PROSPECTIVE STUDY OF A DOUBLE-SENSOR CAPACITIVE PROBE FOR THE MEASUREMENT OF IN-SITU VOLUMETRIC FRACTION IN OIL, WATER AND AIR FLOWS

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Abstract. *The purpose of this work is to report the development of a double-sensor non-intrusive capacitive probe to measure in-situ volumetric fraction. The suggested probe aims to improve the capacitive sign acquisition and obtain an accurate measurement of volumetric fractions in two- and three-phase flows. Several geometries were tested in order to find the best combination of sensitivity and flow pattern imunity. The chosen probe consists of two sensors of different geometries, rings and double helix. An impedance analyser was used to calibrate the probe and verify the function between the measured capacitance and the volumetric fraction inside the pipe. Static tests were performed in two- and three-phase arrangements. Two types of transducer circuits were developed to excite and transmit the measured sign to the acquisition system. In-line dynamic measuremets of in-situ volumetric fraction in air-water flows for several flow patterns were conducted in our multiphase flow loop (25.4 mm i.d. and 12 m length glass pipe). Static three-phase flow tests showed that it is possible to obtain the volumetric fracion of each phase by solving a simple linear system.*

Keywords: *Non-intrusive technique, Capacitive probe, Multiphase flow, In-situ volumetric fraction.*

1. INTRODUCTION

Many techniques have been used to measure in-situ volumetric fraction. Among them it is possible to find in the literature the capacitive and X or Gama rays as non-intrusive measurement techniques. The latter allow for accurate measurements of liquids and gas fractions, but the cost of the equipment is quite often very high. The non-intrusive techniques are more appropriate in practice as they do not disturb the spatial arrangement of the phases and are easier to be attached to the pipeline. Besides, they are not limited by the liquid-phase viscosity.

Hammer *et al*. (1989) studied a helical sensor for liquid-liquid volumetric fraction measurement. They detected a good repetitive response for a spiral helix angle of 180 degrees. According to their model and experiments, the helical geometry has a relatively low dependency on flow pattern. Tests in a heavy-oil production line showed that spiral helix angles of 180 and 360 degrees present the best results. Sensors of diverse geometries have been applied for volumetric fraction measurement and Parallel-plates, Rings and Helix geometries have presented great applicability for that purpose. Tollefsen and Hammer (1998) investigated several geometries. They tested the parallel-plates sensor at arrangements of 0, 90, 180 and 360 degrees and concluded that, despite its high sensitivity, the high dependency on the spatial distribution of the phases limits the applicability to homogeneous mixtures. Their results indicate that the flow pattern dependency can be reduced by using a helix sensor with an arrangement of 180 degrees. Chun and Sung (1986) evaluated the effects of sensor geometry, size and materials. The flow pattern and position of the electrodes with respect to the flow were also taken into account. Among all tested geometries, the parallel-plates sensor produced the strongest signal and its length did not exert any effect on its calibration curve. However, the sensor dependency on flow pattern was so strong that in some cases no sign could be read. No effect of the material of the electrodes was detected.

Reis (2003) designed, constructed and tested a double-sensor capacitive probe for void fraction measurement in air-water slug-flow pattern. Two helix sensors were used to determine the slug length by measuring the slug speed and time. Through standard signal treatment techniques the author managed to accurately measure the amount of slugs at any given time. Reis and Goldstein (2005) also studied the temperature-change effect on the helix sensor's response. They observed that a 10 ^{o}C temperature change may induce an error of 4% in the sensor response due to changes in the liquid electrical permissivity. A correction method based on the change of the voltage signal as a function of the temperature was proposed and successfully tested.

In conventional meters the circuit of bridges is a common solution. It is considered the most accurate way of registering the capacitance variation, since the bridge unbalance is directly related to the measured quantity (Huang et al. 1988). The balance is reached when Z_x equals Z_y in the case of circuits a, b and c shown in Fig. 1. Baxter (1997) indicates that bridges made of capacitors must have identical characteristics in order to avoid any external interference of temperature and humidity. The adequate model should be chosen according to the kind of measurement required.

