2014

Design of a Non-intrusive Electrical Impedance-Based Void Fraction Sensor for Microchannel Two-Phase Flows

P. Valiorgue
Purdue University

S. N. Ritchey
Purdue University

Justin Weibel
Purdue University, jaweibel@purdue.edu

S V. Garimella
Purdue University, sureshg@purdue.edu

Follow this and additional works at: <http://docs.lib.purdue.edu/coolingpubs>

Valiorgue, P.; Ritchey, S. N.; Weibel, Justin; and Garimella, S V., "Design of a Non-intrusive Electrical Impedance-Based Void Fraction Sensor for Microchannel Two-Phase Flows" (2014). *CTRC Research Publications*. Paper 239.
<http://docs.lib.purdue.edu/coolingpubs/239>

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.

Design of a non-intrusive electrical impedance-based void fraction sensor for microchannel two-phase flows¹

Pierre Valiorgue, Susan N. Ritchey, Justin A. Weibel and Suresh V. Garimella²

Cooling Technologies Research Center, an NSF I/UCRC

School of Mechanical Engineering, Purdue University

585 Purdue Mall, West Lafayette, IN 47907 USA

Abstract

A non-intrusive electrical impedance-based sensor is developed for measurement of local void fraction in air-water adiabatic flow through rectangular microchannels. Measurement of the void fraction in microchannels is essential for the formulation of two-phase flow heat transfer and pressure drop correlations, and may enable real-time flow regime control and performance prediction in the thermal regulation of high-heat-flux devices. The impedance response of the sensor to a range of flow regimes is first investigated in a crosswise (transverse) configuration with two aligned electrodes flush-mounted on opposing microchannel walls. Numerical simulations performed on a multi-phase domain constructed from three-dimensional reconstruction of experimentally observed phase boundaries along with the corresponding experimental results serve to establish the relationship between void fraction and dimensionless impedance for this geometric configuration. A reduced-order analytical model developed based on an assumption of stratified gas-liquid flow allows ready extension of these calibration results to different working fluids of interest. An alternative streamwise sensor configuration is investigated with two electrodes flush-mounted along a single wall in the flow direction in view of its potentially simpler practical implementation in arrays of microchannels. It is shown that a correlation between time-averaged impedance and void fraction can be established for this alternative configuration as well.

Keywords: microchannel, two-phase flow, void fraction, impedance meter, sensor design

¹ Submitted for possible publication in *Measurement Science and Technology*, June 2013.

² Corresponding author. Tel.: +1 765 494 5621. E-mail address: sureshg@purdue.edu (S.V. Garimella).

1. Introduction

Integrated liquid cooling of microelectronic devices with embedded microchannel heat sinks offers improved heat dissipation efficiency by avoiding the thermal conduction and contact resistances associated with remote heat rejection. The thermal and hydraulic behavior of fluid flow in microchannels has therefore been extensively investigated [1–3] as a means to address the increasing cooling demands of high-performance electronics. Allowing the working fluid to boil improves heat transfer, but models that predict thermal performance under these conditions are specific to the particular two-phase flow regime encountered [4], which must be mapped as a function of channel dimension, heat input, and mass flow rate [5,6]. Flow regime maps for small channels and transition criteria governing macro-to-microscale boiling behavior have been developed based on visualization of flow boiling for water and refrigerants [6–9]. Regime-based heat transfer [10] and pressure drop [11] correlations developed for microchannels, as well as macrochannel flow boiling correlations [12], require void fraction measurements or predictions as inputs.

Measurement techniques that determine the void fraction during flow boiling in microchannels are required to formulate and employ regime-based heat transfer and pressure drop correlations. Also, from the standpoint of system operation and flow rate control, real-time void fraction sensing can be used to anticipate and avoid conditions of dryout or departure from nucleate boiling [13]. For development of correlations, void fraction is typically measured by image analysis of high-speed flow visualizations performed under conditions where optical access is artificially made available [13–16]. A variety of alternative radiation-, ultrasound-, and electrical impedance-based void fraction sensing methods have been developed to enable real-time measurement without optical access [4,17]. As underlined in [18], the mechanical and electrical

design of electrical impedance techniques is relatively simple and this approach can be implemented at reasonable cost; hence, it is an attractive alternative for the microchannel heat sink application of interest.

Electrical impedance-based methods encompass three primary implementation approaches: intrusive wire mesh sensors that detect phase at discrete locations on a grid over the flow cross-section [19,20]; non-intrusive electrode-pair sensors flush-mounted in a pipe wall [21,22]; and impedance tomography sensors that use sets of circumferential electrodes [21,23]. The current study focuses on void fraction measurement using electrodes flush-mounted in the wall of a microchannel due to the simplicity of incorporation into the channel geometries.

A variety of electrode configurations have been proposed in the literature including helical electrodes wound around the channel [24–26], opposing electrodes [22,27,28], and electrodes placed along the channel length [29]. The last two designs are readily applied to microchannels; however, great care must be taken to characterize the sensor for this unique geometry and scale. Relative electrode position and shape will influence sensor spatial resolution, sensitivity, and linearity, as emphasized by Rosa *et al.* [18]. Also, the response of the sensor to radial and axial non-uniformities in the flow (especially relevant for two-phase flow patterns) is a primary design concern, as highlighted by Tsochatzidis *et al.* [30] for multi-phase flow in cylindrical geometries.

