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Research paper

Influence of wall roughness models on fluid flow and heat transfer in microchannels

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HIGHLIGHTS

- A new roughness model is proposed and compared with others in both 2D & 3D.
- Gauss model is more flexible and convenient in practice than the fractal model.
- 2D model of roughness is unacceptable to describe the real rough surface.
- Roughness is positive on the thermal performance in microchannels.

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ABSTRACT

To disclose the fluid flowing and thermal performance in microchannels with roughness, a novel and effective rough surface model, Gauss model, was proposed and the comparing investigation with other typical models of both 2D and 3D proposed in literature, especially the fractal model, were carried out. The 2D roughness model, whatever regular model or random model, are found failure to reveal the effect of roughness on fluid flow and heat transfer accurately since the 2D model is incompetent to describe the real rough surface. And the 3D Gauss model both with efficiency and accuracy are presented rather than the fractal model in our paper. By investigation of thermal performance in microchannels, both flow resistance and heat transfer are found sensitive to the surface morphology of microchannels. In general, roughness play a positive role on the thermal performance as well as flow resistance under laminar flow.

1. Introduction

In the traditional macro-scale fluid dynamics, the surface roughness effect on fluid flow and heat transfer are usually negligible when the relative roughness is less than 5% [1]. The sizes of channels reduce largely owing to the rapid rising of micro-electromechanical technology. However, limited by the processing technology at present, the surface roughness of materials are hard to control and scaling up with system scale decreasing [2]. Therefore, it is a necessary trend to explore effects of surface roughness on fluid flow and heat transfer in micro-levels.

Much attention has been paid consequently on the roughness effect on flow and heat transfer in microchannels or microtubes by experimental and numerical methods. Tang et al. experimentally explored the gas [3], water [4] and non-Newtonian PAM solution [5] flows in various types of microchannels, and the friction factors in stainless steel microtubes were observed much larger than predictions of the classical theory for regular size pipe, while the measurements of smooth fused silica microchannels were well accord with conventional theory predictions. They pointed out that the discrepancy was caused by the large relative surface roughness in the stainless steel tubes and they also claimed that the roughness effect cannot be ignored if the relative roughness height is larger than 1% in microchannels. Further experimental study were conducted by Li et al. [6] to observe the flow and heat transfer characteristics of liquid under laminar flow in the smooth fused silica and rough stainless steel microtubes. The results indicated that the friction factor increased with the surface relative roughness growing and the conventional friction theory are no longer applicable in rough stainless steel microtubes. A similar conclusion was also presented in experiments of macro tubes by Huang et al. [7,8]. Recently, the influence of surface roughness on flow boiling heat

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Nomenclature

a	side length of square microchannel, (m)
A	independent and random number obeying U (0, 2π)
A_{ex}	heat transfer area of fluid, (m^2)
A_{heat}	heating area of heat flux, (m^2)
B	independent and random number obeying U (0, 2π)
c	specific heat capacity, (J/(kg K))
C	independent and random number obeying N (0, 1)
d	equivalent diameter of microchannel, (m)
D	fractal dimension of roughness profile
f	friction factor
G	characteristic length scale
h	convective heat transfer coefficient, (W/(m^2 K))
H	height of heat sink, (m)
l	length of heat flux, (m)
L	length of square microchannel, (m)
n	natural number
n_1	low cut-off frequency exponent
Nu	Nusselt number
$\overline{Nu}$	average Nusselt number
Pf	performance factor
Δp	pressure drop along channel, (Pa)
Po	Poiseuille number
q	heat flux, (W/m^2)
r	average roughness, (m)
Re	Reynolds number
s	spacing between adjacent peaks, (m)
s_0	width of roughness elements, (m)
s_1	spacing between adjacent roughness elements along x-coordinate, (m)
s_2	spacing between adjacent roughness elements along z-coordinate, (m)
T	temperature, (K)
u	velocity along x-coordinate, (m/s)
y	ideal wall profile
x	random variable

