Flow Measurement and Instrumentation 50 (2016) 102–111

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Capacitive measuring system for two-phase flow monitoring. Part 2: Simulation-based calibration

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ARTICLE INFO

Article history:
Received 12 September 2015
Received in revised form
15 April 2016
Accepted 16 May 2016
Available online 6 June 2016

Keywords:
Two-phase flow
Void fraction
Capacitive probe
FEM simulations
Capacitance measurement

ABSTRACT

Two-phase gas–liquid flows are present in many industrial processes and therefore monitoring of such flow is highly desired for either quality or efficiency assurance. Capacitive probes are widely used for two-phase investigation in experimental facilities and may have the potential for industrial use in the future. In this paper, we apply a simulation-based approach for increasing the accuracy of void fraction measurement of capacitive probes. We also employ the simulation data to find the electric response of a capacitive probe under different flow conditions. Moreover, by means of a horizontal flow test bench, we compare the void fraction measurements of the capacitive probe with the output of a reference wire mesh sensor. Experimental tests for air–water flow were performed. We show that from simple normalization approach (as widely employed) average deviation of measured void fraction values (compared to reference sensor) can be heavily reduced from up to 30% to less than 5% in most cases. The approach presented can be also applied to other types of capacitive probes.

1. Introduction

The flow of two distinct substances in a pipe or vessel is called two-phase flow [1] and can be found in many industrial branches [2]. The way that the phases interact affects the load loss and thermal transfer in the flow [3]. Thus, the development of multiphase flow measurement systems is very important for research purposes and for monitoring the industrial processes in which two-phase flow occurs. The most commonly found two-phase flow in industry is of gas–liquid type and one important parameter for its characterization is the void fraction, which describes the amount in volume of gas into the flow [4].

In [5] we presented the development of a capacitive sensor for void fraction measurement. Capacitive sensors are non-intrusive [6], low cost and have high temporal resolution [7]. Despite this, the response of capacitive sensors relies not only on the void fraction values but also in the flow pattern [8]. The flow pattern describes how the phases are distributed into the flow. Fig. 1 presents some flow patterns investigated in this work, namely stratified flow, annular flow and dispersed bubbles.

As depicted in Fig. 1, for stratified flow (a), only the lower part of the pipe is in contact with water. Conversely, for annular flow (b) and dispersed bubbles (c), the whole pipe wall is always wet. In such a situation, the electric field created by the electrodes tends to deviate from the air core (for annular flow) or the air bubbles (for dispersed bubbles flow) through the water. That said, for the same void fraction values, the electric field distribution and consequently the output of the sensor will differ if the flow pattern changes. A way to deal with that drawback is to find the sensor response curves for all expected flow patterns and select the correct one as the phase distribution changes. The response curve of the sensor could be obtained by means of a test bench that mimics the intended flow pattern [9]. Unfortunately, the test bench will be valid only to the specific situation that it recreates and changes in the pipe or fluid characteristics will require a new batch of tests. Another alternative is to simulate the sensor with the Finite Elements Method (FEM) [10]. Although the response curves obtained with FEM are also not general, the simulation models can be updated with ease if the sensor is to be used under a new situation.

In this paper we describe the characterization of a concave plate capacitive sensor with FEM simulations. First the response curves for stratified, dispersed bubbles and annular flow are obtained. Based on the simulation results we calculate the theoretical voltage output and sensibility of the measurement system, which was already described in [5]. We also propose a method for void fraction calculation without the need of flow pattern identification. The novelty of the method relies in the use of the average gas velocity to improve the results. Finally, we employ the developed system for horizontal air–water flow measurement in a 26 mm internal diameter test bench. The results are compared with the

