THERMO-WETTING AND FRICTION REDUCTION CHARACTERIZATION OF MICROTEXTURED SUPERHYDROPHOBIC SURFACES

ABSTRACT

Microtextured superhydrophobic surfaces have become ubiquitous in a myriad of engineering applications. These surfaces have shown potential in friction reduction applications and could be poised to make a big impact in thermal management applications. For instance higher heat transfer rate with less pumping power might be achievable through the aid of superhydrophobic surfaces. However, past and current research on superhydrophobic surface has focused mainly on modifying either the chemical component or the roughness factors of such surfaces. The purpose of this paper is to account for the thermal effects of the heated fluid flowing in superhydrophobic microfluidic channels. Herein we characterize the wetting behavior as a function of temperature of microtextured superhydrophobic surfaces, for both active and passive thermal management applications.

A series of PDMS microtextured samples were fabricated using micromachining and soft lithography techniques. Flow measurements were performed using the superhydrophobic microfluidic channel. The channel surface roughness was large enough to induce the Cassie-Baxter state, a phenomenon in which a liquid rests on top of a textured surface with a gas layer trapped underneath the liquid layer. This gas layer induces a two-phase flow, and friction reduction can be achieved for the liquid channel flow. With this channel, flow rates were measured by varying the equilibrium temperature of the substrate. The temperature in the constant pressure source was controlled by circulating the water through a water-bath.

As the heating reached a certain threshold the curvature of the liquid-gas interface was reversed and dewetting of the penetrated liquid layer was observed. This result suggests that the Cassie state in fluid flow can be prolonged even under increased pressure drops by increasing the temperature in the gas layer.

INTRODUCTION

Superhydrophobic surfaces that induce slip have recently received attention as a means of achieving surface friction and drag reduction [1]. Other applications of using such surfaces include frost prevention on aircraft flight surfaces to self-cleaning features on solar energy panels [2].

One way to achieve superhydrophobicity is through the modification of the surface geometry. Two models represent the wetting behavior of such textured surfaces: the Wenzel state [3] and the Cassie-Baxter state [4]. The Wenzel state models the amplifying effect that surface texturing has on the Young’s contact angle under fully liquid imbibed conditions. The Cassie-Baxter state models the macroscopic contact angle formed when air pockets exist within the microtexturing. The presence of these air pockets in the Cassie state can lead to friction and drag reduction [5], with research in this area being actively pursued. Such research includes modeling the fluid
flow over random textured surfaces [6], studying the drag reduction of flow over carbon nano-tube forests [7], and the use of chemical coatings in microtextured surfaces to induce superhydrophobic conditions [8]. Studies have also been conducted in utilizing thermally sensitive chemical polymers in order to modify the substrate surface energy [9].

Despite the vast literature on friction and drag reduction from superhydrophobic surfaces, there is very little work aimed at correlating the pressure and thermal effects on the stability and characteristics of this condition. A few researchers have studied the pressure effects on the Cassie-Baxter State, concluding that textured surfaces with isolated gaps result in a lower contact angle hysteresis [10]. However, studies on thermal effects to the trapped gas layer and correlating them to superhydrophobic channel flows have not been conducted to date.

In this paper, we develop a simple model of the compressibility effects associated with the gas pockets under heated conditions, and observe how they affect the stability of the Cassie state and its friction reduction characteristics.

The theoretical model is validated against experimental microchannel flow data, where micro-gaps are used as the surface texturing. The flowing fluid in the microchannels tends to penetrate into the micro-cavity gaps as a result of the imposed pressure gradient. However, as the microfluidic channel is heated, the air in the micro-gaps expands and the penetrating water layer is pushed back to its original state. Consequently, the air gaps can withstand higher liquid pressure, thus prolonging the two phase flow in the microfluidic channel. Correlation of the model results and the experimental data indicate that heated cavities provide more stability to the Cassie state under pressure flow conditions.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\gamma_{LV}$</td>
<td>Surface tension in the liquid-vapor interface</td>
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<tr>
<td>$\mu$</td>
<td>Dynamic viscosity of water</td>
</tr>
<tr>
<td>$\theta_{CB}$</td>
<td>Cassie-Baxter angle</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>Young’s contact angle</td>
</tr>
<tr>
<td>$\phi_s$</td>
<td>Solid contact area ratio</td>
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<tr>
<td>$\Delta P$</td>
<td>Pressure drop</td>
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<tr>
<td>$Q$</td>
<td>Flow rate</td>
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<tr>
<td>$r_c$</td>
<td>Critical roughness</td>
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</table>

