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Bubble nucleation in superhydrophobic microchannels due to subcritical heating

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ABSTRACT

This work experimentally studies the effects of single wall heating on laminar flow in a high-aspect ratio superhydrophobic microchannel. When water that is saturated with air is used as the working liquid, the non-wetted cavities on the superhydrophobic surfaces act as nucleation sites and allow air to effervesce out of the water and onto the surface when heated. Previous works in the literature have only considered the opposite case where the water is undersaturated and absorbs air out the cavities for a microchannel setting. The microchannel considered in this work consists of a rib/cavity structured superhydrophobic surface and a glass surface separated by spacers. The microchannel is 60 mm long by 14 mm wide and two channel heights of nominally 183 μm and 366 μm are explored. The superhydrophobic side is in contact with a heated aluminum block and a camera is used to visualize the flow through the glass side. Thermocouples are embedded in the aluminum to record the temperature profile along the length of the channel. Temperatures are maintained below the boiling temperature of the working liquid. The friction factor-Reynolds product (*fRe*) is obtained via pressure drop and volumetric flow-rate measurements. Five surface types/configurations are investigated: smooth hydrophilic, smooth hydrophobic, superhydrophobic with ribs perpendicular to the flow, superhydrophobic with ribs parallel to the flow, and superhydrophobic with ribs parallel to the flow with several breaker ridges perpendicular to the flow. The surface type/configuration has a significant impact on the mass transport dynamics. For surfaces with closed cell micro-structures, large bubbles eventually form and adversely affect *fRe* and lead to higher temperatures along the channel. When degassed water is used, no bubble nucleation is observed and the air initially trapped in the superhydrophobic cavities is quickly absorbed by the water.

1. Introduction

Superhydrophobic (SHPo) surfaces are currently a topic of interest due to their unique and extraordinary water repelling capabilities. Such surfaces have potential applications for self cleaning systems, drag reduction, microscale heat exchangers, condensers, bio-medical devices, lab-on-chip devices, etc. Superhydrophobic surfaces can be created by combining nano/micro-scale surface texturing with a chemical hydrophobic coating such that water will rest on top of the surface texturing and not penetrate into the space between the texturing and forms a meniscus due to surface tension. This is considered to be the non-wetting or Cassie-Baxter state [1]. An illustration of a SHPo surface with rib/cavity surface features in the non-wetted state is shown in Fig. 1. A surface is deemed superhydrophobic when the contact angle between it and a sessile droplet of water is greater than nominally 145° [2].

Much research has been devoted to the use of SHPo surfaces in the non-wetted state to achieve drag reduction in laminar channel flows [3–9]. A drag reduction is possible since the working liquid is largely suspended above the gas filled cavities and there is a partial slip boundary condition over this liquid/gas interface as opposed to the classic no-slip condition at the liquid/solid interface. The amount of drag reduction is mainly dependent on three factors: the type and orientation of the surface structure, the cavity fraction (defined as the ratio of the projected liquid/gas interface to the overall projected composite interface), and the relative surface feature size to channel height [4]. A variety of surface structures have been studied such as the rib/cavity structure shown in Fig. 1, as well as square posts, circular posts, square holes, and circular holes. These structures can be oriented in different directions with respect to the flow direction; the most studied being ribs and cavities that are aligned parallel or transverse to the flow direction. As the cavity fraction increases, the liquid/gas interface comprises more of the composite interface and more slip at the surface prevails, leading to greater drag reduction [4,5,9–12]. The amount of

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Nomenclature

C_{air}	equilibrium concentration of dissolved air in water
D_h	hydraulic diameter $(2WH/(W+H))$
f	average Darcy friction factor
fRe	average friction factor-Reynolds number product
H	channel height
H^{cp}	Henry's Law constant
L	channel length
P	liquid pressure
P_{air}	partial pressure of air
P_{atm}	local atmospheric pressure
P_g	gas pressure
$\overline{P}$	average pressure in channel
Q	electrical input power
Re	Reynolds number $(\rho\bar{u}D_h/\mu)$
T_a	ambient temperature
T_{Al}	temperature of aluminum block along centerline
T_{in}	inlet bulk temperature
T_{out}	outlet bulk temperature
$\overline{T}_f$	average film temperature in channel
$\bar{u}$	average channel velocity
$\dot{V}$	channel flow-rate
W	channel width
w_c	cavity width
x	streamwise coordinate

Greek symbols

α	saturation level
ΔC_{air}	concentration gradient
ΔP	channel pressure drop
ΔT_{Al}	aluminum temperature difference $(T_{Al} - T_{in})$
μ	dynamic water viscosity
ϕ	contact angle with smooth surface
ρ	water density
σ	liquid surface tension

slip achievable by a SHPo surface is directly related to the underlying feature size. For channel flow, the hydraulic diameter must be of the same order of magnitude as the surface features for appreciable drag reduction to be possible [4,8,11,12]. Secondary effects on the drag reduction in SHPo channels include, but are not limited to, meniscus curvature, Reynolds number inertial effects, and the finite viscosity of the gas in the cavities [4,5,8,13–15].

