NON-INTRUSIVE CAPACITIVE PROBE FOR MEASUREMENT OF IN-SITU VOLUMETRIC FRACTION IN WATER-OIL AND WATER-AIR FLOWS

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Abstract. *Gas-liquid and liquid-liquid two-phase flows are present in many industrial sectors, including petrochemical, metallurgy, pharmaceutical, cooling, etc. Three-phase flows are also very common in practice, however the information found in the literature is quite scarce. The evolution of liquids production and transportation techniques frequently come across difficulties which are connected to measurements of flow properties. One of the main difficulties is related to flow rate measurement in multiphase flows. Currently there is a lack of measurement systems combining simplicity, low cost, reliability and safety features. The main goal of this work is the development of a non-intrusive capacitive probe to measure "in-situ" volumetric fraction in two-phase oil-water and water-air flows. We address the two-phase measurements as a starting point for the more complex three-phase-flow problem. We have experimentally studied three different geometrical configurations and established which type of sensor would be better adapted to our needs. A combination of two different geometries is proposed, applied in parallel as a single probe. An experimental approach was developed and applied to validate the probe using water-oil and water-air mixtures. The two-phase flow results show that the capacitance readings grow lineally as a function of the fractions of the liquids or gas present in the pipe. The actual application of the probe to three-phase flow is promising.*

Keywords: *Two-phase flow, Oil-water flow, In-situ volumetric fraction, Capacitive probe, Non-intrusive technique*

1. Introduction

In many industries the production and control of processes are directly connected to the knowledge of the "in-situ" amounts of liquid and gas in the transport lines. A typical case is found in the oil industry, where during the pumping process the phases may assume several different geometrical configurations or flow patterns, which are related to the input rates, physical properties of fluids, pipe geometry, material and inclination. A few recent studies have been dealing with flow pattern characterization. Alkaya et al. (2000) studied the effect of slight inclinations on the horizontal liquid-liquid flow patterns. Oddie et al. (2003) observed two and three-phase flow patterns in inclined pipes with kerosene, tap water and nitrogen. They compared two different techniques for holdup measurements. Bannwart *et al* (2004) studied experimentally the flow patterns in heavy oil-water pipe flow in horizontal and vertical glass sections. Those authors observed intermittent, dispersed and segregated patterns, including core-annular flow. Angeli and Hewitt (1998) studied the correlation between pressure gradient and pipe material in liquid-liquid flow and detected that roughness can be also an important parameter. They also detected the appearance of peaks of pressure gradient related to phase inversion for the fully dispersed flow patterns. The correct prediction of the flow pattern depends on the prediction of the "in-situ" volumetric fraction of the phases. The steady-state "in-situ" volumetric fraction of the phases (holdup) may be understood as the actual percentage of water, air and oil in the line, i.e. slip ratio effects must be taken into account. Holdup measurement requires an easily measurable quantity that would be linearly related to the volume fraction occupied by each phase. Several techniques have been developed for the measurement of the liquid fraction in two-phase flows. They are as often as not based on the detection of differences between the physical properties of the phases. As an example, absorption or scattering of radioactive emissions have been successfully used, however cost and strict safety standards represent practical limitations. Elseth (2001) and Oddie *et al* (2003) measured for a number of flow conditions local phase fractions using transmiters and a transverse gamma densitometer. The capacitive technique suits quite well this purpose as through the permittivity of each fluid one may obtain a lineal relationship between capacitance and holdup. Sami *et al*. (1980) compared experimental results with a number of capacitive measurements for slug and stratified flows. This work validates the linear relationship between capacitance and volumetric fraction. Reis (2003) studied gas-liquid flow patterns (slug and stratified) and applied two kinds of capacitive sensors for holdup measurements, double helix and rings. He suggests that the double-helix sensor is reasonably immune to flow patterns and states that the non-intrusive capacitive technique is suitable for holdup measurements. This technique is quite interesting from the economical, simplicity and safety points of view. Sttot *et al.* (1985) studied the applicability of two concave-plate electrodes, mounted internally and externally on the pipe wall. That author concluded that the externally mounted electrode would be satisfactory only for fluids with high resistivity and low permittivity characteristics.

