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

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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 $\mu$m × 500 $\mu$m square cross section. Water seeded with 0.5 $\mu$m-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 $\mu$m 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 $\mu$m 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...
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/cm³. 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):

$$\delta z = \frac{n_i}{NA^2} + \frac{n_e}{MNA}$$

In Eq. (1) $\delta z$ 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), $\lambda$ 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
quantum efficiency, in excess of 60% (Photometrics CoolSNAP HQ). The imaging sensor has a pixel pitch of 6.45 \(\mu\text{m} \times 6.45 \mu\text{m}\); images obtained at 1392\%/2 1040 pixels have a spatial resolution of 0.32 \(\mu\text{m}/\text{pixel}\). Due to the high-speed, dynamic nature of the flow, a pulsed illumination light source is required to prevent image motion blur. The illumination source chosen is a 5 ns pulsed 532 nm ND:YAG system with dual lasing heads (Quantel Brilliant Twins). The illumination pulse energy is set to 2 mJ as measured between the output condenser of the fiber optic coupler and the microscope body using a pyroelectric power meter.

2.5. Procedures

In order to maximize the consistency of results, the lasers are turned on for 30 min prior to data acquisition to ensure that the laser heads are at a steady operating temperature, thus yielding a stable energy output. The same procedure is employed for the camera to allow it to cool down to the proper operating temperature. To ensure a uniform distribution of particles in the system, and clear any regions where particles may have settled during idle periods, the magnetic stirrer in the liquid reservoir is turned on, and water is circulated through the lines and test section at an elevated flow rate. Since the working fluid is in a closed-loop configuration it must be changed periodically as the fluorescent signals obtained during imaging degrade due to photobleaching of the fluorophores.

Once the air and liquid flow rates for each test case are set, and the flow regime is stable, quantitative visualization measurements are performed. The imaging begins by initializing the focal plane at \(z = 0 \mu\text{m}\) by focusing on the channel wall closest to the microscope objective. Then, the microscope objective is raised by 20 \(\mu\text{m}\) and 50 frames are recorded at a rate of 6.67 frames/s. This procedure is repeated at 20 \(\mu\text{m}\) increments until the objective is either raised a total of 180 \(\mu\text{m}\) from the wall, or when the liquid film can no longer be successfully visualized, whichever occurs first. Due to the difference in refractive indices of the objective immersion medium and the working liquid in which the visualizations are performed, a 20 \(\mu\text{m}\) increment in the objective position corresponds to a
26.6 μm increment in the focal plane z position within the channel. Thus, for a 180 μm change in objective position, the total distance traversed within the channel is 240 μm, resulting in a final focal plane location near the midpoint of the channel. The setup does not allow for the full channel width to be observed within the camera frame at the magnification used. Therefore, the liquid–gas interface is investigated in one symmetric quadrant of the channel cross section (0 μm ≤ y ≤ 250 μm, 0 μm ≤ z ≤ 250 μm), as illustrated in Fig. 1b.

The visualizations obtained are processed using the MATLAB Image Processing Toolbox (The MathWorks Inc., 2013). Noise is removed from a raw image (Fig. 3a) through an adaptive deconvolution filter (Fig. 3b) and the background is removed through a morphological filter (Fig. 3c) that preserves only the round particles; these steps isolate signals generated by the particles within the frame. The contrast is then enhanced and adjusted in order to convert the frame to a binary image (Fig. 3d), in which pixels representing particles appear as 1 (full white) and background pixels appear as 0 (full black). At this stage it is possible to select particles along the boundary either manually or using a custom automated-selection algorithm, enabling a reconstruction of the interface as shown in Fig. 3d. The algorithm searches for an area devoid of particles in an appropriately cropped frame and identifies this region as the gas phase. An initial particle is then selected on the boundary and neighboring particles are scanned, choosing those along the boundary since the general direction of the interface is known from identifying the separate phases. Since there is no guarantee that a particle is located at the boundary, a threshold maximum distance between selected particles is set manually, based upon the concentration of particles within the frame. By doing so, it is possible to control how far the particles selected by the algorithm deviate from the actual interface. By traversing a larger distance between selected particles, a smoother surface is generated and selected particles are more likely located at the boundary.

