CAPACITIVE PROBE FOR GAS-LIQUID FLOW CARACTERIZATION

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Abstract: The correct measurement of gas-liquid two-phase flow is important in many industrial applications. In this paper, we describe the development and evaluation of a non-intrusive capacitive probe. Care was taken to allow for fast measurements (up to 5 kHz sampling rate). Two calibration procedures for void fraction measurement in annular and stratified flow are also described.

Key words: capacitance measurement, two-phase flow, void fraction

1. INTRODUCTION

Multiphase flow, the flow of distinct substances in a pipe or vessel, can be found in many industrial branches. The interaction between the phases directly affects the load loss and thermal transfer in the industrial processes in which it occurs. Thus, reliable and accurate flow measurement sensors able to recognize the physical characteristics of the fluids in the flow are needed [1]. One very important parameter in order to make the flow characterization possible is the phase fraction, which describes the amount in volume of one substance in the flow. In gas-liquid flows, the phase fraction is often called void fraction, indicating the volumetric ratio between gas and liquid.

Most of the available void fraction measurement systems are based in principles like ultrasound, industrial tomography, magnetic resonance, phase splitting and impedance probes [2]. Ultrasounds are non-intrusive, have a low cost and are not so complex when compared with other technics like industrial tomography, but in the other hand, do not work well when the void fraction is too large. Industrial tomography can effectuate precise measurements and reconstruct the image of the flow in the cross-section of the pipe, with the disadvantage of being expensive and requiring special cares because of the ionized radiation. The transducers based on impedance measurement are simple, low-cost, have a high temporal resolution and can be employed in any range of void fraction [3]. They are based on the fact that the phases of a mixture have different electrical permittivity and/or conductivity.

When the difference between the electrical permittivity of the two phases of a two-phase flow is large enough, the measurement of variations in capacitance, instead of impedance, is sufficient for phase fraction measurement purposes. Researches in this field have already shown good results [4].

The main goal of this paper is to describe the development and evaluation of a non-intrusive capacitive probe, able to measure the gas or void fraction in gas-liquid flows with a sample rate of up to 5 kHz. The electronic circuit that was designed, the characteristics of the capacitive probe and two calibration procedures for stratified and annular flow are described in the following sections.

2. SYSTEM DESCRIPTION

2.1. Capacitive Probe

The capacitive probe comprises of two semi-cylindrical copper plates that are placed one in front of another around the pipe, as shown in Fig. 1. The plates form a capacitor, where the phases are the dielectric medium. As the flow passes through the probe, the measuring capacitance changes and consequently this change is related with the fraction (concentration) of each of the fluids comprising the mixture between the plates.

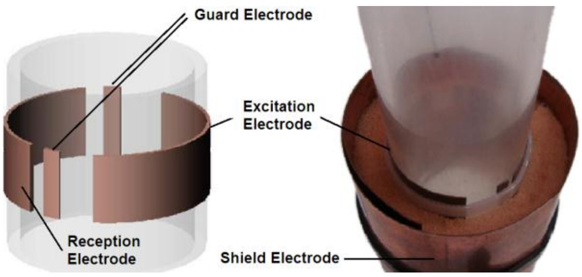

Fig. 1. Capacitive Probe

A sinusoidal signal is applied to the excitation electrode. The reception electrode is connected to the input of a transimpedance amplifier. In a frequency range of up to tens of megahertz, the fluid inside the probe can be modeled as a capacitor in parallel with a resistor [5]. The purpose of the guard electrode is to confine the electrical field into the pipe and to reduce fringing effects, whereas the shield electrode aim is to isolate the probe from external interference and vice versa.

Although the capacitive sensor is non-intrusive, the pipe must consist of a non-conductive material for it to work. In our experiments a Plexiglas pipe was used. A simplified electric model of the whole sensor can be seen in Fig. 2. The capacitances C_a are steady and exist due to the wall of the pipe. The impedance formed by C_m and R_m is dynamic and relates to the void fraction to be measured.

The capacitances C_a and C_m were roughly estimated assuming the sensor was a parallel plate capacitor. The pipe capacitance C_a is in the range of 7 pF, while the capacitance C_m may vary from 750 fF, with the pipe full of air, to 60 pF, with the pipe full of water. The relative permittivity values that were used for Plexiglas and water are respectively $\varepsilon_p = 4$ and $\varepsilon_w = 80$. R_m was also calculated with the same simplification and is in the range of 400 GΩ with the pipe full of air and of 4 kΩ with the pipe full of water. The water and air electrical conductivity values that were used are respectively $\sigma_w = 5$ mS/m and $\sigma_a = 50$ pS/m.

