WIRE-MESH AND ULTRASOUND TECHNIQUES APPLIED FOR THE CHARACTERIZATION OF GAS-LIQUID SLUG FLOW

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Abstract. *Gas-liquid two-phase flows are found in a broad range of industrial applications, such as chemical, petrochemical and nuclear industries and quite often determine the efficiency and safety of process and plants. Several experimental techniques have been proposed and applied to measure and quantify two-phase flows so far. In this experimental study the wire-mesh sensor and an ultrasound technique are used and comparatively evaluated to study two-phase slug flows in horizontal pipes. The wire-mesh is an imaging technique and thus appropriated for scientific stidies while ultrasound-based technique is robust and non-intrusive and hence well suited for industrial applications. Based on the measured raw data it is possible to extract some specific slug flow parameters of interest such as mean void fraction and characteristic frequency. The experiments were performed in the Thermal Sciences Laboratory (LACIT) at UTFPR, Brazil, in which an experimental two-phase flow loop is available. The experimental flow loop comprises a horizontal acrylic pipe of 26 mm diameter and 9 m length. Water and air were used to produce the two-phase flow under controlled conditions. The results show good agreement between the techniques.*

Keywords*: Two-phase flow, wire-mesh, ultrasound, impedance, horizontal pipe flow*

1. INTRODUCTION

Gas-liquid two-phase flows are commonly found in many industrial applications, such as chemical, oil and nuclear industries. In many cases, such flows determine the operation efficiency and security of the equipment and process where they occur. In this way, experimental investigations of two-phase flows are very important not only for a better understanding of the phenomena involved, but also to offer a trustful experimental data base in order to help, for example, the developing of theoretical models or the validation of predictions from computer simulations such as performed by Computational Fluid Dynamics (CFD) software. In addition, advanced measurement techniques are also necessary in industrial applications in order to allow for the monitoring and control of processes.

Many experimental techniques have been used to analyze two-phase flows so far, among them conductive and capacitive probes (Ahmed and Ismail, 2008), high-speed videometry (Guevara-López et al., 2008), and more complex techniques such as x-ray and gamma ray tomography (Hervieu, Jouet, and Desbat, 2002). However, none of the proposed techniques can claim a universal applicability and some of them have considerable drawbacks and may fail in particular practical situations.

Wire-mesh sensors are flow imaging devices and allow the intrusiveinvestigation of multiphase flows with high spatial and temporal resolution (Prasser, Bottger, and Zschau 1998) and overcame many of the drawbacks of alternative techniques. The sensor is a hybrid solution in between intrusive local measurement of phase fraction and tomographic cross-sectional imaging (for details see next section). This type of sensor has been successfully employed by a number of researchers to investigate two-phase flow in the past. The first generation of wire-mesh sensors is based on conductivity measurements. Recently, the capacitance wire-mesh sensor has been developed and tested, which allow the investigation of non-conducting fluids too, such as oil or organic liquids (Da Silva, Schleicher and Hampel, 2007). Therefore, this sensor is a powerful device for detailed flow investigation in laboratories.

For non-intrusive slug flow characterization, an ultrasound technique is appropriated and meets industrial requirements. This method uses an ultrasound transducer attached to the pipe operating in echo-pulse mode (Fig. 1b). Due to the fact that at the interface water-air there is a difference between the acoustic impedances, a reflected wave is generated in this interface, which is monitored by the ultrasonic transducer at high repetition rate. Thus evaluating the transit time of the reflected wave at this interface it is possible to obtain a profile of the water level inside the pipe, which in turn, allows identifying the shape of the bubbles and the slugs passing at the measurement point (M. Meribout et al. 2010).

The aim of this work is to validate the ultrasound's data with the measurements from the capacitive wire-mesh. In this experimental study, the probes are applied to study two-phase (water-air) slug flows in horizontal pipes. First this paper reviews the operating principle of the wire-mesh and ultrasound techniques. Then one details the methodology for the extraction of the parameters of interest such as cross section average void fraction and characteristic slug frequency. Finally, the experimental results are presented and one explains the differences between the measurements, discussing suggestions for future investigations.

