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Technique for quantitative mapping of three-dimensional liquid–gas phase boundaries in microchannel flows

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ABSTRACT

A diagnostic technique capable of characterizing interfaces between transparent, immiscible fluids is developed and demonstrated by investigating the morphology of liquid–gas interfaces in an adiabatic two-phase flow through a microchannel of 500 μm × 500 μm square cross section. Water seeded with 0.5 μm-diameter fluorescent polystyrene particles is pumped through the channel, and the desired adiabatic two-phase flow regime is achieved through controlled air injection. The diagnostic technique relies on obtaining particle position data through epifluorescent imaging of the flow at excitation and emission wavelengths of 532 nm and 620 nm, respectively. The particle position data are then used to resolve interface locations to within ±1 μm in the focal plane. By mapping the interface within individual focal planes at various depths within the channel, it is possible to determine the complete liquid–gas interface geometry across the channel cross section in a dynamic flow environment. Utilizing this approach, the liquid–gas phase boundaries of annular flows within a microchannel have been successfully characterized.

1. Introduction

Two-phase microchannel heat sinks effectively dissipate high heat loads while minimizing temperature gradients across the heat sink (Garimella and Harirchian, 2013), making them an attractive option for thermal management of compact, high-power electronics. There are many experimental studies in the literature that have investigated the performance of single- and two-phase microchannel heat sinks. These studies have proposed a number of predictive empirical correlations characterizing heat transfer and pressure drop performance; the resulting correlations have since been collected and presented in several reviews such as those by Garimella and Sobhan (2003), Thome (2006), and Bertsch et al. (2008).

While many empirical correlations are available, they fail to accurately predict two-phase microchannel heat sink performance over a wide range of operating conditions, especially outside those under which the correlations were derived (Bertsch et al., 2008; Ribatski, 2013). The utility of empirical correlations for heat sink design is therefore limited. A clear need has been identified for more versatile predictive heat transfer and pressure drop models based on fundamental flow physics rather than empirical curvefits to data; however, such physics has not been fully mapped to date (Bertsch et al., 2008). In two recent studies, Harirchian and Garimella (2010, 2012) presented a comprehensive flow regime map for flow boiling in microchannels, as well as theoretical flow regime-based models for heat transfer and pressure drop. While this represented a distinct step towards physics-based performance prediction in preference to correlation-based techniques, the need for a greater understanding of the fundamental flow physics was still highlighted. The regime-based models showed a strong dependence of heat transfer on the thickness of the liquid film surrounding the vapor core in slug and annular flow regimes, a parameter that was approximated from fundamental conservation equations and assumed to be constant around the perimeter of the channel.

Tibirica et al. (2010) published a comprehensive review of thin liquid film measurement techniques, including an assessment of their feasibility and performance when applied to microchannel flows. It was concluded that current measurement techniques are in need of continued refinement, and have yet to reach a level of development where they can successfully be implemented in microchannels. Han and Shikazono (2009a, 2009b) made significant progress in successfully characterizing adiabatic two-phase flow morphology in both microtubes and microchannels through application of laser focus displacement (LFD) meters. While a very fine measurement resolution of 0.01 μm was achieved in these studies, it was only possible to obtain the thickness at two locations along the liquid film cross section where the channel wall was made tangent to the film profile. This was due to the operating

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principle of LFD meters, with which the liquid–vapor interface position is identified based on the reflected intensity of a converging laser beam that must be normal to the film. Results from these limited locations were used to develop models for the complete cross-sectional liquid film thickness and interface profile based on several dimensionless flow parameters. Laser extinction-based methods have also been used to successfully measure thin liquid films in two-phase microgap flow environments (Utaka et al., 2009). Like LFD meters, the operating principle of the laser extinction method limited the measurement of film thickness to a single point.

Adiabatic two-phase micro-particle image velocimetry (PIV) experiments were conducted for slug and annular flow regimes in a single 1.73 mm sapphire tube by Fouilland et al. (2010). While the intent was to investigate velocity profiles within the flow, it was possible to measure the liquid film thickness by adjusting the position of the focal plane within the tube. Due to depth-of-field limitations, the gas phase location was inferred from a decrease in the measured particle concentration with an accuracy of 10 μm. However due to the presence of curved interfaces and mismatched indices of refraction between the immersion medium (air, $n = 1$), tube walls (sapphire, $n = 1.76$) and the working liquid (water, $n = 1.33$) the acquired images contained significant noise and distortion.

