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Sustained drag reduction and thermo-hydraulic performance enhancement in textured hydrophobic microchannels

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ABSTRACT

Drag reduction obtained on flow over textured hydrophobic surfaces has been ascribed to the presence of entrapped air within the surface micro-texture. To sustain the drag reduction, it is important that the entrapped air be maintained on the surface. However, the entrapped air bubbles tend to shrink with time and finally disappear, causing the drag reduction also to reduce and eventually vanish. Recent research shows that by controlling the absolute pressure of water, it is possible to sustain the entrapped air bubbles on the surface and hence the drag reduction for extended periods of time. In this paper, we explore the possibility of sustaining the entrapped air by varying the absolute temperature of water in the vicinity of the textured surface. For this, the textured surface is externally heated and the evolution in the size of trapped air bubbles with time is observed. Simultaneous pressure and temperature measurements are made along with the visualization, to study the concomitant effects on drag and heat transfer. We find that, varying the absolute temperature influences the trapped air bubble dynamics appreciably, which in turn affects the measured pressure drop across the channel. By varying the external heat input, it was found that the trapped air bubbles can be maintained on the surface for prolonged periods of time, at an optimum size suitable for drag reduction, such that sustained and maximized drag reduction can be achieved. The presence of trapped air bubbles is found to inhibit the heat transfer across the surface. However, when the pressure drop reduction achieved due to the presence of air bubbles is significant enough, the combined thermo-hydraulic performance is found to be enhanced. The results, not only provides important inputs towards achieving sustained drag reduction from textured hydrophobic surfaces, but also ascertains the feasibility of using such surfaces in micro-scale heat transfer applications.

1. Introduction

Superhydrophobic surfaces, prepared through a combination of surface texturing and hydrophobic surface chemistry [1–7], have been found to be useful in lowering the liquid flow resistance (drag) in microfluidic passages [8–16]. When a textured hydrophobic surface is immersed in water, an underwater Cassie state is established on the surface, where the penetration of water into the surface cavities is prevented by the entrapped air within [17–19]. Water comes into contact only with a fraction of the solid surface and the rest of the area is covered by the trapped air pockets. When water flows past such a surface, the trapped air bubbles act as near shear free regions reducing flow resistance [20]. In addition to the fractional coverage of air, the size of the air pockets also play a prominent role in determining the quantum of drag reduction achievable [21,22]. For achieving drag reduction, various kinds of micro-textures like pillars/posts [10], ridges [11], holes [15,16] and random surface features [14,23] have been investigated and some of these studies have reported significant reductions in drag of the order of 30–40% [10,14].

Recent research indicates that the drag reduction achieved by using textured hydrophobic surfaces is short lived due to the gradual dissolution of entrapped air into the flowing water [14,29]. The rate of dissolution is dependent on the concentration gradient across the air-water interface (i.e. the difference in concentration of air inside bubble and the concentration of dissolved air in water) and also the convective effects caused by the flow [15,16,23]. The sustainability of trapped air on superhydrophobic surfaces and the factors leading to the breakdown of underwater Cassie state have recently been investigated both numerically and experimentally [23–28]. In order to increase the longevity of drag reduction, it is important that the air bubbles be maintained on the surface. For this, air has to be supplied to the trapped air pockets continuously. Different methods like direct supply of air [30,31] and electrolysis [32,33] have been tried out, to keep the surface cavities replete

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Nomenclature

A	area of the surface
A_s	surface area of bubble
C_p	specific heat
C_∞	concentration of air in water
C_s	saturation concentration of air in water
D	diameter of bubble
D_i	initial diameter of bubble
D_h	diameter of hole
D_H	channel hydraulic diameter
f	degree of saturation
h	heat transfer coefficient
h_m	convective mass transfer coefficient
H_{air}	Henrys constant for air
I	current, amp
k	diffusivity of air in water
k_f	thermal conductivity of fluid
$\dot{m}$	mass flow rate of water
$\dot{m}_a$	convective mass transfer rate
n	number of moles
Nu	Nusselt number
Nu_o	reference Nusselt number
P	pressure
Pe	Peclet number
q	heat transfer
q''	heat flux
Q	volume flow rate of water
Re	Reynolds number
s	parameter defined by Eq. (17)
Sh	Sherwood number
T	temperature
T_i	fluid inlet temperature
T_o	fluid outlet temperature
T_s	textured surface temperature
T_f	mean fluid temperature
$THPI$	thermo hydraulic performance index
u	average velocity of flow
U	velocity of flow relative to bubble
V	voltage
x	height of the channel
y	width of the channel