Interface location data are time-averaged due to possible fluctuation in the liquid–gas interface shape during imaging. This is accomplished by averaging the interface location of multiple frames from the recorded sequence to obtain a single interface location measurement at each xy-plane visualized. Time-averaging over 5 frames yields a standard error of the mean (SEM) of 1.50 μm in the film thickness measurement, on par with the technique accuracy of 1.06 μm (Section 3.2). A larger 25-frame sample size results in an SEM of 1.41 μm, suggesting that 5 frames are sufficient to produce an averaged measurement of the film thickness. Once the interface location is identified for each z location, the air–water interface shape across the channel cross section can be reconstructed.

3. Results and discussion

3.1. Technique demonstration in two-phase microchannel flow

The novel diagnostic technique developed is applied for characterization of interfacial structures during adiabatic two-phase flow in a microchannel across a range of gas/liquid flow rates that yield an annular flow regime. Operating set points tested are listed in Table 1 and shown graphically on a flow regime map in Fig. 4. The flow regime map shows the expected slug-to-annular flow transition lines as predicted by the model of Taitel and Dukler (1976), and the experimental data of Harirchian and Garimella (2009) obtained in 400 μm × 400 μm heated microchannels. The flow transitions observed while operating at conditions near the slug-to-annular transition region agreed closely with the transition line presented by Harirchian and Garimella.

In order to observe the parametric dependence of interfacial structures on gas and liquid flow rates, the interface profile is mapped at a fixed gas flow rate and varying liquid flow rates, and vice versa. Fig. 5 shows representative results from these efforts and plots the measured liquid–gas interface locations, as well
as complete profiles reconstructed with polynomial regressions, within the measurement quadrant in terms of the respective superficial gas and liquid phase velocities \( j_g \) and \( j_f \). The overall interface location is rather weakly dependent on the flow rates for the range investigated in the annular regime, but further inspection shows the interface shape to be influenced by the operating conditions. The interface transitions from being concave (as viewed from the air-side) to convex at high gas flow rates (Fig. 5a, \( j_g = 17, 30 \) m/s), and low liquid flow rates (Fig. 5b, \( j_f = 0.1 \) m/s). As the magnitude of gas velocity increases relative to that of the liquid, the velocity gradients across the channel cross section also increase. This results in a greater pressure variation across the channel cross section, necessitating a change in interface concavity to maintain a stable interface.

All interface location data obtained, as well as interface profile reconstructions produced through polynomial regression, are included in the single plot shown in Fig. 6 to emphasize the tight grouping of interface locations across all test cases, with the exception of case 8 (\( j_f = 0.3 \) m/s and \( j_g = 30 \) m/s). For this anomalous case, the interface location deviates strongly from the general trend. It was found that when the liquid film becomes sufficiently thin near the channel wall due to a large difference between gas and liquid flow rates, the interface curvature information can no longer be propagated circumferentially. The net effect is the possibility for the interface cross-sectional profile to become circumferentially asymmetric. In extreme cases, such as case 8, the liquid is observed to collect preferentially in one corner of the channel, or even stratify completely; however, this behavior occurs only at very high gas flow rates and/or very low liquid flow rates.

<table>
<thead>
<tr>
<th>( j_f ) (m/s)</th>
<th>( j_g ) (m/s)</th>
<th>Case No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.067</td>
<td>8.33</td>
<td>1</td>
</tr>
<tr>
<td>0.067</td>
<td>16.67</td>
<td>2</td>
</tr>
<tr>
<td>0.100</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>0.100</td>
<td>17</td>
<td>4</td>
</tr>
<tr>
<td>0.100</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>0.300</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>0.300</td>
<td>17</td>
<td>7</td>
</tr>
<tr>
<td>0.300</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>0.667</td>
<td>16.67</td>
<td>9</td>
</tr>
<tr>
<td>0.667</td>
<td>30</td>
<td>10</td>
</tr>
</tbody>
</table>

Further investigation revealed a hysteresis associated with these asymmetry phenomena. In case 8, the flow was driven unstable by unintentionally overshooting the desired gas flow rate set point, initiating a circumferentially asymmetric liquid distribution; subsequent throttling to the desired flow rate allowed the channel to operate continuously with this asymmetric liquid distribution. Conversely, slowly raising the gas flow rate to the desired set point from a stable film configuration enabled operation at the same conditions with a circumferentially symmetric distribution of liquid, as shown by the measured interface locations and profile reconstructions in Fig. 7.