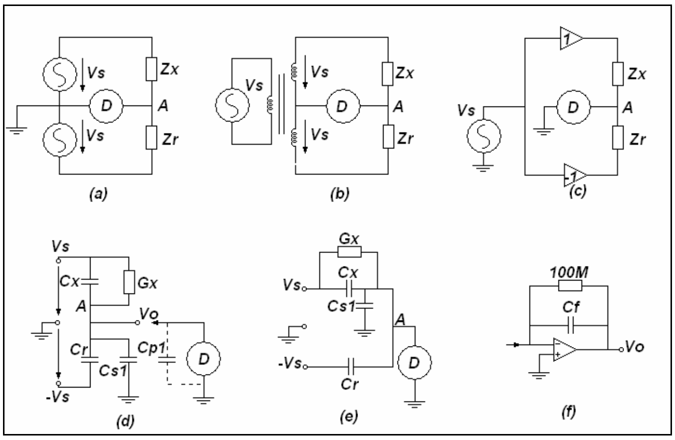


Figure 1. Several models of circuits with electrical bridges (Huang et al. 1988).

We have chosen the capacitive technique for in-situ volumetric fraction measurement as it presents low operational cost and a reliable response. The developed non-intrusive double-sensor capacitive probe was designed to measure volumetric fraction in gas-liquid, liquid-liquid and gas-liquid-liquid flows. This paper presents the probe's technical aspects, design, geometry, calibration and results of static and dynamic tests. The dynamic tests were performed in the inclinable multiphase flow loop of the Thermal-Fluids Engineering Laboratory (NETeF) of the University of Sao Paulo at Sao Carlos (EESC-USP), where several flow patterns such as bubbles, stratified, annular and slug flow were generated. A special data treatment was necessary for the slug-flow pattern and an acquisition system in LabView® platform was used to read and record the signs.

2. SETUP

2.1 Test line for dynamic tests

A hydrophilic glass test line of 25.4-mm i.d., 12 m length was set up on the multiphase flow loop of the NETeF to execute the dynamic calibration and tests of the capacitive probe. A by-pass line allowed the quick-closing-valves technique for the calibrations. It was possible to set up the scales, adjusting the instruments using full pipe conditions. The quick-closing valves guaranteed that no fluid would penetrate into the test line during the measurement.

Three probes, each one composed of two sensors, were positioned at the beginning, middle and end of the test line. The obtaining of values of volumetric fraction in different positions of the test line was meant to either calculate the global averaged volumetric fraction or evaluate the development length of the two-phase flow (Fig. 2).

A schematic view of the facilities is shown in Fig. 2 and Table 1 describes the main instruments. Water and oil are kept in polietilene tanks (RW) and (RO), respectively. A centrifugal water pump (BW), a positive displacement oil pump (BO) and an air compressor (ATM) drive the phases to the multiphase test line. After the test line the fluids enter a gas-liquid separator tank (SGL) and the mixture of water and oil enters the coalescent-plates liquid-liquid separator (SLL). Finally, water and oil return by gravity to their tanks, (RW) and (RO), respectively.

A control algorithm was designed, implemented and operated via LabView to enable the quick-closing-valves technique. Solenoid valves V1 and V3 are normally open and V2 is normally closed (Fig. 2). In case of operational incautiousness, it avoids a pressure increase, which could damage the glass test line. In permanent flow regime, the solenoid valves number V1 and V2 are open, allowing the fluid to pass through the test line, whereas V3 remains closed. During the tests, V1 is suddenly energized and V2 and V3 are off, deviating the flow to the by-pass line and trapping the two-phase flow in the test line. Thus, after the drainage of the test line, it was possible to compare the registered measurement of the sensors with the real value of volumetric fraction.

2.2 Capacitive sensors

Some basic characteristics must be verified to validate the proposed capacitive technique. The instrument must have good sensitivity, be capable of measuring volumetric fractions in liquid-gas, liquid-liquid and liquid-liquid-gas flows, be relatively immune to the phases spatial arrangement, of easy construction, non-intrusive and non-invasive. To satisfy all requirements, three types of configurations were tested. Parallel-plates, double-helix and double-ring geometries were evaluated under similar conditions (Fig. 3). The sensors have different characteristics in terms of sensitivity and immunity to flow pattern. The differences are related intrinsically to the electric field that is formed between the electrodes.

It is worthwhile to point out that in case of dealing with three-phase flow, three variables must be evaluated, i.e., the volumetric fractions of the phases. In that sense, a well-posed mathematical approach demands at least three equations for the direct solution of the problem. Besides the conservation of mass, the other two equations arise from the modeling of the correlation between capacitive signal and volumetric fraction. Therefore, at least two sensors of different geometry are necessary for three-phase flow measurements.