This paper presents a non-intrusive and non-invasive capacitive measurement technique for holdup, initially in two-phase flows as a starting point for the more complex three-phase flow problem. The technique should be immune to any flow pattern effect, i.e., the recorded values of volumetric fraction should be independent of the geometrical arrangement of the phases. The capacitance is measured in a dielectric environment and it is excited by a frequency that does not cause high dissipation. The optimum frequency ranges were selected by the clean capacitance readings, without significant noise due to resistive effects.

2. Capacitive probe for holdup measurements

2.1. Sensor characteristics

A capacitor consists of two metallic plates separated by small distance and submitted to an electric potential difference (V). The observed effect is the accumulation of electric charge between the plates, which can be measured with an impedance analyzer.

Assuming as uniform the electric field that is limited by two plain plates, the charge density (σ) is given by the ratio between the amount of charge (Q) and the area of the plates (A), Eq. (1). The electric field (E) is given by Eq. (2), where ε_0 is the electric permissivity of a fluid in vacuum. The potential difference between the plates can be written according to the Eq. 3, multiplying the electric field (E) by the distance among the plates (d).

$$\sigma = \frac{Q}{A} \quad \textbf{(1)}$$

$$E = \frac{\sigma}{\varepsilon_0} \quad \textbf{(2)}$$

$$V = \int E.dl = E.d \quad \textbf{(3)}$$

Then, using Eqs. (1), (2) and (3) arises:

$$V = \frac{Q.d}{\varepsilon_0 .A} \quad \textbf{(4)}$$

The inverse coefficient of proportionality, Q over V, is the capacitance (C) and can be obtained through Eq. 5:

$$C = \frac{Q}{V} = \frac{\varepsilon_0 .A}{d} \quad \textbf{(5)}$$

Therefore, one may see that there is a linear relationship between permittivity (ε) and the capacitance (C), which is valid for any configuration of plates.

There are several sensor configurations. Each one has its own properties: concave-parallel-plate sensors show high sensitivity, but are highly dependent on the flow patterns; ring sensors show immunity to the flow patterns, but present low sensitivity; double-helical sensors offer intermediate characteristics (Sami et al., 1980, Stott et al., 1985, and Kendoush and Sarkis, 1995). Three types of sensor were studied in this work: concave, rings and helical (Fig. 1).

2.2. Probe characteristics

The ultimate goal of this research still under development is the evaluation of a capacitive probe as a solution for holdup measurement in three phase oil-water-air flow. The in-situ volumetric fraction of water (or water holdup) in oil-water-air pipe flow usually can be correlated as a local quantity and measured as shown:

$$\varepsilon_w = \frac{v_{water}}{v_{oil} + v_{water} + v_{air}} = \frac{a_{water}}{a_{oil} + a_{water} + a_{air}} \quad \textbf{(6)}$$

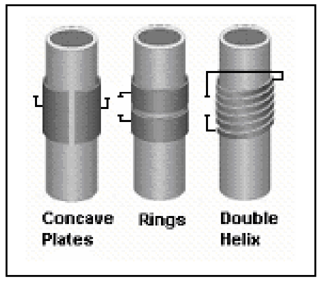

Figure 1. Types of sensors studied (Jaworek and Krupa, 2004)

where "*v*" refers to volume and "*a*" to the pipe´s cross-section area; analogous expressions can be drawn for the other phases.

