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Experimental and theoretical investigations on the flow resistance reduction and slip flow in super-hydrophobic micro tubes

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ABSTRACT

Super-hydrophobic micro tubes with contact angles larger than 150° on inner walls are obtained by solidifying a hydrophobic solution prepared by adding 2% perfluorinated octyl fluorine silane and other additives to modified silicone dilute solution, and diameters of micro tubes are 0.447 mm, 0.728 mm and 0.873 mm, respectively. The changing coefficients of the pressure drops and friction factors in micro tubes due to the super-hydrophobic processing are experimentally measured with Reynolds number ranging from 0 to 2500. A theoretical method is employed to obtain the theoretical correlations of the slip length and velocity in super-hydrophobic micro tubes, so the relationships between the flow resistance reduction and slip flow are quantitatively analyzed. The results illustrate that the changing coefficient of the pressure drop and the friction factor reaches over 60% due to super-hydrophobic surfaces, but the reduction of the pressure drop decreases gradually with the increase of *Re* and the decrease of tube diameter. The theoretical predictions to changing coefficients of pressure drops and friction factors are consistent with the experimental results. Moreover, the reduction rate of slip length and slip velocity with the increase of pressure and *Re* is the dominant factor to decide the total resistance reduction in super-hydrophobic micro tubes.

0. Introduction

Recently, the wide applications of Complementary Metal Oxide Semiconductor in many industries and social life put forwards more and more strict requirement to the capacity and the efficiency of the cooling technology [1]. According to the statistics in the literature [2], the heat flux of the micro processing computer chips has been increased several orders of magnitudes since 1980s. In order to maintain the normal operation of these chips and the systems involving these chips, the compact and high efficient cooling systems are necessary. Therefore, the investigation on micro cooling elements and heat sinks becomes one of the most important topics in the flow and heat transfer, and many heat sinks using micro scale structures like micro channel, micro capillary grooves, micro pin fins, etc., are explored by many researchers in these years. It is known from these investigations that the heat transfer efficiency is enhanced by these micro scale designs, but very high pump power are required in the cooling system using these micro heat sinks. Consequently, the high flow resistance has been a bottleneck problem in the development of micro cooling technologies.

Based on the hydrodynamic theories, the reduction of the surface energy on the flowing surface can be used to reduce the flow resistance in micro/nano channels due to the appearance of a thin layer of liquid with low density near the wall [3–6], so the present manuscript carries out experimental investigations on the flow resistance reduction in micro tubes with super-hydrophobic surfaces, as well as a theoretical analysis to explore the mechanisms of flow resistance reduction due to the slip flow on the inner wall of super-hydrophobic micro tubes.

The existing literatures on micro structures with hydrophobic walls mainly focus on three topics: the single phase flow in hydrophobic micro channels, the two phase flow and heat transfer in hydrophobic micro channels, and the fabrication of the hydrophobic surfaces [6–10]. The present research mainly discusses the flow reduction in hydrophobic micro tubes, and the existing results on the flow and heat transfer in hydrophobic micro channels will be introduced below.

In the researches of single phase flow in hydrophobic micro channels, the flow resistance reduction due to the hydrophobic surfaces is confirmed. Ou [11,12] carried out a series of experiments to study the flow kinematics of water past drag-reducing super-hydrophobic surfaces. They fabricated ultra-hydrophobic

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Nomenclature

A	area (m^2)
b	slip length (m)
C	constant
d	micro tube diameter (m)
dp_coe	changing coefficient of pressure drop
f	friction factor
df_coe	changing coefficient of friction factor
G	flow rate of mass (W/(m K))
K	local friction factor
L	length of the tube (m)
p	pressure (Pa)
Δp	pressure drop (Pa)
r	radius (m)
u	velocity of fluid (m/s)
x	distance from the inlet to the local point in micro tube (m)

Greek letters

ϕ	angle between the projections and the two phase contact surface
θ	contact angle of water
ρ	water density (kg/m^3)
μ	water viscosity (kg/(m s))