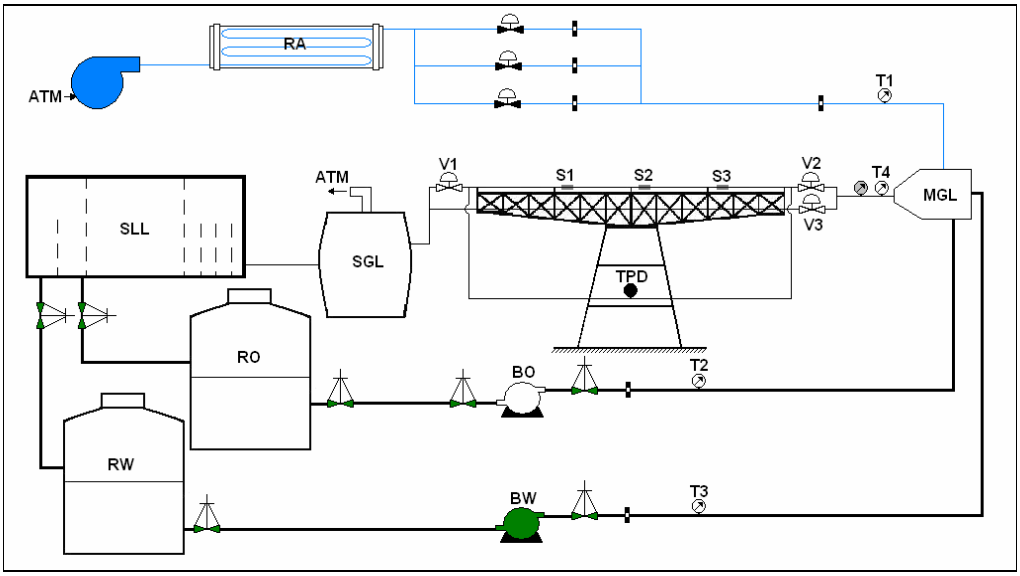
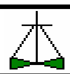
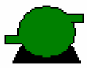
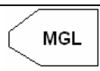
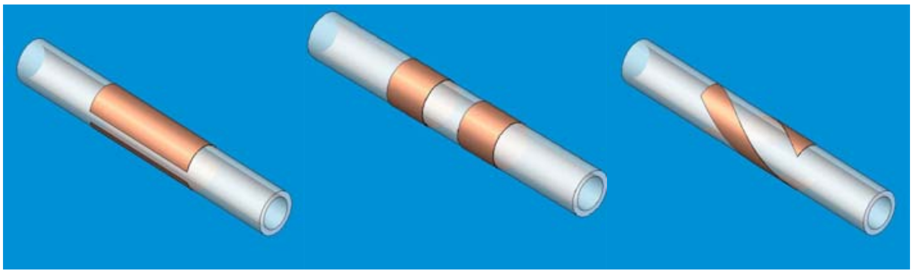


Figure 2. Schematic view of the setup.

Table 1. Main instruments and equipment of the setup.

	Control valve		Pressostate
	Air compressor		Thermocouple
	Oil pump		Pressure differential transducer
	Water pump		Orifice plate
	Solenoid valve		Capacitive sensor
	Pneumatic valve		Multiphase mixer


(a) (b) (c)
Figure 3. Configurations of the sensors; (a) parallel plates, (b) rings and (c) helix.

Initially, benchmark tests (static) were executed with two-phase arrangements. A *4294A Agilent* impedance analyzer was used for this purpose. In a second stage, three-phase experiments were performed in order to obtain a definitive model. Full-pipe tests with each one of the fluids (water, air and oil) showed that the positioning of the sensor in relation to the horizontal plan did not exert any influence on the measured value. However, the same did not occur with partially full pipe, where different results for the same fluid fraction were observed. The sensor's response depends on the distribution of the electric field and it was observed that such a dependence differs significantly from the rings to the helix geometry. The shield of the sensor also interferes in the capacitance reading. An isolating element between the sensor and the environment was necessary to attenuate the effects of capacitive loss. The chosen shield's geometry configured a metallic Faraday cage.

After the static tests, a compromise between sensitivity and flow-pattern immunity led to the choice of a double-sensor probe made of double helix and ring sensors.

2.3 Transducer Circuit

To perform the dynamic tests a transducer circuit was designed and assembled at the NETeF. The circuit used in the experiments is schematized in Fig. 4.

