2015

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Patel, R. P.; Weibel, J. A.; and Garimella, S V., "An Optical Approach for Quantitative Characterization of Slug Bubble Interface Profiles in a Two-Phase Microchannel Flow" (2015). *CTRC Research Publications*. Paper 257.
<http://dx.doi.org/http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.02.067>

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An Optical Approach for Quantitative Characterization of Slug Bubble Interface Profiles in a Two-Phase Microchannel Flow

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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 $\mu\text{m} \times 500 \mu\text{m}$ 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 $\pm 2.8 \mu\text{m}$ 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-

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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.

Keywords

two-phase microchannel flow; slug flow; microfluidic diagnostics; liquid-vapor interface detection; texture-based image analysis

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 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-b) contains a single microchannel with a square cross section of $500\ \mu\text{m} \times 500\ \mu\text{m}$ 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 $1.05\ \text{g/cm}^3$. 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-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 $\times$ objective lens (Nikon CFI Plan Fluor 10 $\times$) having an 8.3 μm depth-of-field and a resulting focal plane positioning accuracy of $\pm 4.15\ \mu\text{m}$. 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 $6.45 \mu\text{m} \times 6.45 \mu\text{m}$ results in a spatial resolution of $0.645 \mu\text{m}/\text{pixel}$ 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 are considered for the purpose of demonstrating the measurement technique: Case 1 has a superficial gas-phase velocity (j_g) of 0.83 m/s and a superficial liquid-phase velocity (j_f) of 0.97 m/s, while Case 2 has a comparable superficial gas-phase velocity ($j_g = 0.86$ m/s) at a significantly smaller superficial liquid-phase velocity ($j_f = 0.57$ m/s). While the present technique can measure instantaneous two-dimensional interface profiles of any arbitrary slug bubble shape, a strictly periodic flow condition within the test section is required to demonstrate a single representative three-dimensional reconstruction from the visualization of interface profiles from multiple slugs obtained at different channel depths. As an indicator of repeatability for purposes of the three-dimensional reconstruction, the slug bubble lengths for both test cases were measured by visualizing the channel at a lower magnification of

4× in a standard backlit configuration. Case 1 had an average measured length of 1052 μm with a standard deviation of 20.4 μm or 1.9% (sample size of 315 bubbles). Case 2 had an average measured length of 1421 μm with a standard deviation of 46.5 μm or 3.3% (sample size of 204 bubbles).

Once the operating conditions have been set, the z position of the imaging focal plane is zeroed by focusing on the channel wall situated closest to the objective lens. After the reference location is in focus, the microscope objective is raised 20 μm and a sequence of 100 frames is recorded at a rate of 6.67 frames/second. The objective lens is raised in 20 μm increments until a total displacement of 180 μm is traversed, with another sequence of 100 frames being recorded at each incremental position. Due to the difference in refractive indices of the working fluid and objective immersion medium, a 180 μm displacement of the objective translates to a 239 μm displacement of the focal plane within the channel, thus yielding a final measurement location near the midpoint of the channel. Fig. 1b shows the depths of each measurement plane at which visualizations are performed within the channel achieved through this procedure. The optical nature of the technique limits investigations to only the first incident liquid-gas interface within the channel when viewed from the lower channel wall, as the presence of the gas-phase slug prevents successful visualization of the interface on the opposite side. In the case of vertically symmetric slug bubbles (*i.e.*, unaffected by gravity), this means that only the lower half of the bubble below the midpoint of the channel can be investigated. In order to characterize the upper half of the slugs the channel must be viewed from the top; however it will be shown that this is unnecessary for the test cases under consideration in the present work.

3 INSTANTANEOUS INTERFACE PROFILE CHARACTERIZATION

The liquid-gas interface position data are extracted from the visualizations using the image processing methods described in the following sections; all processing is performed in MATLAB with aid of the Image Processing Toolbox [19]. Fig. 2 summarizes the processing sequence starting from a sample raw image (Fig. 2a) containing the leading portion of a slug bubble interface obtained at a measurement plane depth of $z = 186.2 \text{ } \mu\text{m}$ into the channel for Case 1. While the liquid-gas interface from the mid-plane within the channel ($z = 250 \text{ } \mu\text{m}$) is visible as an out-of-focus feature in the frame shown, it is obscuring the true in-plane interface, which will be extracted and shown to be different from that of the visible mid-plane profile in the following.

