IMPEDANCE SENSOR FOR INDUSTRIAL MEASUREMENT OF GAS-LIQUID FLOW

Niederauer Mastelari, niede@fem.unicamp.br
Rosa, S. Eugênio, erosa@fem.unicamp.br
Erico Porto, erico@yahoo.com
Faculty of Mechanical Engineering-State University of Campinas

Abstract. *The impedance measurement technique is a practical and cost effective method to the characterization of gas-liquid mixture properties. It has been used since the late 1950s in several multiphase flow measurements. The operational principle is based on the existing proportionality between the impedance and the gas-liquid concentration although, depending on the probe design, it may change with the flow pattern as well. The impedance results from a combination of the conductive and capacitive effects but usually one of these effects prevail. The dominant effect is primarily defined by electrical properties of the liquid and by the circuit oscillator frequency. At a temperature the impedance changes with the proportion of the mixture and its electrical properties. Although the main interest is the former the latter can be important information too. This work presents a study about an intrusive impedance probe suitable for robust applications in laboratories and industries. It consists of a single rod of stainless steel crossing a metallic tube along the diameter line. The rod is insulated from the pipe. Experimental tests have been made with the probe using: oil, deionizated water, tap water, and ionic solution NaCl 60g/l. These experimental tests are compared with simulations and with an analytical model too. Furthermore is present a conditioning circuit that has been developed to measure the amplitude and phase of wide range of the impedances using the probe. The probe plus the conditioning circuit setting up an impedance sensor adequate for flow measurement. The sensor works by measuring the complex impedance between the rod and the pipe wall, and using amplitude and phase of its impedance can be determinate the void fraction and discriminate the electrical characteristics of the fluids. Dynamic tests have been made using air-water mixture in pipelines with size of 29mm in diameter. It is an exploratory work to develop an intelligent instrument that operates with variation on the electrical characteristics of the mixture and/or different fluids in industrial and laboratorial situations.*

Keywords: Two Phase Flow measurement; Impedance measurement

1. INTRODUTION

The two phase gas-liquid flow is characterized by turbulence, deformable two-phase interface, phase interaction, phase slip, compressibility of the gas phase, therefore it is difficult obtain reliable flow models (Ahmed, 2006). Furthermore, in a practical viewpoint, the two phase gas-liquid flow is very important to the industrial environment, for example, it is present in the Petroleum industries, where the measure of the two phase flow characteristics is important to development, operation and monitoring of multiphase pipelines, control of inventory and supply necessary feedback information to oil production optimization. Therefore two phase gas-liquid flow measurements systems are important to obtain reliable flow models, laboratorial studies and field applications. Specially, the void fraction is a fundamental quantity to describe the basic two-phase behavior during diabatic and adiabatic flow conditions and to develop physical models able to predict mass, momentum and energy transfers and make correlations required to design two-phase flow systems (Devia & Fossa, 2003).

There are many principles of two phase flow measurements including irradiation methods, optical methods, differential pressure and tomography; however the electrical method is more popular than any other method from the view of safety, economics and convenience, (Huang, Zhang, Wang, & Lin, 2007). Furthermore, impedance sensors are easy to implement and give fast time respond signals. In the electrical impedance techniques, the phases can be identified by differences in conductivity and/or permittivity between phases. The impedance results from a combination of both, but at frequency one of these effects prevails. The dominant effect is primarily defined by the liquid conductivity and by the circuit oscillator frequency. In a practical viewpoint the impedance method can be classified into two categories depending on the dominant effect: the electrical conductivity method and the capacitance method. The latter is used to measure the void fraction in two-phase systems in which the liquid is a non-conducting material such as an organic refrigerant or oil or when the electrodes are isolated from the fluids. Abouelwafa and Kendall, 1980, presents a variety of capacitive probes designs: parallel plates, concave plates, staggered concave plates, double helix, multiple helix, and four concave plates. The capacitor plates were mounted on the inside of a thick acrylic pipe. They were protected and isolated from the material inside the pipe by a thin acrylic inner sleeve. Although capacitive probes are typically non intrusive, Huang et. all., 2008, present a single wire intrusive capacitance probe. The capacitance measured by this probe is linearly proportional to equivalent water layer height, EWLH, with a high sensitivity of 1.52 pF/mm. Water is used as a plate of the capacitor in this technique. In this case, the fact of capacitive probes are separated from the flow by a dielectric material they aren’t sensitive to conductivity of mixture. These sensors are appropriate for indoor utilization operating in low pressure and mostly with water or another low-viscosity liquid. They efficiently measure the two-phase flow properties (void fraction, film thickness, flow regime detection or just phase detection) of isothermal gas-liquid flows, as well as of phase-change flows, such as evaporating or condensing phenomena (Masuda et al., 1980, and Heerens, 1986). The electrical conductivity method uses conductivity and permittivity effects to measure the void fraction of the two-phase flow, but the dominant effect is defined by the liquid conductivity. The conductive probe plates have direct contact with the flow, although it works with a conducting material like water it is possible make measures with low conductive fluids too. Conductive Probes of various designs have been used by different workers: Brown,et.al., 1978, use wire probes for measurement of liquid film thickness, Coney, 1973 uses flush inner pipe electrodes to monitoring thickness of a rapidly moving wavy film of water, and Yang et.al., 2003, study volume averaged void fraction using different sets of rectangular and cylindrical probes. They use AC excitation, 100 kHz, in all these experiments.

