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Two-phase flow dynamics in a micro hydrophilic channel: A theoretical and experimental study

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ABSTRACT

In this paper, two-phase flow dynamics in a micro hydrophilic channel are experimentally and theoretically investigated. Flow patterns of annulus, wavy, and slug are observed in the range of operating condition. A set of empirical models based on the Lockhart–Martinelli parameter and a two-fluid model using several correlations of the relative permeability are adopted; and their predictions are compared with experimental data. It shows that for low liquid flow rates most model predictions show acceptable agreement with experimental data, while in the regime of high liquid flow rate only a few of them exhibit a good match. Correlation optimization is conducted for individual flow pattern. Through theoretical analysis of flows in a circular and 2-D channel, respectively, we obtain correlations close to the experimental observation. Real-time pressure measurement shows that different flow patterns yield different pressure evolutions.

1. Introduction

Micro-channels are widely used in modern engineering, such as lab-on-chips, PEM (Polymer Electrolyte Membrane) fuel cells, micro-heat pipes, and heat exchangers [1]. In PEM fuel cells, gas flow channels are characterized by their cross-section dimension at micro/millimeter scale and a length scale of around 10 cm [2]. In micro heat pipes, flow channels with 10∼500 μm hydraulic diameter are frequently used for cooling microelectronic chips or electronic devices thanks to their high heat conductance and large capability of heat transfer [3]. Micro-channel heat exchangers (MCHX) of hydraulic diameter ranging from 25 μm to 5∼6 mm are widely applied to HVAC systems [4,5]. Fig. 1 shows the channel system of PEM fuel cells or micro heat exchangers. Two-phase flows are frequently encountered in these devices as a result of water production or phase change. Because of micro-scale flow, surface tension is usually significant, as opposed to the gravitational or inertial forces, for the occasions of small Bond number ($Bo = \rho g L^2/\gamma$) or Capillary number ($Ca = \mu U_G/\gamma$) [6]. In PEM fuel cells, liquid water can block the pathway of air flow and hamper oxygen supply for the electrochemical reactions [7]. In micro heat pipes, liquid-phase working fluid, driven by capillary force, may encounter a large resistance to the evaporator side, leading to dry out of the evaporator [3].

Flow pattern and pressure drop are two important characteristics of multiphase flow in micro channels. To visualize flow pattern, transparent devices are usually designed [8–10]. Cheng et al. [11] reviewed various two-phase flow patterns. As the gas flow rate increases two-phase flow experiences bubbly flow, plug flow, slug flow, churn flow, annular flow and mist flow. The type of flow patterns depend on the channel orientation (vertical/horizontal), surface tension, and contact angle. In micro channels, mist flow, droplet formation, annulus, and slug flow are frequently observed [12–14]. Lately, Neutron radiography is adopted to detect the in situ volume fraction of liquid water [15–18], revealing spatial and temporal variations of liquid water.

To characterize two-phase flow, pressure drop is frequently measured. David et al. [19] developed the correlation between pressure drop and heat flux in MCHXs both numerically and experimentally, and they found flow pattern affects both pressure drop and heat transfer coefficient. Zhang et al. [20] presented the pressure fluctuation in a MCHX with a channel cross-section around 10∼200 μm. They showed that bubble production greatly impacts the pressure. Wu and Cheng [21] studied the pressure drop in boiling instability analysis of MCHXs, and tested eight parallel micro channels under various mass and heat fluxes. Two-phase pressure oscillates when boiling becomes unstable.

Modeling is important to the study of two-phase flow fundamentals. The homogeneous flow assumption is often adopted in modeling, which uses average quantities as major variables regardless flow patterns. [22–23] Various empirical correlations using the Lockhart–Martinelli parameter, following the Martinelli method [24], have been proposed to validate experimental data [25–29]. Physics-based two-fluid models can be developed, which consists

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Nomenclature

A	area [m^2]
C	Chisholm parameter [–]
D_h	hydraulic diameter [m]
f	fanning friction factor [–]
F	Faraday constant [96,485 C/mol]
g	gravitational acceleration [m/s^2]
H	channel height or tube diameter [m, mm]
I	current density [A/cm^2]
k	relative permeability [–]
K	absolute permeability [m^2]
L	channel length [m]
m	mass flux [kg/s]
n	number of electrons transferred in the reaction [–]
p	pressure [pa]
R	gas constant [J/K mol]
RH	relative humidity [–]
s	saturation [–]
T	temperature [K, °C]
U, u	velocity [m/s]
W	channel width [m]
Re	Reynolds number [–]
x	vapor quality [–]
X	Lockhart–Martinelli parameter [–]

