Two-Phase Flow Pressure Drop in Superhydrophobic Channels

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Two-Phase Flow Pressure Drop in Superhydrophobic Channels

Kimberly A. Stevens, Julie Crockett, Daniel R. Maynes, Brian D. Iverson*

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Brigham Young University
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Abstract
Superhydrophobic surfaces have been shown to reduce drag in single-phase channel flow; however, little work has been done to characterize their drag-reducing ability found in two-phase flows. Adiabatic, air-water mixtures were used to explore the influence of hydrophobicity on two-phase flows and the hydrodynamics which might be present in flow condensation environments. Pressure drop measurements in a rectangular channel with one superhydrophobic wall (cross-section approximately 0.37 × 10 mm) and three transparent hydrophilic walls were obtained. Data for air/water mixtures with superficial Reynolds numbers ranging from 22-215 and 55-220, respectively, were obtained for superhydrophobic surfaces with three different cavity fractions. Agreement between experimentally obtained two-phase pressure drop data and correlations in the literature for conventional smooth control surfaces was better than 20 percent, which is within the accuracy of the correlations. The data reveal a reduction in the pressure drop for two-phase flow in a channel with a single superhydrophobic wall compared to a control scenario. The observed reduction is approximately 10 percent greater than the reduction that is observed for single-phase flow (relative to a classical channel).

Keywords: two-phase flow, superhydrophobic surfaces, drag reduction

*Corresponding author email: bdiverson@byu.edu

### Nomenclature

#### Variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi$</td>
<td>Martinelli parameter</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>Mass flow rate</td>
</tr>
<tr>
<td>$\dot{V}$</td>
<td>Volumetric flow rate</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Aspect ratio of the channel, $H/W$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Solid-liquid surface tension</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Viscosity</td>
</tr>
<tr>
<td>$\phi^2$</td>
<td>Two-phase multiplier</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Contact angle for a droplet on a smooth surface</td>
</tr>
<tr>
<td>$CA$</td>
<td>Contact angle</td>
</tr>
<tr>
<td>$D_h$</td>
<td>Hydraulic diameter</td>
</tr>
<tr>
<td>$F$</td>
<td>Frictional component of the pressure gradient</td>
</tr>
<tr>
<td>$F_C$</td>
<td>Cavity fraction</td>
</tr>
<tr>
<td>$H$</td>
<td>Channel height</td>
</tr>
<tr>
<td>$j$</td>
<td>Superficial fluid velocity</td>
</tr>
<tr>
<td>$P$</td>
<td>Pressure</td>
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<tr>
<td>$R$</td>
<td>Radius of curvature</td>
</tr>
<tr>
<td>$Re_G$</td>
<td>Gas-only Reynolds number</td>
</tr>
<tr>
<td>$Re_L$</td>
<td>Liquid-only Reynolds number</td>
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<tr>
<td>$W$</td>
<td>Channel width</td>
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<tr>
<td>$w_c$</td>
<td>Width of the cavity between the ribs</td>
</tr>
<tr>
<td>$x$</td>
<td>Vapor quality</td>
</tr>
<tr>
<td>$Z$</td>
<td>Coordinate orientated along the length of the channel</td>
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#### Subscripts

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<td>$G$</td>
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<tr>
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<td>Hydrophilic Surface</td>
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<tr>
<td>$L$</td>
<td>Liquid phase</td>
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<tr>
<td>$M$</td>
<td>Measured</td>
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<tr>
<td>$P$</td>
<td>Predicted by Kim and Mudawar [1]</td>
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<tr>
<td>$SH$</td>
<td>Superhydrophobic Surface</td>
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<td>$TP$</td>
<td>Two-phase</td>
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#### Highlights

- Significant drag reduction was achieved for two-phase flow in superhydrophobic channels.
- Drag reduction is approximately 10% greater with two-phase than single-phase flow.
• Drag reduction increases with vapor fraction up to fractions of approximately 0.03.