Greek Symbols

ρ	density of water
μ	dynamic viscosity
θ	standard temperature
ΔP	pressure drop
ΔP_o	reference pressure drop

Subscripts

O	oxygen
N	nitrogen

with air. However these methods use a self-regulating mechanism which involves intricate arrangements with active feedback control. Very recently liquid infused surfaces with trapped air (LISTA) have been proposed to reduce the drag force and to counter the air depletion problem [34]. In our previous studies [15,16], we have experimentally demonstrated a simple method to sustain the air bubbles on the cavities, by locally changing the absolute pressure within the channel. By altering the pressure, the solubility of water flowing through the channel was altered. Thus by making the flowing water supersaturated with air, the concentration gradient causing transport of air across the water-air interface was reversed, forcing the dissolved air in water to migrate into the air pockets causing them to grow in size. It was demonstrated that by carefully controlling the solubility of water through pressure, the trapped air bubbles can be sustained for extended periods of time.

To locally supersaturate the water flowing over the surface, it is required that a pressure lower than the atmospheric pressure be maintained within the channel. In many applications, maintaining sub-atmospheric pressures within the channel is often difficult or inconvenient. Moreover in pressure driven flows, the flowing water will be generally undersaturated. Since the solubility of water is a function of temperature as well, an alternate method to control the solubility of water is by locally heating the water as it flows over the textured surface. This would increase the temperature of water flowing over the surface, thus locally supersaturating the water. Hence by local heating, it would be possible to realize the same effect, equivalent to that of reduction in pressure. In this paper, the possibility of sustaining the drag reduction by controlling the local absolute temperature of water is investigated. For this the textured surface is externally heated by means of a resistance heater. By varying the power input to the heater, it is possible to precisely control the local temperature of water near the surface. The consequent effect of this local heating of water on the dynamics of air bubbles and the pressure drop across the channel is systematically studied.

Local heating of water, as it flows over the textured surface, requires that heat be transferred across the textured hydrophobic surface into water. While most of the studies on textured hydrophobic surfaces in microchannels have focused on its drag reducing characteristics, there have been only limited studies on the thermal transport across such surfaces. In many applications at the micro scale, such as electronic cooling, in addition to the pressure drop reduction, achieving higher rates of heat transfer is also important. In the past decade, there have been a number of theoretical and experimental studies that have reported heat transfer enhancement in microchannels by using rough/wavy surfaces as the channel/tube walls [35–39]. These studies, however, have also reported large increase in the pressure drop across the channel, caused by the modified geometry of the surface. Since textured hydrophobic surfaces are capable of delivering substantial pressure drop reduction across the channel even in the presence of roughness, it appears to be a promising candidate for applications at the micro-scale where both heat transfer enhancement and pressure drop reduction are important. However the entrapped air on the surface is likely to have a detrimental effect on the thermal transport performance of the surface, as air is an insulator.

Recent studies on thermal transport have shown that in general hydrophobic surfaces deliver lower thermal transport performance (i.e. lower Nusselt number (Nu)) when compared to hydrophilic ones [40,41]. Surfaces with high contact angles exhibits a decrease in the pressure drop but also display an associated reduction in the heat transfer performance [41]. The thermal transport performance on textured hydrophobic surfaces decreases as the size of the shear free regions is increased [42–44]. An effective medium approach [45] which treats textured surface with trapped air as a single substrate revealed that even though convective heat transport increases due to the modified fluid velocity profile on the surface, the decrease in the thermal conductivity of the substrate due to the presence of air inhibits the thermal transport appreciably.