Impedance methods have been used successfully to measure time and volume averaged void fraction, get and investigate biphasic flow characteristics, identify the flow patterns, measure liquid-film thickness, just phase detection, local detection of bubbly. Regardless this, there are several disadvantages of the impedance technique, which are sometimes difficult to resolve: the impedance measurement is sensitive to the void-fraction distribution and flow regimes, is sensitive to the changes in electrical properties of the mixture, and where works with pressurized lines and abrasive flows it is not possible the use of non-metallic pipes and dielectric thin covering.

A robust conductive probe with wide range conditioning signal is desired specially in energy industries, where there are hardness safety constraints. The wide range amplification is necessary to adapt the electrical characteristics changes with the time, e.g., is the case of petroleum production which is composed by gas and liquid hydrocarbons, salt water and little quantity of solids residuum. The proportion of these components in a non homogenous mixture change slowly, typically the oil predominates in young and salt water predominates in old wells, reducing dramatically the impedance of the mixture with the well life, therefore range amplification control is necessary.

In this work an intrusive conductive probe is presented. This probe consists of a single rod of stainless steel crossing the metallic pipe along the diameter line. The rod is insulated from the pipe and the sensor works by measuring the complex impedance between the rod and the pipe wall. It is robust, simple to build, easy to install, presents high sensitivity, and use the pipe with one earthed electrode. It was developed to withstand the field pressure, temperature, safety requirements and its conditioning circuit is adapted to the changes of electrical characteristics of the flow. This paper starts describing this industrial sensor itself and shows its numerical and analytical analysis. The static tests using different fluids are shown and their dynamic response to the flow patterns: stratified, slug and bubbly. Its electronic circuit conditioning is presented in sequence and finish. The disadvantages of this sensor and its overcoming are approached.

In this paper, the assembly: rod, isolators and the metallic pipe are referred as probe and the arrange probe plus electronic conditioning circuit are referred as sensor.

2. THE PROBE

The probe studied in this work comprises an assembly of a conductive electrode assumed to consist one stainless steel rod, a set of isolators and sealing devices, inserted transversally in a metallic pipe but isolated from it by isolators, as show by the fig.1. The rod crosses the pipe transversally by a line coincident with the pipe diameter line. The rod is kept in place inside the pipe through two pinch points, which, at the same time, keep it electrically insulated from the pipe. Clearly, the centered rod makes this sensor naturally intrusive and operates in contact to the flow, it isn´t recovered.

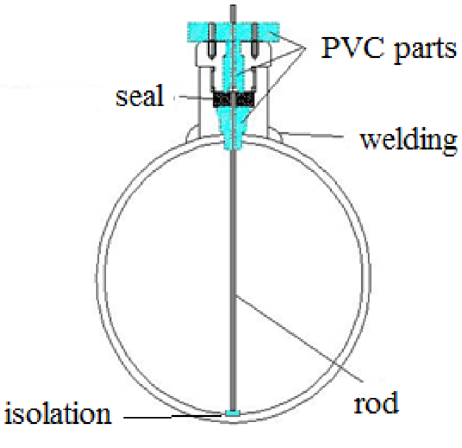

Figure 1. The impedance probe

3. EXPERIMENTAL MEASUREMENTS

An apparatus for static tests was designed and built using a industrial pipe having inside diameter of 59mm, rod and isolators diameters of 2,34 and 13,0 mm respectively. The schematic diagram with the basic dimensions of this assembly is presented in fig.2. The steel pipe received special treatment against corrosion, the rod was made with stainless steel wire and the isolators were machined using PVC. It has an up entrance for the liquid and acrylic lateral viewfinders. The experiments had been made at 25°C filling the apparatus with liquid uniformly in stratified levels. Each increment of level was measured with a pachymeter. The impedance of fluid in this assembly was measured using RLC Bridge, BK Precision model 889B, using 200kHz and 1,0 Vrms of excitation. The tests have been made using oil SAE 20-50, deionizated water, tap water and salt water solution 60g/l. The results are presented in table 1.