1. Introduction

Superhydrophobic surfaces have recently gained media and scholarly attention due to their drag-reducing, self-cleaning, and ice-preventing properties. One particularly promising application for superhydrophobic surfaces is in condensation. It has been shown that condensation on superhydrophobic surfaces promotes drop-wise condensation; drop-wise condensation is known to increase heat transfer around 5-7 times relative to film-wise condensation [2, 3]. A number of researchers have explored condensation on superhydrophobic surfaces and found potential for improving heat transfer rates [4, 5, 6].

Increased heat transfer rates would benefit a number of applications such as desalination, energy conversion [7], atmospheric water harvesting [8, 9], and other high heat flux applications involving condensation [10]. However, very little work has been done with condensation on superhydrophobic surfaces in a flow environment. The objective of this work is to investigate the effect of hydrophobicity on the hydrodynamics of an adiabatic two-phase channel flow.

1.1. Superhydrophobic Surfaces

A superhydrophobic surface has a solid-liquid contact angle (CA) greater than 150° [11], as shown in Figure 1a, and contact angle hysteresis less than 10°.

Superhydrophobic surfaces can be created by combining micro- or nano-structured features with a hydrophobic surface coating. When a static droplet rests on top of a superhydrophobic surface, surface tension can prevent the liquid from penetrating into the cavities, creating a layer of air between the solid and liquid surfaces, as shown in Figure 1. In this case, the droplet is said to be in a non-wetting, or Cassie state. If the pressure in the liquid is high, it can overcome the surface tension and liquid will enter the cavities; the droplet is then said to be in a wetting, or Wenzel state. The Young-Laplace equation describes the surface tension-induced pressure difference between two static fluids:

\[ \Delta P = P_{water} - P_{air} = \gamma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \] (1)
Figure 1: (a) The solid-liquid contact angle determines the hydrophobicity of a surface. Hydrophilic surfaces have a contact angle less than 90°, while hydrophobic surfaces have contact angles greater than 90°. Superhydrophobic surfaces have a solid-liquid contact angle of greater than 150°. (b) For a non-wetting droplet (Cassie state), the liquid interacts with a fraction of the substrate surface. In a Wenzel state, liquid fills surface cavity structures, as shown on right.
where $\gamma$ is the surface tension, and $R_1$ and $R_2$ are the surface radii of curvature. For superhydrophobic microribs, where $R_2$ goes to $\infty$ it can be shown that the threshold for the pressure required to wet the surface, or the Laplace pressure, is
\[
\Delta P = -\frac{2\gamma \cos(\theta)}{w_c}
\]
where $\theta$ is the contact angle for a droplet on a smooth surface, and $w_c$ is the width of the cavity between the ribs.

1.2. Adiabatic Two-Phase Flow

Adiabatic two-phase flows composed of a liquid and gas are commonly studied to gain insight into condensing and boiling flows. In adiabatic flows, the vapor fraction and flow regime do not change along the length of the channel, thereby isolating the hydrodynamic phenomena. In this manner, the time-average streamwise pressure gradient, vapor fraction, and flow regime are constant for a given liquid/gas mixture in a channel flow.

Early work by Lockhart and Martinelli [12] and Chisholm and Laird [13, 14] laid the foundation for predicting the pressure gradient for two-phase flow in channels. In their work, the two-phase pressure gradient is expressed in terms of a two-phase multiplier, $\phi^2$, which is the two-phase pressure gradient normalized by the single-phase pressure gradient that would result if the liquid (subscript $L$) or gas (subscript $G$) component of the two-phase flow was the only fluid in the channel,
\[
\phi^2_L = \frac{(dp/dz)_{TP}}{(dp/dz)_L}
\]
\[
\phi^2_G = \frac{(dp/dz)_{TP}}{(dp/dz)_G}
\]

