International Journal of Heat and Mass Transfer 127 (2018) 813–828

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Two-phase frictional pressure drop and water film thickness in a thin hydrophilic microchannel

James M. Lewis, Yun Wang *

Renewable Energy Resources Laboratory, National Fuel Cell Research Center, and Department of Mechanical and Aerospace Engineering, University of California, Irvine, CA, United States

ARTICLE INFO

Article history:
Received 5 February 2018
Received in revised form 21 May 2018
Accepted 14 August 2018

Keywords:
Two-phase flow
Air-water
Frictional pressure drop
Water film thickness
Microchannel

ABSTRACT

This study focuses on the experimental investigation of the two-phase pressure drop and water film thickness in a thin microchannel. Air-water flow in the thin channel of dimensions 3.23 mm wide by 0.304 mm high produces a stratified flow over a range of test conditions. The experimental data allowed for the assessment of several models including homogeneous, separated, and relative permeability models. A comparison of the two-phase pressure to the recently developed two-fluid model (Wang, 2009) resulted in a new exponent (n_k) of 1.159 for the relative permeability, which produced a mean absolute percent error of 3.25%. Imaging of the air-water flow allowed for measuring the water film thickness, which showed good agreement with the analytical solution of Steinbrenner (2011) and the two-fluid model with a mean error of −0.035. The study demonstrates the applicability for the two-fluid model to predict both the two-phase pressure and the water film thickness in thin microchannels.

Published by Elsevier Ltd.

1. Introduction

Two-phase flow in thin microchannels has become ubiquitous in modern engineering and found in lab-on-chips, PEM (Polymer Electrolyte Membrane) fuel cells, micro-heat pipes, and heat exchangers. In PEM fuel cells, gas supply channels have a cross-section dimension at the micro/millimeter scale and a length scale of one to tens of centimeters. Not only do the gas channels supply air, the channels serve to remove water generated by the oxygen reduction reaction occurring at the cathode catalyst layer that could potentially cause severe flooding [38,37]. The two-phase pressure drop and water content in the channel act as indicators to flooding.

While computational methods exist to study two-phase flows, such as volume-of-fluid (VOF), the level-set method, and the Lattice-Boltzmann Method (LBM), experimentation and semi-empirical models reinforce the numerical results. Researchers have proposed many different semi-empirical models to determine the two-phase pressure drop which typically fall into one of three categories: homogeneous flow, separated flow, and relative permeability models. The homogeneous flow model treats the two-phase flow as an equivalent single-phase flow by averaging the two fluid properties together, particularly the viscosity. Through dynamic similarity Dukler et al. [10] weighted the viscosity based on the ratio of the liquid volumetric flow rate to the total volumetric flow rate. The model predicted the experimental data for two-component flows in tubes of diameter 2.54–12.7 cm (1–5 in.) over a range of viscosities to within −19% to 16%.

The separated flow models follow the work of Lockhart and Martinelli [21] and Chisholm [6], accounting for the interaction of the two phases through Chisholm's parameter, *C*. Lee and Lee [17] conducted experiments in horizontal channels of 20 mm width and 0.4, 1, 2, and 4 mm heights. The authors found that *C* should depend on the liquid-only Reynolds number, the Capillary number, and the liquid-only Suratman number. The model predicted the experimental data within ±10%. Kim and Mudawar [16] arrived at a similar relation to Lee and Lee [17] when correlating a database of adiabatic and condensing flow experiments consisting of 17 different working fluids in tubes/channels of hydraulic diameters between 0.0695 and 6.2 mm. The model predicted the experimental database with a mean absolute percent error of 23.3%.

The relative permeability models use Dary's equations to determine the two-phase pressure by modeling the form of the relative permeability in terms of the liquid saturation. For the X-model, based on the experimental work of Romm [28], the relative permeability linearly varies with the saturation such that the sum of gas and liquid relative permeabilities equal 1. Conversely, Corey [9] investigated oil-gas flows in conventional tubes and showed that the liquid relative permeability equals the liquid saturation raised

* Corresponding author.
E-mail address: yunw@uci.edu (Y. Wang).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.060
0017-9310/Published by Elsevier Ltd.

to the power of 4. This correlated two-thirds of Corey's experimental data well. In general, the relative permeability exponent varies between 1 and 4.

Though various models for the two-phase pressure exist that can accurately predict the two-phase pressure, the models rely on multiple correlation parameters. Wang [36] proposed the two-fluid model to investigate the porous channels in PEM fuel cells, treating the gas flow channels as porous media. Unlike other relative permeability models that require the experimental measurement of the saturation, the two-fluid model poses a model for the saturation. Thus, the use of the two-fluid model requires only a single correlation parameter, the relative permeability exponent n_k. Adroher and Wang [1] and Cho and Wang [7] showed the applicability of the model to standard gas flow channels in PEM fuel cells. In a channel of 1.6 mm wide by 1 mm high, Adroher and Wang [1] found an n_k value of 2 only resulted in a qualitative agreement between the experimentally measured two-phase pressure drop for superficial gas velocities in the range of 5–10 m/s. Cho and Wang [7] applied the two-fluid model to both hydrophilic and hydrophobic channels of dimensions 1.68 mm wide by 1.00 mm high by 150 mm long. The authors found that n_k values varied with flow pattern but remain a constant value of 2.49, 2.15, and 1.96 for slug, wavy, and annulus flow patterns, respectively. However, the two-fluid model has not been applied to thin microchannels nor has the model's ability to predict water film thickness been tested.

