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Wire-mesh sensors: A review of methods and uncertainty in multiphase flows relative to other measurement techniques

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ABSTRACT

Void fraction has always been an important parameter in the study of multiphase flows and its measurement has proven difficult over the years. This paper is a state of the art review of the application of conductivity based wire-mesh sensors (WMS) for the measurement of void fraction, bubble size, and gas fraction velocity in multiphase flows and their associated uncertainties. At this point in time there is no golden standard for void fraction measurement, so a large bulk of this work is on the uncertainty of the WMSs relative to other void fraction measurement methods, namely radiative methods. It is shown using the available data that the WMS have a void fraction measurement uncertainty of ± 10.5% over a variety of flow regimes relative to other measurement methods. However, the accuracy of the instrument is largely based on its applicability to a particular flow. For example, the WMS is an excellent choice when entrapment in the sensor due to surface tension is minimized resulting in best results at higher flow rates compared to radiative methods. An assessment into the uncertainty of velocity and bubble size measurements is also performed: analyzing the current algorithms available and studies on these measurements in comparison with high speed cameras and ultrafast X-ray tomography. The current functioning form of the wire-mesh sensors were developed by Prasser in 1998 as a tomographic technique for the measurement of void fraction using a conductivity approach, as performed by earlier researchers. Later developments with the senors resulted in various techniques that allow for the measurement of velocity and interfacial area concentration.

1. Introduction

Vapor formation (and therefore void fraction) is a highly desired quantity in studying and modeling of two-phase flows especially in regard to nuclear applications not to mention other industries such as oil and gas. Data on the void formation and flow in rod bundle geometry and around spacers is especially important in determining the flow characteristics inside a nuclear reactor. This data is then be used for the validation of models and codes that predict the thermal-hydraulic phenomena relevant to the performance of nuclear reactors, allowing for accurate measures of the safety margins during normal and accident conditions (Cheng, 2014; Manera et al., 2005; Schlegel and Hibiki, 2015). Validation and/or creation of these models requires an accurate measurement of the void fraction and interfacial area concentration[1] in multiphase systems. A variety of instrumentation is capable of measuring void fraction, but the uncertainty in these devices is difficult to quantify. Typically void fraction can be measured using capacitance, conductance, optical, ultrasonic, or radiative methods (Boyer et al., 2002).

Radiative methods such as gamma ray attenuation and high energy X-ray methods are non-intrusive chordal, xy-tomographic, or yz-tomographic measurements of the void fraction, where z is the flow direction. These methods generally involve large or bulky equipment and precautions must be taken for radiation shielding. The radiative methods are also very expensive relative to other void fraction measurement methods. Chordal measurements can generate more uncertainty if the void fraction is a strong function of time or geometrically skewed in the pipe (e.g. flow regime effects) (Abro and Johansen, 1999a; Harms and Laratta, 1973). They also require multiple detectors in order to get accurate measurements in the case of varying

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[1] Interfacial area concentration is defined as $\bar{a}_i = A_i/V$ where A_i is the gas-liquid interface area and V is the measurement volume.

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flow regimes. Both versions of tomographic measurements require significantly more equipment and physical space to acquire measurements. XY tomography measures through the flow plane and can provide an Eulerian[2] view of the flow as it passes through the detection region via post processing of the data with techniques similar to those used for CT and MRI scans in the medical fields. The resolution of these images is dependent on the number of available detection angles. Recently progress has been made with Ultrafast X-ray systems that use an X-ray beam that rotates about a static target along a wave guide with a co-located detection ring. These allow for higher resolution and scanning frequency in a smaller physical space than typical radiative measurement systems (Banowski et al., 2016). The second tomographic imaging technique takes a 2D density picture along the flow direction and one transverse direction. However, this method suffers from geometric problems caused by curved pipe surfaces that lead to distortion of the image and assumes that the image is taken at a sufficiently fast resolution such that the flow is static during the imaging (Banowski et al., 2016; Kumar et al., 1995; Pike et al., 1965; Tsumaki et al., 1984).

Ultrasonic tomography is another non-intrusive technique that employs sound instead of radiative means to measure the void fraction. Ultrasonic pulses are emitted and then read with various receivers located in the test section. In order to record an accurate representation of the void fraction a large number of sensors need to be positioned around the piping and tend to be bulky making them less viable in a space restricted area. This method has limited applicability for low gas fractions due to a loss of the ultrasound transmission, thereby providing incorrect results. The ultrasonic technique require significant amounts of post-processing to view images, so on-line viewing is restricted to approximately 10 Hz. Data can still be collected at much higher rates and post-processed for void fraction measurements. The processing of ultrasonic techniques requires significant computational effort and small changes in the setup geometry can have a large impact on the accuracy of the results (Rahim et al., 2007).

