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COMPARISON OF DIRECT-IMAGING SENSOR AND WIRE-MESH SENSOR APPLIED TO GAS-LIQUID SLUG FLOW INVESTIGATION

Aluisio do Nascimento Wrasse
Eduardo Nunes dos Santos
Rigoberto E. M. Morales
Marco Jose da Silva
Núcleo de Escoamentos Multifásicos (NUEM), Universidade Tecnológica Federal do Paraná (UTFPR)
Curitiba – PR, Brazil
aluisio@alunos.utfpr.edu.br

Abstract. *Two-phase flows are very common in different industrial applications. The knowledge of the parameters and characteristics of the flow can guarantee a safe and efficient operation of plants. In the past, many techniques have been developed to measure multiphase flows. In this study, we apply a direct-imaging sensor to characterize gas-liquid slug flow. Direct images generated by the non-intrusive sensor are compared with the images from a reference sensor called wire-mesh sensor. While the reference sensor produces cross-section images of void distribution, the direct-imaging sensor produces images which still need some further interpretation to describe some flow features. This paper sheds some light on how direct-images can be used for slug flow characterization.*

Keywords: *gas-liquid slug flow, direct-imaging sensor, wire-mesh sensor.*

1. INTRODUCTION

Two-phase flows are present in several industrial applications including oil&gas, chemical and nuclear industries. In industrial environment, online monitoring of two-phase flow parameters such as void fraction and flow regime is important for a safe and efficient operation of the plants and equipment. Therefore simple and robust measurement techniques are needed. On the other hand, in academia, detailed investigation of two-phase flows by measuring the spatial and temporal resolved phase distribution is aimed in order to obtain deeper understanding of flow behavior, which in turn is applied for either developing, or validation of new flow models or engineering correlations. Here, special-developed instrumentation for two-phase flows are required to detailed flow monitoring.

In the past, a number of measurement techniques have been developed and applied, such as impedance, ultrasound and optical techniques (Ofuchi *et al*., 2012). Among the impedance techniques, the wire-mesh sensor (WMS) was first proposed by Prasser *et al*. (1998) and posteriorly it was improved by Da Silva *et al*. (2007) towards capacitance (permittivity) measurements. WMS is an alternative to tomographic techniques (since the technique doesn't use an image reconstruction algorithm to build images of the flow) and in spite of the intrusive characteristics has as advantage its high spatial and temporal resolution. In a recent work, Wrasse *et al*. (2014) have proposed a non-intrusive sensor (here named as direct sensor) to obtain images of the flow by multiple permittivity/capacitance measurements. Authors have built a prototype and tested in static and dynamic conditions and it was possible to extract parameters as flow regime by visual inspection.

In this work, we aim at extracting further details of the slug flow from direct images. For this purpose, the direct sensor and a reference WMS are applied in a horizontal test bench running air-water flow, so the characteristics of the flow pattern are extracted by comparing the direct images with the true distribution from the reference WMS. Results have shown that the direct sensor, even with a lower spatial resolution than the reference WMS, is able to extract details of the slug flow pattern by a visual inspection.

2. WIRE-MESH SENSOR

The wire-mesh sensor is an intrusive measuring technique, which has been applied in the imaging of multiphase flows and appears as an alternative to tomographic systems. The device is able to generate images of phase distribution in the pipe cross-section area with high spatial and temporal resolution. Because of these characteristics, images are in good agreement with reality allowing the extraction of information of the flow as phase fraction, bubble size and velocity of the disperse phase (by cross-correlating the time series of two displaced sensors). WMS geometry consists of two planes (perpendicular to each other and separated by a small distance) of parallel wires stretched along the cross section of pipe where one plane is the emitter and the other one is the receiver. Each crossing point is interrogated by means of a dedicated electronics which measures the electrical permittivity and/or conductivity of the phase present in the gap of two electrodes (Prasser *et al*. (1998), Da Silva *et al*. (2007)). The electronic emitter circuit is responsible to apply a sinusoidal voltage at each emitter wire (one at a time - controlled by a switching scheme) and the receiver circuit is formed basically by transimpedance amplifiers and analog-to-digital converters which allows the parallel sampling of the receiver wires. The provided signals represent the distribution of the phases in the cross section area of the pipe. Figure 1 shows the sensor and the schematic representation of the system.