As a matter of fact, there are three unknowns to be evaluated: water (ε_w), oil (ε_o) and air (ε_a) holdups and one single sensor offers only one equation, represented by Eq. (7):

$$A\varepsilon_w + B\varepsilon_o + C\varepsilon_a = V_1 \qquad \textbf{(7)}$$

where A, B and C are constants, which are function of the fluids properties and sensor geometry, and V_1 is the sensor response. The second equation arises from the continuity equation, i.e.:

$$\varepsilon_w + \varepsilon_o + \varepsilon_a = 1 \qquad \textbf{(8)}$$

The third equation should be given by a second capacitive sensor. The problem can then be represented by the following system:

$$\begin{bmatrix} A & B & C \\ D & E & F \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_w \\ \varepsilon_o \\ \varepsilon_a \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \\ 1 \end{bmatrix} \qquad \textbf{(9)}$$

Although we now have three equations for three unknowns, the well-posedness of this problem still depends on the geometry of the sensors. Nevertheless, it becomes clear that the three-phase probe should comprise two different sensors.

3. Experimental procedure and preliminary results

3.1. Probe geometry

We used an *Agilent 4294A Precision* Impedance Analyzer in order to measure the capacitance signal and evaluate the probes' performance. An experimental setup was designed and constructed for the calibrations (Fig. 2).

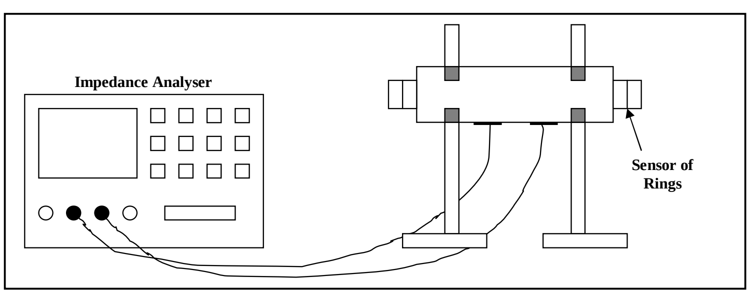

Figure 2. Schematic view of the experimental setup.

The concave-plate sensor offered a high sensitivity signal, in accordance with Jaworek and Krupa (2004). However, it was not immune to the flow pattern. The ring sensor presented immunity to the flow patterns, but a lower sensitivity signal. The helical sensor presented intermediate characteristics. It offered a signal with reasonable sensitivity and immunity to flow patterns, as expected.

The measurements were taken with the pipe first filled up with air, then water and finally oil. It was observed that oil and air possess very close values of capacitance, as expected. The ring sensor presented an almost imperceptible difference in the capacitance signal between oil and air (Fig. 3a). On the other hand, the sensor of double helixes presented a measurable difference of the order of 1.10^{-12} F (Fig. 3b). During the measurements no effect of inclination angle was detected.

We decided to measure the fraction of water with the ring sensor by taking advantage of its good flow-pattern immunity and recognizing that the capacitance signal difference between water and the other fluids is high enough (Fig. 3a). Have in mind that the magnitudes of capacitance signals of oil and air are quite similar in comparison to that of water. That proximity between the capacitance values of oil and air is due to the fact that these substances have very close permittivities. Nevertheless, we would still need a higher sensitivity sensor to differ between oil and air. Hence, we decided to use the helical sensor to measure the fractions of oil and air, since that geometry offers not only a higher sensitivity signal (Fig. 3b), but also reasonably good flow-pattern immunity.