A sensor with electrodes placed in the flow direction along the channel was first used by Swanson [31] to investigate the gas-liquid interface in annular flows. Coney [32] used plane electrodes flush mounted to the wall to measure the thickness of thin liquid films; an analytical model for the dimensionless impedance as a function of liquid height was proposed. Spatial resolution of such probes is limited by the electric field volume of influence; therefore, they cannot be used for making point measurements [33]. Andreussi and co-workers [29,34] used

flush-mounted electrodes in the walls of circular 2.3 to 5 cm-diameter pipes to determine the liquid hold-up for annular, stratified, and bubbly flows. The impedance-based method was found to have a strong dependence on the flow pattern. An electrode separation distance of 1.5 to 2.5 pipe diameters was found to provide a localized measurement at sufficiently close spacing while still providing a reading independent of the flow regime. The linearity of experimental calibrations between the dimensionless admittance and void fraction has been assessed in the literature for stratified fluid in a macroscale pipe [30,35]; a sensor with a streamwise pair of electrodes in the flow direction has never been investigated for microchannel geometries.

The current study investigates the design and calibration of the impedance-based void fraction sensor electrode configurations depicted in Figure 1 for use in microchannels of square cross-section. In the crosswise configuration, the aligned electrode faces are flush-mounted on opposing channel walls. In the streamwise configuration, the electrodes are flush-mounted along the same channel wall successsively in the flow direction. This streamwise configuration is amenable to easier practical implementation in an array of closely spaced channels by embedding the electrodes in a cover plate serving as the top wall of the microchannel heat sink.

In our prior work [27], the crosswise configuration was investigated; calibration test facilities and the impedance sensor construction details were presented. It was demonstrated that flow regime identification could be realized using a self-organizing neural network for classification based on statistical characteristics of the temporal impedance signal. An empirical calibration of void fraction as a function of dimensionless admittance was obtained based on image analysis. The current study extends the instrument output calibration for both crosswise and streamwise configurations via comprehensive analytical, experimental, and numerical characterization. In the crosswise electrode configuration, numerical sensor calibration simulations are performed on

a multi-phase domain obtained from three-dimensional reconstruction of experimental phase boundaries. This novel high-fidelity calibration is compared with reduced-order analytical expressions that enable exploration of sensor design for differing fluids and geometries. The streamwise electrode configuration is introduced and investigated experimentally, and numerical simulation is used as a design tool to assess implementation challenges.

2. Experimental setup and procedures

Experiments were conducted to calibrate the measured sensor impedance against the visualized void fraction associated with a range of relative gas and liquid flow rates through a microchannel. This section summarizes the experimental air-water two-phase flow loop, sensor-equipped microchannel test cells, impedance measurement methodology, and image-based void fraction measurement procedure.

2.1. Microchannel test cell and flow loop

Experimental test cells were fabricated to investigate both the crosswise and streamwise electrode configurations described in Figure 1. The test cells contain a single square $780\text{ }\mu\text{m} \times 780\text{ }\mu\text{m} \times 50.8\text{ mm}$ long microchannel that was fabricated into a transparent acrylic base plate in order to allow visualization of the internal adiabatic air-water flow patterns. An air injection port is located 10 mm downstream from the water inlet of the flow channel. Two electrodes (304 stainless steel) of $780\text{ }\mu\text{m} \times 780\text{ }\mu\text{m}$ square cross-section were flush-mounted in the desired configuration at a location 25.4 mm downstream from the water inlet.

The experimental flow loop used to provide the test cells with known gas and liquid flow rates is shown in Figure 2. The flow loop components and operating procedures are briefly discussed below; additional details are available in [27]. The de-ionized water stream was treated with

small quantities (~ 1 mg per liter) of morpholine and ammonium-hydroxide to set the desired electrical conductivity, σ , and maintain a pH value near 7. The impact of these chemicals on the flow regimes, through a change in the surface tension, is negligible [36,37]. Air flow injection from a compressed-air cylinder was controlled by a needle valve and measured using a mass flow sensor (Omega FMA6704) with a range of 0 to 100 ml min⁻¹. Interpolation between pressures measured at the inlet and the outlet of the channel was used to calculate the actual volumetric flux of air at the impedance measurement location. An in-line storage tank open to the atmosphere served as an air-water flow separator. In the pumped water flow loop, a needle valve controlled the flow rate as measured by a micro-turbine flow meter (McMillan Flo-106) with a range of 0 to 200 ml min⁻¹.

2.2. Impedance measurement

Impedance was measured between the electrodes in crosswise and streamwise configurations. The signal processing scheme and basic electronic circuit are described in detail in [27] and are summarized here. The electrodes were connected to the electronic circuit via 14 gauge copper cables using silver epoxy to minimize the contact resistance. The sine wave exciter signal applied to the electrodes was set with a peak-to-peak voltage difference of 3 V and a frequency of 20 kHz. The voltage measured across a reference resistor in a current-to-voltage amplifier circuit yielded the current flowing through the test cell. The excitation and output voltage signals were logged to a high-speed data acquisition system (National Instruments NI 6259-USB) at a sampling rate of 500 kHz and processed using a MATLAB [38] program developed in-house in order to obtain a measurements proportional to the impedance. The absolute impedance value was then determined using a calibration of the processed measurements against

known impedances from 10^5 to $10^6 \Omega$. As shown in Figure 3, the relationship deviates slightly from a linear profile at 20 kHz.