Optical probes can be used for measurement of the void fraction, but are only point measurements similar to thermocouples. These probes operate based on Snell's reflection law for optics. As different phases pass over the probe tip the index of refraction changes, resulting in a change in the voltage measurement from a photodiode. The probe is a single point measurement, so data is analyzed statistically over a period of time to generate time-averaged multiphase parameters (e.g. void fraction, interfacial area concentration, and interfacial velocity). The nature of the device can not determine bulk parameters unless operating in steady state conditions and multiple measurements are made a various locations (Chabot et al., 1998; Choi and Lee, 1990).

Electrical methods rely on the difference in the permittivity or conductivity between the fluid phases to determine the presence of voids. These can be in the form of a single probe like the optical probes, a large conductance cell across the pipe, or an intrusive method capable of direct tomographic imaging can be employed by forming a grid of sensing points that allow for full reconstruction of the area void fraction. Point probes suffer from the same issues presented with the optic probes, in that they represent a single measurement location so the resulting data is not necessarily representative of the entire pipe or channel flow. Individual probes have been developed with up to four measuring points in order to evaluate bubble size, contact angle, and velocity. Velocity and size measurements are limited in scope, because they require the bubble to contact the probe at 90°. Researchers have attempted to rectify this by using a four-tip probe, which allows for measurement of the bubbles complete velocity vector and bubble curvature. Although, this still requires some assumption on the shape of the bubble which can skew results. Conductance cells have been used in the past for small scale experiments and more recently for full pipe measurements. They operate by measuring the conductance of the fluid in the pipe. However, their accuracy is dependent on the correlation used to relate the measured value to void fraction, which can change significantly with flow regime (Lee et al., 2017). The grid method, formally called wire-mesh sensors (WMS) measures the void fraction in multiple small conductance cells distributed across the pipe cross-section, but also introduces a perturbation in the flow that is not present with radiative and ultrasonic methods. The WMS are able to directly visualize the flow for measurement of the void fraction and can be used in series for measurements of bubble velocity and size.

A review of the uncertainty in the application of conductivity based WMS to two-phase flow is presented here. However, that is not to say that the effects relevant to uncertainty in the measurement of two-phase flow properties aren't relevant to all types of WMS. Pena and Rodriguez (2015) have presented a thorough review on the applications of WMS, which vary widely from single-phase liquid-liquid applications up to three-phase flow tomographic techniques. The sensor geometries include pipe-cross sectional grids as well as surface film sensors. Grids have also been oriented parallel to the pipe flow axis in order to directly measure bubble size and velocities as well as single phase mixing in T-junctions. The fluids measured include water, air, steam, various gases, and oils, although without the presence of a conductive phase in the fluids under test a permittivity based sensor is required as opposed to the conductivity based one presented here. This work reviews the uncertainty of the WMS conductivity technology in multiphase flows relative to other measurement techniques. This results in a suggestion for the operating regimes of the WMS and the expected minimum accuracy of the device for these techniques.

2. WMS operation theory

Wire Mesh Sensors (WMS) in their current form were pioneered by Prasser et al. (1998a) and are designed for measuring and visualizing phase fractions in multiphase flow, when the phases have a significant difference in conductivity. The WMS measures a value proportional to the conductance of the fluid in multiple volumes evenly distributed in the flow. These measurements can be analyzed to determine important multiphase parameters such as phase fraction, phase velocity, and interfacial area.

Measurement of phase with wire-mesh sensors is performed by measuring a value proportional to the conductance of a multiphase flow at multiple cells in a plane across the flow. This is achieved by placing two perpendicularly oriented planes of parallel electrodes separated by a small gap in the direction of the flow (Fig. 1). One plane acts as a transmitter, while the other acts as a receiver. The transmitter plane produces a 6 μs bi-polar voltage pulse on each electrode. A potential builds up between the driven transmitter and the receiver wires. This causes a current, that is proportional on the resistivity of the fluid between the electrodes, to flow to the receiver electrodes. This change in current is measured by a transimpedance amplifier and ultimately passed to an analog-to-digital converter (ADC). The magnitude of the measured pulse is proportional to the conductance of the mixed phase between the electrodes. Each electrode in the transmitter is pulsed individually to isolate the current source location and finally acquire a tomographic image of the flow (Fig. 2).

The current implementation of sensors measures a value proportional to the conductance of the fluid between the transmitter and receiver wires by suppressing cross-talk, reducing electrolysis effects in the sensors, and reducing low frequency electrical noise. The reduction of cross-talk between wires as defined by current moving from the activated transmitter wire to other non-activated transmitter wires and/or unactivated receiving wires was achieved by implementing a zero potential – low impedance circuit (transimpedience amplifier) by Prasser et al. (1998b). Receiver and non-activated transmitter wires do not cross-talk, because they are actively kept at ground potential and

[2] An Eulerian frame of reference is defined as the observation of the fluid as it passes through a specific volume over time as opposed to tracking a fluid parcel as it flows through a system over time.