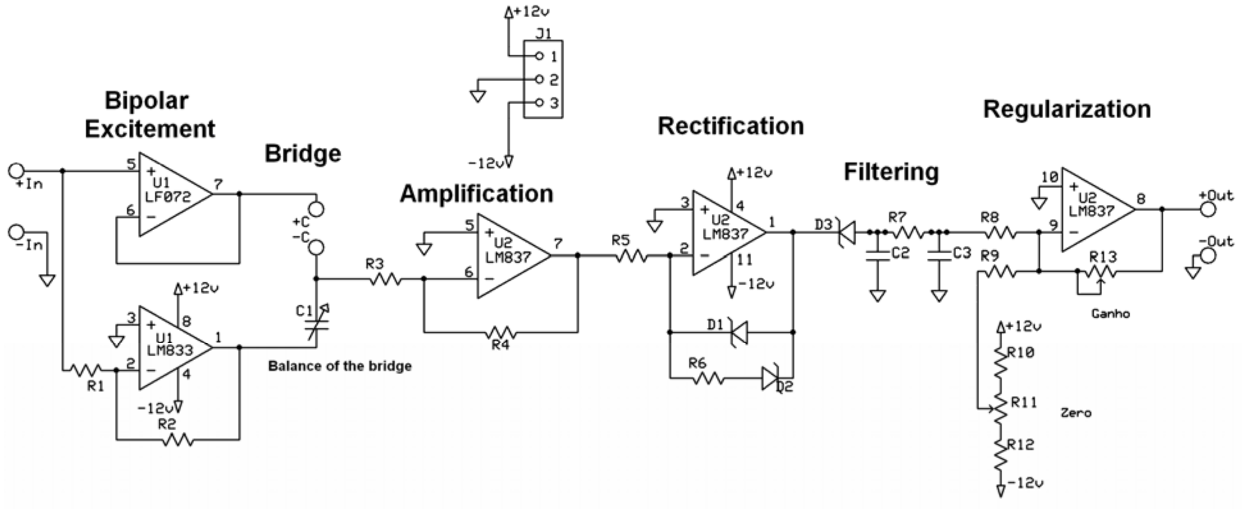


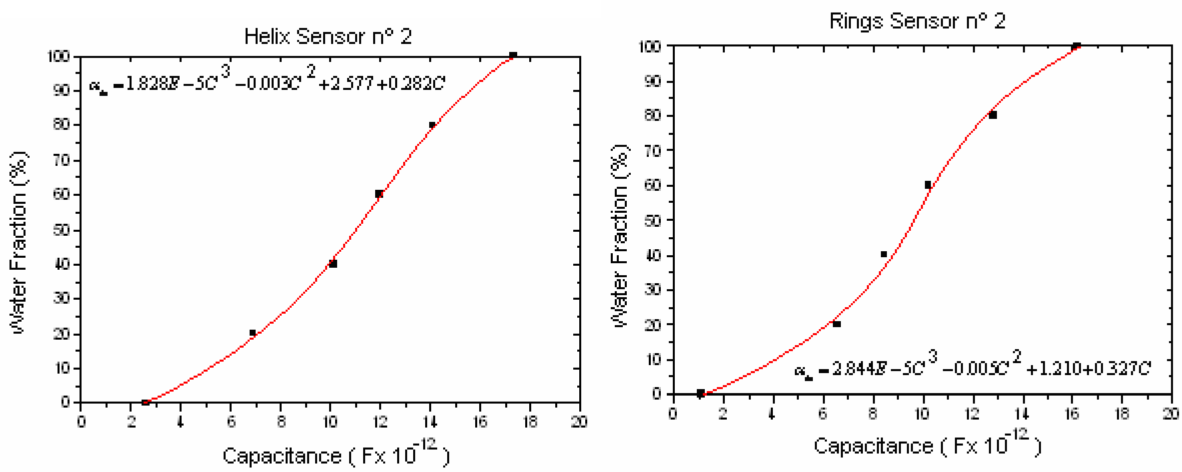
Figure 4. Transducer circuit with bridge of capacitors and sources of tension designed and assembled at NETeF.

The circuit shown in fig. 3 is easy to model as its solution is always a real value, as the tension signals of the circuit and the bridge are in phase. This circuit works with two sources of tension, in different phases, connected to the bridge of capacitors. After the stage of excitement, a pre-amplification is performed. The following stages can be seen in Fig. 3 (rectification and filtering of the signal). The reference capacitor is adjustable so that it guarantees a physical correlation similar to that of the sensor. After signal filtering a last amplification is performed. At this stage, with the help of two potentiometers, it is possible to adjust the zero (0 volts) and full-range (5 volts) of the capacitive meter with the pipe full of air and water, respectively.