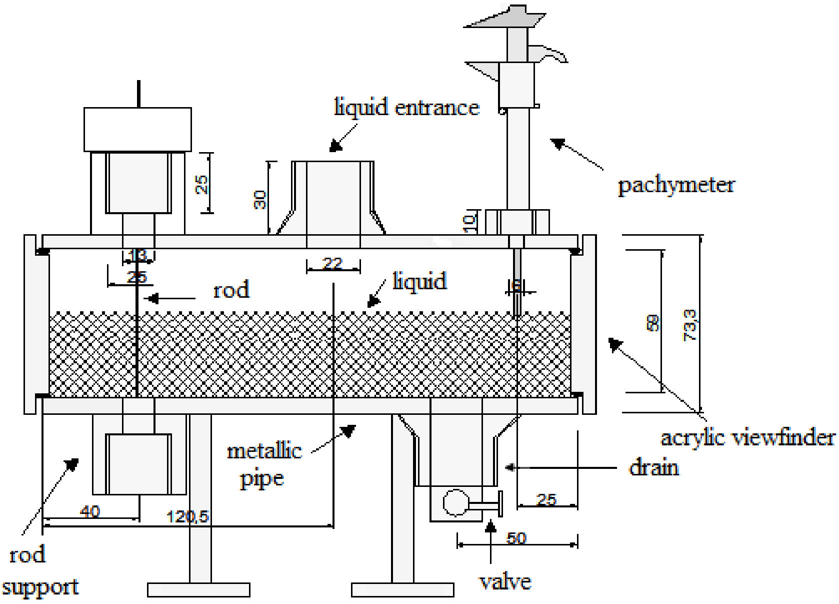

Figure 2. Apparatus for static tests

Table 1. Experimental results for complex impedance of the liquids

Oil SAE 20-50W			Deinonizated Water			Tap Water			Salt Water 60g/l		
h(mm)	|Z| (kΩ)	ang(°)	h(mm)	|Z| (kΩ)	ang(°)	h(mm)	|Z| (Ω)	ang(°)	h(mm)	|Z| (Ω)	ang(°)
0,0 ±0,2	111 ± 2%	-89 ±1	0,0 ±0,2	108 ± 2%	-88,8 ±1	0,0 ±0,2	63530 ± 2%	-78,9 ±1	0,0 ±0,2	112500 ± 2%	-89 ±1
6,6 ±0,2	106 ± 2%	-89 ±1	7,7 ±0,2	24,5 ±1%	-53,0 ±0,5	3,7 ±0,2	4156 ± 0,4%	-5,7 ±0,2	5,8 ±0,2	7,2 ±5%	-6,9 ±1
11,4 ±0,2	104 ± 2%	-89 ±1	10,4 ±0,2	26,7 ±1%	-69,0 ±0,5	9,5 ±0,2	1613 ± 0,4%	-3,6 ±0,2	11,1 ±0,2	4,4 ±5%	-6,8 ±1
15,3 ±0,2	104 ± 2%	-89 ±1	14,8 ±0,2	20,8 ±1%	-64,9 ±0,5	15,4 ±0,2	1045 ± 0,4%	-3,0 ±0,2	16,5 ±0,2	3,2 ±5%	-4,5 ±1
22,3 ±0,2	99 ± 2%	-89 ±1	20,1 ±0,2	16,7 ±1%	-63,7 ±0,5	20,3 ±0,2	823 ±1%	-2,8 ±0,4	20,0 ±0,2	2,7 ±5%	-3,3 ±1
25,1 ±0,2	100 ± 2%	-89 ±1	26,3 ±0,2	14,0 ±1%	-64,6 ±0,5	25,3 ±0,2	688 ±1%	-2,7 ±0,4	26,1 ±0,2	2,1 ±5%	-3,3 ±1
30,4 ±0,2	98 ± 2%	-89 ±1	31,2 ±0,2	12,6 ±1%	-63,6 ±0,5	30,5 ±0,2	588 ±1%	-2,6 ±0,4	31,7 ±0,2	1,8 ±5%	-3,0 ±1
35,5 ±0,2	96 ± 2%	-89 ±1	37,5 ±0,2	10,8 ±1%	-61,4 ±0,5	36,1 ±0,2	514 ±1%	-2,5 ±0,4	35,6 ±0,2	1,6 ±5%	-2,5 ±1
39,9 ±0,2	95 ± 2%	-89 ±1	43,6 ±0,2	9,7 ± 0,4%	-61,7 ±0,5	42,6 ±0,2	446 ±1%	-2,5 ±0,4	40,3 ±0,2	1,5 ±5%	-2,4 ±1
46,3 ±0,2	94 ± 2%	-89 ±1	46,5 ±0,2	9,2 ± 0,4%	-60,6 ±0,2	45,1 ±0,2	418 ±1%	-2,4 ±0,4	46,0 ±0,2	1,3 ±5%	-2,4 ±1
50,4 ±0,2	90 ± 2%	-89 ±1	50,5 ±0,2	8,3 ± 0,4%	-60,3 ±0,2	49,9 ±0,2	383 ±1%	-2,4 ±0,4	50,8 ±0,2	1,2 ±5%	-2,6 ±1
53,5 ±0,2	91 ± 2%	-89 ±1	54,5 ±0,2	7,1 ± 0,4%	-59,1 ±0,2	53,8 ±0,2	351 ±1%	-2,4 ±0,4	55,3 ±0,2	1,1 ±5%	-4,1 ±1
59,0 ±0,2	88 ± 2%	-89 ±1	59,0 ±0,2	6,8 ± 0,4%	-60,4 ±0,2	59,0 ±0,2	319 ±1%	-2,3 ±0,4	59,0 ±0,2	1,0 ±5%	-3,8 ±1