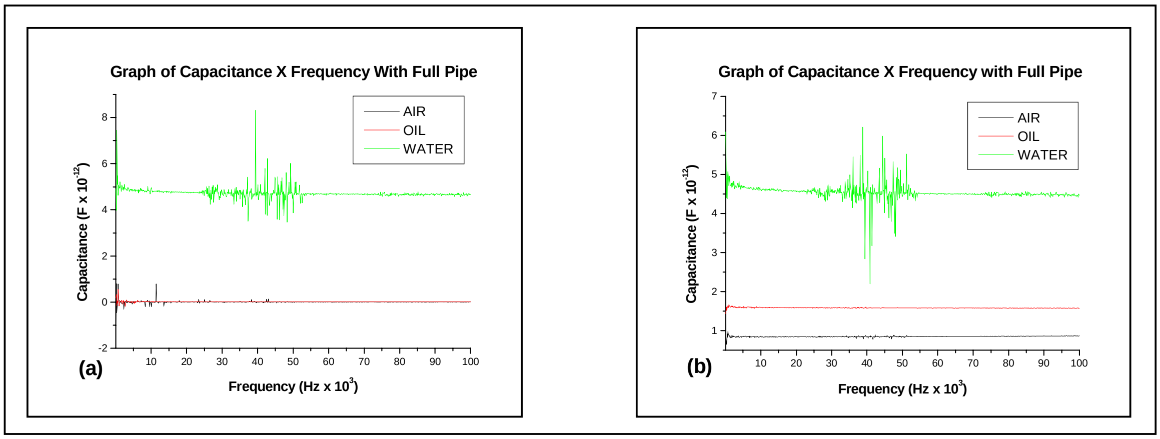

Figure 3. Graph of Capacitance *x* Frequency for Air, Oil and Water; (a) rings sensor, (b) double-helix sensor

At this point some remarks should be pointed out. The ring sensor would allow differing only between water holdup and an effective oil-air holdup (ε_e) (refer to Fig. 3a). The system represented by Eq. (9) would be reduced to the following:

$$\begin{bmatrix} A & B & B \\ D & E & F \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_w \\ \varepsilon_o \\ \varepsilon_a \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \\ 1 \end{bmatrix} \qquad \textbf{(10)}$$

Thus, for the steady-state flow case a solution for the water holdup could be simply given by:

$$A\varepsilon_w + B\varepsilon_e = A\varepsilon_w + B(1-\varepsilon_w) = V_1 \qquad \textbf{(11)}$$

Then, with the help of the helical sensor the oil and water holdup are directly obtained by:

$$\begin{bmatrix} D & E \\ 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_o \\ \varepsilon_a \end{bmatrix} = \begin{bmatrix} M \\ N \end{bmatrix} \qquad \textbf{(12)}$$

where M and N are known parameters. Anyway, for the more general problem that includes transient flow, the complete system must be solved (Eq. 10).

A last remark should be made with respect to a possible dependence of the helical sensor on the water holdup. This is still to be evaluated and if it is the case the problem will require an additional solution algorithm.

3.2. Optimum frequency

We also used the Impedance Analyzer in order to evaluate the optimum frequency ranges for measuring the capacitance signal. The chosen frequency range was from 100Hz to 100KHz. Higher frequencies were discarded to avoid matters related to noise, as we choose to operate with a circuit as simple and reliable as possible. Within this interval we observed suitable regions of relatively low signal spreading, which may be explained by the low resistivity or impedance associated. On the other hand, we also spotted regions of high spreading. Figure 4 shows measurements of voltage versus frequency for air using the double-helix sensor. One may see the clear high-signal-spreading region in between 25KHz and 55KHz. Evidently, such frequency range should be avoided. In that frequency range impedance and resistivity effects supercede the capacitive nature of the sensor. The minimum frequency for which it was observed a low signal spreading was around 60KHz (Fig. 4).

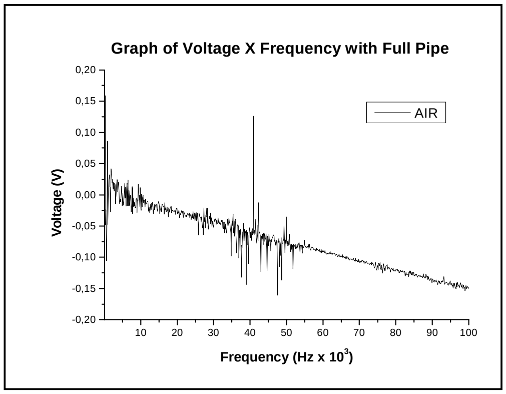

Figure 4. Graph of Voltage X Frequency for air; double helix sensor.

Figure 5 shows measurements of voltage versus frequency for oil using the double helix sensor. The minimum frequency for which it was observed a low signal spreading was also around 60KHz.