3. RESULTS AND DISCUSSION

3.1 Static calibration

The static calibration was carried out with water-air, oil-air and oil-water mixtures. The probe, composed of rings and double-helix sensors, was mounted on a 1 inch, 1.5-m-length hydrophilic-glass pipe. For these tests a *4294A Agilent* impedance analyzer was used and adjusted to range frequencies in the band of 10 Hz up to 100 kHz. The phase fractions were set through the previous knowledge of the volumes of each phase. The capacitance was measured for different phase fractions and graphs of volumetric fraction against capacitance were drawn. The same procedure was repeated later in the multiphase test line using the transducer circuit. The static graphs were used as a benchmark for the dynamic experiments. It is worthwhile to point out that the calibration was done for the stratified flow pattern only. A similar sensor response for other flow patterns was expected, as immunity to flow patterns is a desirable characteristic.



(a) (b)

Figure 5. Water fraction as a function of capacitive reading; (a) sensor of helix nº 2, (b) rings sensor nº 2.

One can verify in Fig. 5, for water-air mixtures, that between volume fractions of 90% and 10% the instrument has a behavior that could be considered quasi-linear. Similar results were obtained for water-oil and oil-air mixtures.

3.2 Dynamic measurements

The sensors' accuracy could be evaluated quantitatively by comparing values obtained statically with those obtained dynamically for stratified flow. For other flow patterns it is possible to infer about the sensor's sensibility and flow-pattern immunity. In the dynamic tests several gas-liquid flow patterns were generated: bubbles, Stratified, Annular and Slug flow. Except for the latter, whose data were independently treated and analysed, for each flow pattern a time average was taken in an interval of 20 seconds after reaching the steady state. For the dispersed or parallel flow patterns the signal given by the circuit was almost constant. Several replicates were taken in order to evaluate the measurement reliability.

Figure 6 shows a comparison between static (solid curve) and dynamic values of water in-situ volumetric fraction taken with the helix sensor in air-water two-phase flow.

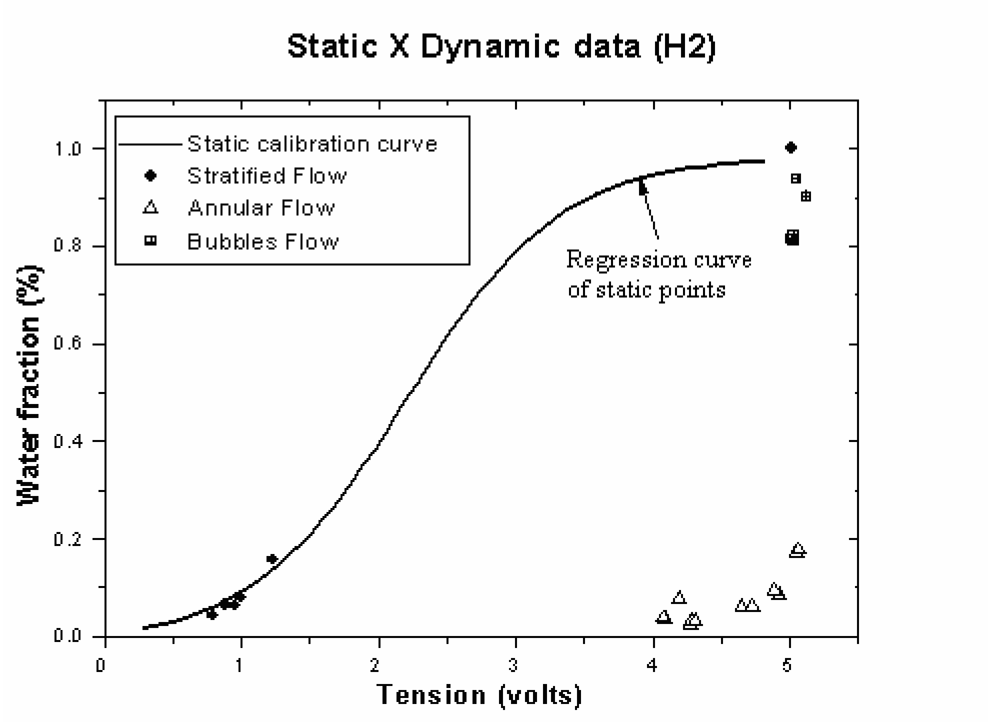


Figure 6. Comparative graph with diverse air-water flow patterns; helix sensor nº2.