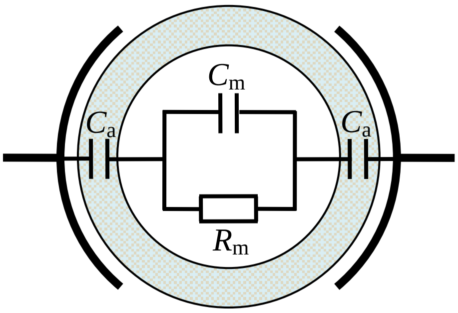

Fig. 2. Equivalent Electric Circuit of the capacitive sensor.

2.2. Measuring circuit

The measuring circuit is based in an inverting amplifier implemented with a high bandwidth operational amplifier, as shown in Fig. 3, where the input impedance is the capacitive probe itself. The operational amplifier that was used is the Texas Instruments OPA656, which has a gain-bandwidth product of 230 MHz and a FET input.

The signal that is applied to the excitation electrode is generated by a DDS chip (direct digital synthesizer), which is controlled by a microcontroller. The amplitude and frequency of the sine wave are digitally selectable and can assume values of up to 6 V peak-to-peak in the range of 100 Hz to 7 MHz.

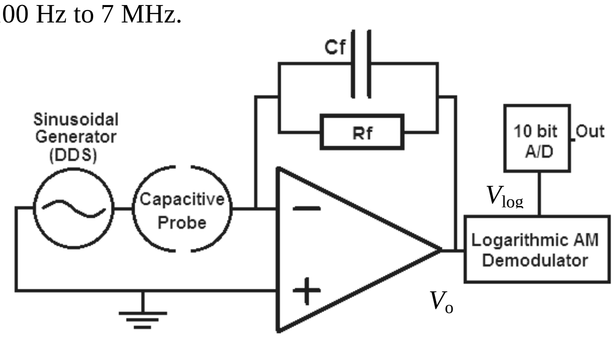

Fig. 3. Schematic diagram of measuring circuit

Assuming that the opamp is ideal and that the fluid is formed by capacitor C_m only, it can be shown that the output voltage V_o is determined by equation (1) (for a complete description see [6]).

$$V_o = -V_i \cdot \frac{C_m}{C_f} \quad (1)$$

An increase in the capacitance of the probe will proportionally increase the output voltage. The change of amplitude in the output of the amplifier is detected by a logarithmic demodulator and acquired by a 10 bit analog-to-digital (A/D) converter.

The logarithmic demodulador AD8307 was employed due to its high speed and the wide dynamic range that is expected with substances such as water and air. The output voltage of the demodulator V_{log} can be obtained from equation (2), where V_o is the amplitude of the signal in the output of the operational amplifier and V_a and V_b are the slope and intercept voltages [7] of the demodulator.

$$V_{\log} = V_a \cdot \log(\frac{V_o}{V_b}) \quad (2)$$

The output of the logarithmic demodulator is read by a microcontroller trough the A/D converter. A serial port is used for the communication between the microcontroller and a computer. The sampling rate of the system is restrained to 5 kHz due to RS232 limitations. A user interface was developed in C#, which allows the user to configure and operate the system as well as to visualize the data.

3. SYSTEM EVALUATION

3.1. Time response

As can be seen in Fig. 4, the use of the logarithmic demodulator gives the system a time response of 28 µs. This is the time that the output takes to rise from 10% to 90% of its final value. The first signal displayed in Fig. 4 consists of a 1 MHz sinusoid modulated with a 10 kHz square wave. It was injected in the electronics while the sensor was full of water. The second signal is the output of the logarithmic demodulator. With such a rise time, the system is able to detect flow transitions of up to 35 kHz in its input.

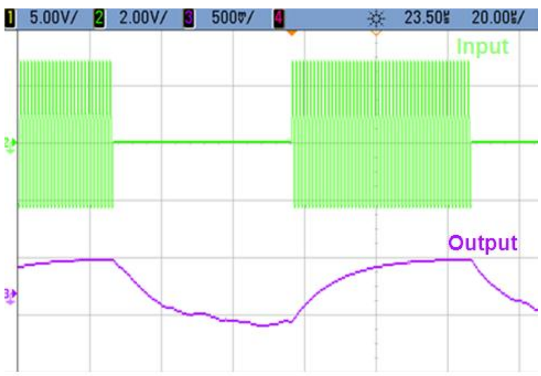

Fig. 4. Rise time of the system. Input signal on top and output at bottom.

3.2. Frequency response

The frequency response of the system is shown in Fig. 5. It was obtained both for the pipe full of water and full of air. The greatest values for the gain of the circuit are in the range of 100 kHz to 10 MHz. We have chosen an excitation frequency of 5 MHz. Both substances can be clearly distinguished with the chosen operating frequency.

