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The impact of contact angle on flow resistance reduction in hydrophobic micro pin fins

Ning Guan, Guilin Jiang, Zhigang Liu *, Chengwu Zhang, Ning Ding

Key Lab for Flow & Enhanced Heat Transfer, Energy Research Institute of Shandong Academy of Sciences, Jinan 250014, Shandong, China

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ABSTRACT

The pressure drops and the friction factors are measured when ultra pure water flows through the elliptical, diamond and circular hydrophobic micro pin fins with different contact angles of $\theta = 99.5°$, 119.5° and 151.5°, and the coefficients of pressure drop reduction *dp_coe* and friction factor reduction *df_coe* are calculated respectively. It is found that the value of *dp_coe* becomes large with the increase of θ in elliptical and diamond micro pin fins, but for circular micro pin fins it increases at first and then decreases. With the increase of θ, both values of *dp_coe* and *df_coe* are reduced with the increase of the flow rate in elliptical micro pin fins, but the values are reduced at first and then become almost constants in diamond and circular micro pin fins. Besides, the minimal value of *df_coe* is over 50% in diamond and circular micro pin fins with contact angle of $\theta = 151.5°$. When $\theta \geqslant 119.5°$, the values of *dp_coe* and *df_coe* in diamond and circular micro pin fins are both larger than those in elliptical test sections, but for $\theta = 99.5°$ the former are slightly smaller than the latter at $Re < 600$.

0. Introductions

In recent decades, the Complementary Metal Oxide Semiconductor industries and other microelectronics industry have been developed rapidly. According to Moore's law, the component density and performance of integrated circuits will be doubled every 18 months [1], which results in an exponential increase of the heat flux in the smaller and smaller space. In order to maintain the operating temperature of the microelectronics elements, the investigation on micro cooling elements and heat sinks becomes one of the most important topics in flow and heat transfer. Many heat sinks with micro scale structures are explored by many researchers in these years. The micro pin fin heat sink is one of the most potential cooling structures due to the high cooling capacity [2,3], thus many researchers carried out investigations on the flow and heat transfer characteristics in micro pin fins. These investigations verify the cooling capacity of micro pin fins, but the flow resistance through the micro pin fins is so high that it hinders the further development of the micro pin fin heat sinks in the cooling system of microelectronic elements.

Many literatures explored the reduction of flow resistance in micro pin fins by optimizing the geometry or changing the working fluid. According to the hydrodynamic theories, the reduction of the surface energy on the flowing surface can be employed 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 [4–7], so it may be an effective way to reduce the high pressure drop and flow resistance in micro pin fins. Therefore, many researchers have investigated the influence of hydrophobic surface on the flow and heat transfer characteristics in micro channels.

Three topics have been mentioned in the existing literatures about the flow and heat transfer in hydrophobic micro channels: the single flow characteristics and the resistance reduction in channel with hydrophobic surfaces, the effect of hydrophobic characteristics on the mass transfer in porous media, and the condensation heat transfer in hydrophobic channels.

As mentioned above, the researches of single phase flow confirm the flow resistance reduction in micro channels with hydrophobic surfaces. Ou [8,9] carried out a series of experiments to study the flow kinematics of water past drag-reducing superhydrophobic surfaces. They fabricated ultra-hydrophobic 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 microchannel geometries and ultra-hydrophobic surface designs. The results demonstrated that the primary mechanism responsible for the drag reduction was the flow slip along the shear-free air–water interface supported between the hydrophobic micrometer-sized ridges in the flow on ultra-hydrophobic surfaces. A maximum

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* Corresponding author.
E-mail address: zgliu9322@163.com (Z. Liu).

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Nomenclature

d	hydraulic diameter (m)
dp_coe	changing coefficient of pressure drop
df_coe	changing coefficient of friction factor
f	friction factor
G	flow rate of volume (ml/min)
h	hight of the channel (m)
L	length of the channel (m)
m	flow rate of mass (kg/s)

Greek letters

ϕ	angle between the projections and the two phase contact surface
γ	interfacial tension (N/m)
θ	contact angle of water

Subscript

air	air
D	inclined direction
f	fin
L	vertical direction
lv	interface between the liquid and the vapor
hy	surface with hydrophobic layers
N	number of the rows
NL	maximal number of the lines
p	pressure (Pa)
Δp	pressure drop (Pa)
Re	Reynolds number
S	distance between the pin fins m
u	velocity of fluid (m/s)
W	width of the channel/distance between the nano projections (m)
ρ	water density (kg/m^3)
μ	water viscosity kg/(m s)
max	maximal value
$no\text{-}hy$	surfaces without hydrophobic layers
sl	interface between the solid and the liquid
sv	interface between the solid and the vapor
T	transverse direction
$water$	water

slip velocity of more than 60% of the average velocity in the microchannel was found at the center of the shear-free air–water interface whereas the no-slip boundary condition was found to hold along the surface of the hydrophobic ridges. 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 [10] carried out experiments with micro-PIV technology to measure the velocity profiles of water flowing through 30 × 300 μm channels. The velocity profiles were measured in the zones within 450 nm from the microchannel 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 it must be considered at the micro and nano scales. Markus Hilpert [11] carried out analytical investigations on the effects of dynamic contact angle (contact angle of water on the surface of a capillary tube when the water flows through the tube) on liquid infiltration into inclined capillary tubes, and obtained an analytical solution for travel time (the average time between successive collisions of the gas molecules) as a function of interface position. Mohammad [12] presented a theoretical prediction of friction drag reduction in turbulent channel flow with 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 stream wise slip velocity. In addition, a noticeable effect on the turbulence structure occurred when the slip length was greater than a certain value. Yu [13] measured the pressure drops of slugs with triple-lines for various diameters, fluids, and a range of velocities (0.01–0.4 m/s). Dynamic contact angles were calculated from an equation describing the pressure drop of a triple-line, and it was found that the previous correlations had underestimated the dynamic contact angles in comparison with the experimental values, and then a new dynamic contact angle correlation for a regime was proposed. Lyua [14] employed processes with the advantages of simplicity and cost effectiveness to obtain durable super-hydrophilic and super-hydrophobic surfaces, and the results of measurements on a super-hydrophobic surface were compared to those 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 [15] 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 held 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 [16] 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. Mastrokalos [17] performed a computational investigation of flow past a circular cylinder with slip conditions at low Re, and the results showed that a proper use of partial hydrophobic surface could lead to a significant reduction in passive control effort for both full and partial suppression of the Karman vortex street, and the flow stabilization was attained when a global intensity of absolute instability was sufficiently reduced.

Except for the single phase flow in channels, the hydrophobic surface also affects the flow performance in porous media. For an instance, the gas diffusion layer (GDL) in fuel cell and the metal meshes with hydrophobic properties was also researched. Cai [18] simulated the mobility of water droplets and water films inside a straight micro-channel of a proton exchange membrane fuel cell to study the effects of the hydrophilic/hydrophobic properties on water behavior. The results showed that water moved faster on a hydrophobic surface, and water and gas distribution under this condition was advantageous for water discharge and gas diffusion. Yin [19] numerically investigated the two phase cross flow in micro structures of gas diffusion layer with variable contact angle, it was found that water transport characteristics in different cross