2.3. *Image-based void fraction determination*

The volumetric void fraction α was determined from flow visualization. Images were acquired at 100X magnification using a Photron Fastcam-Ultima APX high-speed camera and a Keyence VH-Z50L lens. Videos were recorded at 24,000 frames per second with a shutter speed of 120,000 Hz. The image processing algorithm described in [27] was used to map the three-dimensional air and water regions from the acquired frames. The key procedural steps are listed here. The air-water interfaces in the binary images of the frames were detected using the Canny algorithm implemented in MATLAB [38]. Unphysical cusped and concave boundaries caused by light reflections were subsequently removed. To determine the volumetric void fraction in the region of interest, three-dimensional air volumes are generated from the two-dimensional phase boundaries assuming that the air regions are axisymmetric about their major axis.

Examples of two-phase flow distribution images acquired for bubbly, slug, and churn flow regimes are given in Figure 4. In order to assess the validity of the image-based void volume reconstruction, the void fraction, α , was computed and compared to the gas volumetric flow fraction, β , as determined from the volumetric liquid flow meter and gas mass flow meter measurements.

The gas volumetric flow fraction is defined as the ratio of volumetric flow rates, $Q_1 \times (Q_1 + Q_0)^{-1}$, where subscripts 1 and 0 designate the gas and liquid phases, respectively. In the case of homogeneous flow, *i.e.*, under the assumptions of uniform phase distribution in the flow cross-section and equal phase velocities, the void fraction is given by

$$\alpha = \beta \quad (\text{homogeneous flow model}). \quad (1)$$

According to the drift flux model for small tubes, for which the mean drift velocity tends to zero, empirical correlations in [39,40] suggest the following relationship for $\beta < 0.9$:

$$\alpha = 0.8\beta \quad (\text{drift flux model}). \quad (2)$$

Figure 5 shows the void fractions obtained from visualizations as a function of values determined from the measured air and water volume flow rates; a comparison against the homogeneous flow and drift flux models is also shown. Visualizations were obtained for a range of gas and liquid flow rates which ensure coverage of the entire void fraction range. The void fraction appears to match the homogeneous flow model better than the drift flux model, for $\beta < 0.8$. In [41], the homogeneous flow model was also found to provide the best prediction of the experimental void fractions in bubbly and slug flow patterns; it was noted that the homogeneous flow assumptions did not apply for annular flow with high void fractions. Figure 5 confirms the deviation of the estimated void fraction from the homogeneous flow model and the improved match with the drift flux model for void $\beta > 0.8$. This observation offers a validation of the visual reconstruction method developed for void fraction estimation.

3. Numerical simulation

A numerical simulation implemented in Fluent [42] was used for design and characterization of the impedance-based microchannel void fraction sensor. Steady-state simulations of the electric field were used to predict the overall complex impedance between the electrode pair in the microchannel flow domain. The numerical simulation approach was validated against theoretical values for full-gas and full-liquid impedance in the crosswise electrode configuration.

3.1. *Solution domain and mesh*

The domains, boundary conditions, and uniform cubic volume mesh of length L (cell edge length of $d/50$) created for the simulation of the impedance of a two-phase mixture in crosswise and streamwise configurations are shown in Figure 6. Electrical properties were assigned to the mesh locally using either the void phases reconstructed from experimentally acquired image frames or based on the desired conditions for design/validation. Numerical computation of impedance could then be performed as presented in the next section.

3.2. *Governing equations for electric field*

Numerical simulation of the three-dimensional electric field was implemented in Fluent [42] for both the crosswise and the streamwise configurations. The electric potential was obtained by solving the following Laplace equations:

$$\nabla \cdot \left(\frac{1}{\rho} \nabla \varphi \right) = 0 \quad (3)$$

$$\nabla \cdot (\varepsilon_0 \varepsilon_r \nabla \varphi) = 0 \quad (4)$$

where ρ is the electrical resistivity, ε_0 is the permittivity of free space, ε_r is the relative permittivity of the phase, and φ is the electric potential field. An analogy with steady-state heat diffusion is used to solve for the current and charge fields using the energy equation solver in Fluent [42]. A potential difference of 4 V was applied across the electrodes using Dirichlet boundary conditions. Zero-flux Neumann boundary conditions were imposed on the other boundaries. An electrical conductivity of $100 \mu\text{S cm}^{-1}$ and a relative permittivity of 80 were assigned to the water phase, while an electrical conductivity of $2.5 \times 10^{-10} \mu\text{S cm}^{-1}$ and a relative

permittivity of 1 were assigned to the air phase. The default Fluent [42] convergence criterion of 10^{-6} was used for the Laplace equations.

The resistance, R , and capacitance, C , between the electrodes were obtained from the resolved current and charge at the surface of the electrodes, respectively. The resistive component, $\Re$, and reactive component, X , as well as the magnitude, $|Z|$, of the impedance were calculated assuming the overall resistance and capacitance of the domain are in parallel:

$$\Re = \frac{R}{1 + \omega^2 C^2 R^2} \quad (5)$$

$$X = \frac{\omega C R^2}{1 + \omega^2 C^2 R^2} \quad (6)$$

$$|Z| = \sqrt{\Re^2 + X^2} \quad (7)$$

3.3. DC simulation of AC sensor measurements

The overall impedance for an AC driving signal is predicted based on the overall resistance and capacitance values obtained from steady-state electrical field simulations. This assumes that the DC and AC overall resistance and capacitance are similar for the selected driving frequency. This assumption is justified in the following.

