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Two-phase flow dynamics in a micro channel with heterogeneous surfaces

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ABSTRACT

In this paper, two-phase flows in a micro channel with heterogeneous surfaces are investigated both experimentally and numerically. The heterogeneity in a micro rectangular channel is characterized by three hydrophilic channel walls plus one hydrophobic one; and the hydrophobic surface is either smooth or rough (roughness: 226–550 nm rms for the smooth surface and 21.5–28.9 μm rms for the rough). Results on an entirely hydrophilic smooth channel (roughness ~1.3 nm rms) are also presented for comparison. Two-phase flows are visualized through two different angles: (1) a top view; and (2) a cross-sectional view. It is observed that the surface wetting property and roughness affect the presence site of liquid water flow: liquid water is preferentially present in the two hydrophilic corners when one channel wall is hydrophobic. As a result, two-phase pressure, patterns, and stability differ from the purely hydrophilic channel. Rough surface is found to affect two-phase flow. Model predictions, obtained from both empirical formula based on the Lockhart–Martinelli parameter and two-fluid approach, along with model parameters optimization using experimental data. Real-time pressures are presented to show the effects of channel surface properties on pressure drop.

1. Introduction

Two-phase flows in micro channels are encountered in a wide range of industrial applications. In channels, liquid flow usually stays over wall surface while gas flow stays in the core region of a channel, thus channel surface properties can greatly influence two-phase flow characteristics [1]. In PEM fuel cells, liquid water, originated from water production by the oxygen reduction reaction (ORR) in the cathode, must be removed efficiently by channel gas flow. To avoid liquid coverage over gas diffusion layers (GDL) and ensure effective oxygen transport to the reaction site, GDLs are generally treated hydrophobic, thus liquid flow preferably stays on the other three hydrophilic channel surfaces. In micro channels, surface tension and capillary force are important [2,3]. In addition, physical conditions (e.g., roughness) on the channel surface and channel geometry may impact two-phase flow.

Several studies have been attempted to understand effects of surface properties on two-phase flow. Cubaud et al. [4] experimentally investigated surface modification and its effects on two-phase flow in micro channels. Air–water two-phase flow was tested in 525 μm square channels for both hydrophilic ($9° < \theta < 25°$) and hydrophobic surfaces ($\theta = 120°$). It is stressed out that contact angle is important in determining flow patterns. Choi et al. [5] investigated two-phase flow in rectangular channels with a hydraulic diameter of 490–507 μm and the impact of surface condition on flow pattern and pressure drop. Bubbly, elongated bubble and liquid bridge flow patterns were observed in hydrophilic channels while stratified and stratified with entrainment patterns were observed for the case with hydrophobic surface. They also pointed out flow patterns affect pressure drop. Takamasa et al. [6] evaluated the effect of wall wettability on the flow characteristics in a vertical pipe. The tube of a 20 mm diameter was coated with a thin film (thickness <10 μm) for wettability control. Hydrophilic ($\theta \leqslant 7°$), acrylic ($43° < \theta < 47°$) and hydrophobic ($135° < \theta < 150°$) pipes were tested. Surface properties may alter the boundary of pattern transition. The surface's impact on pressure drop was found to be insignificant in their study. Lee and Lee [7] conducted a similar study in mini channels of a 1.46–2.00 mm diameter. The pattern transition between slug and annulus shifts towards lower gas velocity when using hydrophobic surface. Phan et al. [8] investigated surface wettability and two-phase pressure experimentally. A 0.5 × 5 mm rectangular channel with surface contact angle of 26°, 49°, 63° and 103°, respectively, was tested; and they found that a higher contact angle leads to a higher pressure drop. Lee and Lee [9] tested three different surface conditions (glass, polyurethane, Teflon) in tubes with a diameter ranging 1.62–2.16 mm. They found that two-phase pressure increases with contact angle. A prediction model was also proposed.

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In addition, surface roughness can affect single-phase pressure drop [10]; few works were reported on the effects of surface roughness on two-phase flow. Wu and Cheng [11] indicated that single-phase pressure can be affected by surface roughness even for laminar flow in micro-channels. Olekhnovitach et al. [12] investigated inaccuracy of existing two-phase models that arises from neglecting surface roughness. Cavallini et al. [13] measured two-phase pressure for smooth and rough circular tubes (stainless and copper tubes with mean roughness of 1.3–2.0 μm). Previous correlations under-predict pressure for micro-channels with rough surface. A new correlation was proposed to take into account surface roughness.