Using experimental interface position data in one quadrant of the channel cross-section, it is possible to recreate the three-dimensional liquid–gas interface by first reconstructing the complete interface circumference in a single \( yz \)-plane cross section assuming symmetry in each quadrant. As shown by the plot in Fig. 8 for case 1, a spline produced from the measured interface location is extrapolated into a complete cross-sectional profile. The symmetric assumption is valid as flow is in a circumferentially stable configuration and the Bond number, the dimensionless ratio of buoyancy to surface tension forces, is much less than unity.
Bo = 0.0337), suggesting that surface tension forces dominate over gravitational forces. Once the complete interface is reconstructed over the channel cross-section, it is extruded along the length of the channel in the inset to Fig. 8.

3.2. Assessment of measurement technique performance characteristics

The utility of the present technique for characterization of thin liquid films may be assessed based on the minimum measurable film thickness and the measurement accuracy and resolution. In the present study, the lower limit of measurable film thickness is observed to be approximately 10 μm when the liquid–vapor interface is perpendicular to the focal plane. The noise in the signal due to reflections from the wall and internal reflections from the interface prevents measurement of thinner films below this threshold. Measurement resolution is dictated purely by optical magnification limits, rather than diffraction, because the interface is located by visualizing individual particles with separation distances much greater than the particle size. Resolution is calculated from the camera pixel pitch and objective lens magnification; the spatial resolution is 0.32 μm for the 20 x objective used.

Accuracy assessment for the present technique requires comparison against known liquid–gas interfaces profiles, which are difficult to establish under dynamic flow conditions using available alternative measurement approaches. In previous work by the authors (Patel and Garimella, 2012), special conditions were considered for which it was possible to obtain interface location information using standard optical microscopy in order to gauge the accuracy of measurements obtained using the present technique. The liquid–gas interface of a static meniscus in a capillary tube can be visualized with both standard microscopy and by detection of fluorescent particles in the liquid phase when the focal plane of the objective coincides with the centerline of the tube. The position of a static air–ethanol meniscus in a 400 μm diameter fluorinated ethylene propylene capillary tube was measured using both...
approaches at a magnification of 10×, the analysis has been repeated for the current study at a magnification of 20×. Comparison of the interface location data, shown in Fig. 9 along with a splined reconstruction of the measured interface, reveals that the 20 × objective results in a mean absolute error (MAE) of 1.06 μm over all points compared with the present measurement technique.

4. Conclusions

A novel measurement approach capable of investigating gas–liquid interfacial morphology in multiphase microchannel flows has been developed and demonstrated. The technique is shown to have a measurement accuracy of 1.06 μm and resolution of 0.32 μm using a 20 × objective lens, with a minimum measurable film thickness of 10 μm. This approach is capable of capturing dynamic interface structures at a level of detail not yet achieved in the literature; by incorporating fluorescent particles into the liquid phase, it is possible to resolve the interface across all three dimensions in a highly controlled manner. Due to the small length scales, relatively high flow speeds, and weak fluorescent signals present while performing the visualizations, careful optimization of the optical system within the experimental facility is required.

The measurement approach has been successfully demonstrated in adiabatic two-phase flow in a microchannel test section operating over a wide range of gas and liquid flow rates in the annular flow regime. The experimental results obtained show that the interface location is weakly dependent on operating conditions; however, the interface shape does vary depending on flow conditions. At comparatively elevated gas flow rates combined with reduced liquid flow rates, the interface shape transitions from concave to convex, as viewed from the gas phase. Additionally, a threshold is identified at which the liquid film breaks down and no longer sustains a circumferentially symmetric profile due to insufficient liquid flow, as seen in case 8 (jg = 0.3 m/s, jl = 30 m/s) when the target gas flow rate was exceeded. When this occurs, the liquid can preferentially redistribute itself in one or more corners of the channel.

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