The effect of frequency on the overall impedance has been addressed in the literature [32–34] with respect to impedance sensors. It was observed that the overall impedance was altered at low frequencies by the presence of a number of capacitive and resistive elements which arose at the electrode-electrolyte interface [33]. The origin of such elements was discussed in [33], and attributed to the deposition of surface active ions. This has been reported to be responsible for

long term drift of the impedance magnitude and phase at operating frequencies of less than 1 kHz [33].

Mitigation of this phenomenon at similar geometric scales as the current study was investigated in [32] by varying frequencies over the range of 60 Hz to 150 kHz for a water conductivity value of $250 \mu\text{S cm}^{-1}$. The water solution resistance became asymptotic for frequencies above 10 kHz, while the capacitance continued to decrease at a frequency of 100 kHz. As the frequency used in the current study is 20 kHz, it is assumed that the liquid resistance corresponds to this asymptotic value. The electrical properties for the calculation of the impedance of air were approximated to those of vacuum and are therefore considered to be independent of frequency.

3.4. Validation of numerical simulation

Simulated impedances for a single-phase domain, with the flow length limited to one electrode width in a crosswise configuration, are in agreement with impedances predicted analytically for parallel plates as shown in Table 1.

Simulations were performed for increasing domain size to determine when the impedance becomes independent of the domain length in the flow direction. For the crosswise electrode configuration, the predicted impedance changes by less than 1% for a domain flow length increase from $3d$ to $5d$; a domain flow length of $3d$ was chosen for further analysis of the electric field.

The electric field was simulated for a full-water domain to identify the fluid zone that influences sensor response. Figure 7 plots the electric field in the crosswise direction, as well as envelopes of the percentage of the total current passing through planes parallel to the electrodes. Approximately 30% of the current flows outside the fluid region bounded by the ends of the

electrodes. The fluid in the region beyond the electrode cross-section has a smaller weighted influence on sensor impedance; however, the current flow path curvature in this region would cause a differing impedance response to voids at the center and near the side walls of the channel. This spatial dependence illustrates the difficulty in defining the instantaneous void fraction observed by the sensor for purposes of calibrating against the numerical simulations. In this work, the sensor calibration curve is generated for convenience based on the void fraction defined as the fraction the volume of gas occupying the channel between the electrodes for a simulation domain flow length of d .

The 95% envelope shown in Figure 7 is also a useful design parameter that dictates the minimum pitch required for independent operation of multiple sensors placed along a channel.

4. Results and discussion: Crosswise configuration

Reduced-order analytical expressions are presented to explain the crosswise electrode sensor behavior from first principles assuming a simplified liquid-gas flow structure. A simplified calibration developed from these analytical predictions is compared to the experimental measurements and to high-fidelity numerical analyses that take into account realistic flow structures.

4.1. Analytical prediction of stratified air-water flow impedance

Theoretical expressions for the full liquid (Z_0) and full gas (Z_1) impedance between electrodes in a crosswise configuration are given as

$$Z_0 = \frac{-id\rho_0}{A\varepsilon_0\varepsilon_{r_0}\left(\rho_L - \frac{i}{\varepsilon_0\varepsilon_{r_0}\omega}\right)\omega} \quad (8)$$

$$Z_1 = \frac{-id^2\rho_1}{A^2\varepsilon_0\varepsilon_{r_1}\left(\frac{d\rho_1}{A} - \frac{id}{A\varepsilon_0\varepsilon_{r_1}\omega}\right)\omega} \quad (9)$$

where ω is the angular frequency, ε_0 the vacuum permittivity, ε_{r_1} the relative permittivity, and i the imaginary unit. At the operating frequency used, the sensor impedance behavior is dominated by the liquid-phase resistance and the air-phase capacitance. The impedance of a continuous phase is proportional to the length and inversely proportional to the cross-sectional area of the path between two electrodes. The simplified analytical model assumes that the liquid and gas phases are perfectly stratified as illustrated in Figure 8. Under this assumption, the length of the path between electrodes is equal to the distance between the electrodes, d . The gas and liquid phase cross-sectional areas are respectively proportional to α and $(1-\alpha)$, as shown in Figure 8. Simplified gas and liquid impedances are expressed as a function of the geometry and void fraction in Table 2. The stratified flow impedance for the gas and liquid phases in parallel is:

$$Z = \frac{1}{\frac{d(1-\alpha)}{\rho_0} + i\omega\varepsilon_{r_1}\varepsilon_0d\alpha} \quad (10)$$

As noted by Fossa [35], two-phase flow electrical impedance across an electrode pair with a conductive liquid behaves as a resistor for tap water and an AC excitation frequency of 10 kHz. At excitation frequencies above 1 kHz for the air-water system investigated, the overall impedance estimated using a stratified flow assumption is also predicted to be largely

independent of frequency at void fractions up to 99%, as can be seen in Figure 9. The overall impedance is governed by the resistive behavior of the liquid, and is largely independent of the gas phase capacitance.