Suman and Kumar [14] analytically showed that surface tension is an important factor determining the critical heat input of micro heat pipes. Peterson and Ma [15] also showed impact of contact angle on heat transport capacity. Wong and Lin [16] experimentally studied the effects of evaporator's surface wettability for micro heat pipe. The evaporative resistances under a given heat flux are different among surface contact angles. Qu et al. [17] compared various surface contact angles of a micro heat pipe with triangular cross-section. Both conventional surface (uniform wettability) and functional surface (different wettabilities for evaporator, adiabatic section, and condenser) are tested. They showed the functional surface with contact angle of 10°–30°–45° has the highest liquid flow rate in the adiabatic section. Wu and Cheng [18] experimentally investigated the effects of surface wettability and roughness on the Nusselt number and friction constant for micro heat exchangers. In most cases, a more hydrophilic surface led to a higher Nusselt number and friction constant. A rougher surface yields a higher friction factor and Nusselt number. Hsieh and Lin [19] tested deionized water, methanol, their mixture, and ethanol solution in rectangular micro channels. Hydrophilic and hydrophobic surfaces are prepared using the Ultra Violet (UV) treatment. They showed a higher heat transfer coefficient for hydrophilic surface than that for hydrophobic surface.

Though many studies were attempted to explore the effects of surface properties on two-phase flow characteristics in micro/mini channels, few works investigated two-phase flow in a micro-channel with both hydrophobic and hydrophilic walls. In the first paper of this research series [20], we explore two-phase flow in a hydrophilic micro channel. In this paper, the focus is placed on surface conditions, more specifically, smooth hydrophilic, smooth hydrophobic, and rough hydrophobic walls. Cross-sectional views of two-phase flow are presented, along with pressure measurement and model prediction. A great amount of effort is made on visualization of two-phase pattern and location, which is necessary to reveal two-phase dynamics and explain experimental observation in two-phase pressure measurement.

2. Experimental

2.1. Experimental setup

A rectangular micro channel (dimension: $1.68 \times 1.00 \times 150\ \text{mm}^3$), similar to that used in Ref. [20], is prepared for experiment and visualization. Fig. 1 shows schematic of the experiment setup and the test section. To modify channel surface property, a thin layer, either a carbon paper or PTFE sheet, was placed between the base and channel plate. Three surface conditions were chosen

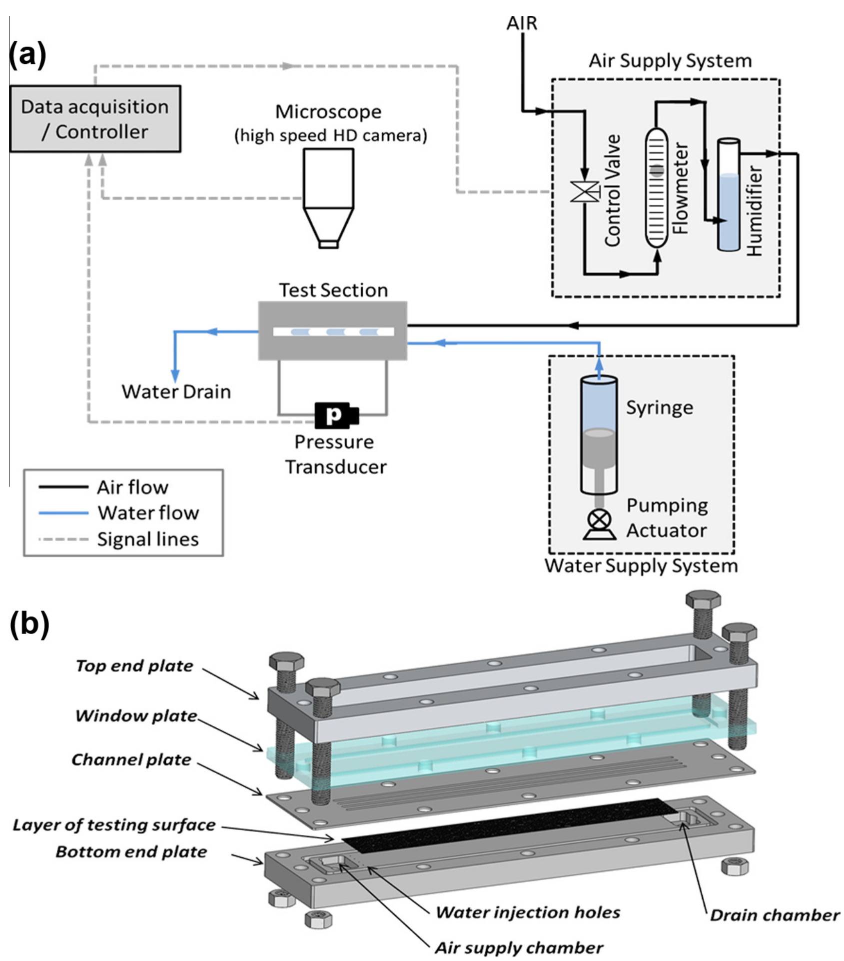

Fig. 1. Schematic of: (a) flow loop of the experiment; (b) the test section for two-phase flow experiment.