Here, $F$ denotes the component of the pressure gradient necessary to overcome friction, as opposed to that associated with a phase change or gravity. The multipliers are often correlated in terms of the Martinelli parameter, $\chi$, which is a ratio of the gas to liquid two-phase multiplier,
\[
\chi = \left[\frac{(dp/dz)_L}{(dp/dz)_G}\right]^{1/2}
\]
In practice, $\chi$ reduces to:
\[
\chi = \frac{m_L}{m_G} \sqrt{\frac{\rho_G}{\rho_L}} = \sqrt{\frac{\mu_L \bar{V}_L}{\mu_G \bar{V}_G}}
\]
Chisholm and Laird [13] found that the two-phase multipliers could be roughly correlated with the Martinelli parameter using the following relations:

\[
\phi_L^2 = 1 + \frac{C}{\chi} + \frac{1}{\chi^2} \quad (7)
\]
\[
\phi_G^2 = 1 + C\chi + \chi^2 \quad (8)
\]

where C is a constant, dependent on the flow regime of the liquid and gas phases. Though it is known that these correlations deviate significantly from reality for many flow conditions, they are the basis for much of the two-phase flow work that followed. Dozens of correlations exist for predicting two-phase flow for a variety of channel geometries and orientations, working fluids, and velocities. Sun and Mishima [15] and Asadi et al. [16] have provided excellent reviews specifically for mini- and micro-channel flows. Kim and Mudawar developed a universal correlation for a wide range of fluids, flow rates, and channel shapes, constructed from over 7000 data points compiled from over 36 studies [1, 17]. However, with all the work that has been done for pressure drop in two-phase flow, there has been limited discussion of the effect of surface wettability, and even less exploration of the specific influence of the combination of structuring and hydrophobicity associated with superhydrophobic surfaces.

1.2.1. Wettability and Two-Phase Flow

It is recognized that changing the contact angle has an influence on the transition between the flow regimes that occur in two-phase flow [18, 19]. Huh et al. [20] observed more flow regimes for hydrophobic than hydrophilic microchannels for contact angles in the range CA=35 to 111°. Barajas and Panton [21] found different flow maps for hydrophilic relative to hydrophobic 1.6 mm I.D tubes with contact angles in the range CA=34 to 106°. The degree of influence of wettability on flow regime transition is likely to vary with factors such as the size of the channel, since the boundary condition will exert a larger influence on a smaller channel; however, each of the studies above showed that wettability did influence the location of the flow regime transition.

While it is clear that wettability influences the flow regime, there is wide disagreement between studies on the effect of wettability on pressure drop. Takamasa et al. [22] found the effect of wettability for contact angles in the range of CA=7 to 146° to be insignificant on the pressure drop in fairly
large 20 \textit{mm} diameter tubes. Phan et al. [23] investigated flow boiling in a 0.5 × 5 \textit{mm} rectangular channel with surface contact angles of 26, 49, 63 and 103°, mass fluxes of 100 and 120 \textit{kg/m}^2\textit{s}, and a vapor quality range of 0.01-0.06. They found that a higher contact angle leads to higher pressure drop. Cho and Wang [18] observed differences in pressure drop for three surfaces of varying wettability (CA=80, 103, and 124°). The surface with the highest contact angle had a significantly higher pressure drop, but it was also much rougher than the other surfaces. There was no conclusive difference in pressure drop between the other two surfaces. Choi et al. [24] measured flow in two different 530 × 499 \textmu m channels with walls exhibiting contact angles of 25° and 105°, respectively. The liquid and air superficial velocities ranged from 0.25-0.43 m/s and 4.5-40 m/s, respectively. They found that the hydrophobic channel had a smaller pressure drop, but also pointed out that the fluid was in a different flow regime. Wang et al. [25] observed a decrease in pressure drop for two-phase flow in a square channel (4 \textit{mm} × 4 \textit{mm}) with a superhydrophobic surface created from randomly distributed silica particles coated with PDMS (CA=155°) of approximately 40%. The vapor quality ranged from 0.2-0.4 with a single superficial liquid velocity of 0.015 m/s and superficial gas velocities ranging from approximately 3 to 9 m/s.