4. SIMULATIONS

The probe has been studied using the open software FEMM-Finite Element Method Magnetics, Meeker, 2009. The simulation models were developed using the same previous described apparatus dimensions in axisymmetric symmetry.

4.1. Simulation theoretical principles

The electrical impedance is defined as the opposition that a device or material presents to the electrical current flow under oscillatory electrical tension. The impedance value is frequency dependent composed by resistive and reactive terms, the oscillatory frequency determines the dominance of one of them.

The working principle of an impedance sensor is a current flow problem. At the audio frequencies the current flow is a quasi-electrostatic problem in which the magnetic field terms in Maxwell's equations can be neglected, but in which the displacement current terms are relevant. Using Maxwell's Equations, the electric and magnetic fields must obey:

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{1}$$

Applying the divergence to eq.(1) the left-hand side becomes zero, leading to:

$$0 = \nabla.J + \nabla.(\frac{\partial D}{\partial t}) \tag{2}$$

Give that:

$$J = \sigma E \quad ; D = \varepsilon E \quad ; E = -\nabla V \quad ; \varepsilon = \varepsilon_0 \varepsilon_r \quad ; \varepsilon_0 = 8{,}854\ pF/m \tag{3}$$

The difference of electrical potential, which is a sine excitation, and its differentiation with respect to time replaced by multiplication by jω, are substituted into eq. 2 to:

$$\nabla.[(\sigma + j\omega\varepsilon)\nabla V] = 0 \tag{4}$$

Finally the current flow problem can be described by eq. 5.

$$(\sigma + j\omega\varepsilon)\nabla V^2 = 0 \tag{5}$$

Where: H is magnetizing field, D is electric displacement field, J is current density, E is electric field, V is electrical potential, ω is angular frequency, and σ, ε are conductivity and permeability respectively adopted as constants in this work. In this model the constants σ and ε define the electrical characteristics of the mixture. If the fluids are dielectrics σ can't be considered, when the liquid fluid has both effects, e.g. deionizated water, both are considered using the equation 5. Finally, when the conductive characteristic of the liquid is predominant, the term associated with electrical permittivity vanishes, leaving eq. 6.

$$\sigma \nabla^2 V = 0 \tag{6}$$

The equations, 5 and 6, are used in numerical simulation, and are very suitable on the study of newer different probes topologies and its complex geometries. In this work different liquids were used, the constants used on simulations are described in tab. 2. The angular frequency used in the simulation was ω= 2*π*200e3 rad/s.

Table 2. Constants used in the simulations

	air	Oil	Deinonizated Water	tap water	salt water
ε_r	1	2,23	80	80	80
σ (s/m)	0	0	9,40E-05	0,025	6,7

4.1. Simulation results

Figure 3 maps an electric field distribution inside the pipe for a stratified pattern in a simulation. It encloses the sectional area and the electrical field distribution is symmetrical with the rod center line. Because of the symmetry, only half of the device need be modeled. The electric field is more intense and can be assumed approximately constant near the probe. Therefore the flow of current is directly proportional to level of liquid.

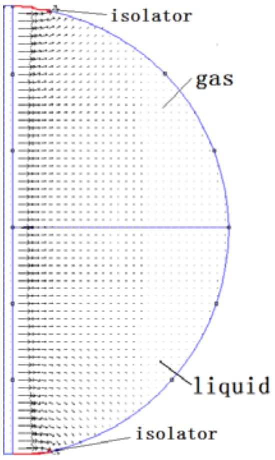

Figure 3. Simulation of the electrical field inside the sensor

Figure 4 presents the potential distribution on the seven simulations using tap Water. The horizontal line represents the water-air interface.

