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A methodology to quantify the uncertainty in liquid holdup measurements with wire mesh sensor

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ABSTRACT

The uncertainty in the holdup measurements of a capacitance based WMS with 32×32 wires has been experimentally evaluated, and a methodology for its quantification is proposed for horizontal flow. Investigation is performed in laboratory and in-situ experiments under stagnant conditions with an emphasis on the effect of the mesh grid orientation on the measurements. Also, potential impact of misalignment in the pipe inclination is explored by slightly inclining the pipe for both tests. Finally, dynamic flow conditions are tested in a high pressure (1.37 MPa) facility with horizontal stratified-wavy oil/air two-phase flow for gas and liquid superficial velocity ranges of $2.8\ \text{m/s} \le v_{Sg} \le 6.9\ \text{m/s}$ and $0.01\ \text{m/s} \le v_{SL} \le 0.05\ \text{m/s}$, respectively.

The angle between the phase interface and the sensor wires is ineffective while the misalignment in the pipe inclination plays a major role in the deviations of the holdup measurements. Using the proposed methodology, the measurement uncertainty from laboratory tests is shown to follow a logarithmic increase as a function of the measured holdup for smaller holdup values ($H_L \le 15\%$) and to be lower than 1.5% for $H_L > 15\%$. This behavior is intrinsic to WMS and a representative of the measurement uncertainty in the actual flow loop installation.

Under actual flow conditions, the holdup measurements of the trapped liquid by WMS show an offset compared to the measurements via flow imaging which can be corrected by using the uncertainty quantified in the laboratory tests. However, the dynamic measurements with WMS show a good agreement with the holdup of the trapped liquid volume within the quantified uncertainty bounds.

1. Introduction

Experimental investigation of multiphase flow has an important role in extending our understanding of the physical mechanisms governing this complex flow phenomenon encountered in the applications of nuclear, chemical and petroleum engineering. As a result of the continuous industrial interest, various types of experimental techniques and instrumentations have been developed, and can be grouped into two main categories such as (i) intrusive; iso-kinetic probes, capacitance/conductivity probes, velocity measuring probes (CTA, pitot-tube), and (ii) non-intrusive; optical techniques (PIV, LDA, high-speed imaging) or tomographic techniques.

Wire Mesh Sensor (WMS) is a state-of-the-art intrusive instrumentation measuring the instantaneous distributions of the phases in two-phase flows. WMS consists of two planes of wire electrodes, transmitter and receiver planes. The wires at each plane of WMS are stretched parallel to each other and separated by a few millimeters. The wires of the two planes virtually cross each other with an angle of typical 90° and a small axial distance, typically smaller than the lateral resolution. These virtual wire crossings are defined as the crossing points. The number of the crossing points in a WMS device vary from 8×8 wires [18,22,9] to 64×64 wires [17,21]. The measurement of the phase distributions are conducted at these crossing points by measuring the electrical conductivity or permittivity depending on the physical properties of the fluids. From these conductivity or permittivity measurements, the amount of liquid and gas in the single volume elements, defined by the crossing points, is calculated by applying specific calibration models depending on the system, the fluids, and their physical occurrence e.g. stratified or emulsion. The easiest of these models is the assumption of a linear relation between the measured values and the

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Nomenclature

Symbols

v_{Sg}	Gas superficial velocity, (m/s)
v_{SL}	Liquid superficial velocity, (m/s)
H_L	Liquid holdup, (-)
$\in_{H_L}$	Measurement uncertainty, (-)
β	Wire mesh orientation angle, (°)
θ	Pipe inclination angle, (°)
ρ_o	Oil density, (kg/m^3)
μ_o	Oil viscosity, (kg/m^3)
σ_o	Oil surface tension, (N/m)

Acronyms

ID	Pipe inner diameter, (m)
CTA	Constant Temperature Anenometry
PIV	Particle Image Velocimetry
LDA	Laser Doppler Anenometry
WMS	Wire Mesh Sensor
QCV	Quick Closing Valve
ECT	Electrical Capacitance Tomography
GCT	Gamma Photon Computed Tomography

gas/liquid holdup in the sample volume. Successful demonstrations of such measurements at high frequencies (in the order of 10^4 Hz) are originally reported by Prasser et al. [18] for water/air applications, and by Da Silva et al. [7] for silicone oil/air applications.