In summary, there are inconsistent findings in the literature on the effect of wettability on two-phase flow pressure drop. The variation can be accounted for by the fact that the range of flow rates and channel sizes tested, as well as the degree of hydrophobicity, likely influence the effect of wettability on two-phase pressure drop. In single-phase liquid flows in the Cassie state, it is well established that channels with superhydrophobic walls experience a reduction in pressure drop due to the slip that occurs at the wall (shear-free condition above a gas-filled cavity), and this reduction in pressure drop becomes more significant with smaller channels [26, 27, 28, 29, 30]. It is significant to note that in the studies cited above, only two included superhydrophobic surfaces. Of those, only one used a channel sufficiently small that the presence of a superhydrophobic boundary would cause a measurable decrease in pressure drop. Therefore, it is not surprising that this is the only study that found a reduction in pressure drop. With the exception of the study by Wang et al. [25], the influence of a superhydrophobic microchannel wall on two-phase pressure drop has not been explored. The focus of the Wang et al. paper was to determine how superhydrophobic surfaces affect the performance of polymer electrolyte membrane fuel cells. For their ap-
plication, an appropriately narrow range of flow rates was explored. Other potential applications of two-phase flow on superhydrophobic surfaces, such as flow boiling or flow condensation, would span a much larger range of flow rates. Data for a wider range of flow rates is necessary to understand how superhydrophobic surfaces influence two-phase pressure drop.

As fundamental understanding of condensation on superhydrophobic surfaces continues to improve, exploration of condensation behavior will move from quiescent vapor environments to more industrially relevant, internal flow environments. Torresin et al. [31] performed experiments with flow condensation in superhydrophobic channels and found that the shear provided by the vapor flow can decrease droplet departure size, which has tremendous implications for heat transfer. Birbarah and Miljkovic [32] proposed that a convective environment could entrain drops that have departed the surface due to coalescence induced jumping, preventing their return to the surface and thereby improving heat transfer. The potential for superhydrophobic surfaces in a flow-condensing environment lies not only in its drag reducing abilities, but in its ability to improve heat transfer rates. Understanding of the fundamental fluid dynamics governing two-phase flows over superhydrophobic surfaces will become increasingly important as exploration of flow condensation on superhydrophobic surfaces continues. The results of the present study are an important initial contribution to the understanding of how flow rate impacts the pressure drop in a channel with superhydrophobic walls.

This paper specifically addresses how the pressure drop of a two-phase (air and water) flow is affected when flowing in a channel with a single superhydrophobic wall. Comparison is made relative to classical channels for a range of flow rates corresponding to superficial gas and liquid Reynolds numbers from 22-215 and 55-220 (superficial velocities from 0.48-4.7 and 0.07-0.29 m/s), respectively. These ranges result in a vapor quality range from 0.002 to 0.08, which is much lower than that explored by Wang et al. [25] and includes multiple liquid flow rates.

2. Methods

An adiabatic flow loop was designed and constructed to measure and observe two-phase channel flow, as shown in Figure 2. Compressed air was used to pressurize a tank containing deionized water. The air and water flow rates were controlled with needle valves and pressure regulators and then
Figure 2: Schematic of the air/water, two-phase flow loop.

measured with in-line flow meters (Omega FLR1004-D, 200-1000 mL/min with accuracy +/- 30 mL/min and Omega FLR1007, 13-100 mL/min with accuracy +/- 1 mL/min). The air and water flows were mixed in a 1/16 inch T-shaped junction before entering the rectangular channel detailed in Figure 3a. The flow was allowed to develop for approximately 120 hydraulic diameters before the differential pressure (Omega PX409-2.5DWU5V, accuracy +/- 0.02 psi) was measured across the test section, which had a length of approximately 150 hydraulic diameters. The taps leading to the pressure transducer were filled with water, and positioned on the bottom of the channel to prevent air bubbles from entering the taps. The flow exited the test section to atmosphere approximately 70 hydraulic diameters downstream from the downstream pressure tap. Temperature was measured with T-type thermocouples directly upstream and downstream of the test section. Flow rate, pressure, and temperature were recorded at 200 Hz. The pressure signal was filtered with a Butterworth filter at 45 Hz to remove electrical noise. During testing for each flow rate, the two-phase flow was allowed to reach steady behavior (approximately 5 minutes) and the flow rate, pressure, and temperature measurements were time-averaged over a period of greater than 30 seconds, sufficiently long that the mean signal was not influenced by the fluctuations in the flow.