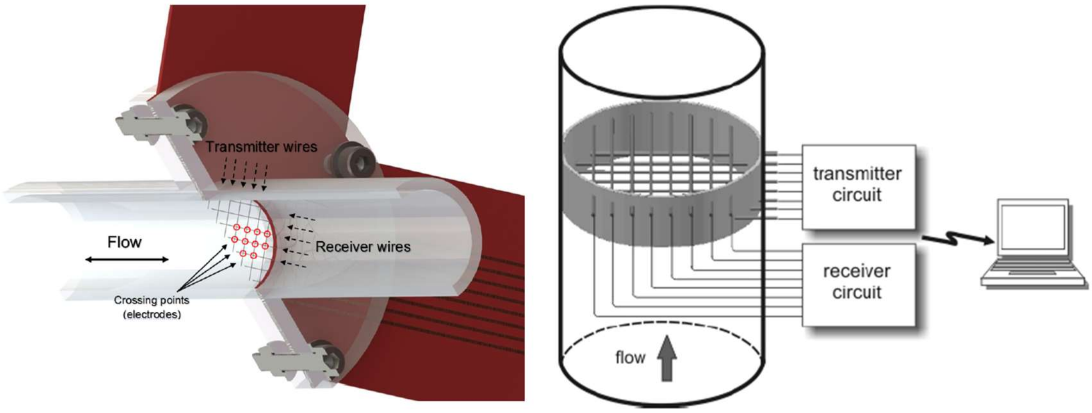

Figure 1. Wire-mesh sensor and the schematic diagram.

In this work, a capacitive 12x12 WMS (26 mm inner diameter) was applied as reference for the measurements. Twelve central vertical pixels of wire-mesh images were selected and disposed along the time (side view of pipe) forming a similar image to those generated by the direct sensor.

3. DIRECT SENSOR

The non-intrusive direct sensor works based on multiple capacitance (permittivity) measurements that allows the characterization of non-conductive liquids as very common in industrial applications such as oil or organic liquids. The sensor is fabricated in a thin (100 mm thickness) flexible printed circuit board (PCB) and its geometry is compound by a ring transmitter electrode and by eight receiver electrodes evenly distributed over pipe circumference. The PCB is manually glued to the internal pipe wall and an electrical insulating layer of the PCB avoids any electrical contact between the electrodes and the phases. Figure 2 shows the sensor attached inside the pipe and the schematic diagram of the system.

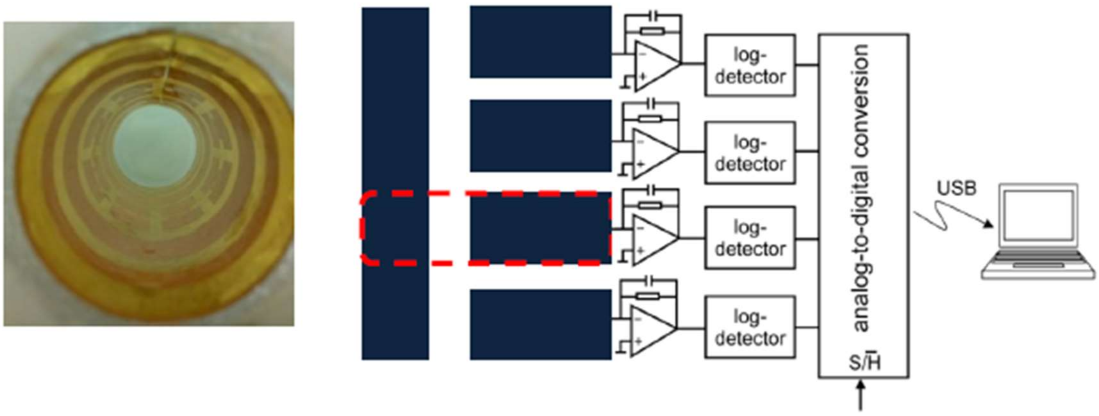

Figure 2. Direct image sensor attached to the pipe wall and the schematic diagram of the measuring system.

