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# Sensitivity studies on the multi-sensor conductivity probe measurement technique for two-phase flows

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## HIGHLIGHTS

- Revised conductivity probe circuit to eliminate signal "ghosting" among sensors.
- Higher sampling frequencies suggested for bubble number frequency and $a_i$ measurements.
- Two-phase parameter sensitivity to measurement duration and bubble number investigated.
- Sensors parallel to pipe wall recommended for symmetric bubble velocity measurements.
- Sensor separation distance ratio ($s/d$) greater than four minimizes bubble velocity error.

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## ABSTRACT

The objective of this study is to advance the local multi-sensor conductivity probe measurement technique through systematic investigation into several practical aspects of a conductivity probe measurement system. Firstly, signal "ghosting" among probe sensors is found to cause artificially high bubble velocity measurements and low interfacial area concentration ($a_i$) measurements that depend on sampling frequency and sensor impedance. A revised electrical circuit is suggested to eliminate this artificial variability. Secondly, the sensitivity of the probe measurements to sampling frequency is investigated in 13 two-phase flow conditions with superficial liquid and gas velocities ranging from 1.00–5.00 m/s and 0.17–2.0 m/s, respectively. With increasing gas flow rate, higher sampling frequencies, greater than 100 kHz in some cases, are required to adequately capture the bubble number frequency and $a_i$ measurements. This trend is due to the increase in gas velocity and the transition to the slug flow regime. Thirdly, the sensitivity of the probe measurements to the measurement duration as well as the sample number is investigated for the same flow conditions. Measurements of both group-I (spherical/distorted) and group-II (cap/slug/churn-turbulent) bubbles are found to be relatively insensitive to both the measurement duration and the number of bubbles, as long as the measurements are made for a duration long enough to capture a collection of samples characteristic to a given two-phase flow system (or a statistical ensemble). Fourthly, investigation into the orientation of a double-sensor probe in the pipe indicates that the sensors should be oriented parallel to the pipe wall to ensure symmetric bubble velocity measurements. Lastly, Monte Carlo simulations are performed to study the effects of the axial ($s$) and lateral ($d$) probe sensor separation distances. In addition to previous criteria on the ratio of $s$ to the bubble diameter, it is found that $s/d$ should be greater than four to minimize errors in the measured bubble velocity.

## 1. Introduction

With continuing advances in the state-of-the-art of the description of two-phase flows, accurate measurement of local two-phase flow parameters becomes ever more indispensable to support model development and benchmarking efforts. Two-phase flows present unique challenges to measuring parameters of interest, particularly due to the complicated interfacial structure that separates the phases. Over the past 50 years, there has been great progress since the seminal work of Neal and Bankoff (1963) that has established the local conductivity probe as one of the few two-phase flow measurement techniques capable of obtaining detailed measurements of local time-averaged two-phase flow parameters,

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such as the void fraction ($\alpha$) and interfacial area concentration ($a_i$) (Cartellier and Achard, 1991; Kataoka et al., 1986; Kim et al., 2000; Serizawa et al., 1975).

The conductivity probe measurement principle is based on the inherent difference in the electrical conductivities of the gas and liquid phases in a two-phase flow. Consider a needle-like sensor that is electrically insulated except for the tip. The sensor and a separate ground, typically the metal sensor casing, are placed in a two-phase flow, and a voltage is applied to the sensor. When the tip is in the conductive liquid phase, the circuit is complete, yielding a baseline voltage signal. However, when the tip is occupied by the gas phase, the circuit is broken, yielding a high voltage signal. As such, the voltage signal from a single-sensor conductivity probe can be used to measure the local time-averaged void fraction, according to:

$$\alpha = \frac{1}{T}\sum_{j=1}^{N_b} \Delta t_{g,j} \tag{1}$$

where $T$ is the measurement duration, $N_b$ is the number of detected bubbles, and $\Delta t_{g,j}$ is the residence time of the $j$th bubble at the sensor tip. With two sensors separated by an axial distance ($s$) in the direction of the flow, the average axial bubble velocity ($v_g$) can be estimated as:

$$v_g = \frac{1}{N_{eff}}\sum_{j=1}^{N_{eff}} \frac{s}{t_{delay,j}} \tag{2}$$

where $t_{delay,j}$ is the time delay between the front interface of the $j$th bubble contacting the upstream and downstream sensors, and $N_{eff}$ is the number of bubbles that register effective signals at both sensors. The time-averaged interfacial area concentration is defined as (Ishii, 1975):

$$a_i = \frac{1}{T}\sum_{j=1}^{N} \left(\frac{1}{|\boldsymbol{v}_i \cdot \boldsymbol{n}_i|}\right)_j \tag{3}$$