The parasitic impedance of the electronic circuit, Z_{circuit} , should be subtracted from the measured overall impedance, Z_{measured} , to obtain an isolated measurement of the impedance across the electrodes. The overall impedance is measured for a microchannel filled with a liquid of known resistance (up to 200 k Ω) to assess the circuit impedance. For this assessment, great care was taken to minimize the effects of contact resistances by using silver epoxy at electrical junctions. The measured impedance was compared to the numerical simulation value, which is taken as the actual microchannel impedance without circuit impedances included. Since the analytical model showed that the overall impedance is essentially resistive, the circuit impedance contribution to the real part of the measured impedance was removed from the measured value according to:

$$Z = Z_{\text{measured}} - Z_{\text{circuit}} \quad (11)$$

4.2. Dimensionless impedance parameters

Once extraneous circuit impedance is accounted for, the experimental data can be directly compared to the numerical and theoretical models. To report such measurements, the dimensionless impedance Z/Z_0 and the dimensionless admittance $1 - G^*$ are both used in the literature:

$$\frac{Z}{Z_0} = \frac{Zd}{\rho_0} \quad , \quad (12)$$

and

$$1 - G^* = \frac{G - G_0}{G_1 - G_0} = \frac{\frac{1}{Z} - \frac{1}{Z_0}}{\frac{1}{Z_1} - \frac{1}{Z_0}}, \quad (13)$$

where G is the admittance. The admittance for a channel filled with water is obtained by measurements using the calibration curve shown in Figure 3. The impedance for a channel filled with air is four orders of magnitude larger than when the channel is filled with liquid, and outside the measurement range of the sensor; hence, the impedance obtained from numerical simulation of a channel with only air is used for normalization.

The dimensionless impedance parameter Z/Z_0 only takes into account the liquid impedance properties, and is equivalent to $1/(1 - \alpha)$ regardless of the dielectric or resistive properties of the liquid under the assumption of stratified flow. As a consequence, this number is appropriate when the overall impedance is dominated by the liquid impedance.

When the overall microchannel impedance predicted for stratified flow given by equation (10) is substituted in the equation for $1 - G^*$, it simplifies to

$$1 - G^* = \alpha. \quad (14)$$

Therefore, for stratified flow in the crosswise configuration, the dimensionless admittance $1 - G^*$ is predicted to behave linearly with void fraction, regardless of the electrical properties of the phases. Since equation (14) is derived while taking into account the impedance magnitude and phase when the measured impedance is not dominated by the liquid resistance, the impedance phase of $1 - G^*$ must be measured to be relevant over the entire void fraction range, as measurements of only the impedance magnitude would not approximate the admittance.

4.3. *Comparison between experiment, simulation, and theory*

A comparison between the numerical simulations, experimental data, and stratified flow theory is presented in Figure 10 for both the dimensionless impedance and admittance parameters. The data trends are generally well predicted by the stratified flow model. The void fraction and impedance measurements were performed for a gas superficial velocity ranging between 0.13 m s⁻¹ and 2.65 m s⁻¹ and a liquid superficial velocity ranging between 0.80 m s⁻¹ and 5.1 m s⁻¹. The numerical simulation uses reconstructed three-dimensional void phases obtained directly from image frames corresponding to the experimental data points. Good agreement was found between experimental data and the numerical simulations even though the numerical simulations were obtained only for a domain flow length of one channel width for instantaneous frames representative of their flow regime. The numerical validation lends confidence to the sensor measurements and calibration; deviation from the stratified flow model can thereby be attributed to the different two-phase flow structures present in the actual flow. The influence of frequency is predicted to be negligible for the void fraction range investigated. The impedance is predicted by numerical simulation to be independent of frequency from 1 kHz to 100 kHz for the range of void fraction investigated.

As shown in Figure 10(b), the dimensionless impedance calibration of the sensor was found to be well predicted by Maxwell's model [43]:

$$1 - G^* = \frac{3\alpha}{(2 + \alpha)} \text{ for } \alpha < 10\% . \quad (15)$$

4.4. *Application of sensor for boiling and dielectric fluids*

While the experimental calibration is performed in this work under adiabatic conditions, practical microchannel applications involve boiling of the working fluid. The liquid-phase electrical conductivity and dielectric constant would remain constant during boiling at the saturation temperature. The overall impedance would also continue to be dominated by the liquid resistance. Therefore, the overall sensor behavior in terms of dimensionless numbers as shown in Figure 10 is expected to remain the same.

The stratified flow model (equation (10)) is used to predict the overall impedance as a function of void fraction for a representative perfluorinated dielectric fluid, FC-72, in Figure 11. For a dielectric fluid, the measured impedance range as a function of void fraction would span an order of magnitude, and the impedance sensor circuit would need to be designed for this range. Both the liquid and gas contributions to the overall impedance are represented in Figure 11 and it is clear that the overall impedance would no longer be dominated by the liquid-phase impedance due to its amplitude relative to the value for the gas-phase impedance. Therefore the dimensionless parameter $1-G^*$ should be used instead of (Z/Z_0) , since (Z/Z_0) would only be relevant for a small range of void fractions. Depending on the liquid and gas resistivity, the impedance phase may also have to be measured. Further, the parasitic impedance of dielectric components in the system will affect the measurement.