A novel measurement technique capable of detecting interfaces between transparent, immiscible fluids has been developed and demonstrated in an adiabatic two-phase microchannel flow environment. Three-dimensional reconstruction of the liquid–vapor interface profile within the two-phase mixture is achieved by optical identification of the interface at thin, discrete focal planes at various distances from the wall. The phases are distinguished by incorporating fluorescent particles into the liquid phase. The feasibility of this approach was previously demonstrated by the authors for characterization of a static meniscus formed within a 400 μm capillary with interface location measurement accuracy of 2.08 μm (Patel and Garimella, 2012). Anastasiou et al. (2013) recently conducted an investigation of falling liquid film thickness in an open, inclined channel, in which the feasibility of interface mapping via an analogous micro-particle detection technique was also demonstrated. The present study extends the technique to operate in a dynamic microchannel flow environment with an improved accuracy of 1.06 μm. The present work advances state-of-the-art microfluidic metrology for characterization of liquid–gas interface shapes in the slug and annular flow regimes, where the film geometry plays a critical role in determining performance.

2. Experimental setup and procedures

2.1. Test section

The test section consists of a single microchannel of 500 μm × 500 μm square cross section that is milled into an acrylic block (Fig. 1a–c). The channel is sealed by an acrylic cover plate that contains liquid inlet and outlet plenums fitted with pressure taps connected to an absolute pressure sensor and a differential pressure transducer, with a resulting sealed channel length of 51.6 mm (Fig. 1c). By ensuring that the optical axis of the objective lens and channel wall are perpendicular, the distortion issues encountered by Fouilland et al. (2010) 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, $n = 1.33$). Adiabatic two-phase flow is achieved through controlled injection of air through a port machined into the channel. A schematic illustration of the channel cross section is shown in Fig. 1d; a detailed discussion of the measurement domain identified in this diagram is presented in Section 2.5. The coordinate axes referenced in this work are defined in the illustration.

2.2. Working fluids

The working liquid is water seeded with 0.5 μm-diameter fluorescent polymer microspheres (Magsphere Inc.) at a 0.025% volume fraction. The fluorescent 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 working gas is compressed air that is filtered for particulates and passed through an oil/water separator to remove any suspended contaminants prior to introduction into the flow loop.

2.3. Experimental facility

The experimental facility shown in Fig. 2 consists of a closed liquid-flow loop and an open air-injection loop. The liquid loop contains a gear pump, microturbine flow meters, the microchannel test section flow path, and a liquid reservoir that is vented to the atmosphere. The reservoir contains a magnetic stirrer that ensures uniform suspension of particles in the water. A bypass liquid return loop is incorporated into the facility to maintain the minimum flow rate required for stable operation of the gear pump and microturbine flow meters. By metering the flow using the bypass loop, it is possible to achieve liquid flow rates below the minimum equipment thresholds through the test section, yielding greater flexibility in experimental operating points.

The air injection loop is straightforward. Compressed air is passed through a regulator where the pressure is reduced to 70 kPa, and then throttled to the desired flow rate via a needle valve. The air flow is metered with a thermal mass flow sensor (Omega model FMA3105) and injected directly into the microchannel through a tap in the test section. The loop is also configured to allow the use of compressed air to purge or prime liquid lines as necessary.

2.4. Imaging and illumination

Visualizations are obtained through an inverted optical microscope (Nikon Eclipse Ti-U) using a 20 × objective with a numerical aperture of 0.45 (Nikon CFI S Plan Fluor ELWD 20×). The infinity-corrected objective enables illumination in an epifluorescent configuration, whereby illuminating light is delivered to the target through the objective. Illumination and return signals are passed through a filter cube with three primary components: a band-pass 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 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 microscope is parallel to the xy-plane in the coordinate system identified and has a depth of field of 3.1 μm, as approximated using an expression developed by Meinhart et al. (1999):

$$\delta z = \frac{n\lambda}{NA^2} + \frac{ne}{MNA} \tag{1}$$

In Eq. (1) δz is the depth of field, n is the refractive index of the immersion fluid between the sample and the objective lens ($n = 1$ for the present study where an objective immersion oil was not used), λ is the wavelength of the light signal being observed ($\lambda \sim 620$ nm based on the filters used), NA is the numerical aperture of the objective, M is the object magnification, and e is the minimum resolvable distance of the camera.

The images are recorded by a 12-bit monochrome CCD camera optimized for low-light imaging by a cooled sensor with high