where $\boldsymbol{v}_i$ and $\boldsymbol{n}_i$ are the interfacial velocity and interfacial unit normal vectors for the $j$th interface, and $N$ is the number of interfaces passing a point within the time interval $T$. $a_i$ can be evaluated in general using the three measured velocities obtained from a four-sensor conductivity probe (Kataoka et al., 1986). Alternatively, under certain statistical assumptions about $\boldsymbol{v}_i$ and $\boldsymbol{n}_i$, $a_i$ can be evaluated from the measured velocities obtained from a double-sensor probe (Kataoka et al., 1986; Wu and Ishii, 1999). In modern conductivity probe measurements, a data acquisition (DAQ) system is used to record the raw voltage signals from the sensors. Post-processing software is then used to condition the signals, pair the signals from the upstream and downstream sensors, and calculate two-phase flow parameters. Details about the signal processing scheme used for measurements in the current study are given by Kim et al. (2000).

To characterize the uncertainties of measured two-phase flow parameters obtained with the conductivity probe, theoretical studies using the Monte Carlo method have been performed that provided probe design criteria and correction factors for $a_i$ measurements obtained with double-sensor (Wu and Ishii, 1999) and four-sensor (Le Corre and Ishii, 2002) probes. Moreover, experimental benchmarking studies have demonstrated the accuracy of the conductivity probe in comparison to image analysis (Kim et al., 2000), the optical fiber probe (Le Corre et al., 2003), and the wire mesh sensor (Manera et al., 2009).

However, few studies have been performed to systematically assess the effects of different components of a conductivity probe measurement system on the two-phase flow parameters that are obtained. Therefore, the present study seeks to investigate several practical aspects of a conductivity probe measurement system including: (1) signal “ghosting” electrical interference among probe sensors, (2) data acquisition sampling frequency, (3) measurement duration, (4) sensor orientation in the flow channel, and (5) probe sensor axial and lateral separation distances. The first four items are investigated experimentally using an experimental facility that is briefly described in Section 2. The last item is studied through Monte Carlo simulations of a double-sensor probe.

## 2. Experimental facility

Experiments are performed in a vertical-upward air-water two-phase flow test facility. The facility is capable of generating a wide range of two-phase flow conditions at room temperature, 20 °C, and near atmospheric pressure. The test section is constructed from clear cast acrylic pipes with an inner diameter of 5.08 cm. Along the length of the facility, there are four instrumentation ports with centers located at 7.5, 18, 34.5, and 63 pipe diameters (D) downstream from the two-phase flow inlet. The instrumentation ports provide access to the flow to install a conductivity probe and traverse it to various radial positions in the pipe cross-section using a linear traverse. National Instruments (NI) PCI-6259M-Series data acquisition boards are available at the facility to acquire voltage measurements from the conductivity probe sensors and other instrumentation. The NI PCI-6259 DAQ board is capable of acquiring data at sampling frequencies up to 1 MHz, aggregate, for multichannel measurements (DAQ M Series User Manual, 2008). NI LabVIEW data acquisition software is used to control the NI PCI-6259 DAQ board and record voltage measurements to a computer for post processing. Additional details about the experimental facility are given by Worosz and Kim (2014).

## 3. Effect of signal “ghosting

In a study on horizontal bubbly two-phase flows, Talley (2012) noted that owing to the relatively high liquid flow rates (i.e. liquid superficial velocities greater than approximately 4.0 m/s) required to produce horizontal bubbly flow, higher data acquisition sampling frequencies ($f_s$) are required to maintain signal quality in conductivity probe measurements. While determining an appropriate sampling frequency for his conductivity probe measurements, Talley (2012) observed artificially high bubble velocity measurements and, consequently, artificially low interfacial area concentration measurements with increasing sampling frequency. This behavior was attributed to a data acquisition hardware related issue known as signal “ghosting” (DAQ M Series User Manual, 2008).

For modern conductivity probe measurements, a data acquisition system typically consists of a DAQ board, a computer, and data acquisition software. The conductivity probe sensors are connected to the DAQ board, which is used to measure the voltage signals from the probe sensors. Thus, the DAQ board is the hardware interface between the conductivity probe and the computer where the signals measured by the DAQ board are recorded by the data acquisition software.

Signal ghosting is an inherent electrical interference that occurs when a multiplexing DAQ board, such as the NI PCI-6259, samples multiple high impedance voltage sources, such as the conductivity probe sensors. In a multiplexing DAQ board, a common instrumentation amplifier and analog-to-digital converter (ADC) are shared among the input channels to the DAQ board, where the sensors to be measured are connected. A multiplexer on the DAQ board is used to switch in rapid succession between each input channel and the common instrumentation amplifier/ADC.