Through an experimental study, this work seeks to demonstrate the applicability of the two-fluid model in the common flow range of operational PEM fuel cells for thin microchannels. In addition to selected existing models, Section 2 introduces the two fluid model. The analytical solution to stratified flow proposed in dimensionless form by Steinbrenner [33] used for comparison to the optically measured water film thickness follows in Section 3. Section 4 details the experimental apparatus to produce air-water flow in a 3.23 mm wide by 0.304 mm high by 164 mm long microchannel and the testing method. Finally, Section 5 discusses the validation of the experimental setup and the assessment of existing models. Section 5.4 discusses the new relative permeability exponent and its validation in predicting the experimental two-phase pressure and water film thickness measurements.

2. Two-phase pressure drop models

Multiple mechanisms contribute to the overall two-phase pressure drop (ΔP_{tp}) [16]:

$$\Delta P_{tp} = \Delta P_F + \Delta P_g + \Delta P_A + \Delta P_{loss} \tag{1}$$

where ΔP refers to pressure drop and the subscripts F, g, A, and $loss$ refer to frictional, gravitational, acceleration, and loss, respectively. The models in this section refer only to the frictional pressure drop. The current study focuses on the adiabatic flow of air and water in a horizontal microchannel. Under adiabatic conditions, the flow will not accelerate and ΔP_A equals zero. With the channel aligned horizontally, the gravitational pressure loss also equals zero. The experimental technique seeks to minimize losses caused by entrance/exit effects and thus the loss term equals zero. This leaves that the two-phase pressure equals the two-phase frictional pressure loss.

2.1. Homogeneous flow model

The homogeneous flow model treats the two-phase flow as an equivalent single-phase flow with weighted properties under the condition that the two phases move with the same velocity. The two-phase pressure drop would thus follow:

$$\left(\frac{dP}{dz}\right)_{tp} = f_{tp}\frac{G^2}{2D_H\rho_{tp}} \tag{2}$$

where P equals the pressure, z the downstream coordinate, f the Darcy friction factor, G the total mass flux, D_H the hydraulic diameter, and ρ the density. The subscript tp stands for two-phase. The total mass flux (G) equals

$$G = \frac{\rho_G Q_G + \rho_L Q_L}{A_c} \tag{3}$$

where A_c stands for the cross-sectional area and Q the volumetric flow rate. The subscripts G and L stand for gas-phase and liquid-phase, respectively. The friction factor follows the standard definition for laminar flow:

$$f_{tp} = \frac{\overline{C}}{Re_{tp}} \tag{4}$$

where the correlation constant ($\overline{C}$) equals its single-phase equivalent but the Reynolds number becomes the two-phase Reynolds number (Re_{tp}) defined as:

$$Re_{tp} = \frac{GD_H}{\mu_{tp}} \tag{5}$$

Therefore, determination of the two-phase pressure drop only requires knowledge of the two-phase density (ρ_{tp}) and the two-phase dynamic viscosity (μ_{tp}). Researchers often agree that the two-phase density has the form:

$$\rho_{tp} = \left(\frac{\chi}{\rho_G} + \frac{1-\chi}{\rho_L}\right)^{-1} \tag{6}$$

where χ represents the gas quality defined as:

$$\chi = \frac{\rho_G Q_G}{\rho_G Q_G + \rho_L Q_L} \tag{7}$$

Table 1
Viscosity models for the homogeneous flow model.

Reference	Viscosity model	Test conditions
McAdams et al. [24]	$\frac{1}{\mu_{tp}} = \frac{\chi}{\mu_G} + \frac{1-\chi}{\mu_L}$	Benzene-oil, 2.69 cm tubes
Cicchitti et al. [8]	$\mu_{tp} = \mu_G\chi + (1-\chi)\mu_L$	Steam-water, 0.51 cm tubes
Lin et al. [20]	$\mu_{tp} = \frac{\mu_L\mu_G}{\mu_G + \chi^{1.4}(\mu_L - \mu_G)}$	R-12, 1 mm tubes
Dukler et al. [10]	$\mu_{tp} = \mu_L\lambda + \mu_G(1-\lambda)$	Two-component, 2.54–12.7 cm tubes
Fourar and Bories [12]	$\mu_{tp} = \lambda\mu_L + (1-\lambda)\mu_G + \sqrt{\lambda(1-\lambda)\mu_g\mu_L}$	Fractures, 0.18–1 mm gaps
Beattie and Whalley [3]	$\mu_{tp} = \mu_L(1-\beta)(1+2.5\beta)\mu_G\beta$	Multiple fluids
Awad and Muzychka [2]	$\mu_{tp} = \mu_G\frac{2\mu_G + \mu_L - 2(\mu_G - \mu_L)(1-\chi)}{2\mu_G + \mu_L + (\mu_G - \mu_L)(1-\chi)}$	Refrigerants; 2.46, 2.58 mm tubes; 0.148, 1.44 mm channels
where	$\lambda = Q_L/(Q_L + Q_G)$	
	$\beta = \frac{\rho_L\chi}{\rho_L\chi + \rho_G(1-\chi)}$	