**THEORETICAL MODEL**

Cassie-Baxter Model

In order to ensure a proper two phase flow through friction reduction in the microchannel flow, a microtextured surface that induces a stable Cassie state is desirable. A liquid meniscus, resting on top of a textured surface, is under a Cassie state if the liquid does not wet the gaps beneath the liquid interface. As a result the liquid resting on top of the textured surface will experience a decrease in surface resistance since a portion of the contact surface underneath is gas. The conventionally used Cassie-Baxter model [4] is,

$$\cos \theta_{CB} = \phi_s \cos \theta_s - (1-\phi_s) \quad (1)$$

where $\theta_{CB}$ is the Cassie-Baxter angle, $\theta_s$ is the Young’s contact angle, and $\phi_s$ is the ratio of solid contact area to the nominal area. Also, in order to ensure the Cassie state, the surface topography must be rougher than the critical roughness factor [11],

$$r_c = \phi_s - \frac{1-\phi_s}{\cos \theta_s} \quad (2)$$

where $r_c$ is the critical roughness factor. A roughness factor lower than $r_c$ will result in a Wenzel state where full wetting of the microtextured surface will occur, or a metastable Cassie state where the liquid initially under Cassie state may transition to Wenzel state if disturbances occur. On the other hand, a roughness factor higher than $r_c$ will lead to a stable Cassie state. In our experiments, we have conducted tests on textured microfluidic channels with roughness factors higher and lower than the critical roughness factor.

**EXPERIMENT SETUP**

Fabrication of the Micro-cavity Substrate Microchannels

The microfluidic devices were fabricated by soft-lithography. A bare wafer was coated with SU-8 2050 (Microchem) and a negative mold for the PDMS microfluidic channel was fabricated through standard photolithographic procedures. The thickness of the SU-8 mold pattern was measured using a profilometer (Veeco) to confirm the channel thickness. The wafer was then silanized (UCT specialties, LLC) for at least an hour in a vacuum desiccator to fluorinate the SU-8 mold. A PDMS base and solvent (Dow Corning) mixture, at a volume ratio of 10:1, was poured on the silanized SU-8 mold. The entire wafer was cured at 95°C for 2 hours. The cured PDMS microfluidic channel replicas were peeled off from the wafer and were bonded to glass substrates. Prior to bonding, the glass substrates were spin coated with a thin layer of PDMS to ensure uniform properties within the microfluidic channel. Both PDMS slabs and PDMS coated glass substrates were treated with oxygen plasma (Harrick Plasma) at 29Watts for 20 seconds. Once the bonding was complete, the treated samples were then baked overnight on a hot plate at 65°C.

The channel dimension for the baseline channel with no surface textures is 100µm × 110µm × 2cm (width × height × length). For the channels with micro-textured surface, the liquid flow channel dimension is identical to the baseline channel and an array of micro-trenches with dimensions of 60µm × 500µm (gap size × depth of cavity) on the side walls are added.
Heating of the Microfluidic Channel

A water reservoir with a controllable column height was used to generate a constant pressure source. The outlet of the water column device was connected to the inlet of the microchannels. By controlling the height of the water column, constant pressure conditions of 2500Pa, 3500Pa, and 4500Pa were applied to the microfluidic channel. A pressure transducer was used to measure the gauge water pressure supplied to the channel.

A resistive heating pad was placed directly underneath the microfluidic device to provide a constant heat flux to the channel. The heat transfer rate was controlled by varying the voltage to the heat pad. Under a fixed pressure head, the liquid-gas interface was initially observed under unheated conditions. Then, the temperature of the bottom substrate was increased from 26°C to 32°C, with increments of 1°C. Measurements were performed with a microscope after the substrate temperature was stabilized.

RESULT

Heating Effects on Penetration Depth

Water flow in the microfluidic channel was generated by a constant pressure source. With a constant pressure applied to the microfluidic channel, the pressure is $\rho gh$ at the inlet and is assumed to drop linearly to the outlet pressure. Depending on the inlet pressure, this pressure gradient will either wet the cavity or maintain the Cassie State. Since the pressure required to prevent penetration throughout the entire channel is calculated to be 1000Pa, the inlet pressures were large enough (2500Pa, 3500Pa and 4500Pa) to induce penetration near the inlet region, as can be seen in Figure 3.
The images in Figure 3 visually depict the relationship between pressure and penetration depth in the cavities, where the penetration depth is measured using a micro-ruler. The pressure is the largest near the inlet and the smallest near the outlet.

However, as heat was applied to the channel, the gas layer started to expand with increasing heat transfer. For the case where the substrate temperature was 28°C, the curvature of the penetrating liquid interface was convex, indicating that the liquid pressure is greater than the gas pressure. As the substrate temperature reached 30°C (Figure 4), the curvature gradually reduced to a near flat shaped profile, and at 32°C the curvature was reversed to a concave profile. Once the curvature was reversed, it became apparent that the penetrated liquid started to retract because of the expanding air pockets. This indicates that the temperature of the gas layer was high enough that the pressure of the gas pocket became greater than that of the water layer.

The penetration depth as a function of channel location under different temperature conditions is presented in Figure 5. The inlet pressure was fixed at 3200Pa. From the graph, it is apparent that the penetration depth along the channel decreased as the temperature was increased.