3.1 Preprocessing of Raw Frames

The images captured in the experiments contain a high level of inherent contamination due to the high excitation illumination intensities required to source even very weak emission signals that must be imaged; this fluorescence technique employed is required to attenuate out-of-focus features and visualize only the focal plane. Contamination is present in two separate forms: pixel-level noise that is introduced by the imaging sensor, and variation in background intensities across the frame that result from reflection and refraction of light off the liquid-gas and liquid-solid interfaces present in the flow field. In order to facilitate subsequent processing using segmentation techniques, the images must first be filtered to preserve only the particles within the flow. This is accomplished by scale-space representation of the images, *i.e.*, breaking down into a sequence of sub-images at varying levels of resolution [20]. First, each image is converted into a frequency domain representation using a discrete two-dimensional Fourier transform. Then, a low-pass filter is applied to remove pixel-level noise features resolved at a

very small scale (*i.e.*, high frequency) by scaling the frequency-domain representation of the image by a two-dimensional Gaussian distribution centered at the zero-frequency point, and having a standard deviation of 530 pixels. Lastly, the background light contamination that is resolved at a large scale (*i.e.*, low frequency) is removed by normalizing the noise-filtered image by a low-pass filtered image produced in the same manner as before but with a standard deviation of 50 pixels. The filter parameters are chosen sequentially in order to: first, maximally reject noise while preserving particle images; and second, attenuate background features without affecting particle images. After filtering, the resulting image has uniform background intensity with noise attenuated to a minimum level. A sample filtered frame is shown in Fig. 2b; while this image should ideally only contain particles, certain features – such as channel edges – are not completely removed. Additionally, the initial contamination has rendered particle signals too weak to use in conjunction with direct particle-tracking methods, such as those previously employed by the authors for an interface detection technique [14, 15].

3.2 Identification of Phases Within Frames

Texture-based image processing techniques are employed for phase identification to overcome the poorly resolved particle data. These methods offer superior robustness, in the form of additional noise rejection and enhanced arbitrary shape detection [21], over particle-tracking methods. Texture-based identification techniques rely on localized pixel neighborhood statistics to quantify the texture of an image using statistical metrics such as variance [20], Shannon entropy, range, or standard deviation [19]. Entropy-based texture mapping resulted in the greatest contrast levels for the present application, and was thus chosen for generation of the texture co-occurrence matrix (Fig. 2c). As seen in the figure, regions within the channel

occupied by particle-seeded liquid appear brighter than the area within the slug bubble (devoid of seeding particles). The pixel neighborhood-based calculation of entropy limits the minimum detectable film thickness to half of the window size used in the calculation. The present imaging setup yields a minimum film thickness measurement of 10.2 μm using a window of 32 pixels $\times$ 32 pixels.

The elements of the texture matrix were scaled between a minimum of zero and a maximum of one. Next, binary segmentation of the texture matrix was attempted using a fixed threshold of 0.175 determined based on the average intensity within the gas and liquid phases, above which all elements in the matrix are considered liquid and all remaining elements are considered gas. After performing the segmentation by this direct thresholding, it can be seen in Fig. 2d that the method yields very poor edge definition at the phase boundaries and is not by itself suitable for interface detection. An alternative active contour segmentation method, designed for applications with poor edge definition [22], was used for the final step of phase identification. The active contour segmentation method requires an initial estimate of the region that is to be segmented; the direct thresholding segmentation result is used as this initial estimate for subsequent evolution of the active contour boundary. The final binary segmentation of the texture co-occurrence matrix after active contour segmentation is shown in Fig. 2e, with the gas phase shown in white and the liquid phase in black. The technique yields smooth, continuous edges representing the actual liquid-gas interface; however, interfaces are falsely identified near the border of the frame (*e.g.*, leftmost edge in Fig. 2e) as the contour seeks to smoothly close itself, and must be discarded. The coordinates of the liquid-gas interface within the frame are extracted and superimposed over the example raw image in Fig. 2f. It is seen that the liquid-gas profile found within this off-center plane is smaller than the out-of-focus profile from the mid-

plane that is also visible in the image. Fig. 3 shows the results of the interface extracted at varying depths within the channel. The images have been selected such that the bubble is approximately in the same streamwise location within each frame, as visible from the out-of-focus mid-plane interface features. In each image, the true in-plane interface shape is extracted by taking advantage of the small depth-of-field of the objective lens in order to visualize the fluorescent particles at only the desired z positions within the channel.

