International Journal of Heat and Mass Transfer 86 (2015) 31–38

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

An optical approach for quantitative characterization of slug bubble interface profiles in a two-phase microchannel flow

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ARTICLE INFO

Article history:
Received 22 October 2014
Received in revised form 22 February 2015
Accepted 24 February 2015
Available online 12 March 2015

Keywords:
Two-phase microchannel flow
Slug flow
Microfluidic diagnostics
Liquid–vapor interface detection
Texture-based image analysis

ABSTRACT

A new measurement technique is developed for quantitatively mapping the liquid–gas interface profiles of air bubbles in an adiabatic microchannel slug flow environment. Water seeded with 0.5 μm-diameter fluorescent polystyrene particles is pumped through a single acrylic microchannel of 500 μm × 500 μm square cross section. A periodic slug flow is achieved by the controlled injection of air into the channel. Particles are constrained to the liquid phase, and their distribution in the flow is visualized through an optical microscope in an epifluorescent configuration with pulsed laser illumination to resolve the instantaneous liquid–gas interface profile to within ±2.8 μm in the focal plane.

This approach is able to identify the interface profile within individual focal planes at various depths within the channel, unlike conventional backlit optical profile detection approaches that can only resolve the interface at the midplane. A similar particle-tracking technique was previously demonstrated for interface reconstruction in annular flows; however, the additional noise within images due to the reflection and refraction of background light at the compound-curvature interfaces characteristic of slug bubbles requires texture-based image analysis to obtain interface profiles. The varying interface profile of the slug bubbles in the streamwise direction also greatly complicates the tracking procedures for achieving a three-dimensional reconstruction of slug bubbles based on the measured two-dimensional interface profiles, which requires spatial alignment of the streamwise position of liquid–vapor interfaces realized at varying depths within the channel. This is addressed during reconstruction by using the measured mid-plane slug bubble cap curvature to assign the relative streamwise positions of interface profiles obtained at other measured depths. The characterization of two different selected bubble morphologies presented here demonstrates a critical improvement in metrological capability which can provide greater insight into microchannel flow phenomena in the slug-flow regime.

1. Introduction

Liquid–gas multiphase flows in microscale channels are encountered in a wide range of technologies. Multiphase microchannel flows have aided in achieving higher efficiencies and power densities from fuel cells [1], as well as greater mass transfer and reaction rates in contactors resulting in a decrease of overall system sizes [2]. Additionally, dissipation of large heat loads by evaporating a coolant that flows through a microchannel heat sink is an effective option for thermal management of compact, high-power electronic devices. While microscale two-phase flows have led to performance improvements in various technologies, quantitative experimental investigation of flow morphologies has been limited. Greater knowledge of these flows would serve to further improve performance and would aid in device design; however current experimental techniques are not capable of providing detailed characterizations of flows due to the difficulties associated with high-speed diagnostics in sensitive microfluidic environments [3].

Two-phase microchannel heat sinks have the ability to minimize temperature variations over the device, increase the overall energy efficiency of large-scale cooling systems, and occupy a smaller form factor over traditional single-phase cooling approaches [4], albeit with increased complexity and uncertainty in prediction of performance. Heat sink design is hampered by reliance on largely empirical, correlation-based modeling attempts that do not meet the demand for accuracy or flexibility sought in performance prediction, only yielding accurate results under narrowly defined conditions for which the correlations were originally obtained [5]. In response, researchers have developed mechanistic performance models that take into account the fundamental

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.02.067
0017-9310/

physics governing two-phase flow phenomena at the microscale [6–8]. Models of this type have demonstrated improved predictive accuracy and flexibility when compared to correlation-based approaches.

Jacobi and Thome [9] considered thin-film evaporation to be the predominant heat transfer mechanism in microchannel slug flows, and developed a mechanistic heat transfer model for slug flow in circular microchannels characterized by two hypothetical zones: a liquid plug, and a two-phase region containing the vapor slug in which the walls are uniformly coated by an evaporating liquid film. The authors noted that the film thickness played a determining role in successful performance prediction; however, it was left as a free parameter to be chosen by the user implementing the model. A subsequent modification to this two-zone model was presented by Thome et al. [6] in order to more faithfully represent the actual flow structures, and to eliminate free parameters that must be chosen arbitrarily. This three-zone model consisted of an additional dry zone trailing the two-phase region. The authors predicted the initial film thickness empirically by modifying a correlation for the film thickness during bubble nucleation in a gap between parallel plates [10]. Subsequent developments included a fourth zone added by Wang et al. [7] to capture partial dryout in rectangular microchannels, as well as an alternative correlation for determination of the initial film thickness used by Harirchian and Garimella [8] in the three-zone model.

As demonstrated above, mechanistic models for the slug flow regime available in the literature rely heavily on the liquid-film geometry within the channel; this geometry is currently indeterminate due to insufficient available techniques for characterizing this film in a microchannel flow environment [3]. Mechanistic models therefore rely on approximate theoretical film thicknesses and assumed shapes, contributing to a lower degree of accuracy [8]. Tibirica et al. [3] presented a comprehensive review of metrological approaches and their practical utility in characterizing liquid–gas interface shapes in microchannel flows; they concluded that extant approaches needed further development for meaningful quantitative investigations in this environment.