The emitter electrode of the direct sensor has 10 mm of width and every receiver electrode spaced by 2.21 mm one another has 20x8 mm of size. These dimensions are based on the pipe diameter, 26 mm, and on the expected capacitance (C) values, which are estimated by following the equation for coplanar capacitive sensors (Chen *et al.,* 2009)

$$C = \frac{2\varepsilon_r \varepsilon_0 l}{\pi} \ln\left[\left(1+\frac{2w}{a}\right)+\sqrt{\left(1+\frac{2w}{a}\right)^2 - 1}\right], \tag{1}$$

where ε_r is the relative permittivity, ε_0 is the permittivity of vacuum, l and w are the length and width of electrodes respectively and a is the gap between emitter and receivers. Equation (1) is valid for emitter and receiver with same dimensions but here it can be applied as a good first approximation for estimating the capacitance values. The electronic circuit (based on wire-mesh's electronics) detects the permittivity changes over the electrodes with a high temporal resolution (up to 1000 frames per second). The emitter circuit comprises a DDS (direct digital synthesizer) for generating a programmable sine wave (200 kHz up to 5 MHz). For every receiver electrode there is a similar circuit compound by transimpedance amplifiers that converts the current flowing from transmitter to receiver electrodes into a proportional voltage (similar to ac-based capacitance measurement proposed by Yang and York, 1999). Voltage signals are simultaneously acquired by a data acquisition (DAQ) card. The amplitude of the sinusoidal signal $V_o(k)$ at the output of transimpedance amplifier is proportional to the capacitance of the transmitter-receiver pair $C_x(k)$ in the form (Da Silva *et al.*, 2007)

$$V_o(k) = -V_i(k)\frac{C_x(k)}{C_f}, \tag{2}$$

where V_i is the amplitude of the sinusoidal voltage applied, C_f is the feedback capacitor of the transimpedance amplifier and k is the number of electrode. After a calibration routine, the normalized values of capacitance $C_x(k)$ (liquid holdup - ranging between 0 and 1) are obtained which are plotted representing the phase distribution in the pipe.

4. RESULTS

The direct sensor was tested in a horizontal air-water test plant located at NUEM - UTFPR (Curitiba). The plant, schematically represented in Fig. 3, has independent lines of air and water and a controlled system allows to generate the slug flow pattern by controlling the gas and liquid superficial velocities. The test facility comprises a horizontal acrylic pipe of 26 mm inner diameter and 9 m long. The direct sensor was located downstream at 8 m from pipe inlet and distanced by 30 cm from the reference WMS.