2. MATERIALS AND METHODS

2.1. Wire-Mesh Sensor

The wire-mesh sensor comprises of two sets of wires (electrodes) stretched over the cross-section of a vessel or pipe forming a grid of electrodes (Fig. 1) (Prasser, Bottger, and Zschau, 1998; Da Silva, Schleicher and Hampel, 2007). Each plane of parallel wires is positioned perpendicular to each other with a small axial separation between them of 1.5 mm. In each layer there are eight stainless steel wires with diameter of 100 µm spaced 3.25 mm between them. The associated electronics applies a 5 MHz sinus signal to measure the local capacitance in the gaps of all crossing points at high repetition rate through a multiplexed approach. Each of the measured signals reflects the constitution of the flow within its associated sub-region, i.e. each crossing point acts as local phase indicator. Hence, the set of data obtained from the sensor directly represents the phase distribution over the cross-section and no reconstruction procedure is needed as usual for tomographic imaging systems. A complete image can be measured with a frame rate up to 1 kHz. Therefore, this technique allows the visualization of the cross-sectional phase distributions with a high temporal resolution.

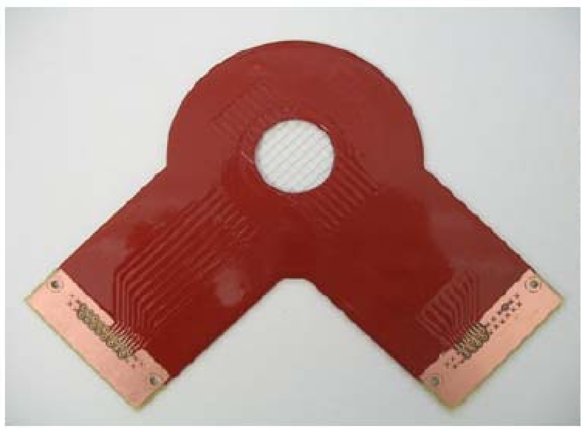

Figure 1: Photography of a 8 × 8 electrode sensor used in this measurement.

2.2. Ultrasound Sensor

The ultrasound technique has been applied in industrial process control for 50 years, mainly as a method for on-line monitoring, control and characterization of composition, reaction state, mixing and multiphase flows. The advantages of ultrasonic instrumentation are the robustness due to the simplicity of the transducers and the fact that it is a non-invasive technology, enabling the use in various types of equipment and measurements.

The ultrasound technique is based on acoustic waves, whose frequencies are above 20 kHz, generated by transducers that convert electrical energy into mechanical, and vice versa, by the piezoelectric effect (Krautkrammer, 1990). The wave, which interacts with the flow, may be reflected by the interfaces between phases and return to the transducer, which deforms and generates an electrical signal - echo-pulse mode. This wave can still pass through the flow and be detected by another probe, which by the same piezoelectric effect captures the signal – transmission-reception mode (Chang et al, 1982). In this work, we used the technique of ultrasonic echo-pulse mode, to characterize a two-phase water-air intermittent slug flow.

Figure 2 shows a schematic view of ultrasonic instrumentation. We applied one transducer placed below the pipe so that the ultrasound pulse found the liquid phase before the gas phase in the slug flow. Thus, it was possible to apply echo-pulse technique described earlier to characterize the slugs and bubbles of the flow.

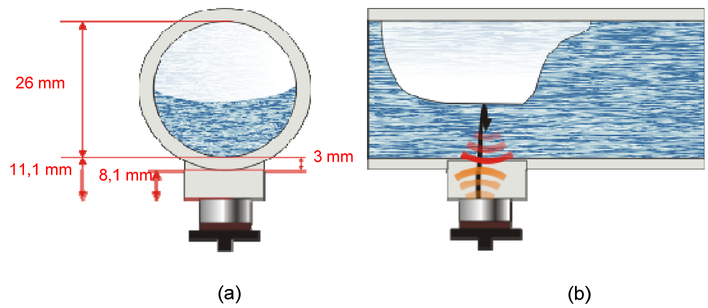

Figure 2: (a) Cross section of the ultrasonic instrumentation, (b) Schematic side of ultrasonic instrumentation.

Between the sensor and the pipe, an acrylic adapter is placed (see Fig. 2) to interface the signal to the inside of the pipe. To improve acoustic coupling between the parts, a thin layer of Vaseline was applied on the sensor-adapter-tube interfaces. For intermittent flow, the ultrasonic wave is reflected by the gas-liquid interface and hence parameters such as bubble length and frequency can be estimated. Figure 2(b) illustrates this situation.

In this study we used an ultrasonic measuring system developed at the Federal University of Technology – Paraná (UTFPR) in the Laboratory of Automation and Advanced Control Systems (LASCA) for the experiments. The equipment consists of two main modules: signal generation, responsible for the excitation of ultrasound transducers with a frequency of 2.25 MHz at 500 Hz sampling rate, and signal acquisition, responsible for the capture of signals through analog digital converters at a 40 MHz rate, and subsequent transmission of ultrasound waves to a computer where the signals are processed.