The agreement between the statically taken calibration curve (Fig. 6, solid curve) and the points acquired during the steady-state two-phase flow is quite good for bubbles and stratified flow patterns. The error is estimated through the global relative averaged error:

$$e = \frac{1}{N}\sum_{1}^{N}\sqrt{\left(\frac{a_p - a_v}{a_v}\right)^2} \tag{1}$$

where a stands for measured water volumetric fraction, subscripts p and v are the capacitive probe and quick-closing-valves, respectively, and N is the number of runs. The error was 10% for both bubbles and stratified flow. On the other hand, the results are clearly unsatisfactory for annular flow (Fig. 6, open triangles), which is not surprising. The water annulus should have a significant effect on the electric field. Water has an electrical permissivity 80 times higher than air and in annular flow it stays concentrated adjacently to the pipe wall. Obviously, the electrical charge would preferentially flow through the water annulus, avoiding the air core. Another phenomenon that could be further investigated is the likely relation between electrical permissivity and density of the flowing gas. In our experiments a significant increase in the tension signal was detected under high-pressure-fluctuation conditions, which occurred mainly in the annular and slug flow patterns.

The rings sensor presented similar results (Fig. 7). The error was also 10% for both bubbles and stratified flow. Although less intense, the same unsatisfactory results were observed for the annular flow. Despite its relatively weaker signal, the rings sensor showed less susceptibility to flow pattern. Such qualitative results are in perfect agreement with several works found in the literature. As the quasi-linear response of the instrument is apparently between 10% and 90% of water fraction, it is likely that the data would present a best fit in that region. However, due to experimental limitations it was not possible to include any point within that region.

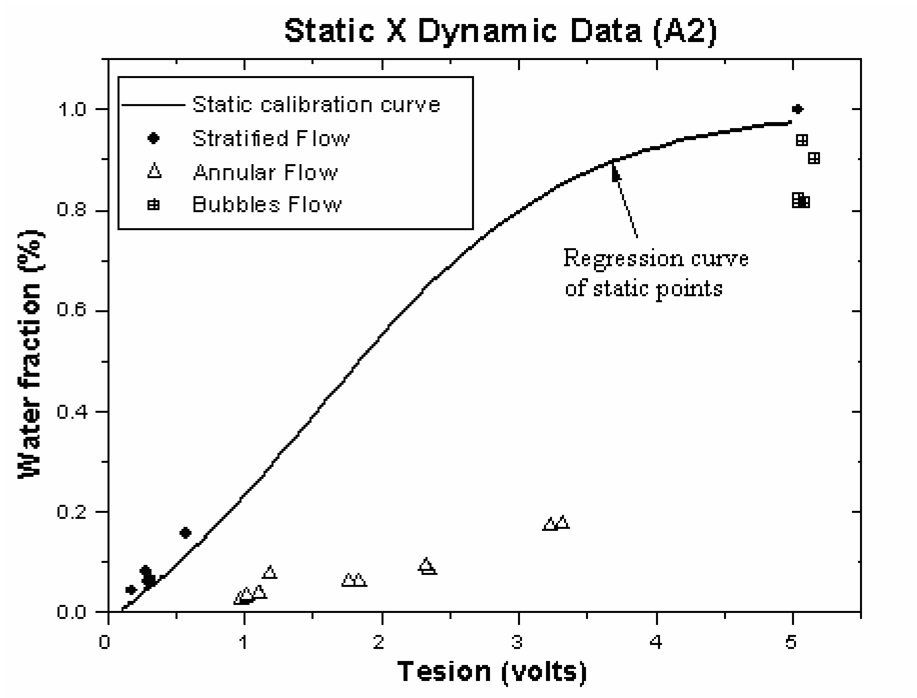
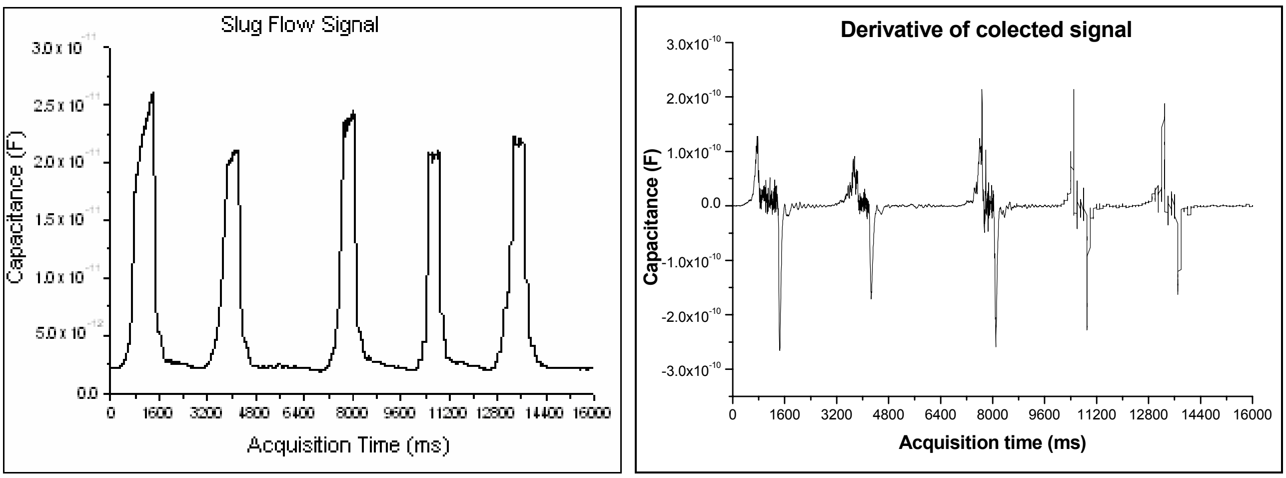