Subscript

1	connector
air	air
c	inlet
e	outlet
hy	with super-hydrophobic surface
m	measured by pressure transducer
$no-hy$	without super-hydrophobic surface
s	slip flow
water	water

surfaces from silicon wafers using photolithography, and experimentally measured the velocity profile and the pressure drop as a function of the flow rate for a series of rectangular cross-section micro-channel geometries and ultra-hydrophobic surface designs. The results demonstrated that slip flow along the shear-free air–water interface supported between the hydrophobic micrometer-sized ridges was the primary mechanism responsible for the drag reduction observed for flows over ultra-hydrophobic surfaces. A maximum slip velocity of more than 60% of the average velocity in the micro-channel was found at the center of the shear-free air–water interface. Besides, their investigations showed that pressure drop reductions up to 40% and apparent slip lengths larger than 20 μm were obtained using ultra-hydrophobic surfaces. In order to clarify the slip flow in hydrophobic in micro channels, Tretheway and Meinhart [13] carried out experiments with micro-Particle Image Velocimetry (PIV) technology to measure the velocity profiles of water flowing through 30 × 300 μm channels. The velocity profiles were measured within 450 nm of the micro-channel surface, and the results showed that an apparent velocity slip was measured just above the solid surface. This velocity was approximately 10% of the free-stream velocity and yielded a slip length of approximately 1 μm. For this slip length, slip flow was negligible for length scales greater than 1 mm, but must be considered at the micro- and nano scales. Nouri et al. [14] presented a theoretical prediction of friction drag reduction in turbulent channel flow which was achieved by using super-hydrophobic surfaces. The predicted drag reduction was approximately 30%, which concurred with results obtained from Direct Numerical Simulation (DNS). An important implication of the present finding was that the near-wall turbulence structures were modified with streamwise slip velocity. In addition, a noticeable effect on the turbulence structure occurred when the slip length was longer than a certain value. Sungnam et al. [15] employed processes with the advantages of simplicity and cost effectiveness to obtain durable super-hydrophilic and super-hydrophobic surfaces, and the flow resistance was measured on a super-hydrophobic surface and was compared to that on smooth and super-hydrophilic surfaces. The experimental results illustrated that the flow resistance in micro channels could be reduced apparently at $Re < 200{,}000$, especially at low Re. Wang et al. [16] designed the transverse grates to be dense and deep to sustain air pockets in the gaps of hydrophobic grooves for a long time. Direct optical measurements were conducted to observe the entrapped gas when water flowed over the surface in the perpendicular direction of grating pattern. Visualization of gas indicated that the gas could be hold in the designed structures within water flowing time. When grooves were optimized, a drag reducing efficiency of more than 13% was achieved, which did not vary during the test lasting 1 h. The drag reduction mechanism of this specially designed surface was attributed to an “effective” slip which was generated by the steady gas in the microgrooves underwater. Li et al. [17] simulated the characteristics of flow in a micro-channel with patterned super-hydrophobic surfaces by using an incompressible lattice Bhatnagar–Gross–Krook (LBGK) model. They found that the depth-to-width ratio of the cavities between adjacent micro-ridges was an important effect parameter for the flow in the micro-channel. For the larger depth-to-width ratio, it was easy to keep air in the cavities. Moreover, they also found that the smaller the solid area fraction, the greater the slipping velocity at the air–water interfaces by keeping the air in the cavities. With a decrease of the solid area fractions, the average exit velocity increased and the flow drag coefficient decreased.

Except the single phase flow in micro channels, the hydrophobic surface also impacts the two phase flow and heat transfer in micro channels. Michael and Ben [18] introduced an approximation procedure and provided existence results for two-phase flow equations in porous media that have hydrophobic and hydrophilic components such that the capillary pressure function was degenerate for extreme saturations. Then the outflow boundary condition which modeled an interface with open space was investigated. The results showed that the approximate system introduced standard boundary conditions and could be used in numerical schemes. It allowed the derivation of maximum principles. Choi et al. [19] conducted experiments of water flow boiling in hydrophilic and hydrophobic rectangular micro-channels to investigate the wet ability effect on flow boiling in rectangular micro-channels. The boiling heat transfer coefficient in the hydrophobic rectangular micro-channel was higher than that in the hydrophilic rectangular micro-channel, which was highly related with nucleation site density and liquid film motion. The pressure drop in the hydrophobic rectangular micro-channel was higher than that in the hydrophilic rectangular micro-channel, which was highly related with unstable motions of bubble and liquid film. Liu et al. [20] fabricated three different micro-channels with identical sizes at 105 × 1000 × 30,000 μm but at different wet ability of 36° and 103°. In addition, a vapor–liquid–solid growth process was