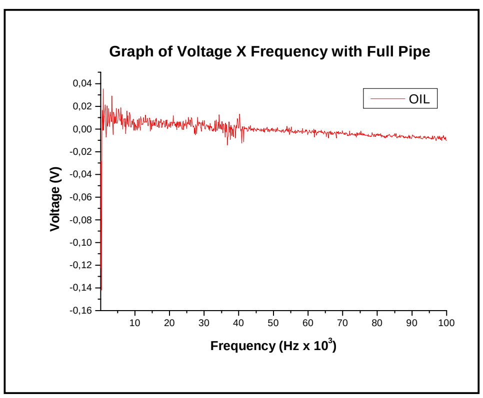

Figure 5. Graph of Voltage X Frequency for oil; double helix sensor.

Figure 6 shows measurements of voltage versus frequency for water using the ring sensor. A frequency considered suitable for the capacitance measurements was around 15KHz.

Therefore, the chosen frequency for air and oil holdup measurements was 60 KHz (helical sensor). For water holdup measurement it was 15KHz (ring sensor). These will be the frequencies of excitement of the probe's circuit. The circuit is still to be designed and will allow the correlation between the voltage associated to capacitance and the in-situ volumetric fractions of water, air and oil.

3.3. Static calibration

After the determination of the probe's geometry, static calibrations were carried out. The ring and helical sensors were firstly calibrated with two-phase mixtures by varying the volume fractions of each phase by about 5%. Although the capacitance readings were recorded in frequencies from 100Hz to 100KHz, only the results related to 15KHz and 60KHz, for the ring and helical sensor, respectively, were considered. At these frequencies we have assured a clean signal without dissipation due to resistivity or any other phenomenon.

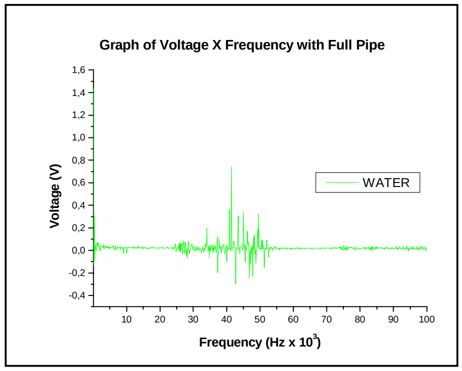

Figure 6. Graph of Voltage X Frequency for Water; rings sensor.

Figure 7 shows readings of capacitance as a function of water holdup taken with the ring sensor. A linear relationship between the capacitance signal and the volume fraction of water was detected for both water-oil and water-air combinations. Such result reassures the potentiality of the non-intrusive capacitive technique as a measuring tool. Furthermore, the water-oil and water-air results almost math, as expected. This result supports the argument exposed in Sections 3.1 about treating oil and air as a single pseudo-phase for water holdup measurements.

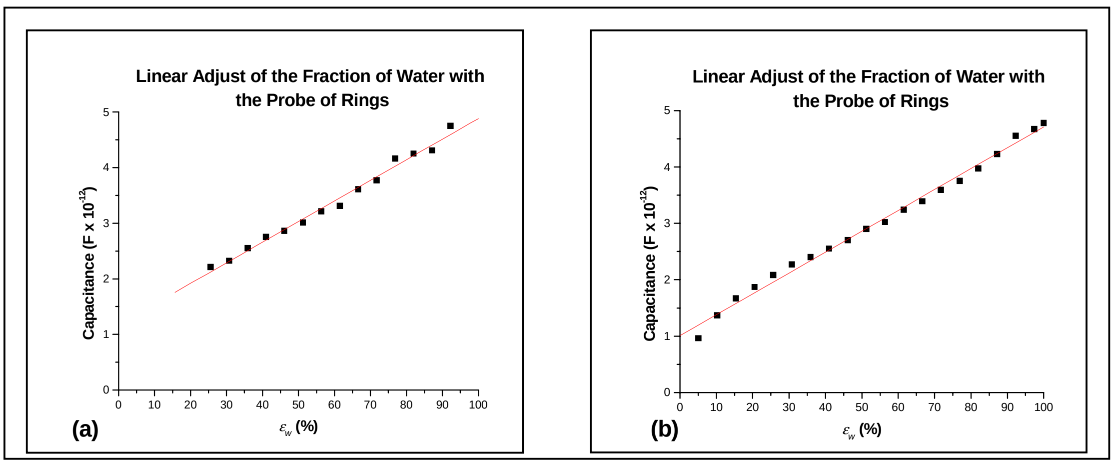

Figure 7. Capacitance as a function of water holdup; ring sensor; (a) water and oil, and (b) water and air.

