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Refined reconstruction of liquid–gas interface structures for stratified two-phase flow using wire-mesh sensor

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A B S T R A C T

Wire-mesh sensors (WMS), developed at HZDR [13,4], are widely used to visualize two-phase flows and measure flow parameters, such as phase fraction distributions or gas phase velocities quantitatively and with a very high temporal resolution. They have been extensively applied to a wide range of two-phase gas–liquid flow problems with conducting and non-conducting liquids. However, for very low liquid loadings, the state of the art data analysis algorithms for WMS data suffer from the comparably low spatial resolution of measurements and from boundary effects, caused by e.g. flange rings – especially in the case of capacitance type WMS. In the recent past, diverse studies have been performed on two-phase liquid–gas stratified flow with low liquid loading conditions in horizontal pipes at the University of Tulsa. These tests cover oil–air flow in a 6-inch ID pipe and water–air flow in a 3-inch ID pipe employing dual WMS with 32 × 32 and 16 × 16 wires, respectively. For oil–air flow experiments, the superficial liquid and gas velocities vary between 9.2 m/s ≤ ν_{SG} ≤ 15 m/s and 0.01 m/s ≤ ν_{SL} ≤ 0.02 m/s, respectively [2]. In water–air experiments, the superficial liquid and gas velocities vary between 9.1 m/s ≤ ν_{SG} ≤ 33.5 m/s and 0.03 m/s ≤ ν_{SL} ≤ 0.2 m/s, respectively [17,18]. In order to understand the stratified wavy structure of the flow, the reconstruction of the liquid–gas interface is essential. Due to the relatively low spatial resolution in the WMS measurements of approximately 5 mm, the liquid–gas interface recognition has always an unknown uncertainty level. In this work, a novel algorithm for refined liquid–gas interface reconstruction is introduced for flow conditions where entrainment is negligible.

1. Introduction

Wire–mesh sensors for gas/liquid two-phase flow measurements have been introduced in 1998 by Prasser et al. [13]. Two planes of equally distributed parallel wires are spanned over a cross-section of a pipe, perpendicular to each other and with a small axial gap. One of those planes is operated as a transmitter plane and the other one as a receiver plane. While switching the transmitter wires consecutively to an excitation signal, the current flow through the media at the virtual crossing points with the receiver wires is measured and recorded fully in parallel. With this technique, the cross-sectional images of the liquid–gas distributions can be obtained with frame rates up to 10,000 frames per second (fps). Since then, wire-mesh sensors have been used in dozens of different applications all over the world by researchers in the field of multiphase flow to study gas–liquid phase distributions. From the cross-sectional images, physical flow parameters, such as radial void fraction profiles, bubble size distributions and interfacial flow structure velocities can be computed [14,15]. Da Silva et al. [4] have extended the wire-mesh sensor principle towards non-conducting liquids by changing the electronics from a conductivity-based one to a capacitance measurement system, which applies a high-frequency sinusoidal wave signal as excitation and detects its signal amplitude. This new technique enables measurements with two non-conducting fluids, such as oil and gas [5,6].

In most of the applications, researchers have studied liquid dominated flow regimes and have focused on the extraction of the flow quantities related to the gaseous phase, e.g. bubble size and velocity distributions [11,12,14,15]. However, the gas dominated flows such as stratified flow in horizontal pipes with low liquid

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loading conditions are rarely studied. Such flow regimes are critical for the operation of wet gas pipelines, and most of the multiphase models fail in the prediction of two-phase flow characteristics. The wave topology information related to the gas dominated stratified flow, to be obtained from the use of wire-mesh sensors, will improve the closure relationships in the two-phase models.

Recently, Aydin et al. [3] have applied a double layer capacitance wire-mesh sensor in a horizontal 6-inch flow loop to study oil–gas flows with very low liquid loadings. Vieira et al. [17,18] applied double layer conductivity wire-mesh sensors to investigate flow in horizontal flow in annular and stratified flow regimes with high gas flow rates (up to 33.5 m/s) and low liquid loadings in a 3-inch water–air flow loop. Different liquid viscosities have been used by mixing CMC (carboxymethylcellulose) to water. The influence of liquid viscosity on flow regimes in a horizontal pipe has been studied by Taitel and Dukler [16] and Andritsos et al. [2]. Andritsos and Hanratty [1] has shown that the dimensionless height, h/D, increases with increase of liquid viscosity. Recently, Vieira et al. [17,18] observed that when the liquid viscosity is increased from 1 cP to 10 cP and 40 cP in stratified-wavy flows at moderate superficial gas velocities in 3-inch (76.2 mm) ID pipes, the time-averaged holdup and the amplitude of the gas–liquid interface increases due to the shear effect between liquid and gas phases. Also, experiments at lower superficial gas velocities clearly showed that the high viscosity liquids tend to promote slug flow. Despite the amount of data accumulated in the last decades, important questions still remain open about the 2D and 3D effects of liquid viscosity on flow patterns in a horizontal pipe.

