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Two-phase frictional pressure drop in a thin mixed-wettability microchannel

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ABSTRACT

This study focuses on the experimental investigation of the two-phase pressure drop in a thin mixed-wettability microchannel. Air-water flows in a thin microchannel of dimensions 3.23 mm wide by 0.304 mm high. The test conditions primarily produce rivulet flow. The two-phase pressure drop increases when the base contact angle changes from 76° to 99°, with the other walls remaining the same. Combining the result with existing literature demonstrates that consistent behavior in the change of the two-phase pressure when comparing different wettabilities arises with careful consideration of the experimental parameters to classify experiments of adiabatic two-phase flow in a single microchannel into three categories: homogeneous, hydrophobic mixed-wettability, and superhydrophobic mixed-wettability microchannels. The two-phase pressure measurements also allow for the assessment of homogeneous, separated, and relative permeability models. Limiting the analysis to the rivulet flow regime allows for the determination of a new relative permeability exponent of 1.747 in the two-fluid model, which produces a mean absolute percent error of 14.9%. However, the models do not fully collapse the data, indicating differing air-water interactions. The work discusses possible causes of this behavior from experimental limitations to instabilities of the rivulet flow.

1. Introduction

Surface characteristics of microchannels can impact the performance of various devices. For example in thermal management devices, hydrophobicity impacts flow transition and heat transfer rate for condensing flow in microchannels [1]. Similarly, hydrophobic surfaces influence the heat transfer characteristics of flow boiling in microchannels [2,3]. The change in hydrophobicity leads to a change in the pressure drop of the channel, in which a significant increase could render the design impractical for its intended application. Polymer-electrolyte membrane (PEM) fuel cells represent another application that relies on differing surface wettabilities to manage water generated by the hydrogen-oxygen reaction. In PEM fuel cells, a gas-diffusion layer (GDL) forms one side of cathode gas supply channels, with the remaining three sides formed by the bipolar plate. To prevent water retention, commercial GDLs undergo a hydrophobic treatment [cf. 4,5]. The bipolar plate can have a different wettability than the GDL [cf. 6–8], resulting in a mixed-wettability microchannel. Understanding the two-phase flow behavior and corresponding pressure drop can aid in designing a successful water management strategy for optimal performance.

Research focuses on understanding the impact of surface wettability on the behavior of the flow and the corresponding two-phase pressure. Unfortunately, studies of the two-phase pressure drop as a function of channel wettability have produced inconsistent results in how the two-phase pressure drop changes when comparing similar microchannels with different wettability (Section 2.1). Furthermore, the prediction of the two-phase pressure drop in hydrophobic microchannels usually relies on models experimentally determined for flows in hydrophilic microchannels. Some alternatives exist such as the separated flow models of Lee & Lee [9] and Wang et al. [10] but require assessment in their applicability to other flows. Therefore, improvements in predicting the two-phase pressure in hydrophobic channels relies on the continual assessment of existing models and an understanding of how the flow characteristics influence the accuracy of the prediction.

Through an experimental study in a mixed-wettability microchannel compared to a previous study in an identical hydrophilic microchannel [11] this work seeks to: (1) determine how the flow behavior changes between the two cases, (2) address the differences in existing literature for the two-phase pressure trend with contact angle to provide guidelines for future work, and (3)

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assess the predictive accuracy of existing two-phase pressure drop models including determining new relative permeability exponents (n_k) in the two-fluid model for the flow patterns observed in this work. Section 2 details the conflicting results for the two-phase pressure drop presented in literature (Section 2.1) and a discussion of the stability of rivulets (Section 2.2), the primary flow pattern observed in this study. A discussion of the methods used to predict the two-phase pressure follows in Section 3. Section 4 details the experimental method to produce air-water flow in a mixed-wettability microchannel of dimensions 3.23 mm wide by 0.304 mm high by 164 mm long. The subsequent section presents the validation of the experimental set-up (Section 5.1), the two-phase pressure drop results (Section 5.2), and the observed flow patterns (Section 5.3). Section 5.4 discusses classifying the results of existing literature and the current work to provide consistent trends for the two-phase pressure change with contact angle. The comparison to the existing two-phase pressure models follows in Section 5.5 with the determination of an optimized relative permeability exponent (n_k) for rivulet flow (Section 5.6). The work concludes with a discussion of experimental limitations and rivulet stability that can influence the predictive ability of the assessed two-phase pressure models (Section 5.7).

2. Background

2.1. Two-phase pressure and flow pattern

Investigations of two-phase flow in microchannels consisting of at least one hydrophobic surface have produced inconsistent findings in terms how the two-phase pressure drop changes when comparing the hydrophobic to hydrophilic experiments. A mixed-wettability rectangular microchannel has at least one wall of a distinctly different wettability than the other three. The contact angle (θ) defines the surface wettability (Table 1). Specifically, surface wettability falls into two categories: hydrophilic when $\theta < 90^\circ$ and hydrophobic when $\theta > 90^\circ$.