Three sides of the rectangular test section were made of clear acrylic to allow visual access, and the remaining side was an interchangeable silicon surface that could be designated as superhydrophobic or hydrophilic, as shown in Figure 3b. The interchangeable surface was held in place with a strip of double-sided tape that ran the length of the surface. The height of the
channel was measured with a depth micrometer (accuracy of +/- 0.01 mm) before and after pressure measurements were recorded. The acrylic channel was precision machined to be flat, and the channel was held together with two steel plates that ran the length of the channel in order to prevent any deflection caused by the rubber gasket seal. The two sides of the channel were held together with eight bolts, which were each tightened with a torque wrench to 17 N·m. The height of the channel varied from 360 to 380 µm, measured to an accuracy of +/- 10 µm. For each test case, the measured height was used to calculate the Poiseuille number, Reynolds number, superficial velocities, and other variables. The width of the channel was 9.92 +/- 0.01 mm. This corresponded to a range of hydraulic diameters of 690 to 730 µm and an aspect ratio (W/H) of approximately 27. For this high aspect ratio, the channel approached parallel plate conditions.

After assembling the channel for testing of each surface, the single-phase liquid flow pressure gradient was measured for a range of liquid-only flow
rates corresponding to the two-phase flow rates to be tested. Subsequently, the two-phase pressure gradient measurements were conducted. Finally, the pressure gradient measurements for single-phase liquid flow were retaken to ensure the two-phase testing did not significantly influence the integrity of the test surface. After multiple sets of tests, the hydrophobic Teflon coating on the superhydrophobic surfaces began to wear off in certain locations on the surface and portions of the surface would irreversibly wet, impacting the single-phase pressure gradient. Thus for all superhydrophobic surfaces tested here, each surface was only tested once at each of the twelve flow rates measured. Repeatability was ensured by testing multiple surfaces under the same conditions. Importantly, the two-phase multiplier was calculated using the measured single-phase (liquid) pressure gradient in order to eliminate any differences in channel assembly from affecting the results.

The superhydrophobic surfaces were manufactured using standard photolithography and a deep reactive ion etch before coating with a thin layer of Teflon, as described in [33]. All of the superhydrophobic surfaces had a structure that consisted of parallel ribs 15-20 microns in height, as shown in Figure 4. Three different cavity fractions (ratio of the surface area between the ribs to the total surface area) were tested: $F_c = 0.5$, 0.8, and 0.91. The cavity width was held constant at 32 microns. By maintaining a constant cavity width, the Laplace pressure was constant for all superhydrophobic surfaces tested. The implication of a constant Laplace pressure is that the propensity of surface wetting was the same regardless of cavity fraction. In the present study, the liquid flow rates were chosen such that the pressure in the channel was at or below the Laplace pressure (2.8 kPa) during single-phase flow, ensuring that the surfaces were in a Cassie, or non-wetting state during testing. Wetting of the structured surface was visually apparent in reflection from the surface due to the absence of the air layer between the water and surface. During single-phase testing, the surfaces were visually monitored to ensure wetting did not occur over the majority of the surface. During two-phase testing, alternating slugs caused local pressure spikes significantly larger than the Laplace pressure. However, the air present in the two-phase flow continually re-filled the cavities with air so that neither long term nor widespread wetting occurred on the surfaces. Breaker ridges, or ribs 8 microns wide were placed perpendicular to the ribs every 2.5 mm in order to locally contain any wetting that might occur during the two-phase tests. Static contact angles for the 0.5, 0.8, and 0.91 cavity fraction surfaces were 146, 157, and 155° in the longitudinal direction and 132, 149, 146° in the
transverse direction, respectively. Contact angle measurements had a \( \pm 2^\circ \) accuracy. Control, or hydrophilic, surfaces were smooth silicon surfaces with no Teflon coating and a static contact angle of 60\(^\circ\).

Figure 4: SEM image of a surface with cavity fraction \( F_C = 0.80 \). The perpendicular rib pictured is a breaker rib, which was placed every 2.5 mm in order to compartmentalize any wetting that occurred.