Several recent efforts are providing insight into film geometry in two-phase microchannel slug flows based on limited and localized measurements of the interface location. Fries et al. [11] used confocal microscopy in conjunction with fluorescent dyes to resolve the thickness of the liquid film at multiple depths within a 200 μm square microchannel, thus yielding information about the complete cross-sectional interface geometry. Despite a high in-plane measurement resolution of 0.46 μm, the extended exposure times associated with the confocal microscopy technique yielded a single highly time-averaged film thickness measurement at each depth investigated, rather than a complete streamwise-varying profile that is characteristic of a slug bubble. Han and Shikazono [12,13] measured the liquid film thickness in microchannels of circular and square cross section using laser focus displacement (LFD) meters. The operating principle of the LFD meters necessitated a perpendicular orientation between the liquid–gas interface and the probing laser beam, restricting the measured film thickness in the square channels to only two locations in the interface cross section. Information gathered from these two points was then used to formulate a correlation for the cross-sectional interface shape.

The present work develops a novel measurement technique to quantitatively characterize the two-dimensional interface profiles of slug bubbles at various depths within the channel, and demonstrates reconstruction of the complete three-dimensional liquid–gas interface of a slug bubble from experimental data obtained in an adiabatic two-phase microchannel flow environment. Measurement of the interface profiles is achieved through fluorescent optical visualizations of the flow at thin, discrete focal planes located at various distances from the wall. Within each plane, the phases are distinguished by incorporating fluorescent seeding particles into the liquid phase. Using a similar approach, the authors have previously demonstrated three-dimensional interface reconstruction of a static meniscus in a 400 μm capillary tube [14], as well as reconstruction of the interface cross section in adiabatic annular flows through a 500 μm square microchannel [15]. The streamwise-varying, three-dimensional slug flow interfaces, in combination with the inherent visualization difficulties in such a flow environment, have necessitated the development of a new reconstruction approach that overcomes these challenges specific to slug flows.

2. Experimental methods

2.1. Experimental setup

Key features of the experimental test section and flow loop are summarized here, and greater detail is available in a prior publication by the authors [15]. The experimental test section (Fig. 1a and b) contains a single microchannel with a square cross section of 500 μm × 500 μm and a length of 51.6 mm milled into acrylic. Adiabatic two-phase flow is generated by the controlled injection of air into the liquid stream at a T-junction located 40 hydraulic diameters upstream of the measurement location. The working liquid is deionized water seeded with 0.5-μm diameter fluorescent polystyrene particles (Magsphere Inc. PSFR500NM) at a volume fraction of 0.025%. The particles have a peak excitation wavelength of 542 nm, a peak emission wavelength of 612 nm, and a density of 1.05 g/cm^3. The addition of these seeding particles at the concentration specified has negligible impact on the flow structures through any change in density, viscosity [16], or surface tension [17,18] of the working liquid. The experimental facility shown in Fig. 1c and d contains a closed liquid-flow loop and an open air-injection loop; the reservoir is vented to atmosphere and serves as an air–water separator to maintain stable operation of the liquid loop.

Visualizations of the flow within the test section are obtained through an inverted optical microscope (Nikon Eclipse Ti-U) using a 10× objective lens (Nikon CFI Plan Fluor 10×) having an 8.3 μm depth-of-field and a resulting focal plane positioning accuracy of ±4.15 μm. Epifluorescent imaging is accomplished with the aid of a filter cube fitted with an excitation filter having a center wavelength of 525 nm and a full width at half maximum (FWHM) of 25 nm, a dichroic mirror with a reflection band of 525–556 nm and a transmission band of 580–650 nm, and an emission filter with a center wavelength of 620 nm and FWHM of 52 nm. The focal plane of the objective is parallel to the xy-plane of the coordinate system identified in the schematic illustration of the channel cross section in Fig. 1b. By ensuring that the optical axis of the objective lens and intermediate channel wall are perpendicular, distortion issues can be avoided despite the mismatch in indices of refraction between the immersion medium (air, $n = 1$), channel wall (acrylic, $n = 1.49$) and working liquid (water, $n = 1.33$). Images are recorded using a 12-bit monochrome CCD camera (Photometrics CoolSNAP HQ) at a resolution of 1392 × 1040 pixels; the camera pixel pitch of 6.45 μm × 6.45 μm results in a spatial resolution of 0.645 μm/pixel for the imaging. Volumetric illumination of the channel is delivered to the test section through the objective lens and is provided by a 5-ns pulsed ND:YAG laser (Quantel Brilliant Twins) at a wavelength of 532 nm and pulse energy of 2 mJ.

2.2. Experimental procedures

Experiments are initialized by setting the desired gas and liquid flow rates through the microchannel test section. Two test cases