5. Results and discussion: Streamwise configuration

The impedance sensor response was measured experimentally for electrodes placed on top of the channel in a streamwise configuration with a spacing of d . To evaluate the sensor response, a numerical simulation was performed in this configuration for a channel filled with water. For electrodes separated by one electrode width, 50% of the current flows across the cross-section

below the mid-horizontal plane of the channel in the region directly between the electrodes, as illustrated in Figure 12. The electric field in the region between the electrodes is thus well distributed for this geometric configuration, and is suitable for detection of voids even in the lower part of the microchannel. It is therefore expected that the impedance measurement will remain sensitive to void fraction for the predominant flow regimes within the flow channel. The overall impedance for the streamwise configuration is of the same order of magnitude as for the crosswise configuration, allowing use of the same sensor electronics.

Due to the inhomogeneous electric field distribution (a representative curved streamline is shown in Figure 12), the streamwise electrode configuration is not expected to yield a calibration curve for measurement of the instantaneous void fraction, *i.e.*, the same void volume may result in different instantaneous impedance values based on the local values of the electric field. Instead, a calibration is obtained based on the time-averaged experimental impedance measurement versus time-averaged void fraction. This calibration was performed for the streamwise electrode configuration at gas superficial velocities ranging between 0.17 m s^{-1} and 13.7 m s^{-1} and liquid superficial velocities ranging between 0.68 m s^{-1} and 5.5 m s^{-1} . Such a calibration is shown to be independent of liquid-phase conductivity for the range shown in Figure 13 indicating that the same dimensionless numbers as in the crosswise configuration can be used. Furthermore, the continuity of the calibration curve does not seem to be affected by the flow regime, as was observed for the crosswise configuration. This demonstrates that it is possible correlate the void fraction to the impedance using a streamwise electrode configuration.

6. Conclusion

The response of an impedance-based microchannel void fraction sensor with electrodes placed in a crosswise configuration was characterized analytically, experimentally, and numerically. An analysis that assumed stratified gas-liquid flow allowed for reduced-order prediction of the observed trends in dimensionless impedance and dimensionless admittance as a function of void fraction. This behavior was compared against experimental impedance measurements over a range of controlled air-water adiabatic flow regimes and numerical simulations. The sensor response was validated by performing numerical simulations to predict the impedance of a three-dimensional reconstruction of the actual flow domain; this dual experimental/numerical calibration approach established the void fraction versus dimensionless impedance relationship for the crosswise electrode configuration.

A streamwise electrode configuration was also investigated experimentally for its potentially simpler implementation in arrays of microchannels that are typically encountered in heat sinks for thermal management applications. The numerical simulation approach, which was validated for the crosswise electrode configuration, was used as a design tool to predict the sensor range, current penetration depth, and magnitude of circuit impedance in the streamwise electrode configuration. It was experimentally confirmed for this configuration that a correlation between the time-averaged impedance and void fraction can be established over the range of investigated liquid conductivities.

Acknowledgements

This work was funded by the Office of Naval Research (Grant No. N000141010921). The authors are grateful to Dr. Mark Spector for his support.

References

- [1] Sobhan C B and Garimella S V 2001 A comparative analysis of studies on heat transfer and fluid flow in microchannels *Microscale Thermophys. Eng.* **5** 293–311
- [2] Garimella S V and Sobhan C B 2003 Transport in microchannels—a critical review *Annu Rev Heat Transf.* **13** 1–50
- [3] Bertsch S S, Groll E A and Garimella S V 2008 Review and comparative analysis of studies on saturated flow boiling in small channels *Nanoscale Microscale Thermophys. Eng.* **12** 187–227
- [4] Hewitt G F 1981 Two-phase flow and its applications: past, present, and future *Heat Transf. Eng.* **4** 67–79
- [5] Harirchian T and Garimella S V 2009 Effects of channel dimension, heat flux, and mass flux on flow boiling regimes in microchannels *Int. J. Multiph. Flow* **35** 349–62
- [6] Harirchian T and Garimella S V 2010 A comprehensive flow regime map for microchannel flow boiling with quantitative transition criteria *Int. J. Heat Mass Transf.* **53** 2694–702
- [7] Brauner N and Ullmann A 2004 Modelling of gas entrainment from Taylor bubbles. Part A: Slug flow *Int. J. Multiph. Flow* **30** 239–72
- [8] Ullmann A and Brauner N 2007 The prediction of flow pattern maps in minichannels *Multiph. Sci. Technol.* **19** 49–73
- [9] Kew P A and Cornwell K 1997 Correlations for the prediction of boiling heat transfer in small-diameter channels *Appl. Therm. Eng.* **17** 705–15

- 423 [10] Kattan N, Thome J R and Favrat D 1998 Flow boiling in horizontal tubes: Part 3 -
 424 Development of a new heat transfer model based on flow pattern *J. Heat Transf.* **120** 156–
 425 65
- 426 [11] Lee P S and Garimella S V 2008 Saturated flow boiling heat transfer and pressure drop in
 427 silicon microchannel arrays *Int. J. Heat Mass Transf.* **51** 789–806
- 428 [12] Christians M 2007 *Flow-pattern-based heat transfer and pressure drop correlations for*
 429 *condensing refrigerants in smooth tubes* (University of Pretoria)
- 430 [13] Singh S G, Jain A, Sridharan A, Duttagupta S P and Agrawal A 2009 Flow map and
 431 measurement of void fraction and heat transfer coefficient using an image analysis
 432 technique for flow boiling of water in a silicon microchannel *J. Micromechanics*
 433 *Microengineering* **19** 075004
- 434 [14] Serizawa A, Feng Z and Kawara Z 2002 Two-phase flow in microchannels *Exp. Therm.*
 435 *Fluid Sci.* **26** 703–14
- 436 [15] Kawahara A, Sadatomi M, Nei K and Matsuo H 2009 Experimental study on bubble
 437 velocity, void fraction and pressure drop for gas–liquid two-phase flow in a circular
 438 microchannel *Int. J. Heat Fluid Flow* **30** 831–41
- 439 [16] Kawaji M, Ahmad W, DeJesus J M, Sutharshan B, Lorencez C and Ojha M 1993 Flow
 440 visualization of two-phase flows using photochromic dye activation method *Nucl. Eng.*
 441 *Des.* **141** 343–55