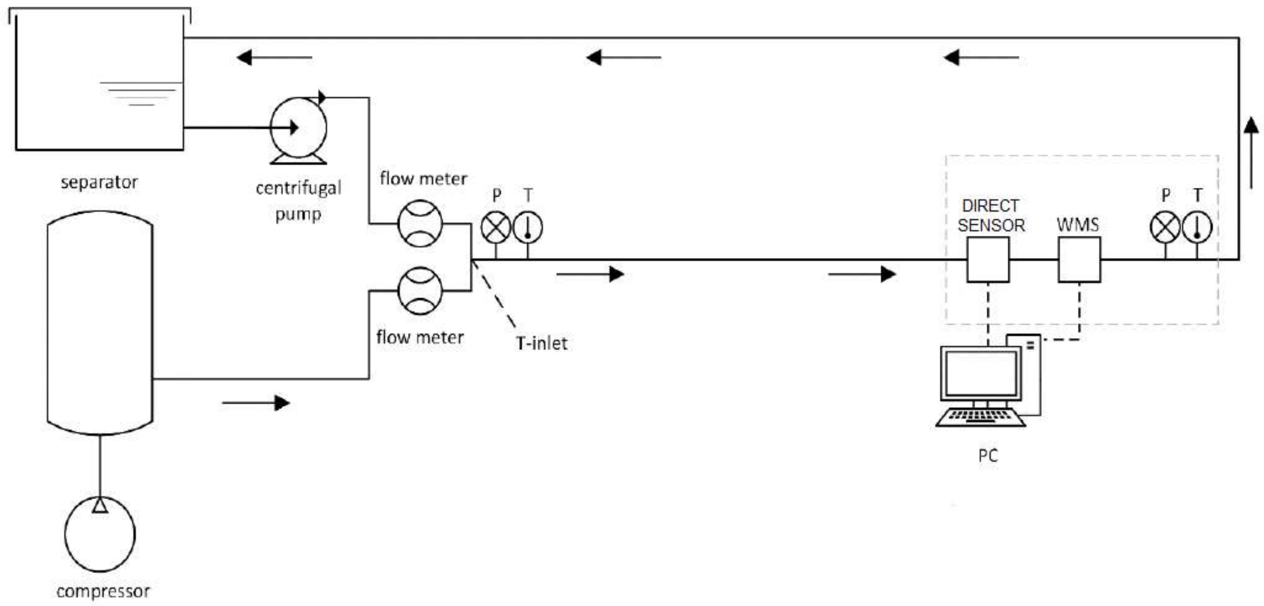

Figure 3. Schematic diagram of the horizontal air-water test plant.

Firstly, slug flow with gas superficial velocity j_g = 2.2 m/s and water superficial velocity j_l = 0.9 m/s was generated. The direct images and WMS image are shown in Figure 4. To generate the images, data from both sensors are normalized by a calibration routine. In the scaled image the maximum value (1 - blue color) represents the liquid holdup. Y-axis of direct images represents the angle of a specific electrode at the pipe perimeter, $\pm\pi$ represents the bottom of pipe. Once the two sensors are displaced at the longitudinal space of pipe, a time shift was made in one of the generated images to override the equivalent slugs in the results. By the results, it is observed similarity with the reference: slugs and air bubbles have a similar length, in a same way the liquid height is visibly close. In the slugs, it is possible to observe the presence of small air bubbles immersed in the liquid phase (named as aerated liquid slug) and this is confirmed by the true distributions.

A second experiment was made with the superficial velocities being j_g = 0.6 m/s and j_l = 0.3 m/s, the results are shown in Figure 5. In the same way to previous results, direct image is in good agreement with reference – liquid height, number and length of slugs. In this experiment, small bubbles immerse in the liquid phase are not observed but by an approximation in an elongated bubble it can be seen a bubble tail as confirmed by the reference WMS. In 35 seconds in direct image, the coalescence of two consecutives elongated bubbles is noticed.

