



Drag reduction and heat transfer characteristics of water flow through the tubes with superhydrophobic surfaces



F.Y. Lv, P. Zhang*

Institute of Refrigeration and Cryogenics, MOE Key Laboratory for Power Machinery and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

In the present study, the drag reduction and heat transfer characteristics of water flowing through the tubes with superhydrophobic surfaces were investigated. The tubes with inner superhydrophobic surfaces in diameters of 4.0, 8.0 and 12.0 mm were fixed along the center axis of an outer tube to form the counter-current double-tube heat exchanger with a length of 1000.0 mm. Hot and cold water were used as the working fluids flowing through the inner tube and annular space of the heat exchanger, respectively. The experiments were performed at the Reynolds numbers ranging from 3000 to 11,000. The results showed that the drag reduction ranged from 8.3% to 17.8% for superhydrophobic surfaces. The effect of superhydrophobic surface on drag reduction increased with the decrease of tube diameter, and it also decreased with the increase of the Reynolds number. The friction factors of superhydrophobic tubes were smaller than those of smooth tubes at the same Reynolds number. The Colebrook equation was not applicable to estimate the friction factors of superhydrophobic surfaces, and the modified equation was proposed to describe the experimental results. The heat transfer performance was suppressed by the air cavities on superhydrophobic surfaces. The Gnielinski equation also failed to predict the heat transfer coefficients of superhydrophobic surfaces, and the calculated results by the modified equations were consistent with the experimental results. The PECs of combined performance of the drag reduction and heat transfer for superhydrophobic tubes with inner diameter of 8.0 mm was relatively larger than those of superhydrophobic tubes with inner diameters of 4.0 and 12.0 mm.

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1. Introduction

It is well known that both the flow and heat transfer characteristics of liquid flow in tubes are significant for applications, and a lot of research works have been done on those topics [1–4], where the liquid flow and heat transfer are two very important aspects. The water flow through tubes arouses pressure drop, and the pumping power is needed to overcome the frictional flow resistance [5], so that reducing the frictional flow resistance is imperative. The drag friction that is generated in the thin viscous layer in the vicinity of liquid–solid interface accounts for a large portion of the total pressure drop. If the frictional flow resistance at the liquid–solid interface can be decreased, the pressure drop of water flow can also be reduced. The superhydrophobic surface can reduce the frictional flow resistance because of the existence of air cavities on superhydrophobic surface. The slip flow occurs on the superhydrophobic surface, and the pumping power for water flow is also reduced, and finally the enormous economic benefits can be obtained [6,7].

In order to achieve the optimal operation state in applications, not only the drag reduction but also the heat transfer need to be considered. Actually, it is very important to consider both the drag reduction and heat transfer which are the two aspects of the thermo-hydraulic performance of flow. The drag reduction and heat transfer can be applied in the heat exchanger to enhance the performance of flow and heat transfer. The practical application of superhydrophobic tube is still in its infant stage. For example, the tubes with inner superhydrophobic surfaces were used to generate ice slurry by Wang et al. [8], and the ice slurry generation was improved because the superhydrophobic surface could avoid ice blockage. If the combined performance of drag reduction and heat transfer can reach the optimum, the thermo-hydraulic performance of the devices can be improved. Therefore the characteristics of slip flow and heat transfer of superhydrophobic surfaces need more investigation to achieve the combined performance of drag reduction and heat transfer. It is necessary to investigate the drag reduction and heat transfer performance of water flow through tubes with inner superhydrophobic surfaces which are composed of micro/nanostructures with hydrophobic substance. The shear-free region is formed between the interfaces of air

* Corresponding author. Tel.: +86 21 34205505; fax: +86 21 34206814.

E-mail address: zhangp@sjtu.edu.cn (P. Zhang).