3.3. Technique Performance Assessment

The accuracy of the developed measurement technique was characterized by comparison against a known liquid-gas interface profile; however, there are no alternative methods available to determine the complete interface profiles in a dynamic flow environment. For this reason, special conditions must be considered in a static environment for which it is possible to visualize a liquid-gas interface using both standard and fluorescent optical microscopy as a baseline for comparison of performance of the technique. Prior analysis under such conditions consisted of visualizing a static liquid-gas meniscus at the centerline of a 400 μm diameter capillary tube wherein the liquid was seeded with fluorescent particles at a seeding density identical to the present work [14]. Subsequent processing of the fluorescent image to extract interface data using the new technique developed herein enables a comparison to the known interface profile determined from the non-fluorescent image with a pixel-limited accuracy of 0.645 μm . The results of the comparison are shown in Fig. 4 and the observed error is shown in the inset; the difference between the known and measured profile is seen to manifest in discrete steps due to the pixel-limited resolution of the imaging system. The fluorescent technique is able to locate the interface with a mean absolute error of 2.8 μm . This is slightly worse than the 2.08 μm

accuracy obtained by the authors at the same magnification in conjunction with direct particle-tracking methods [14], and is due to the pixel neighborhood-level texture mapping operation that inevitably results in loss of sensitivity in the measurement. However, it is critical to note that while a slightly lower accuracy is achieved, the present technique offers far superior noise rejection capabilities, as it utilizes imaging data of neighborhoods of particles rather than individual particles. These traits are well suited for segmentation of arbitrary shapes, making the technique extensible to a broader range of applications.

4 TIME-AVERAGED SLUG RECONSTRUCTION

4.1 Interface Profile Alignment

The low temporal resolution of the imaging system (6.67 frames/sec) is not able to capture a continuous video of the passage of a single bubble due to the high-speed nature of the flows under consideration. However, the periodicity of the flow regime allows for a sequence of images to be captured at a given depth within the channel, which when combined, contain information about the complete interface profile of the slug bubbles at that depth. The approach is analogous to stroboscopic imaging techniques, but without the offset between images being controlled to match the characteristic frequency of the flow regime. Therefore, individual frames may contain interface data from the front cap of a slug, the rear cap, or an intermediate region between the two caps. Once the interfaces are identified in all frames of a sequence of recordings, they must be combined to yield a single, average cross section of the slug interface profile at that given depth within the channel.

Within a fixed plane, interface data are assigned a location in the streamwise direction using a point of relative reference – either the front or the rear cap; this properly located interface

data can then be averaged across the frames. For interface data obtained at intermediate locations where the caps are not in the frame, positions are assigned relative to these established average interface profiles near the caps by scanning the intermediate interface profile along the streamwise direction and performing a cross-correlation with the known profiles near the caps. After the streamwise location of the intermediate profile is determined it is then included in the averaged interface profile. This procedure yields a single, time-averaged, closed liquid-gas interface profile of the slug within the visualized plane, and is repeated for each image sequence obtained at planes of varying depth into the channel. This time-averaging procedure is not able to resolve transient phenomena such as interfacial waves; however, the individual frames containing the instantaneous interface profiles prior to averaging (as described in Section 3.2) indeed include all transient information if it is desirable to investigate interfacial wave structures for a particular application. The current test cases do not contain any interfacial waves based on interrogation of the instantaneous profile data.

Once complete in-plane interface profiles are known at each measurement depth within the channel, they must be spatially aligned relative to one another in the streamwise direction. Two different reference features were separately used for this alignment, both yielding interchangeable results. The known in-plane curvature of the front cap of the slug from visualizations at the midpoint of the channel can be used to position the leading tip of the slug cap in the remaining off-center planes. Alternatively, the specific flow regime examined exhibited a circumferential protruding ridge at the rear of the slug that could also be used to align planes. The ridge is manifested as a y -coordinate maximum and minimum point on the profile that serves as reference within each of the x - y planes visualized. The interface profile within each observation plane is measured with an accuracy of $2.8\text{ }\mu\text{m}$, as was shown in Section 3.3;

therefore, the resulting accuracy of the assigned streamwise position of off-center planes relative to the center plane is 5.6 μm .

4.2 Demonstration of Three-Dimensional Slug Reconstructions

The technique developed was used to successfully obtain a time-averaged reconstruction of slug bubbles in a dynamic microchannel flow environment based on quantitative measurement of interface profiles at varying channel depths. Fig. 5a,b show measured in-plane interface profiles at varying depths within the channel for Cases 1 and 2, respectively. In Case 1 (higher superficial liquid-phase velocity), visualizations did not reveal any interfaces near the bottom wall of the channel at $z = 26.6 \mu\text{m}$ due to the thicker liquid film (*i.e.*, presence of only the liquid phase at this depth) for this case. In contrast, the technique detected both liquid and gas phases at this depth for Case 2; however, the thinner liquid film in this case yields unusable results at the $z = 26.6$ and $53.2 \mu\text{m}$ depths as the interface approached a tangent orientation relative to the focal plane, leading to poor interface edge definition. As the interface approaches this orientation, any minor variation in interface shape, such as waviness seen near the rear of the bubble, manifests as large variations in the measured y -position of the interface within the visualized plane.