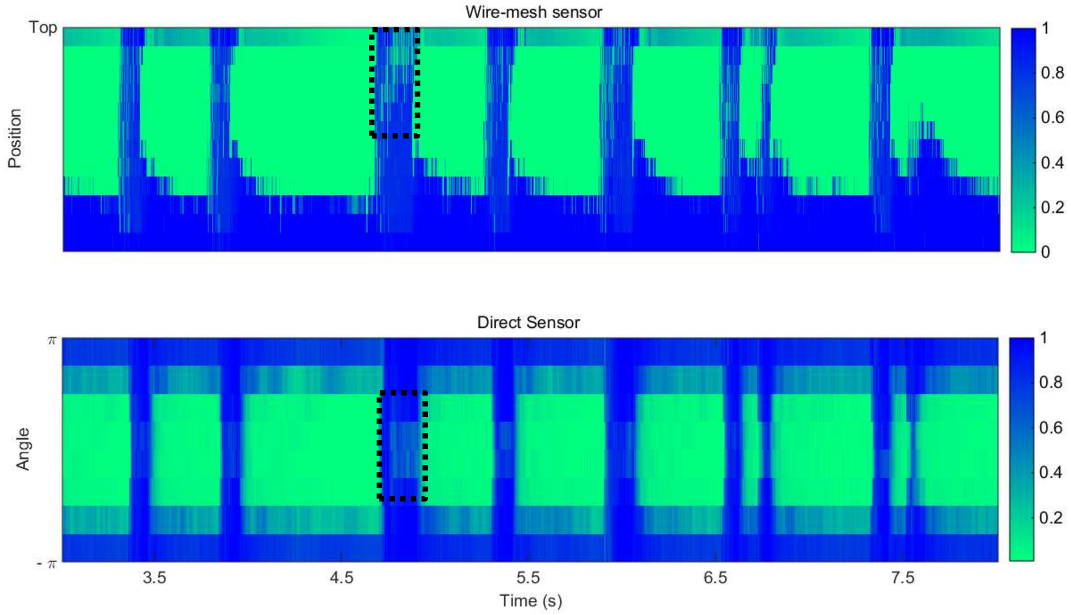

Figure 4. Direct image of measured point (j_g =2.2 m/s and j_l =0.9 m/s). Slug flow pattern is noticed by visual inspection and characterized by the aerated liquid slugs (dotted box at images).

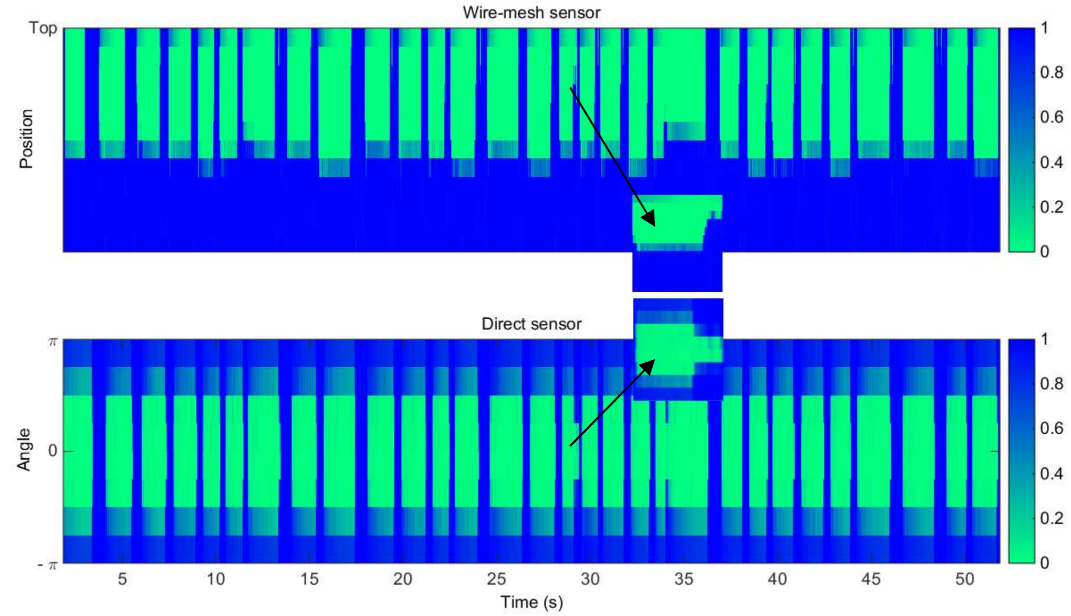

Figure 5. Direct image of a slug flow pattern (measured point - j_g=0.6 m/s and j_l=0.3 m/s). In the approximated view of the selected elongated bubble, it can be seen a bubble tail.

5. CONCLUSIONS

A direct imaging sensor was applied to investigate air-water slug flow. The true distribution of a reference wire-mesh sensor was used as a support for flow details extraction. Two experiments were made with different air and water superficial velocities. With high superficial velocities is common the presence of small air bubbles immerse in the water phase, named as aerated slugs, and here we could observe that characteristics by the direct images and confirmed by the reference sensor. The second experiment run with low superficial velocities and the bubble tail characteristic was detected. Despite having a low spatial resolution, the direct sensor was able to extract details of the slug flow based on the real information of a higher resolution reference sensor. So besides the advantage of be a non-intrusive technique, which means avoiding the possibility of occurs change in pressure and/or in flow profile, direct sensor can be applied as tool in the slug flow investigation. Future work shall focus on the image processing on generated images in order to obtain automatically the slug flow characteristics.

6. REFERENCES

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7. RESPONSIBILITY NOTICE

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