Investigation on the above-mentioned flow regimes, especially with capacitance wire-mesh sensors, suffer from the comparably low spatial resolution of the sensor matrix (app. 5 mm) and wall effects due to unequal electric field distributions for crossing points close to the stainless steel flanges. Small liquid films may be missed by the standard WMS detection algorithms due to these boundary effects, since the large capacitance of the stainless steel flanges reduces dramatically the measured signals for near-wall crossing points. For very low liquid loadings (holdup values less than 10%), this also affects the overall accuracy of the cross-sectional liquid holdup calculations. To overcome the measurement uncertainties of the technique and to allow a more accurate representation of liquid film thicknesses, we applied a combination of a priory information and state of the art filtering and interpolation techniques to reconstruct a binary liquid–gas interface with a spatial resolution ten times higher than the original wire-mesh sensor cross-sectional images.

2. Experimental setup

The WMS measurements for oil–air experiments were conducted in Tulsa University Fluid Flow Projects (TUFFP) low-pressure large-scale pipeline, and water–air experiments were carried out in Erosion/Corrosion Research Centre (E/CRC) located at the University of Tulsa.

2.1. TUFFP facility

For the capacitance measurement, the low pressure flow loop of Tulsa University Fluid Flow Projects (TUFFP) has been utilized. This flow loop is able to handle two-phase oil–air flow. The test section consists of two runs, each run with a 0.152 m (6-inch) ID pipes and 56.4 m in length. The test section is horizontal. The liquid phase is mineral oil (IsoparL^{TM}, $\rho = 760$ kg/m^3, $\mu = 1.35$ cP, $\tau = 24$ dynes/cm), and is pumped from the container tank by using a Blackmer^{TM} progressive cavity pump (PV20B) with maximum pumping capacity of 11.5 GPM for the pressure and temperature conditions prevailing in the experiments. Compressed air is continuously supplied to the flow loop by a diesel powered portable rotary screw compressor and an electrically powered stationary two-stage compressor connected in parallel, with a combined capacity of 2640 SCFM at 100 psig. The oil and the air are mixed using a specially designed mixing tee (for details, see [10]). Following the oil and the air flow through the flow loop, the phases are separated by a preliminary separator followed by a vertical final separator. Following the phase separation, the air is vented out to the atmosphere, and the oil is re-circulated to the storage tank. Fig. 1 shows a schematic sketch of the low pressure test loop.

During the experiments, the air flow rate is measured using Micro Motion CMF300 Coriolis mass flow meter located before the mixing tee. Oil flow rate and density are monitored using Micro Motion CMF100 mass flow meter. The calibrations of the flow meters are performed by the manufacturer and have a mass flow rate uncertainty of $\pm 0.1\%$ of the measured flow rate. The density measurements have an uncertainty of $\pm 0.5\%$ of the measured value.

For each case considered, the liquid was trapped with two quick-closing ball valves (QCV) in the test section. The total volume of this pipe section, between two QCVs, is 2×10^5 ml. After the flow is trapped, a sphere with the same diameter of the pipe ID is inserted into this pipe section, and, then, the pipe segment is closed. Finally, the pipe segment is pressurized from one end, which in turn pushes the sphere towards the other end, and drains the liquid. This method of liquid drainage, referred to as *picking mechanism*, has a systematic uncertainty of $\pm 5\%$ of the measured value in the liquid amount [8]. The drained liquid is stored in graduated cylinders, and a liquid holdup is calculated as the ratio of the drained liquid volume to the total volume (2×10^5 ml).

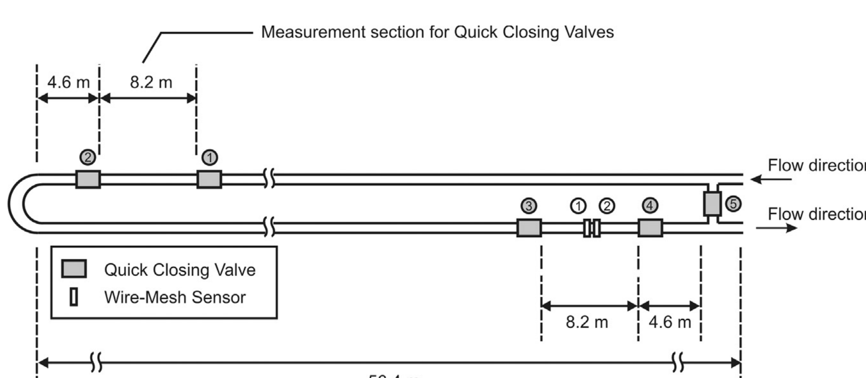

Fig. 1. Schematic layout of the 6-inch low-pressure flow loop test section.