- 442 [17] Hammer E A, Johansen G A, Dyakowski T, Roberts E P L, Cullivan J C, Williams R A,
 443 Hassan Y A, Claiborn C S and Crowe C T 2006 Advanced experimental techniques
 444 *Multiph. Flow Handb. Taylor Francis New York* 14.1–14.125
- 445 [18] Rosa E S, Flora B F and Souza M A S F 2012 Design and performance prediction of an
 446 impedance void meter applied to the petroleum industry *Meas. Sci. Technol.* **23** 5304–17
- 447 [19] Silva M J D, Schleicher E and Hampel U 2007 Capacitance wire-mesh sensor for fast
 448 measurement of phase fraction distributions *Meas. Sci. Technol.* **18** 2245–51
- 449 [20] Barnea D, Roitberg E and Shemer L 2013 Spatial distribution of void fraction in the liquid
 450 slug in the whole range of pipe inclinations *Int. J. Multiph. Flow* **52** 92–101
- 451 [21] Wang M, Yin W and Holliday N 2002 A highly adaptive electrical impedance sensing
 452 system for flow measurement *Meas. Sci. Technol.* **13** 1884–9
- 453 [22] Canière H, Bauwens B, T’Joel C and De Paepe M 2010 Mapping of horizontal refrigerant
 454 two-phase flow patterns based on clustering of capacitive sensor signals *Int. J. Heat Mass*
 455 *Transf.* **53** 5298–307
- 456 [23] Huang Z, Wang B and Li H 2003 Application of electrical capacitance tomography to the
 457 void fraction measurement of two-phase flow *IEEE Trans. Instrum. Meas.* **52** 7 – 12
- 458 [24] Abouelwafa M S A and Kendall E J M 1980 The use of capacitance sensors for phase
 459 percentage determination in multiphase pipelines *IEEE Trans. Instrum. Meas.* **29** 24–7
- 460 [25] Gregory G A and Mattar L 1973 An in-situ volume fraction sensor for two-phase flows of
 461 non-electrolytes *J. Can. Pet. Technol.* **12** 48–52

- 462 [26] Geraets J J M and Borst J C 1988 A capacitance sensor for two-phase void fraction
463 measurement and flow pattern identification *Int. J. Multiph. Flow* **14** 305–20
- 464 [27] Paranjape S, Ritchey S N and Garimella S V 2012 Electrical impedance-based void
465 fraction measurement and flow regime identification in microchannel flows under adiabatic
466 conditions *Int. J. Multiph. Flow* **42** 175–83
- 467 [28] Shu M T, Weinberger C B and Lee Y H 1982 A simple capacitance sensor for void
468 fraction measurement in two-phase flow *Ind. Eng. Chem. Fundam.* **21** 175–81
- 469 [29] Andreussi P, Di Donfrancesco A and Messina M 1988 An impedance method for the
470 measurement of liquid hold-up in two-phase flow *Int. J. Multiph. Flow* **14** 777–85
- 471 [30] Tsochatzidis N A, Karapantsios T D, Kostoglou M V and Karabelas A J 1992 A
472 conductance probe for measuring liquid fraction in pipes and packed beds *Int. J. Multiph.*
473 *Flow* **18** 653–67
- 474 [31] Swanson R W 1966 *Characteristics of the gas-liquid interface in two-phase annular flow*
475 (University of Delaware)
- 476 [32] Coney M W E 1973 The theory and application of conductance probes for the
477 measurement of liquid film thickness in two-phase flow *J. Phys. [E]* **6** 903–11
- 478 [33] Brown R C, Andreussi P and Zanelli S 1978 The use of wire probes for the measurement
479 of liquid film thickness in annular gas-liquid flows *Can. J. Chem. Eng.* **56** 754–7
- 480 [34] Asali J C, Hanratty T J and Andreussi P 1985 Interfacial drag and film height for vertical
481 annular flow *AIChE J.* **31** 895–902