Figure 7. Comparative graph with diverse air-water flow patterns; rings sensor nº2

3.2.1 Dynamic measurements of volumetric fraction in slug flow

As the slug flow is an intermittent flow pattern, it was treated differently. The signal delivered by the transducer circuit suffers extreme variations, alternating tension values that correspond to a pipe full of water and rather full of air. The implementation of a signal reconstruction technique was necessary for the volumetric fraction determination. Five different time-averaged techniques were tested and implemented in *LabView®* to directly obtain the volumetric fraction. The single-cut derivative was the technique that presented the best results. Figure 8(a) shows a typical capacitance signal acquired in our experiments, taken in a time interval of 16 seconds.



(a) (b)

Figure 8. (a) Extracted signal of slug flow with rings sensor nº2; (b) respective derived signal.

Figure 8(b) shows the derivative of the signal shown in Fig. 8(a). The interval between subsequent superior and inferior peaks could be related to the length of the water slug. The positive and negative derivatives indicate the beginning of the water slug and the end of it, respectively.

The described method needed a fine adjustment of the cutting level in order to eliminate noise interference. The determined cutting limit for the rings sensor was -1.5 volts below the mean value of acquisition, i.e., zero for the derivative technique. For the helix sensor the cut was made at -0.5 volts.

Figure 9 shows the results of the rings sensor after treatment in comparison with water fraction values taken via the quick-closing-valves technique. The response of the helix sensor was quite similar. The agreement is quite good, except for 7 points (Fig. 9, encircled points), 5 below 25% and 2 above 70% of water fraction. Those strange results are related to the transition to annular and bubbles flow patterns, respectively, as observed in our experiments. The proposed data treatment technique is obviously applicable only to slug-flow pattern. Excluding the points related to transition regions, the error given by Eq. (1) was 5% for the rings sensor and 2,5% for the helix sensor.

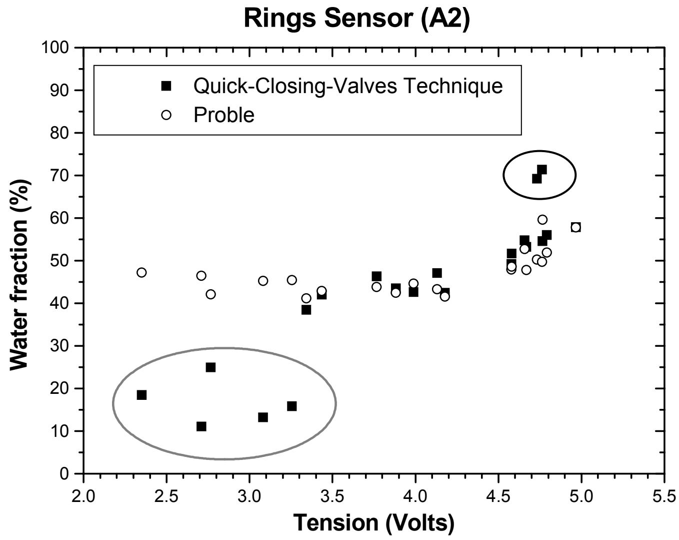


Figure 9. Comparative graph for slug flow pattern using rings sensor nº2

3.3 Static measurements in three-phase conditions

The double-sensor capacitive probe was also tested in three-phase conditions. The probe's working principle is the simultaneous reading of two sensors: the low-sensibility low-flow-pattern-dependent rings sensor determining the water fraction and the high-sensibility helix sensor determining the oil or air fraction. The mathematical problem is considered well-posed. As a first approach a linear system of three equations and three variables was considered. Such simplification seems reasonable within the range of 10% to 90% of volumetric fraction (Figs. 5, 6 and 7). The system of equation shown below describes how the problem was treated.