Some of the derived flow features from WMS data are, but not limited to, quantitative information on the instantaneous liquid holdup (averaged over the pipe cross-section), time histories of the liquid film thickness and wetted wall fraction [2,3], bubble size distribution [17,19,4] and 3D reconstruction of the phase interface [15,22,24,29,30]. In addition, the velocity of the topological structures can be extracted via the synchronized use of two WMS sensors in the flow loop [2,29,30].

In the literature, there are many experimental studies employing WMS on various flow configurations with pipe inclinations ranging from horizontal to vertical including upward and downward orientations [1,11,2,4,5,8,9,16,18,20–22,24,28–31,12,13]. Observed flow patterns in these studies are stratified, annular, slug, churn and bubbly flow. Some experimental results are also reported on the distribution of the liquid holdup within the particle packings [6], liquid distributions in the trickle beds [14], and liquid velocity distributions in trickle bed reactors [23]. Moreover, WMS is shown to be applicable to flow conditions with high temperature and pressure conditions up to 286 °C and 7 MPa, respectively [17,21]. While most of the WMS applications are for gas/liquid flows, the measurements are conducted for liquid/liquid two-phase flows [9] and gas/liquid/liquid three-phase flows [10] as well.

The intrusiveness of WMS and the spatial measurement resolution (due to the number of wires related to the diameter of the cross section used in the device) give rise to questions on the accuracy of the measurements by WMS. Therefore, it is necessary to quantify how the measurements with WMS deviate from the actual flow conditions. For this purpose, some researchers have reported comparisons of their WMS data with the data obtained from other experimental techniques such as; ECT [1,14,4], GCT [6], QCV [11,16,2,9], gamma-ray device [18], X-ray Computed Tomography [20], gamma densitometer [26] and flow imaging [32]. Overall, the accuracy of WMS in the measurements of the liquid holdup is observed to be reasonable. For example, Matusiak et al. [14] report the difference between the liquid holdup measurements via ECT and WMS is $\Delta H_L = 0.02$ at most. The intrusiveness of WMS is observed to affect the bubble sizes and shapes in downstream regions of the sensor but negligible in the region of the measurement [19]. The spatial resolution in the qualitative phase imaging with WMS is found to be better than the non-intrusive tomographic techniques [6].

Based on the literature review presented above, it is clear that the application of WMS technology in the multiphase flow research is becoming a widely used methodology with high spatial and temporal resolutions in the measurements. Although the previous studies on the overall accuracy of the measurements provide valuable information, a detailed study on the uncertainty in the WMS measurements is not reported. In this paper, a methodology for the quantification of the uncertainty in the liquid holdup measurements for horizontal pipe inclination is presented under stagnant fluid conditions employing capacitance based WMS system and the “parallel model” for holdup calculation [4,9]. This is followed by a case study on actual two-phase flows with different experimental conditions where the WMS data and its uncertainty are compared with the liquid holdup measurement obtained by using quick closing valves and flow imaging.

2. Experimental set-up

There are two types of experiments conducted throughout this study. Initially, the measurement uncertainty of WMS is quantified by performing measurements of the liquid holdup using known volumes of liquid within in a pipe segment under stagnant conditions (see Section 2.1). Then, the liquid holdup measurements in the actual flow conditions are compared with the measurements obtained by quick closing valves (QCV) and flow imaging (see Section 2.2).

Throughout this study, Isopar L mineral oil is used as the liquid phase with the following physical properties; $\rho_o = 760$ kg/m^3, $\mu_o = 0.0013$ Pa s and $\sigma_o = 0.025$ N/m. Air and nitrogen is used as the gas phase for the laboratory and in-situ tests, respectively. The values of the density and viscosity for nitrogen at different temperature and pressure conditions are obtained from Span et al. [27] and Seibt et al. [25], respectively. The WMS sensors used in this study consist of a transmitter/receiver wire configuration with 32 × 32 wires. The inner diameter of the sensor is 154.2 mm to fit to the pipes used in the laboratory and the flow loop. The lateral distance of the wires is 4.819 mm and the axial distance between

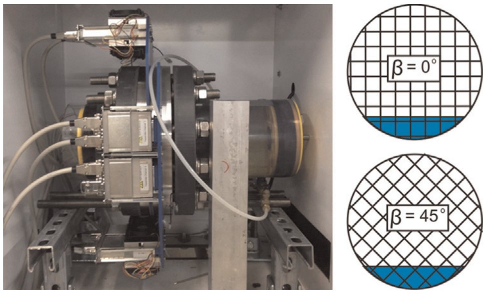

Fig. 1. Wire-mesh sensor installed in the laboratory (on the left) and its grid orientation at $\beta = 0°$ and 45° to with respect to the liquid free surface (on the right).