The helical probe was applied for the oil-air calibrations. Figure 8 shows a clear linear relationship between the capacitive reading and the oil holdup. Once more, the results are encouraging.

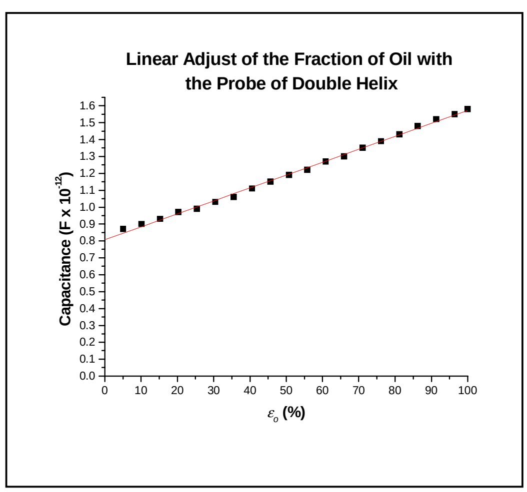

Figure 8. Calibration with Oil and Air

Three-phase tests are also necessary to evaluate the water holdup effect on the double-helix sensor. As explained before, the coefficients *D*, *E* and *F* of Eq. (10) are also function of the sensor geometry. For instance, during the actual oil or air holdup measurements the presence of a water layer at the bottom of the pipe might be equivalent to a change in the probe's geometry. There was a first attempt to evaluate this effect, however the results were unsatisfactory. The three-phase static calibration proved to be infeasible due to limitations of the experimental setup. The detected high experimental uncertainties were associated with edge effects, which would disguise the actual volumetric fraction of the phases. In Fig. 9 one may notice the water (bottom) and oil (center) interfacial curvatures associated to interfacial tension effects (air at the top).

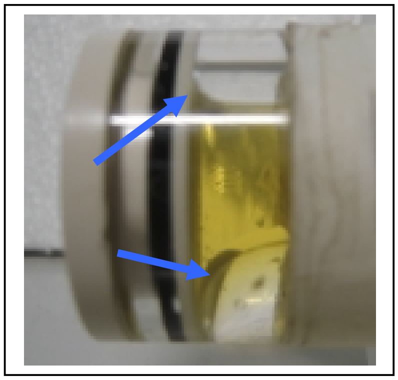

Figure 9. Test tube with oil, water and air

Therefore, this prospective investigation is still incomplete. The next step forward comprises three-phase flow tests as well as dynamic calibrations to be carried out in our experimental facilities. Nevertheless, the preliminary results thus far presented are encouraging.

4. Conclusion

A non-intrusive/non-invasive capacitive technique for in-situ volumetric fraction measurements in liquid-liquid and liquid-liquid-gas pipe flows is proposed. In order to measure in-line oil, water and air holdups a probe composed of two sensors is necessary. An evaluation of the well-posedness of the governing equations was carried out. The solution for three-phase holdup measurement is straightforward as long as the response of the probe is a function of the physical properties of the fluids and the geometry of the sensors only. A ring sensor (high immunity to flow patterns) was chosen for water holdup measurement and a double-helix sensor (reasonable immunity to flow patterns and high intensity signal) was chosen for oil or air holdup measurements. The best frequencies of excitement of the probe were detected, for which we get the lowest noise. Frequencies of 60 KHz for the ring sensor and of 15 KHz for the double-helix sensor were chosen. Both sensors presented a suitable linear relationship between the capacitive signal and the volumetric fraction for any two-phase arrangement tested. Three-phase tests are still to be carried out for the ultimate validation of the probe; nevertheless the prospective results herein presented are promising.

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