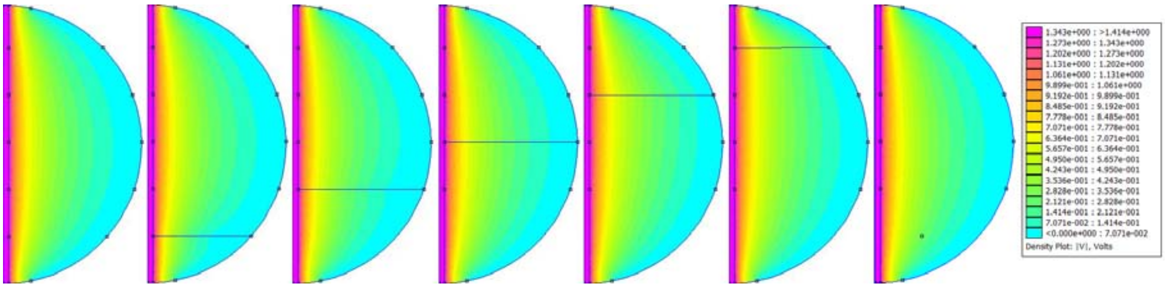

Figure 4. Electric Potential distribution in FEMM-Simulation using different levels of tap water

The results of impedance values are showed by the Tab. 3 for convenience the numerical results are in the modulus, |Z|, and angle format. The simulations were made with oil, deionizated water, tap water and salt water constants.

Table 3 - The simulation results

	Oil SAE 20-50W		Deinonizated Water		Tap Water		Salt Water 60g/l	
h(mm)	|Z| (Ω)	ang(°)	|Z| (Ω)	ang(°)	|Z| (Ω)	ang(°)	|Z| (Ω)	ang(°)
0	626037	-90,0	627819	-89,8	625708	-89,8	627819,1	-89,8
10	498891	-89,8	39179	-84,3	1458	-2,3	5,0	0,0
20	431909	-89,9	22901	-84,1	830	-2,3	2,8	0,0
30	385620	-90,0	16660	-84,0	597	-2,2	2,1	0,0
40	348820	-89,9	13168	-84,0	469	-2,2	1,6	0,0
50	315592	-90,0	10732	-84,0	381	-2,2	1,3	0,0
59	280756	-90,0	8552	-84,0	303	-2,2	1,0	0,0

5. ANALYTICAL MODEL

The probe can be modeled as an assembly of incremental electrical devices with cylindrical symmetry, fig. 5. Each one, fig.6, is setting up by inner and outer conductive film filled by dielectric and conductive material, representing the fluid. The electrical admittance, ΔY, of each incremental part is defined by the eq. 7. This equation is an approximation and doesn't consider the fringing field around the device. Considering the inner material homogenous, it only depends on the physical devices dimension and the permittivity and conductivity of the medium.

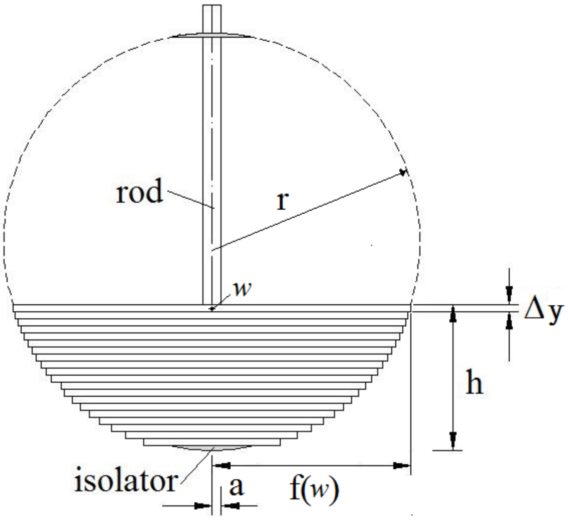

Figure 5. The admitance probe calculus using incremental cylinders

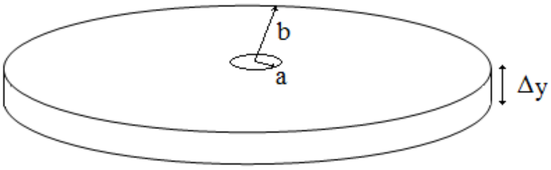

Figure 6. Elements of the incremental Cylindrical device

$$\Delta Y = 2\pi(\sigma + j\omega\varepsilon)\frac{\Delta y}{\ln(\frac{b}{a})} \tag{7}$$

The admittance, Y, of the device depends on h level fluid. Using the center of the pipe as coordinate origin and integrating in y axis, it can be calculated by eq. 8.

$$|Y| = \lim_{\|P\|\to 0}\sum_i K.\frac{\Delta y_i}{\ln(\frac{\sqrt{r^2 - w_i^2}}{a})} = K*\int_0^h \frac{dy}{0,5.\ln(r^2 - y^2) - \ln a} \quad where, \quad K = \sqrt{\sigma^2 + (\omega*\varepsilon)^2} \tag{8}$$

Using the eq. 8 programmed on Matlab, which inputs are geometries characteristics of the probe and the electrical constants σ and ε, listed in tab. 2, of the inner materials is possible to calculate its admittance. Furthermore, it is possible to calculate the probe capacitance and resistance from the complex and real component of the complex admittance. This approximated model is important to quick estimations for probe development and design.