2.3. Experimental test facility

The experiments were performed in the Thermal Sciences Laboratory (LACIT) at the UTFPR, in an exerimemtal flow loop which comprises a horizontal acrylic pipe of 26 mm diameter and 9.0 m long and associated devices to produce a two-phase flow under controlled conditions. Tap water (electrical conductivity of 380 µs/cm) and air were used as fluids and their flow rates are independently measured by means of a Coriolis flow meter for water and a rotameter for air. Water is circulated in close loop with help of a pump. The air coming from a compressor is mixed with the flowing water in the pipe entrance through a gas-liquid mixer. In the pipe exit, there is a separator/reservatory, where air is expelled to the atmosphere and water is storage. A wire-mesh sensor is installed 7.5 m from the pipe entrance, (288 times internal diameter). The ultrasound probe is placed 0.5 m flow downwards from the wire-mesh. In this way, relatively well developed flow is expected to be evaluated. Water temperature as well as air temperature and pressure at pipe entrance are monitored by means of industrial sensors connected by a Foundation Field Bus and controlled by a host computer running a supervisory program. Furthermore, the absolute pressure of two-phase mixture close to the measurement plane, where the wire-mesh sensor is installed, is measured. This value is used to obtain the exact air flow rate at the measurement point, i.e. rotameter readings are compensated by the pressure difference at pipe entrance and pressure at measurement plane. Figure 3 shows the schematic of the test facility.

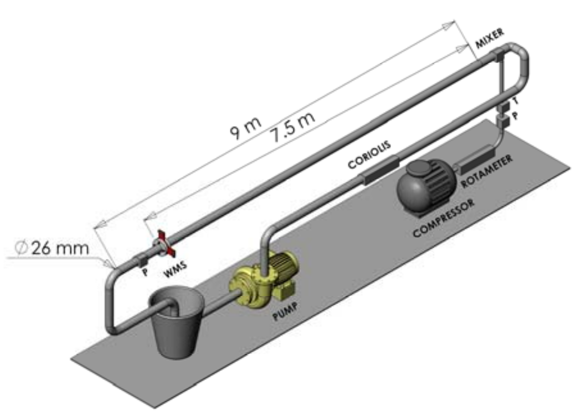

Figure 4: Schematic representation of the measurement plant. P and T denote respectively pressure and temperature transducers.

3. DATA PROCESSING AND ANALYSIS

3.1. Wire-mesh sensor

The voltage levels measured by the wire-mesh sensor are stored in a three-dimensional matrix at the computer memory $V(i,j,k)$, with k being the time index and i and j spatial indexes respectively (Da Silva, Schleicher and Hampel, 2007). These voltages are proportional to the electrical permittivity ε of each crossing point, which is proportional to the void fraction (for further details Da Silva *et al.*, 2009). In order to convert the measured voltages to permittivity values and further obtain the phase fraction distributions, a calibration routine is used. First, a measurement of a matrix V_L for a substance of low permittivity covering the whole sensor cross-section is performed. The procedure is then repeated with the entire cross-section covered with another substance having a higher permittivity V_H, which gives a second reference data matrix. In this way the void fraction α can be obtained

$$\alpha(i,j,k) = \frac{V_H(i,j) - V(i,j,k)}{V_H(i,j) - V_L(i,j)} . \tag{1}$$

To analyze the void fraction data $\alpha(i,j,k)$, which is a 3D matrix, different levels of complexity were used. Images sequences of the flow as well as cross section images from the pipeline can be generated. Important quantitative insights of the flow are obtained by averaging the measured void fraction in space and/or time. Hence, averaging the data over cross section, time series of the void fraction can be obtained in the form

$$\alpha(k) = \sum_i \sum_j a_{i,j} \cdot \alpha(i,j,k) . \tag{2}$$

where $a_{i,j}$ is the contribution of each crossing point (i,j) for the total cross section area (details in Prasser, Krepper and Lucas, 2002). These time series $\alpha(k)$ can be analyzed by a histogram (Probability Density Functions - PDF) or by their spectral components. This last analysis is done through the estimation of the power spectral density function (PSD), by the Welch modified periodogram (Marple, 1987). Through the PSD it is possible to identify the characteristic frequency of the bubbles and slugs in the studied flows. In the last and lower level of complexity, the 3D data matrix is integrated in its three components resulting in the mean void fraction during the experiment, in the form:

$$\bar{\alpha} = \frac{1}{N} \sum_{k=1}^{N} \alpha(k) , \tag{3}$$

where N is the total number of time samples of the signal.