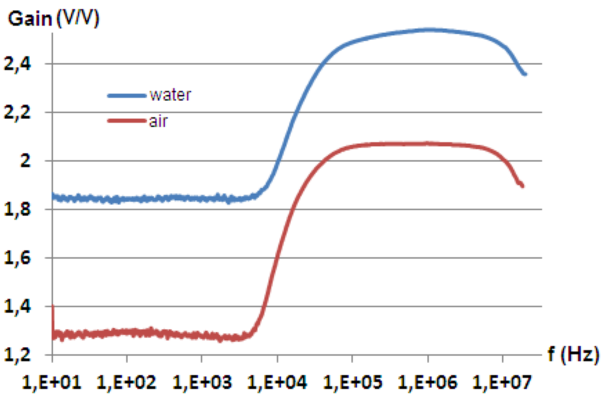

Fig. 5. Frequency response of the system. Curves for the sensor full of water on top and full of air at bottom.

3.3. Flow measurement

The graphical interface that was developed is shown in Fig. 6 during a typical air-water flow measurement. This flow is known as slug flow, which is characterized by the alternating stream of a gas bubble and a liquid body. The picture displays raw data, which means that the values are not yet converted from volts to void fraction. A drawing of a flowing bubble was superimposed to the picture for illustrative purposes.

For the conversion of the systems output voltage into a void fraction value, a calibration procedure is needed. Nevertheless, changes in the flow pattern may lead to a redistribution of the electric field inside the measurement section of the probe and consequently to a change in the capacitance of the sensor. Because of that, for different flow patterns and the same void fractions, the outputs of the system may differ.

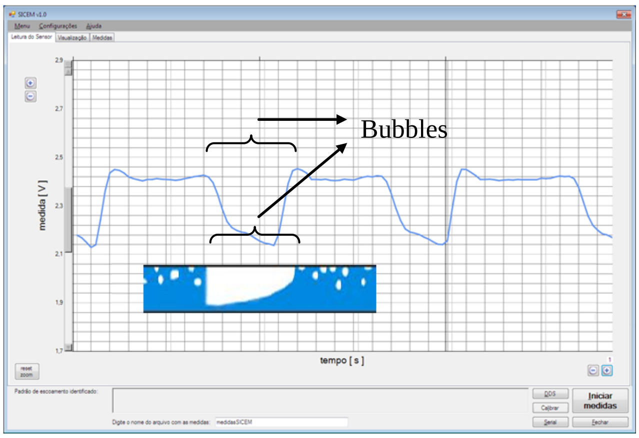

Fig. 6. A picture of the software during slug flow measurements.

In order to increase the accuracy of the measurements, a calibration procedure should be adopted for every possible flow pattern of the system. Although that seems to be a problem in practice, that is acceptable when the flow pattern is well-known, like in gas-lift applications where the flow is known to be annular [8]. The system could also be used for qualitative purposes. In that case a low accuracy global calibration procedure could be used for flow pattern identification.

4. CALIBRATION PROCEDURE

4.1. Stratified Flow

In order to correlate the output measured voltage with void fraction values for stratified flow, the following procedure was realized. The capacitance probe was placed around a piece of 47.5 mm diameter pipe in which both of the sides were closed. A schematic representation is given in Fig. 7. The pipe was gradually filled with water through a hole in the top of it. Knowing the geometry of the pipe, the density of water and weighting the amount of water that was being injected into the pipe we were able to calculate the void fraction.

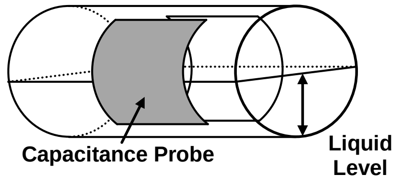

Fig. 7. Stratified flow calibration scheme

We took twelve different measuring points with a void fraction varying from 0 % to 100 % and recorded the output of the system for each of these points. The excitation frequency of the system was of 5 MHz. After that, the voltage was normalized with equation (3), based on the logarithmic response of the demodulator in the electronics.

$$V^* = \frac{10^{Vfull/k} - 10^{Vmeasured/k}}{10^{Vfull/k} - 10^{Vempty/k}} \tag{3}$$

where V^* is the normalized voltage, V_{full} is the voltage with the pipe full of water, V_{empty} is the voltage with the pipe full of gas, $V_{measured}$ is the measured voltage and k is a constant of the logarithmic amplifier which was empirically determined to the value of 0.45.