6. RESULTS COMPARATION

The Figure 7 presents four graphics that compare experimental results, FEMM – simulations and Matlab calculus using different liquids. The experimental data is represented by star points, simulations results by crosses and the Matlab Calculus by continuous line. In the oil left up and deionizated water right up graphs the experimental curl to move away from the other ones, this can be explained by the apparatus strain capacitances. There are strain capacitance between the electrodes: rod and pipe (including the leads the measuring circuit), Huang, 1988. It wasn’t considered in the FEMM-simulation and Approximated model. The results converge for tap water because in this case the strain capacitance hasn’t significant influence. By all graphs can be notice that the proportionality between liquid level and mixture admittance.

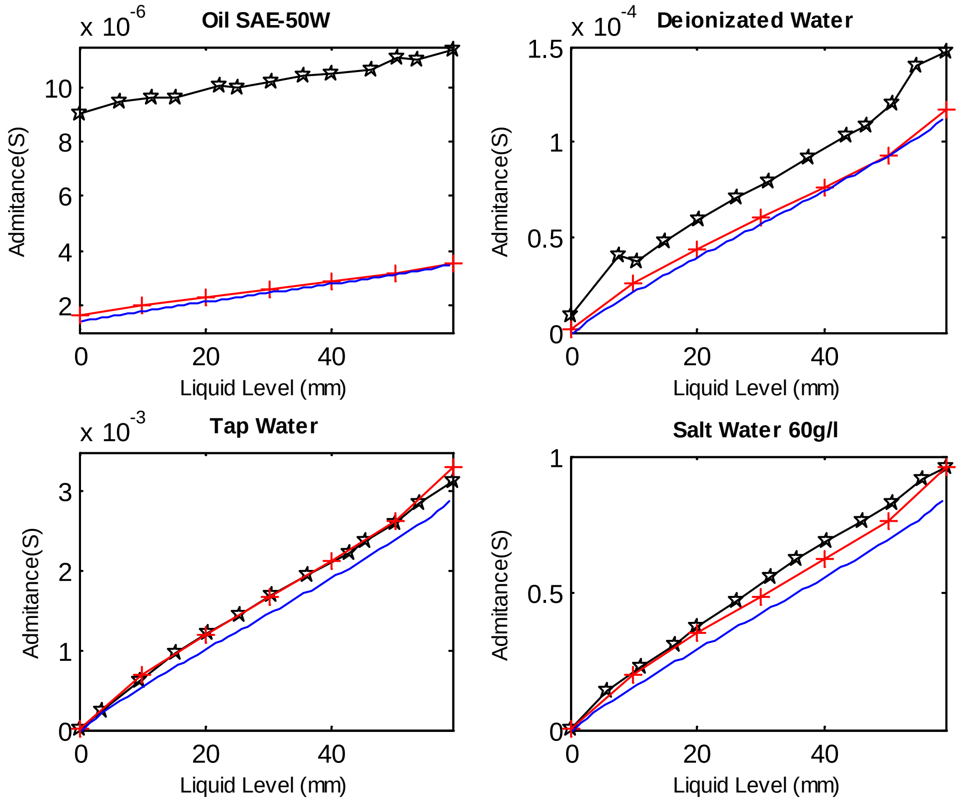

Figure 7. Comparative results using experimental apparatus(stars-black line), FEMM simulations(crosses-red line) and Matlab Approximated Model (blue line)

7. THE ELECTRONIC CIRCUIT CONDITIONING

The sensor comprises the probe, a sinusoidal signal source and the electronic circuit conditioning. The probe is represented by its electrical equivalent circuit Z. The value Z represents the flow measured between the rod and the pipe, and can be expressed by Eq.9, Song et al. 1998.

$$Z(f)=\frac{1}{R+\frac{1}{j.2.\pi.f.C_p}}+j.2.\pi.f.C_d \tag{9}$$

Where R is the resistance corresponding to fluid conductivity, Cp is capacitance due to the polarization of fluid molecules near electrodes, Cd is capacitance due to the dieletric constant of fluid and f is the frequency of excitation which is supplied to electrodes by one AC voltage source. The excitation source can be adjusted to work above 100 kHz, at this frequency the effects of the double layer on the impedance are negligible. Therefore the term C_p doesn’t have to be considered. If two phase mixture is based at only in dielectric fluids then first term of Eq.9 is canceled and the probe behaves as a capacitive probe. If the mixture consists of a conductive material, e.g. salt water, else the second term can be neglect and parameter R dominates.