3.2. Ultrasound

The measurement of water level between the bubble and the tube Plexiglas was obtained according to (Faccini, 2008):

$$H_L = V_S \frac{\Delta T_{PA}}{2} \tag{4}$$

where H_L is the water level high, V_S is the sound speed in water and ΔT_{PA} is the transit time between the Plexiglas tube and the air bubble. The value of V_S used was 1,494 m/s following the equations Lubbers and Graaf (1998) given to the liquid temperature around 25 ºC.

Calculating the water depth of an acquisition of ultrasound waves is still possible to visualize the elongated bubble, represented by the localities where the transit time is shorter, and the piston water, where the transit time is greater. Figure 5 shows an exemplary measurement of H_L over time for a slug flow.

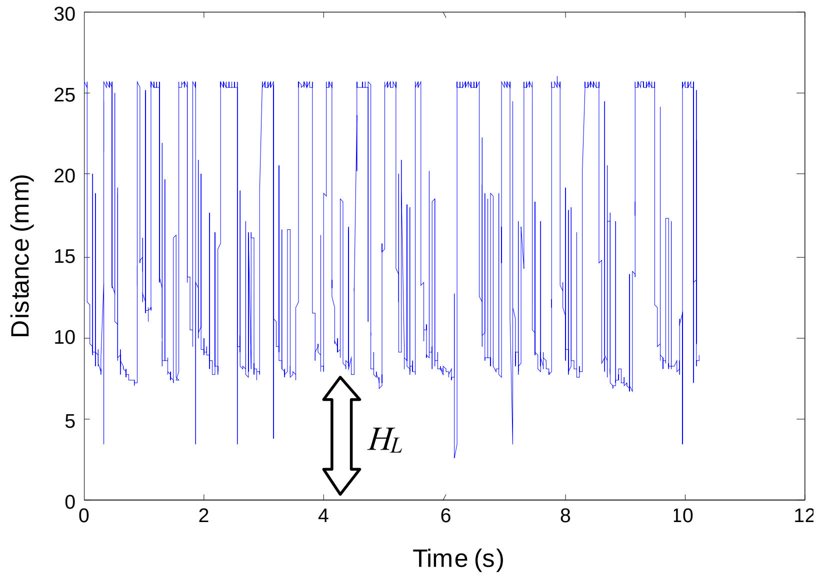

Figure 5: Exemplary H_L measurement for a slug flow.

The void fraction is the part of the pipe section occupied by the gaseous flow. Considering the height of the water depth as the liquid phase that occupies the pipe. The gas phase is the difference between the diameter of the pipe (total) and the height of the liquid. This will measure the void fraction in the cross section where is the ultrasonic sensor. The expression of the void fraction, expressed as a percentage value, is represented by Equation 5:

$$\alpha = \frac{(\phi_t - H_L)100}{\phi_t} \tag{5}$$

Where ϕ_t is the diameter of the Plexigass tube and α is the void fraction of the cross section.

The void fraction of the entire acquired signal is obtained by the arithmetic mean of n samples:

$$\overline{\alpha} = \frac{\sum_{i=1}^{n} \alpha_i}{n}$$

4. RESULTS

Figure 6 illustrates the profile of the bubbles and slugs in the axial section of the tube with the time with a superficial gas velocity of *Usg* = 0.5 m/s and liquid superficial velocity of *Usl* = 0.5 m/s.. Despite some discrepancies, both signals show the same behavior of the flow, i.e., the alternating passage of bubbles and slugs, thus showing the shape of the gas-liquid interface. The raw data are further applied for statistical analysis in order to extract some flow parameters such as characteristic frequency, void fraction, etc.

Using the wire-mesh technique the tridimensional shape of the bubbles and slugs can be extracted from the raw data with high resolution, as shown in Figure 7. The 3D image of the wire-mesh shows measurements in a slug flow with a superficial gas velocity *Usg* = 0.5 m/s and liquid superficial velocity *Usl* = 0.5 m/s. The gas is represented in yellow and the water in light blue. In order to compare the results between both methods, one extracted the profile of the bubbles in the flow from the wire-mesh images.

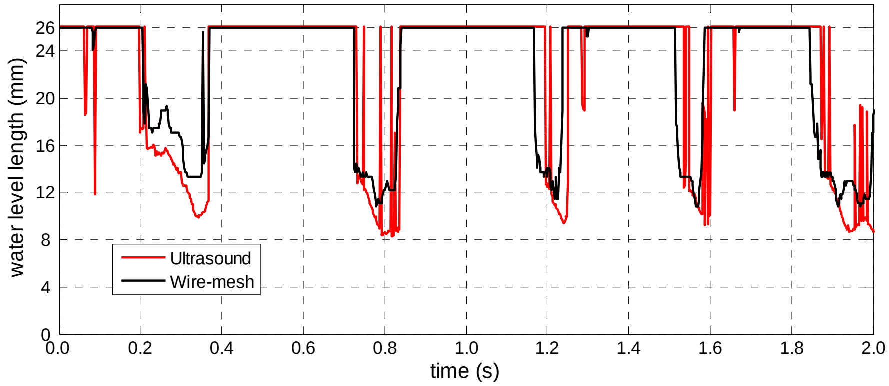

Figure 6: Profile of the liquid level extracted through images generated by the wire-mesh probe and the travel time of the ultrasonic wave.