Stevens et al. [12] conducted air-water experiments in a microchannel 9.92 mm wide by 360–380 μm high. The microchannel consisted of three hydrophilic acrylic surfaces with a contact angle of 64° and one interchangeable surface. The interchangeable surface consisted of a hydrophilic silicon surface of $\theta = 60^\circ$ for the control tests and a superhydrophobic surface for the remaining tests. The superhydrophobic surface consisted of parallel ribs 15–20 μm in height with differing cavity ratios (ratio of rib surface area divided by the total plate surface area). The superhydrophobic surface had contact angles of 146°, 157°, & 155° in the streamwise direction and 132°, 149°, & 146° in the transverse direction, depending on the cavity fraction. The pressure measurements by Stevens et al. [12] showed little influence of the cavity fractions on the two-phase flow multiplier (ϕ) but saw a reduction of 10% in ϕ—beyond the 5–15% reduction in the single-phase measurement—relative to the prediction of Kim & Mudawar [13]. The control experiments agreed within a mean absolute percent error within 20% of the prediction of Kim & Mudawar [13]. The gas Reynolds number (Re_G) varied between 22 and 215 and the liquid Reynolds number (Re_L) varied between 55 and 220, which generated slug flow.

Table 1
Definition of wettability.

Contact angle [°]	Wettability
0	Wetting
$0 < \theta < 90$	Partially wetting
$90 \leqslant \theta < 180$	Partially non-wetting
180	Non-wetting

Wang et al. [14] also studied the influence of superhydrophobic surfaces on the two-phase pressure, finding inconsistent results. The microchannel had a 4 mm square cross-section with a 150 mm length consisting of a plexiglass top with the remaining walls formed by graphite with different surface treatments. It remains unclear as to the contact angle of the plexiglass, although typically plexiglass behaves hydrophilicly. The surface treatment of the graphite produced a contact angle of 35° with silica particles, 145° when treated with PTFE, or 155° when treated with silica combined with PDMS-2. At a superficial liquid velocity (U_L) of 0.015 m/s with superficial gas velocities (U_G) between 2 and 9 m/s, the PTFE treatment resulted in a higher two-phase pressure drop than the silica treatment. The silica-PDMS-2 treatment resulted in the lowest two-phase pressure drop of the three configurations.

Cho & Wang [15] investigated two-phase air–water flow in a microchannel of dimensions $1.68 \times 1.00 \times 150$ mm^3 with $0.55 \leqslant U_G \leqslant 9.36$ m/s and $5.0 \times 10^{-5} \leqslant U_L \leqslant 1.0 \times 10^{-3}$ m/s. The hydrophilic surface had a contact angle of 80° and the smooth hydrophobic PTFE surface had a contact angle of 104°. Identical hydrophilic surfaces formed the remainder of the microchannel in both cases. Contrary to Stevens et al. [12] and Wang et al. [14], the two-phase pressure drop increased with the increased base contact angle. A comparison to existing two-phase pressure models showed good agreement between the prediction and the experimental data, with increasing agreement as U_L increased. When optimizing the relative permeability exponent (n_k), Cho & Wang [15] found a slight increase from 1.96, 2.15, & 2.49 in the hydrophilic case to 2.47, 2.58, and 2.89 in the hydrophobic case for annular, mixed flow, & slug flow, respectively. In both the hydrophilic and hydrophobic cases, similar flow patterns existed, with a slight redistribution of fluid to the hydrophilic corners in the hydrophobic case. A rough carbon paper with a contact angle 128° also showed a pressure increase but existing two-phase pressure models did not compare well to the experimental data.

Lu et al. [8] investigated the influence of surface wettability in 8 parallel rectangular channels, 0.4 mm deep by 0.7 mm wide. Water injection occurred through a gas-diffusion layer (GDL) with a contact angle of 138–145°. Different surface treatments on the remaining three walls produced contact angles of 11°, 85°, and 116°. At $U_L = 3.0 \times 10^{-4}$ m/s, the two-phase pressure increased with the contact angle in a range of superficial gas velocities between 0.98 m/s and 15 m/s but became similar for U_G between 15 and 29.5 m/s. Conversely, at $U_L = 7.5 \times 10^{-4}$ m/s, the two-phase pressure generally decreased as the contact angle increased between $U_G = 0.98$–29.5 m/s. The authors noted the hydrophilic channel meets the Concus-Finn condition for water to wick into the corners. As a result, the water moved in the channel as a continuous film instead of being sheared by the air flow, which caused the slightly higher two-phase pressure.

Unlike the four previous works in which the authors conducted experiments under adiabatic conditions, Phan et al. [16] conducted flow boiling experiments with different surface wettabilities. Different surface treatments resulted in contact angles of 26°, 49°, 63°, and 103° for three of the walls, with a hydrophilic Pyrex glass top. The microchannel had dimensions 0.5 mm high by 5 mm wide by 180 mm long. Under total mass fluxes of water between 100 and 120 kg/m^2 s, the two-phase pressure increased with increasing contact angle but existing two-phase pressure models did not well predict the behavior.

The five aforementioned works studied mixed-wettability channels, in which at least one surface had a differing wettability than the remaining three. Several authors have studied homogeneous rectangular channels, where all four walls have the same wetting properties. Wang et al. [10] studied 200 μm wide by 100 μm deep microchannels of glass, modified glass, and PDMS that