Figure 8 shows schematically the impedance sensor. The charge resistor, Rc, is known. By means of the tension in its terminals it is possible measure the current. Cs represents all the stray capacitances due the capacitance between the electrode and earthed places. The conditioning circuit is based on current tension conversion principle. This method is conceptually simple and it is appropriated to probe that has one earthed electrode. It isn’t intrinsically stray-immune therefore the stray capacitances Cs affect the measure of Z mainly when it is large. The effect of Cs can be minimized by using active guard method. The guard is one screen layer between the live electrode and the earthed screen so that there is no direct capacitance between them. In this system based in sinusoidal excitation the guard can be driven using a unity gain voltage follower following the potential of the electrode. The efficiency of the driven guard depends on the gain error and phase shift of the follower, Huang 1988.

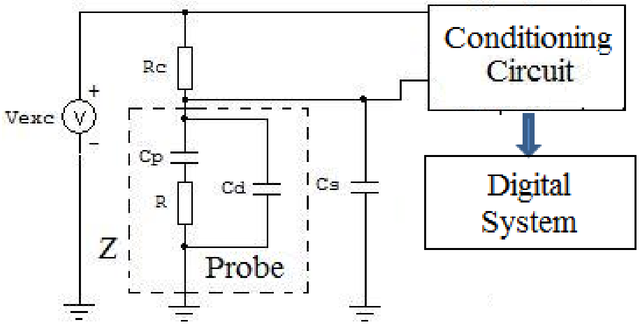

Figure 8. Impedance Measurement System

This Impedance Measurement System was implemented using a HP 1002 wave generation oscillations source. To adapt the sensor to the wide range of Z, the amplitude of the excitation tension Vexc and the value of the resistor R_C can be changed. Low impedances need low values, typically $0.1V_{rms}$ of V_{exc} and Rc=10Ω; high impedances need high values, typically $1V_{rms}$ of V_{exc} and R_c=33kΩ. The other values of charge resistance are: 100 Ω, 1kΩ,10KΩ. The choice of electrical charge resistance depends on the liquid impedance. Its value must be next to the impedance of full pipe of liquid. The oscillator frequency is 200KHz. The conditioning circuit was implemented using high precision AD8608 operational amplifiers. It amplifies the voltage in the charge resistor using an instrumentation amplifier configuration. The amplified signal is rectified and filtered. A Low Pass Filter is used with 1,5 KHz cutoff frequency. This analog signal is converted to digital and acquired by a NI-DAQ 6024e system. Dynamic measurements can be made using this system.

8. THE DYNAMIC MEASUREMENTS

Dynamic tests were done on an air-water vertical two-phase flow test line. The setup consists of a vertical Plexiglas tube with 27 m length and inner diameter =26mm, where the sensor was installed in a small segment of metallic pipe. Air coming from a compressor is mixed with a tap water pumped out of a tank downstream of the line. Flow rates can be controlled and the superficial gas velocity J_G and the superficial liquid velocity J_L were changed from 0 to 29 m/s and 0 to 3,8 m/s respectively. Flow regimes were determinated by a human specialist. Using the sensor and the acquisition systems has been made one minute tests at 3ksamples/s on a vertical two phase flow. The test signals were normalized by the full pipe voltage. The results of tests at different patterns are showed in Fig. 9.