2.1. Validation

In order to validate the channel setup, liquid single-phase pressure drop measurements were compared with predictive models in the literature. Differential pressure measurements for single-phase flow were taken in a classical hydrophilic channel and channels with one hydrophilic and one superhydrophobic surface. The Poiseuille number in a classical, hydrophilic, rectangular channel was predicted with a correlation developed by Shah and London [34],

\[
f \cdot Re = 24(1 - 1.3553\eta + 1.9467\eta^2 - 1.7012\eta^3 + 0.9564\eta^4 - 0.2537\eta^5), \quad (9)
\]

where \( \eta \) is the aspect ratio of the channel, \( H/W \). The pressure drop for parallel plate flow with one superhydrophobic surface was predicted using relations
developed by Philip [26] and Enright et al. [30]. These relations are for parallel-plate flow with asymmetric slip at the wall. It was assumed that the percent reduction in Poiseuille number predicted for parallel plate flow with one superhydrophobic wall would be very similar to the percent reduction for a high aspect ratio rectangular channel with one superhydrophobic wall. Therefore, the predicted Poiseuille number for a rectangular channel with one wall superhydrophobic was calculated by applying the appropriate percent reduction to the value obtained using Equation 9. A 5.4, 10.6, and 14.7% reduction in Poiseuille number is predicted for surfaces with cavity fractions $F_C=0.5$, 0.8, and 0.91, respectively. The predicted and average measured Poiseuille numbers for hydrophilic (HL) and superhydrophobic (SH) channels with single-phase flow are shown in Figure 5. The average percent error between the measured and predicted Poiseuille number was 2.2, 2.5, 4.2, and 2.6% for the hydrophilic, 0.5, 0.8, and 0.91 cavity fraction superhydrophobic surfaces respectively.

3. Results

Twelve different two-phase flow rates were tested, corresponding to liquid-only Reynolds numbers ($Re_L$) of 55-220 and gas-only Reynolds numbers ($Re_G$) of 22-215. The liquid- and gas-only Reynolds numbers refer to the Reynolds number that would occur if the liquid or gas portion of the flow were the only fluid in the channel,

$$Re_{(L,G)} = \frac{\rho_{(L,G)}j_{(L,G)}D_H}{\mu_{(L,G)}},$$  

where $j_{(L,G)}$ is the superficial liquid or gas velocity. The value of liquid- and gas-only Reynolds numbers are listed in Table 1 for each test scenario. Representative images of three test conditions are shown in Figure 6. The flow regime is slug for all flow rates tested, as described in Wambsganss et al. [35].

Four types of surfaces were tested, with multiples of each type for repeatability. Four hydrophilic surfaces were used as control surfaces; three $F_C=0.5$, four $F_C=0.8$, and three $F_C=0.91$ superhydrophobic surfaces were also tested. The square root of the two-phase multiplier, $(\phi_M$, see Equation 3) was calculated for each of the 14 surfaces. The single-phase pressure gradient in the equation was obtained using measurements taken directly before and after the two-phase flow tests. Results were averaged for each surface
Figure 5: Poiseuille number using the Fanning friction factor for single-phase channel flow in channels for the hydrophilic and $F_C=0.5$, 0.8, and 0.91 surfaces. The dashed lines indicate the average of the measured values. The solid lines/markers show the predicted Poiseuille number based on the percent reduction used by Philip [26] and Enright et al. [30] applied to Eqn. 9. The average percent error between the measured and predicted Poiseuille number was 2.2, 2.5, 4.2, and 2.6% for the hydrophilic, 0.5, 0.8, and 0.91 cavity fraction superhydrophobic surfaces respectively.

type; error bars on experimental measurements indicate the maximum and minimum of the values used for averaging.

The square root of the measured two-phase multiplier ($\phi_M$) for all channels was compared with that predicted ($\phi_P$) using a universal correlation for classical channels developed by Kim and Mudawar [1] as a percent difference, as shown in Figure 7. Agreement between the prediction and that measured for the control (hydrophilic) channels is better than 20%; this is excellent agreement given that the accuracy of the correlation is expected to be within $\pm 30\%$.