Nomenclature

A	surface area (mm ²)
C_p	specific heat (kJ/(kg K))
D	diameter (mm)
f	friction factor
h	heat transfer coefficient (W/(m ² K))
L	tube length (mm)
l	length (mm)
m	mass flow rate (kg/s)
Nu	Nusselt number
Pr	Prandtl number
PEC	performance evaluation criterion
ΔP	pressure drop (Pa)
Q	heat transfer rate (W)
R	radius (mm)
Re	Reynolds number
T	temperature (°C)
u	velocity in x direction (m/s)
u^*	friction velocity (m/s)
x	Cartesian coordinates along the flow direction
y	Cartesian coordinates originated from the tube wall
ε_M	eddy diffusivity of momentum (m ² /s)

Greek symbols

ε	absolute roughness (μm)
μ	dynamic viscosity (kg/(m s))
ρ	density (kg/m ³)
Π	drag reduction

ν	kinematic viscosity (m ² /s)
α	overall heat transfer coefficient (W/(m ² K))
τ	shear stress (Pa)
λ	thermal conductivity (W/(m K))

Subscripts

alu	aluminum
ave	average
c	cold
eff	effective
exp	experimental
h	hot
in	inlet
i	inner
out	outlet
o	outer
sf	slip flow
s	surface
SS	smooth surface
SHS	superhydrophobic surface
th	theoretical
w	water

Superscripts

+	dimensionless parameters normalized by u^* or ν/u^*
–	time average value

cavities on superhydrophobic surface and water. The drag is reduced significantly when the water flows over the air cavities because the dynamic viscosity of air is remarkably smaller than that of liquid. It should be noted that most of the researches of drag reduction focused on laminar liquid flow through micro-scale channels with superhydrophobic surfaces [9,10]. The drag reduction and heat transfer of turbulent flow through macro-scale superhydrophobic tubes or channels are also very important in practical application, therefore the drag reduction and heat transfer characteristics of turbulent water flow through macro-scale tubes or channels with superhydrophobic surfaces are needed for further investigation, because the turbulent flow is encountered more frequently compared with laminar flow in industries where the superhydrophobic surfaces can find the potential applications.

The drag reduction of water flow through circular pipe with water-repellent surface, namely superhydrophobic surface, was investigated by Watanabe et al. [11], and the results showed that the pressure drop of tap water flowing through the pipe in diameter of 16.0 mm with inner superhydrophobic surface was reduced by 14.0% compared with the pipe with smooth surface, which demonstrated that superhydrophobic surface could reduce the flow resistance. The drag reduction of water flow over superhydrophobic plates at high Reynolds number was studied by Aljallis et al. [12], and the experimental results revealed that the drag reduction for superhydrophobic plates reached up to 30% at the transition flow region, but the drag reduction decreased in the fully developed turbulent flow, which was ascribed to the removal of trapped air at high Reynolds number. The mechanisms of drag reduction of turbulent flow over superhydrophobic surface were investigated by Zhang et al. [13], and the results showed that the drag reduction of turbulent flow reached up to 23.1% compared with the smooth surface, which was due to the reason that the slip flow on the interface weakened the turbulent structures of flow.

The drag reduction of turbulent water flow on superhydrophobic surface was studied by Martell et al. [14] using direct numerical simulation, and the results suggested that the slip velocity and drag reduction of turbulent flow for superhydrophobic surface reached as high as 80% of bulk velocity and 50% of total friction drag compared with smooth surface, respectively. The superhydrophobic drag reduction of turbulent water channel flow was also studied by Park et al. [15] using direct numerical simulation, and the results revealed that drag reduction of turbulent flow significantly depended on the flow structures in the vicinity of near wall region of the superhydrophobic surfaces.

In most cases, it is very important not only for the drag reduction but also for the heat transfer performance. With the increase of the energy consumption, the optimal thermo-hydraulic performances of the flow in tubes are necessary for energy conservation because the drag reduction and heat transfer enhancement are two aspects. The heat transfer performance also needs to be discussed here because it plays an important role in the applications such as heat exchanger. The heat transfer of laminar water flow in circular microchannels with hydrophobic surfaces was investigated by Sun et al. [16]. The heat transfer coefficient of superhydrophobic surface was reduced significantly due to the fact that the additional thermal resistance of the trapped air within the cavities on superhydrophobic surface inhibited the heat transfer from the surface to liquid. The heat transfer performances of laminar water flow through microchannels with hydrophobic and hydrophilic surfaces were studied by Hsieh and Lin [17], and they found that the Nusselt number changed from 2.62 for hydrophilic surface to 2.42 for hydrophobic surface under the constant heat flux conditions, which illustrated that the heat transfer was deteriorated by the thermal resistance of hydrophobic surface. Li and Alvarado [18] numerically studied the influence of superhydrophobic surface on heat transfer performance and found that the heat transfer

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