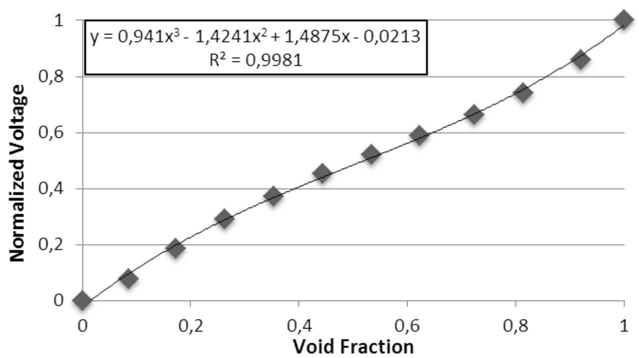

Fig. 8. Calibration line relating the normalized output voltage with the void fraction value.

Relating the normalized values with the calculated void fractions, the graphic of Fig. 8 was obtained. Its shape was already expected because of the curvature of the pipe. It can be seen that the response is more linear for midrange values, where the walls of the tube tend to be more flat. The fitted third order polynom can then be used to assess the void fraction of the flow.

4.2. Annular Flow

For the annular flow calibration, the scheme displayed in Fig. 9 was followed. A piece of 47.5 mm diameter pipe was placed vertically over a flat surface and its bottom was closed. The capacitance probe was placed around it. Afterwards, four Nylon rods with different radii were machined. Each of those rods was inserted concentrically into the pipe and it was filled with water. Since the relative permittivity of Nylon ($\varepsilon_n \approx 4$) and air ($\varepsilon_a = 1$) are close to each other in comparison to waters ($\varepsilon_w = 80$), a annular flow with air core was approximated.

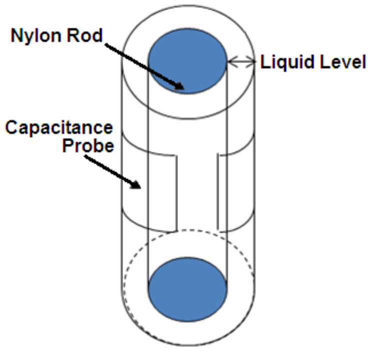

Fig. 9. Annular flow calibration scheme.

An increase in the liquid film thickness can be obtained with the insertion of a rod with smaller radius and vice-versa. That way, we were able to obtain six measurement points, one point for each of the rods, plus two points for the pipe full of air and water.

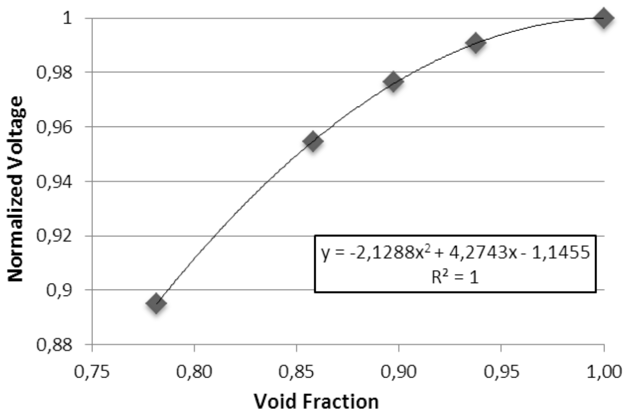

Fig. 10. Calibration line relating the normalized output voltage with the void fraction value.

Before the comparison of the measured data and the respective void fraction values, the data was applied to equation (4) with the intention to minimize the interference of the Nylon rod.

$$V_{adj} = \frac{V_{full,rod} - V_{empty,rod}}{V_{full} - V_{empty}} \quad (4)$$

, where $V_{full,rod}$ and $V_{empty,rod}$ are the values measured with the rods inside the pipe and the pipe full and empty of water. V_{full} and V_{empty} are the values measured without the rods and with the pipe full and empty of water. After that procedure, the values of V_{adj} were also normalized with equation (5), where V^* is the normalized voltage and k is the same constant from equation (3).

$$V^* = \frac{10^{1/k} - 10^{Vadj/k}}{10^{1/k} - 1} \quad (5)$$

The normalized output and a fitted second order polynom are shown in Fig. 10. Although void fraction values were obtained only in the range from 75 % to 100 %, smaller values are rare in real annular flow systems.

5. CONCLUSION

In the present paper, the development of a non-intrusive capacitive void fraction measurement system was presented. The designed system can operate with an acquisition speed of up to 5 kHz, making the detection of transient two-phase flow feasible. A program allows the user to configure and operate the probe. First measurements with real flow show promising results.

During the calibration procedure, a relation of the systems output voltage with the void fraction values has been found both for annular and stratified flow. Further work will be related in testing the system under real operational conditions and comparing the results with other reference systems.

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