$$\begin{bmatrix} A & B & C \\ D & E & F \\ 1 & 1 & 1 \end{bmatrix} . \begin{pmatrix} a_w \\ a_o \\ a_a \end{pmatrix} = \begin{pmatrix} V_{an} \\ V_{he} \\ 1 \end{pmatrix} \tag{2}$$

α_w – *Volumetric fraction of water;*
α_o – *Volumetric fraction of oil;*
α_a – *Volumetric fraction of air;*
V_{an} – *Tension signal of the rings sensor;*
V_{he} – *Tension signal of the helix sensor.*

The first and second equations relate the volumetric fractions to the rings and helix sensor responses, respectively. The third equation is simply the principle of conservation of mass. The coefficients of the matrix can be experimentally obtained. The well-posedness requires that the coefficients have different values. Nevertheless, coefficients B and C are expected to have similar values, since the rings sensor should not have enough sensibility to distinguish oil from air.

In order to validate our methodology, static three-phase tests were carried out to obtain the coefficients that would satisfy the equations. The tests evaluated the probe's performance through a simulation of stratified oil-water-air flow conditions. Table 2 shows the adopted volumetric fractions. All tested fractions were between 90% and 10%. The test procedure was the same adopted for the two-phase static tests. The impedance analyser was once more applied in order to avoid any possible noise or imperfection of the transducer circuit. The coefficients of the matrix (Eq. 2) were inversely calculated through the capacitance values measured by the sensors (Table 2) and by referring to the previous values obtained in the two-phase tests (liquid-liquid and gas-liquid).

Table 2. Fluid fractions in the static three-phase tests

Water Fraction (%)	Air Fraction (%)	Oil Fraction (%)	Rings sensor capacitance (pF)	Helix sensor capacitance (pF)
20	60	20	7,07998	9,02017
30	50	20	7,35967	9,16232
30	40	30	7,45001	9,26998
30	30	40	7,55078	9,38412
40	20	40	7,82519	9,52667

The final model can be seen below (Eq. 3).

$$\begin{bmatrix} 9{,}08943 & 7{,}30088 & 6{,}34533 \\ 9{,}93837 & 9{,}62187 & 8{,}51287 \\ 1 & 1 & 1 \end{bmatrix} . \begin{pmatrix} a_w \\ a_o \\ a_a \end{pmatrix} = \begin{pmatrix} C_{an} \\ C_{he} \\ 1 \end{pmatrix} \tag{3}$$

The coefficients are of picofarad order. One may notice that capacitance was directly used for the determination of the coefficients, instead of tension. Differently from the transducer circuit, the impedance analyser delivers capacitance. The maximum capacitance variation observed was of 0.7 pF. Therefore, a very accurate meter would be necessary to guarantee a reliable measurement in three-phase flow. Under the controlled conditions described above, the oil, water and air volumetric fractions were obtained via Eq. (3) with a maximum error of 2.5%.

4. CONCLUSIONS

A non-intrusive double-sensor capacity probe has been proposed and evaluated for in-situ volumetric fraction measurement in two-phase and three-phase flows. A compromise between sensibility and flow-pattern immunity led to the choice of double-helix and rings as sensor geometries. The rings sensor had a less intense signal, but good flow-pattern immunity. On the other hand, the helix sensor was more sensitive to flow pattern, but produced a more intense signal. A single calibration curve obtained statically was applied for the two-phase flow measurements. In-situ volumetric fractions were measured with quite good accuracy in water-air stratified and dispersed flows (global relative averaged error of 10%). Quite good results were also obtained for slug flow after a special time-averaged treatment based on the derivative of the signal (global relative averaged error of 5%). Unsatisfactory results were obtained for annular flow. Such results suggest the implementation of flow patterns dependent method, i.e, a specific calibration curve for each flow pattern. The function between capacitance and volumetric fraction was clearly non linear (Figs. 5-7). However, it was observed that between 10% and 90% of volumetric fraction the relation can be approximated to quasi-linear. A model for volumetric fraction measurement in three-phase flow was proposed and studied for prospective purposes. It is based on a linear system of three equations and three variables. Therefore, at least two sensors with different characteristics are necessary. The model can be applied only within the quasi-linear region and a meter with excellent accuracy is required for the determination of the coefficients of the system. Under controlled static condition it was possible to measure simultaneously and with very good accuracy volumetric fractions of water, oil and air (maximum relative error of 2.5%).

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