- 482 [35] Fossa M 1998 Design and performance of a conductance probe for measuring the liquid
483 fraction in two-phase gas-liquid flows *Flow Meas. Instrum.* **9** 103–9
- 484 [36] Maham Y, Chevillard A and Mather A E 2004 Surface thermodynamics of aqueous
485 solutions of morpholine and methylmorpholine *J. Chem. Eng. Data* **49** 411–5
- 486 [37] Perry R H, Green D W and Maloney J O 2008 *Perry's chemical engineers' handbook* vol 7
487 (McGraw-Hill New York)
- 488 [38] MATLAB Release 2013a, The MathWorks, Inc., Natick, Massachusetts, United States
- 489 [39] Ali M I, Sadatomi M and Kawaji M 1993 Adiabatic two-phase flow in narrow channels
490 between two flat plates *Can. J. Chem. Eng.* **71** 657–66
- 491 [40] Mishima K and Hibiki T 1996 Some characteristics of air-water two-phase flow in small
492 diameter vertical tubes *Int. J. Multiph. Flow* **22** 703–12
- 493 [41] Triplett K A, Ghiaasiaan S M, Abdel-Khalik S I and Sadowski D L 1999 Gas–liquid two-
494 phase flow in microchannels Part I: two-phase flow patterns *Int. J. Multiph. Flow* **25** 377–
495 94
- 496 [42] ANSYS, Inc., 2009, ANSYS Fluent, Release 12.0.
- 497 [43] Maxwell J C 1954 *A treatise on electricity and magnetism* vol 1 (Dover Publications)
- 498 [44] Anon 3MTM FluorinertTM Electronic Liquid FC-72
- 499

Tables

Table 1. Comparison of the overall impedance obtained analytically and by numerical simulations for crosswise electrodes and a domain flow length equal to one electrode width.

Parameters		
ε_0 [F/m]	8.85×10^{-12}	
d [m]	7.80×10^{-4}	
A [m ²]	6.08×10^{-7}	
ε_{r0}	80	
ε_{r1}	1	
σ_0 [μ S cm ⁻¹]	100	
σ_1 [μ S cm ⁻¹]	2.50×10^{-10}	
Comparison for $f=20$ kHz	Theory	Simulation
R_0 [Ω]	1.28×10^5	1.28×10^5
C_0 [F]	5.52×10^{-13}	5.53×10^{-13}
Z_0 (20 kHz) [Ω]	1.28×10^5	1.28×10^5
R_1 [Ω]	5.13×10^{16}	5.12×10^{16}
C_1 [F]	6.91×10^{-15}	6.92×10^{-15}
Z_1 (20 kHz) [Ω]	1.15×10^9	1.15×10^9

Table 2. Analytical expressions for the liquid and gas phase impedances under stratified flow; the expressions assume the liquid and gas behave respectively as a pure resistor and a pure capacitor.

Conditions		$Z=f(\alpha)$
Liquid	$\sigma_0 > 10 \mu S \text{ cm}^{-1}$ and $f < 100 \text{ kHz}$	$Z_0 \approx \frac{\rho_0 d}{A} = \frac{\rho_0}{d(1-\alpha)}$
Gas	$f < 100 \text{ kHz}$	$Z_1 \approx \frac{1}{\omega \varepsilon_r \varepsilon_0 \frac{A}{d}} = \frac{1}{\omega \varepsilon_r \varepsilon_0 d \alpha}$

509 **Figures**

511 **Figure 1.** Schematic diagram of (a) crosswise and (b) streamwise electrode pair configurations.

512 The electrodes and microchannel have square cross-sections of side length d and area A .

514 **Figure 2.** Diagram of the adiabatic air-water flow loop used to control two-phase flow through
515 the crosswise and streamwise microchannel test cells described in Figure 1.

516

517 **Figure 3.** Calibration of the electronic circuit output against known impedances.

(a) Bubbly flow

(b) Slug flow

(c) Churn flow

Figure 4. Selected two-phase flow visualization frames for (a) bubbly, (b) slug, and (c) churn flow regimes obtained at a liquid volumetric flow rate of 100 ml min^{-1} and respective gas flow rates of 10 ml min^{-1} , 50 ml min^{-1} and 100 ml min^{-1} .

Figure 5. Relationship between the void fraction α estimated using image-based reconstruction and the measured inlet air volumetric flow fraction, β . The trend is assessed against the homogeneous flow and drift flux models.

(a) Crosswise configuration

(b) Streamwise configuration

Figure 6. Schematic diagram of the solution domain, mesh, and electric field boundary conditions imposed for the (a) crosswise and (b) streamwise electrode configurations.

Figure 7. (a) Electric field in the crosswise direction and (b) envelopes of the percentage of the total current passing through planes parallel to the electrodes in the crosswise configuration.

Figure 8. Sketch of the stratified flow hypothesis in the crosswise electrode configuration.

Using the stratified flow analytical expression for overall impedance given by equation (10) and parameters from Table 1, the impedance is plotted as a function of void fraction in Figure 9.

Figure 9. Theoretical stratified flow impedance given by equation (10) as a function of void fraction for frequencies of 1, 20 and 100 kHz and the properties given in Table 1.

Figure 10. Comparison of experimental data, numerical simulations, and stratified flow predictions for overall microchannel (a) dimensionless impedance Z/Z_0 and (b) dimensionless admittance $1-G^*$ as a function of void fraction.

Figure 11. Analytical model prediction using the stratified flow hypothesis for a dielectric fluid, FC-72 ($\rho_0 = 10^{13} \Omega \text{ m}$; $\epsilon_{r0} = 1.8$ [44]).

Figure 12. Numerical simulation of the normalized potential field in water created using a streamwise impedance sensor.

549

550

Figure 13. Time-averaged dimensionless two-phase flow impedance ($1-G^*$) as a function of

551

time-averaged void fraction for different water electrical conductivities (obtained for an

552

electrode pitch of d and a sine wave exciter signal frequency of 20 kHz).