At 28°C, 100% of the cavities were penetrated, where approximately 60% of the cavities were fully wetted. As the temperature was increased to 30°C, the penetration depth started to decrease as the gas layer expanded due to the increase in gas pressure. Approximately 10% of the channel showed that the liquid layer retracted back to a non-penetrating state. It should be noted that the fully wetted cavities throughout 60% of the channel remain wetted. When the temperature was increased to 32°C, the gas layer expanded further and the partially wetted cavities transitioned to a fully non-wetted state. For this case, the gas layer continued to expand and started to invade the liquid layer instead. The bubble growth is presented in the graph as the negative penetration depth.

![Flow direction](image1)

**FIGURE 4. MICROSCOPIC PHOTOGRAPHS (NEAR THE INLET) OF HEATING EFFECTS ON LIQUID PENETRATION AT (A) 30°C AND (B) 32°C. THE INLET PRESSURE IS AT 2400Pa (GAGE).**

![Flow direction](image2)

**FIGURE 5. PENETRATION DEPTH VS. LOCATION UNDER DIFFERENT SUBSTRATE TEMPERATURE CONDITIONS. THE INLET PRESSURE IS AT 3200Pa (GAGE).**

![Image 3](image3)

**FIGURE 6. MICROSCOPIC PHOTOGRAPHS (NEAR THE OUTLET) OF HEATING EFFECTS ON LIQUID PENETRATION AT (A) 30°C AND (B) 32°C. THE INLET PRESSURE IS AT 2400Pa (GAGE).**

From the above results, it can be seen that the liquid penetration can be prevented by heating the air trapped inside the microcavities. With sufficient heating, penetration can be prevented even under higher liquid pressures.
Pinching Effects and its Reduction to Flow Rate

At increased temperatures, the air pockets in the cavities continued to grow. The growth of this gas layer continued until it invaded the main channel, where the liquid flow started to experience a ‘pinching’ effect due to the reduced cross-sectional area of the flow (Figure 6). This pinching effect is analogous to a closing valve. At lower inlet pressures, even a slight increase in temperature resulted in a reduced flow rate until the flow was eventually disrupted (Figure 7). For higher inlet pressures, the flow rate was maintained at higher temperatures. However, once the temperature reached a certain threshold, the pressure in the air pockets exceeded the liquid pressure, and a drastic drop in flow rate was observed.

![Figure 6](image)

**FIGURE 6.** FLOW RATE VS. TEMPERATURE GRAPH OF 60µm×500µm CAVITY CHANNELS UNDER (A) 800Pa, (B) 1600Pa, (C) 2400Pa AND (D) 3200Pa INLET PRESSURES.

This phenomenon can also be observed in Figure 8. At lower pressures, the flow rate was very sensitive to the change in temperature. For this case, the air pockets expanded even under a slight increase in temperature. It was observed that the liquid flow was disrupted at a substrate temperature of 28°C. At higher inlet pressures, the flow rate became less sensitive to temperature, and the flow rate for all temperatures converged to a similar slope. This indicates that increasing the temperature of the channels, and consequently the air pockets, did not reduce the friction in the channel and was, in fact, detrimental to the flow. However, if the linear trend continues on the flow rate versus pressure drop plot, it may be possible to achieve reduced frictional effects on the flow at pressures higher than the currently tested results.

![Figure 8](image)

**FIGURE 8.** FLOW RATE VS. ΔP GRAPH OF 60µm×500µm CAVITY CHANNELS UNDER DIFFERENT HEAT SUBSTRATE TEMPERATURES.

CONCLUSION

In this paper we investigated the heating effects of the air pockets trapped between the roughness elements in a microchannel flow. The side walls of the PDMS microchannels were grooved to form air pockets in the liquid channel flow. A constant pressure source was used to flow water into the microfluidic channel and the flow rate was measured using a flow meter. It was observed that the flow rate for microchannels with microcavities on the side walls were greater than that of the channels with no cavities. We also observed that the flow rate was increased under heated conditions. Moreover, the liquid-air interface in the heated channels withstood higher pressure ranges than the unheated channels.

It was also found that the penetrated liquid layer was pushed back due to the expanding gas layer if the heat transfer...
was increased. This is the result of a penetration resistance effect arising from the compressibility of the entrapped air as a function of temperature.

The results indicate that Cassie state can be prolonged if the air cavities are heated, and that surfaces with isolated air pockets may actually be more stable than a surface that is non-isolated. However, with the current pressure range, the effect of prolonging the Cassie state did not significantly affect the friction in the channel. By testing at higher pressure range, it may be possible to achieve reduced frictional effect in the heated channel. Hence, we anticipate that the thermal effect of air pockets can be extended to the designing of super-hydrophobic surfaces exposed to external fluid flow.

REFERENCES