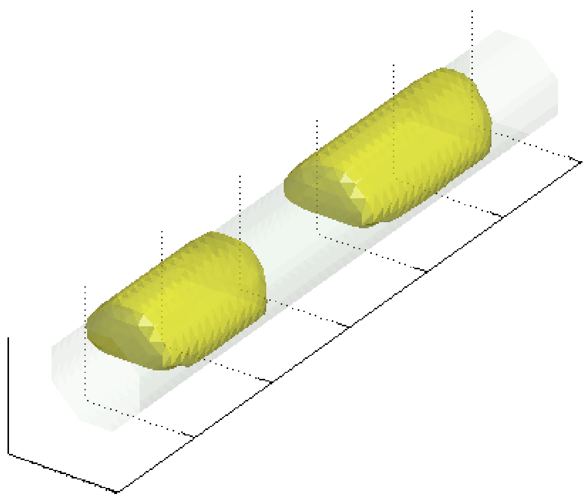

Figure 7: 3D Image of the wire-mesh measurements showing details of the bubble.

Table 1 shows six experiments performed at different gas and liquid superficial velocities. All cases fall within the range of slug flow pattern. For each experiment, data from the wire-mesh sensor was measured during 20 seconds with a repetition rate of 500 Hz. Before the flow measurements were carried out, reference measurements of empty and full pipe were collected, i.e. matrices V_H e V_L in order to measure the values of the void fraction by Eq. (1). The ultrasound values were measured during 12 seconds and, despite the smaller sample size, it showed similar results as the wire-mesh. In order to evaluate the both techniques, the void fraction ($\alpha\sigma$) and the bubble mean frequency ($Freq.\sigma$) deviations were calculated through Eq. (5):

$$\alpha\sigma = 100\left|\frac{\alpha US - \alpha WM}{\alpha WM}\right|,\ Freq.\sigma = 100\left|\frac{Freq.US - Freq.WM}{Freq.WM}\right| \tag{5}$$

where αUS is the mean void fraction of the ultrasound measurement and αWM is the mean void fraction of the wire-mesh measurement. The average void fraction obtained by the ultrasonic technique showed deviations up to about 20%, explained by the lack of compensation for temperature, which alters the speed of sound in the middle. Another reason for the difference could be spatial resolution of the wire-mesh which is limited in 3 mm. On the other hand, the analysis of the bubble frequency resulted in a maximum deviation of 0.29%, which shows the good precision and validates the use of ultrasound to be used in this kind of flow.

Table 1: Experimental conditions adopted for liquid superficial velocities (*Usl*) and gas (*Usg*), as well as values of mean void fraction and characteristic frequency of the flow.

Usl (m/s)	*Usg*	*α US* (%)	*α WMS* (%)	*ασ* (%)	*Freq. US*	*Freq. WMS*	*Freq.σ* (%)
0.71	0.24	22.62	20.58	9.9	3.40	3.05	0.11
0.70	0.30	24.31	21.00	15.7	3.09	2.93	0.05
0.51	0.54	38.62	34.05	13.4	1.62	1.59	0.02
0.51	0.55	39.03	33.87	15.2	1.88	1.46	0.29
0.31	0.72	52.65	43.95	19.8	0.61	0.61	0
0.31	0.71	53.24	44.19	20.4	0.65	0.61	0.06

5. CONCLUSIONS

We have reviewed the operation principle of the wire-mesh sensor, as well as the methodology for extraction of some quantitative parameters of the flow based in the raw data measured. This methodology was applied to a series of experiments of horizontal slug flow, showing some details of the studied pattern. The ultrasonic signal acquired at the time showed good agreement with images obtained by wire-mesh sensor. Thus, the wire-mesh technique proved a powerful tool in the validation of ultrasound signals. The use of wire-mesh as a reference, makes possible the development of the technique in ultrasonic flow analysis of non-intrusive way. Future work requires a detailed analysis of the speed of sound in the liquid and the calculation of void fraction based on the area of the pipe and not only in cross section where this sensor.

6. ACKNOWLEDGEMENTS

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