Prior research has also focused on studying the effect that SHPo surfaces have on heat transfer in microchannel flows [11,12,16–23]. In general, SHPo surfaces have been found to reduce convective heat transfer for channels in all cases. Since the cavities are occupied by gas, which usually has a thermal conductivity much less than that of the surface features, they act as an insulating region and increase the resistance to heat transfer. The amount of convective heat transfer reduction is dependent on the same parameters as the hydrodynamic drag reduction and follows similar trends. However, if the drag reduction is great enough so that the flow-rate can be substantially increased, an overall heat transfer enhancement can theoretically occur respective to a smooth walled channel given the same driving pressure and dimensions [19]. Such behavior could prove advantageous in microscale heat exchangers.

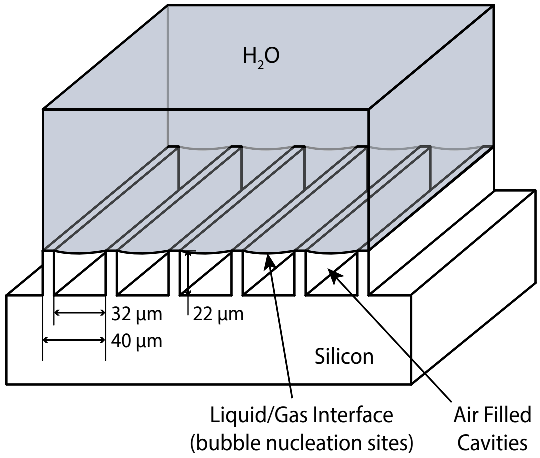

Fig. 1. A rib/cavity structured SHPo surface.

Critical to the performance of SHPo surfaces is the maintenance of a stable gas layer or plastron. A SHPo surface can lose its gas layer and transition from the non-wetted to wetted state due to a number of causes. If the liquid pressure becomes too great, the meniscus can no longer support the liquid and the surface features will wet, resulting in a loss of drag reduction [4]. The pressure at which the meniscus fails mechanically in this manner is referred to as the Laplace pressure. For a rib/cavity structure such as that pictured in Fig. 1, the Young-Laplace equation can be used to calculate the Laplace pressure, which is the difference: $P - P_g = 2\sigma\cos(\pi - \phi)/w_c$ where, P is the pressure of the liquid, P_g is the pressure of the gas, σ is the surface tension of the liquid/-gas system, ϕ is the contact angle of the liquid with the smooth surface, and w_c is the width of the liquid/gas interface [4,9]. An additional failure mechanism of the gas layer is caused by the mass transport that can occur at the liquid/gas interface [24–28]. If the liquid is sufficiently undersaturated it can absorb the gas from the plastron and over time a SHPo surface will eventually wet.[1]

Alternatively, Vakarelski et al. have shown that the air layer on a submerged SHPo sphere can be maintained and actually grow when submersed in water that is supersaturated with air [29]. The solubility of dissolved air in water is dependent on temperature [30]. In the work by Vakarelski et al. [29] the mass transport was a direct result of the water being heated, which caused it to become supersaturated with air, and led to the growth of the plastron. Wang et al. [31] also reported bubble growth from SHPo micro-patterns on a submerged copper substrate at very low sub-boiling temperatures when degassed water was used. Lv et al. [32] also showed that air trapped in micro-pores on SHPo surfaces can grow and/or shrink via mass transport when the saturation level of the bulk liquid is altered by depressurization.

Previous works considering heat transfer in SHPo microchannels have not considered this dynamic mass transfer effect in their analysis. Haase et al. [33] numerically considered mass transport over a transverse rib/cavity structure where the protrusion angle of the bubbles could be specified, and in a separate study Haase and Lammertink [34] obtained results for both mass and heat transfer assuming a flat meniscus. However, in these two studies [33,34] the meniscus shape is specified and is unable to change

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[1] Note that SHPo surfaces with sub-micron pores may be able to retain gases indefinitely even when exposed to degassed water [26].