As mentioned previously, measurements are obtained only within half of the channel cross section. Thus, in order to achieve a full reconstruction of the slug, the measured interface data was mirrored to the upper half of the channel. In doing so, the interface shape is assumed to be symmetric about the middle plane of the channel, which is validated by calculating the Confinement Number (Co) of the channel:

$$Co = \frac{1}{D_h} \sqrt{\frac{\sigma}{g(\rho_f - \rho_g)}} \quad (1)$$

In Eq. (1), D_h is the hydraulic diameter of the channel, σ is surface tension, g is gravitational acceleration, and ρ_f and ρ_g are the liquid and gas phase densities, respectively. Ong and Thome [23] conducted experimental visualizations of two-phase flows through microtubes to study the effect of buoyancy forces on the symmetry of flow structures at the microscale. It was shown that buoyancy forces were negligible for $Co > 1$, and as a result, the flows were symmetric. The Confinement Number for the microchannel test section used in the present study is $Co = 5.5$, validating an assumption that the flow could be treated as symmetric in the z -direction.

For qualitative visualization purposes, complete reconstructions of the three-dimensional interfacial surface are shown in Fig. 5c,d for both test cases. The slug bubble for Case 2 is larger in the streamwise and radial directions owing to the lower superficial liquid-phase velocity. Despite the observation of a thinner liquid film in Case 2 the rear caps for both cases are very similar in size/morphology, spanning nearly the full width of the channel due to the circumferential ridge that is present towards the rear of the slug bubbles in both cases. Han and Shikazono [13] observed a transition in the cross-sectional interface shape of slug bubbles from non-axisymmetric to circular, or axisymmetric, above a capillary number, $Ca = \mu U / \sigma$, of 0.02, where μ is viscosity and U is flow velocity. While some minor surface irregularities are present in the reconstruction as artifacts introduced by the surface fitting procedure, non-axisymmetric bubble shapes arise from the presence of the channel walls for both Cases 1 and 2. The respective capillary numbers, $Ca = 0.024$ and $Ca = 0.020$, suggest these cases are near the threshold for such asymmetries to appear.

A model for the liquid-gas interface shape proposed by Han and Shikazono [13] is presented in terms of the dimensionless radii of curvature $R_{corner} = \sqrt{2} - 2\delta_{corner}/D_h$ and $R_{center} = 1 - 2\delta_{center}/D_h$, which correspond to the film thicknesses δ measured at the corner

and center of the channel wall, respectively. The models were derived for a simulated slug flow environment wherein gas is drawn into one end of a capillary tube initially filled with liquid [13]. In the present study, periodic slug flow with a trailing edge present on the slug bubble contributes to the difference between the measured and predicted film structures. With a longer slug bubble, the conditions for Case 2 are more representative of those under which the model was derived, and good agreement is shown between the experimentally measured $R_{corner} = 0.97$ and $R_{center} = 0.93$, and the predicted $R_{corner} = 1.0$ (a 3.1% difference) and $R_{center} = 1.0$ (7.5% difference).

5 CONCLUSION

The present work develops and demonstrates a novel approach to quantitatively characterize slug bubble interface profiles in microchannel two-phase flows. The study discusses the challenges of performing flow diagnostics in such an environment, namely, difficulties associated with obtaining high-quality visualizations under conditions conducive to noise and contamination by stray light. A robust texture-based image processing procedure is adopted that offers superior noise rejection and background removal, as well as improved arbitrary interface profile-shape detection capabilities, compared to previous direct particle-tracking methods that were only applicable in annular flows. The technique is experimentally demonstrated in two-phase adiabatic air-water slug flows generated in a $500\text{ }\mu\text{m} \times 500\text{ }\mu\text{m}$ square cross section microchannel with an interface profile measurement accuracy of $2.8\text{ }\mu\text{m}$. Time-averaged, three-dimensional slugs are reconstructed based on quantitative interface profile data obtained at a level of detail not yet achieved in the literature for two different flow conditions. This is a critical advancement in microfluidic metrology that enables experimental

investigation of the liquid-gas interface structures central to two-phase flow mechanistic performance models.

ACKNOWLEDGEMENTS

Financial support for this work provided by the Cooling Technologies Research Center, a National Science Foundation Industry/University Cooperative Research Center at Purdue University, is gratefully acknowledged.

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