The channels containing a superhydrophobic surface showed an average reduction in $\phi$ of approximately 10% more than the hydrophilic control channels, regardless of the cavity fraction. This reduction of approximately 10% is observed in Figure 7 by comparing the deviation from the classical channel prediction (from Kim and Mudawar [1]) for a channel with a superhy-
drophobic boundary to a corresponding hydrophilic channel, at a given test condition. It should be noted that $\phi_M$ is obtained by normalizing by the single-phase liquid pressure gradient. The single-phase liquid pressure gradient is approximately 5-15% lower for channels with a superhydrophobic surface than a corresponding hydrophilic channel, depending on the cavity fraction. Therefore the 10% reduction observed in Figure 7 for a channel with a superhydrophobic boundary is an additional reduction in pressure drop beyond the 5-15% reduction experienced for single-phase flow. Further, the effect of cavity fraction on the two-phase multiplier (as seen in Figure 7) appears to be small, and generally within the measurement uncertainty. However, averaged values of the two-phase multiplier seem to indicate that
Table 1: Liquid and gas only Reynolds number \((\text{Re}_L, \text{Re}_G)\) and superficial velocities \((j_L, j_G)\) for each test condition.

<table>
<thead>
<tr>
<th>test condition</th>
<th>(\text{Re}_L)</th>
<th>(\text{Re}_G)</th>
<th>(j_L) (m/s)</th>
<th>(j_G) (m/s)</th>
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<tr>
<td>1</td>
<td>55</td>
<td>22</td>
<td>0.07</td>
<td>0.48</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
<td>107</td>
<td>0.07</td>
<td>2.34</td>
</tr>
<tr>
<td>3</td>
<td>55</td>
<td>215</td>
<td>0.07</td>
<td>4.7</td>
</tr>
<tr>
<td>4</td>
<td>109</td>
<td>22</td>
<td>0.15</td>
<td>0.48</td>
</tr>
<tr>
<td>5</td>
<td>109</td>
<td>107</td>
<td>0.15</td>
<td>2.34</td>
</tr>
<tr>
<td>6</td>
<td>109</td>
<td>215</td>
<td>0.15</td>
<td>4.7</td>
</tr>
<tr>
<td>7</td>
<td>163</td>
<td>22</td>
<td>0.22</td>
<td>0.48</td>
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<tr>
<td>8</td>
<td>163</td>
<td>107</td>
<td>0.22</td>
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</tr>
<tr>
<td>9</td>
<td>163</td>
<td>215</td>
<td>0.22</td>
<td>4.7</td>
</tr>
<tr>
<td>10</td>
<td>220</td>
<td>22</td>
<td>0.29</td>
<td>0.48</td>
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<tr>
<td>11</td>
<td>220</td>
<td>107</td>
<td>0.29</td>
<td>2.34</td>
</tr>
<tr>
<td>12</td>
<td>220</td>
<td>215</td>
<td>0.29</td>
<td>4.7</td>
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</table>

the two-phase multiplier may decrease slightly with increasing cavity fraction.

In order to compare the influence of flow rate on the two-phase multiplier, the ratio of the square root of the two-phase multipliers for a parallel-plate channel with one superhydrophobic wall and a channel with both hydrophilic walls is plotted in Figure 8, and defined as.

\[
\phi_{\text{SH}} = \sqrt{\frac{\left(\frac{dp}{dz}\right)_{TP,\text{SH}}}{\left(\frac{dp}{dz}\right)_{L,\text{SH}}}}
\]

\[
\phi_{\text{HL}} = \sqrt{\frac{\left(\frac{dp}{dz}\right)_{TP,\text{HL}}}{\left(\frac{dp}{dz}\right)_{L,\text{HL}}}}
\]

For two-phase flow in a channel with no reduction in pressure drop relative to a control channel with hydrophilic control surfaces, this ratio would be 1. The lower the value of the ratio, the greater the reduction in pressure drop. Each data marker in Figure 8 represents the average \(\phi_{\text{SH}}\) for all ten of the superhydrophobic surfaces divided by the average \(\phi_{\text{HL}}\) for the four hydrophilic surfaces for the same test condition. The variation in \(\phi\) for the different cavity fractions was significantly smaller than the difference between the hydrophilic and superhydrophobic surfaces; therefore the average of all the superhydrophobic surfaces, regardless of cavity fraction, is presented in Figure 8.
Figure 7: The square root of the two-phase multiplier obtained from the average measured value ($\phi_M$) for each test condition in Table 1 compared with prediction by Kim and Mudawar [1] ($\phi_P$). Test conditions correspond to $Re_L$ of 55-220 and $Re_G$ of 22-215. The three superhydrophobic surfaces have cavity fractions of 0.5, 0.8, and 0.91.