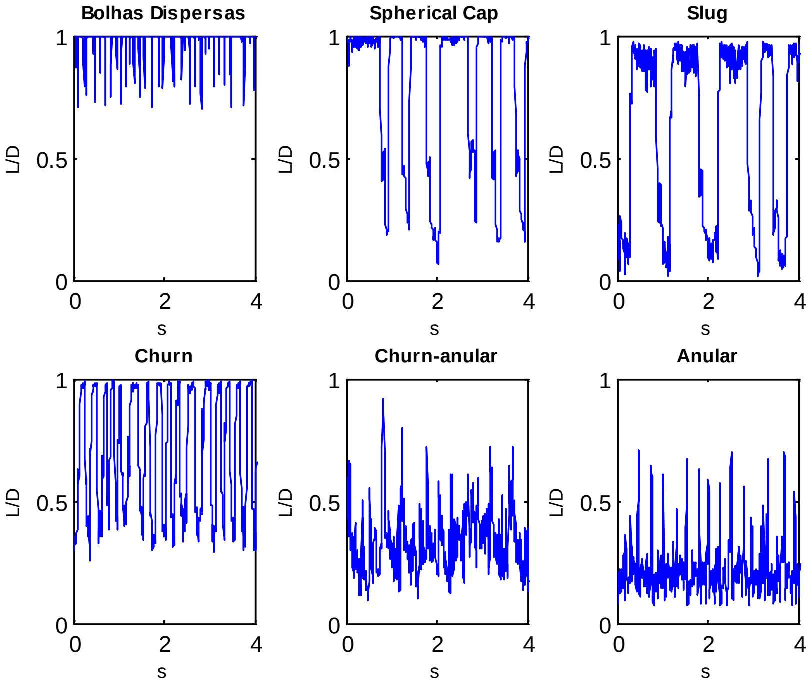

Figure 8. Dynamical signal on different patterns acquired using the Impedance Measurement System

9. CONCLUSIONS

In this work was presented the study of an intrusive probe. Its design is appropriate to industrial and laboratories, where is very common the biphasic flow in metallic pipes. The probe conceptually it is very simple, easy to build and to install, does not require complex electronic guard electrodes neither especial electrostatic shield because the pipe itself is one electrode. It can work with fluids that have different electrical characteristics, from dielectric to resistive liquids. Its measured admittance is proportional to liquid level, what is very convenient. Clearly, the centered rod makes this sensor naturally intrusive and operates in contact to the flow, but this make the probe more sensitive and is least subject to incrustation problems.

The experimental static measurements are present, and the results are coherent with simulations and analytic model implemented with Matlab. An electronic conditioning circuit was developed to realize dynamic measurements. It is an exploratory work to develop a robust two phase flow measuring instrument that operates with variation on the electrical characteristics of the mixture and/or different fluids in industrial and laboratorial situations.

10. ACKNOWLEDGEMENTS

The authors thank PETROBRÁS for the support.

11. REFERENCES

Abouelwafa, M., Kendall, E.J.,1980, “The Use of Capacitance Sensors for Phase Percentage Determination in Multiphase Pipelines”, Instrumentation and Measurement, IEEE Transactions on , Vol. 29,pp. 24-27.

Ahmed, W., 2006, “Capacitance Sensors for Void-Fraction Measurements and Flow-Pattern Identification in Air-Oil Two-Phase Flow”, Sensors Journal, IEEE ,Vol.6,pp. 1153-1163.

Brown, R., Andreussi, P.,and Zanelli, S.,1978, “The use of wire probes for the measurement of liquid film thickness in annular gas-liquid flows”, The Canadian Journal of Chemical Engineering, Vol. 56, Issue 6, pp. 754–757,.

Ceccio, S.L., George, D.L.,1996, “A Review of Electrical Impedance Techniques”, Journal of Fluids Engineering, Vol. 118, Issue 2.

Coney M.W.E.,1973, “The theory and application of conductance probes for the measurement of liquid film thickness in two phase flow”, Journal of Physics and Science Instrumentation ,Vol. 6,pp. 903-907.

Devia, F., Fossa, M.,2003, “Design and optimization of impedance probes for void fraction measurements”, Flow Measurement and Instrumentation ,Vo.14,pp. 139-149.

Heerens, W.C.,1986, “Application of capacitance techniques in sensor design”, Journal of Physics and Science Instrumentation ,Vol. 19,pp. 897-906.

Huang, S. M., Stott, A. L., Green, R. G., & Beck, M. S.,1988, “Electronic transducers for industrial measurement of low value capacitance”, Journal of Physics and Science Instrumentation ,Vol. 21,pp. 212-250.

Huang, S.-F., Zhang, X.-G., Wang, D., & Lin, Z.-H., 2008, “Equivalent water layer height (EWLH) measurement by a single-wire capacitance probe in gas–liquid flows”, International Journal of Multiphase Flow, Vol.34, pp 809-818.

Masuda, Y., Nishikawa M., Ichijo B., 1980, “New Methods of Measuring Capacitance and Resistance of Very High Loss Materials at High Frequencies”, Instrumentation and Measurement, IEEE Transactions on , Vol. 29,pp. 28-36.

Meeker D., 2009, “Finite Element Method Magnetics Version 4.2 User’s Manual”.

Song N., C., Chung, M. K., No, H.C., 1998, “Measurements of void fraction by an improved multi-channel conductance void meter”, Nuclear Engineering and Design 184, 269-285.

Yang, H. C., Kim, D. K., & Kim, M. H.,2003, “Void fraction measurement using impedance method”, Flow Measurement and Instrumentation,Vol. 14,pp.151-160.

12. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.