Greek symbols

γ	scaling parameter
ε	relative roughness, (%)
ε_h	roughness height, (m)
λ	thermal conductivity, (W/(m K))
μ	fluid viscosity, (Pa·s)
ρ	fluid density, (kg/m^3)
σ	root mean square roughness
ω_l	low cut-off frequency
ω_h	high frequency limit

Subscripts

s	smooth
x	local
w	wall
f	fluid
ave	average
max	maximum

transfer, pressure drop and instability in microgap heat sink were investigated by Alam et al. [9]. In their experiment, heat transfer performance was enhanced by rough surface as well as the pressure fluctuation. However, According to experimental data of air and CO_2 flow in micro-tubes achieved by Lin et al. [10], it was found that there are apparent roughness effect on flow characteristics but thermal performance are almost no difference for both smooth and rough rube. In general, it is hard to find a regular law or reason of surface roughness effect on fluid flow and heat transfer characteristics since it is closely connected to roughness and fluid type. Moreover, measurement uncertainty is inevitable experimentally at such small scales and it is hard to exclude other relevant factors aside from roughness, which are both possible to result in totally different or even contradicted experimental conclusions.

To deeply reveal the roughness contribution to fluid flowing and thermal behaviors, it is an efficient way by numerical simulation to describe the surface imperfections, isolating the roughness effect from other factors formed in micro size. For establishing numerical approach, it is most crucial part of constructing physical model to describe the random rough feature of material surface as accurate as possible. Up to now, different roughness models, involving 2D/3D, have been proposed.

Hu et al. [11] simulated the three dimensional rough surface by rectangular prism roughness elements and numerically investigated pressure-driven flow in microchannels. They found that the geometry parameters of rough surface are a very sensitive factor of the velocity and pressure drop. Giulio and Paola [12] configured a two dimensional surface roughness model with a series of peaks which are randomly generated. The flow resistance in the rough channel was larger than that in the smooth one while the heat transfer was similar between the rough channel and smooth channel. Kleinstreuer and Koo [13] captured relative surface roughness in terms of a porous medium layer model (PML) on the hypothesis that triangle roughness elements were identically distributed. As a result, the friction factor was found enlarged. Rawool et al. [14] proposed a three dimensional roughness model by arranging rectangular, triangular and trapezoidal obstructions along the channel and studied the influences of geometry parameters on the fluid flow in microchannels. The results showed that the friction factor decreased as the Reynolds number increasing. It should be noted that the variation of friction factor in microchannels differs in roughness element shapes, which indicated that the fluid flow was sensitive to the geometry of roughness elements. Croce et al. [15] characterized the rough surface with a set of conical peak roughness elements and simulated the effects of geometrical details on the fluid flow in microchannels. A correlation was proposed to fit the numerical results. Majumdar [16] qualitatively observed the surface topography of magnetic thin film in the power spectrum. The spectra suggested that the surface consists of random roughness at all scales and could be characterized by fractal geometry. Therefore, Chen et al. [17] introduced the Weierstrass-Mandelbrot function to simulate the fractal surface. The result showed that the pressure drop increased with the increase of the relative roughness and the fractal dimension, which was accounted for the flow recirculation and separation induced by the rough surface. Zhang et al. [18] modeled the two dimensional rough surface through triangular, rectangular and semicircular roughness elements and the result shows that both the Poiseuille number and average Nusselt number are independent of Reynolds number and higher than the classical value. Chen et al. [19] characterized the rough surfaces by using a Cantor set structure. It was found that the local Nusselt numbers in the fully developed region fluctuated along the rough surfaces. In addition, the average Nusselt number increases with the Reynolds number, relative roughness and fractal dimension. Xiong and Chung [20] presented a three-dimensional random surface roughness by combining a bi-cubic Coons patch with roughness heights following the Gauss distribution and investigated the