The reduction in pressure drop (smaller values of $\phi_{SH}/\phi_{HL}$) is more significant for increasing $Re_G$ over the range of flow rates tested. As $Re_G$ increases, the flow increasingly departs from a single-phase flow behavior and the influence of the slip condition becomes more pronounced, resulting in a larger drag reduction (lower values of $\phi_{SH}/\phi_{HL}$). With the exception of a $Re_G = 22$, the ratio is relatively constant with liquid-only Reynolds number, indicating that the percent drag reduction may not change appreciably with liquid flow rate in this flow regime. For $Re_G = 22$, the vapor quality is very low and approaches single-phase flow behavior with increasing liquid-only Reynolds number. As the quality approaches zero, the square root of the two-phase multiplier for both the superhydrophobic channel ($\phi_{SH}$) and the hydrophilic control channel ($\phi_{HL}$) approaches one, causing the ratio between them to also approach one.

In order to more closely examine the effect that increasing vapor quality has on drag reduction, the ratio $\phi_{SH}/\phi_{HL}$ is also shown as a function of vapor quality ($x$) in Figure 9. The maximum uncertainty associated with
measuring the vapor quality is 0.0026. The ratio decreases with increasing vapor quality, for $x \lesssim 0.03$. For qualities $x \gtrsim 0.03$, the impact of quality on drag reduction appears to have a minimal effect for the gas and liquid flow rates considered here.

The results presented here are consistent with the approximately 40% drag reduction Wang et al. [25] observed for a channel with superhydrophobic walls. In contrast to the present study, all of the walls of their study were superhydrophobic. Furthermore, the range of flow rates in their study was at a much higher vapor fraction (0.2-0.4). While direct comparison cannot be made, the outcome that superhydrophobic walls causes drag reduction is the same. The present study indicates that vapor fraction does impact the magnitude of the drag reduction. In addition, it is anticipated that channel size would also impact drag reduction, with smaller sized channels leading to a greater percentage of drag reduction (relative to classical channels), as
is true in single-phase flows.

4. Conclusion

The use of superhydrophobic surfaces in applications involving two-phase flow, including flow-boiling and -condensing, has the potential to be transformative across several industries. However, it is important to understand how the presence of superhydrophobic walls will impact the hydrodynamics of two-phase channel flow. The results of this study suggest that for a parallel plate channel (approximately $0.37 \times 10^{-3}$ mm) with a single superhydrophobic wall, an average reduction of about 10% in the square root of the two-phase multiplier ($\phi$) relative to a classical channel can be expected for superficial gas and liquid Reynolds numbers from 22-215 and 55-220, respectively. This corresponds to a reduction in drag of 10% in addition to that observed for single-phase liquid flow in a channel with a superhydrophobic boundary for the same conditions. The ratio of the reduction in drag for a superhydrophobic surface relative to a hydrophilic surface decreases with increasing vapor qualities, indicating that the effect of the superhydrophobicity is greater with increasing vapor fraction. Previous studies in channels
with hydrophobic walls have found that a hydrophobic wall either slightly increases the drag or has no effect, dependent on the flow regime and channel size. [18, 22, 23, 24] In contrast, from the present study and that of Wang et al. [25], it is clear that superhydrophobic walls have the potential to reduce drag in two-phase flows, again, depending on the channel size and flow regime. When conducting and reporting experiments involving two-phase flows in micro- and mini-channels, the wettability of the surfaces should be considered and reported.

5. Acknowledgments

This project was funded by a fellowship from the Utah NASA Space Grant Consortium, NASA Grant NNX15A124H.
References