Greek letters

α	charge transfer coefficient [–]
γ	surface tension [N/m]
ξ	Stoichiometric number [–]
μ	viscosity [kg/m s]
ρ	density [kg/m^3]
Φ^2	two-phase friction multiplier [–]

Subscripts

2φ	two-phase
c	critical
C	cathode
e	effective
G	gas phase
L, l	liquid phase
mem	membrane
w	water

of two sets of governing equations to describe individual flow of the two phases. In porous media or capillary tubes, fluid flows can be described by Darcy's law. The relative permeabilities are usually defined to account for phase interaction [30–35]. Table 1 summarizes several empirical models using the Lockhart–Martinelli parameter and correlations for the relative permeability. In this work, flow pattern, two-phase friction multiplier, and real-time pressure drop are visualized/measured and presented under various conditions in a hydrophilic channels. Model predictions are compared with experimental data.

2. Experimental

2.1. Experimental setup

A single straight rectangular channel (1.68 × 1.00 × 150 mm^3) was designed and fabricated for experiment. Micro channels were fabricated in a hydrophilic plate of 1.00 mm thickness using a high-precision CNC machine. The plastic components of the testing device were machined using the laser facility (precision: 50 µm) of the RapidTech on UCI campus. Fig. 2 shows schematic of the experimental test section. The machined channel plate of 1 mm thickness and the transparent window (polycarbonate) of 5.0 mm thickness are clamped between a base and an aluminum endplate with O-rings in between to seal the device. Micro holes were machined in the base plate and proper fittings were added for liquid water injection and air supply as well as pressure measurement. Humidified air (RH 100%) is supplied by a mass flow controller, whereas liquid water is injected by a microfluidic pump with accuracy (±0.35%, ±5.83 × 10^{-10} m^3/s). The total channel length is 150 mm; and the distance for pressure drop measurement is 130 mm, which excludes the inlet and outlet areas (5 mm after the liquid injection site, and 10 mm ahead of the outlet). As the testing portion is away from the injection inlet and outlet ports, any unexpected disturbances arising from the presence of the inlet or outlet are diminished. In past, we observed two-phase flow in these areas caused local flow instability and liquid accumulation [30]. A camera-integrated microscope was placed over the transparent window to record flow pattern. The pressure drop was measured by a pressure transducer (Setra Model 230) with accuracy of ±0.25% FS. A NI DAQ system (6025E & SCB100) was linked to the pressure transducer to record the data at a frequency of 10 Hz. In experiment, various flow conditions were investigated, with each condition repeated twice during the day (i.e. without restarting the test) and more than twice in different days (i.e. restart the testing). Fig. 3 shows the schematics of experimental setup.

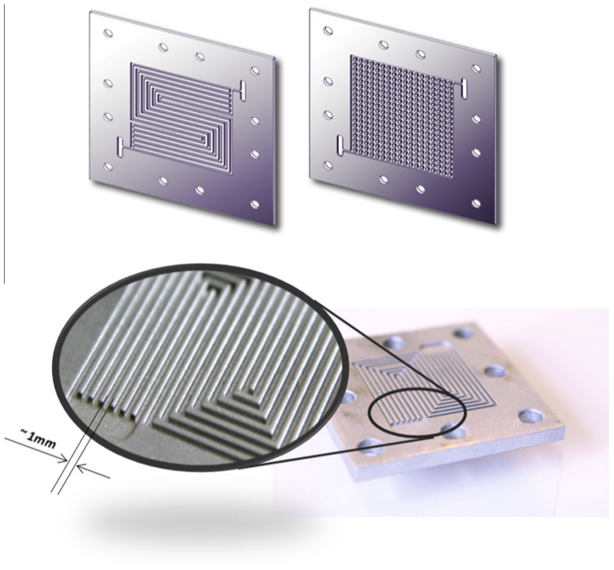

Fig. 1. Micro channels in PEM fuel cells or micro heat exchangers.

2.2. Experimental procedure and method

Real-time pressure drop was measured in duration of up to 30 min. The camera records the real-time flow pattern in the last five minutes. Under high air flow rates, two-phase flow is stable with small fluctuation demanding short recording duration. Under low air flow rates, slug formation causes significant periodic fluctuation in pressure drop, thus it takes longer for measurement. In experiment, both single- and two-phase flows were tested for a