surface in the current study. As shown in Fig. 1(a), the fractal Cantor structure can be generated by joining the segments obtained at successive stages of the Cantor set, and the horizontal length and the salient height of the $(n+1)$th level of this structure are,

$$L_{n+1} = \left(\frac{1}{f_x}\right) L_n = \left(\frac{1}{f_x}\right)^{n+1} L_0 \tag{1}$$

$$h_{n+1} = \left(\frac{1}{f_y}\right) h_n = \left(\frac{1}{f_y}\right)^{n+1} h_0 \tag{2}$$

where L_0 is the length of rough surface profile, h_0 is the zero level roughness height ($h_0 = 2\delta$ [17], in which δ is the root mean square height), f_x, f_y are the proportionality coefficients.

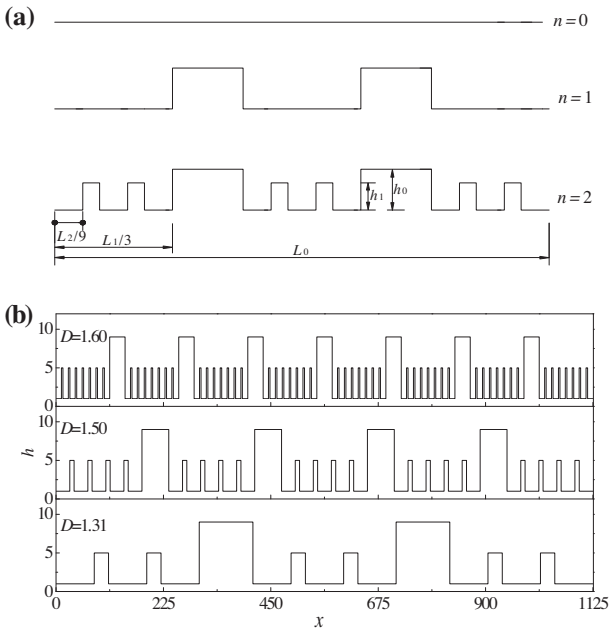

Fig. 1. Fractal characterization of rough surface: (a) construction of fractal Cantor structure ($s = 3$), (b) rough surface characterized by fractal Cantor structure.