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http://dx.doi.org/10.1016/j.flowmeasinst.2016.05.011
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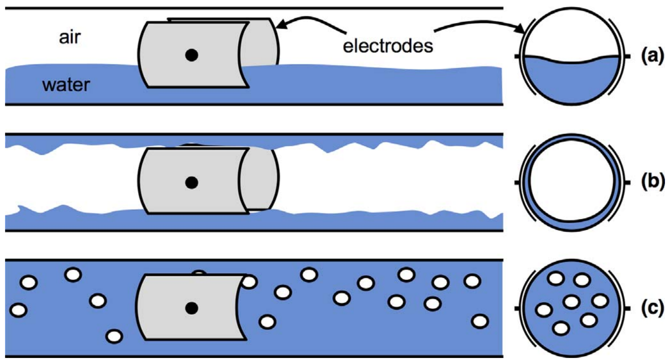

Fig. 1. Longitudinal and transversal cuts of a pipe with a pair of measuring electrodes for three different flow patterns. Stratified flow (a), annular flow (b) and dispersed bubbles (c).

output of a reference wire-mesh sensor.

2. Theoretical background

In this section we review some concepts from electromagnetism that are necessary for the choice of the physical model employed in the FEM simulations.

2.1. Electroquasistatic fields

According to Maxwell's Laws a variation in an electric field entails an oscillatory magnetic field, which in turn results in another electric field [11]. That coupling between electric and magnetic fields is the reason for the existence of the electromagnetic waves. When the period of a wave is much greater than the time that it takes to travel a region of interest, the electromagnetic coupling can be neglected. That simplification results in the electroquasistatic field model [12], which can be described by

$$\nabla \cdot \left[\left(\sigma\left(\vec{r}\right) + j\omega\varepsilon_0\varepsilon\left(\vec{r}\right) \right) \nabla V\left(\vec{r}\right) \right] = 0 \quad (1)$$

where $\sigma\left(\vec{r}\right)$ and $\varepsilon\left(\vec{r}\right)$ are the electrical conductivity and dielectric constant of the medium. Both are functions of the position $\vec{r}$. The permittivity of free space is represented in the equation by ε_0, whereas $j = \sqrt{-1}$ is the imaginary unit, $\omega = 2\pi f$ is the angular frequency and $V\left(\vec{r}\right)$, the electric potential. Eq. (1) yields from the charge conservation equation when both Gauss's law and the two constitutive relations for the current density J and the electric displacement D (for linear and isotropic materials) are applied to it [12].

The excitation frequency of our capacitive sensor is of 5 MHz. That way, the oscillation period T of the electric field accounts for 200 ns. Considering that the capacitive sensor length is about 10 cm [5], the propagation time of an electromagnetic wave through it would be of $T_P = 333.3$ ps (with a speed of $c = 3.10^8$ m/s). As $T \gg T_P$, the electromagnetic coupling is negligible and the use of the electroquasistatic field model is feasible.

We will use the finite element method to solve (1) and find the electric response of the concave plate electrodes as a function of void fraction values.

2.2. Electrodes equivalent circuit and wall capacitance

Fig. 2a shows a capacitive measurement cell that will be used in this section due to its simple geometry. It comprises of a pair of parallel plates electrodes, which are in contact with an acrylic wall

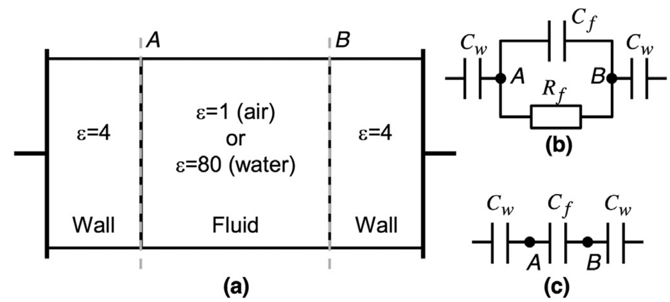

Fig. 2. Simplified measurement cell (a) and its equivalent circuit for conductive (b) and non-conductive (c) fluids. The cell is composed of a pair of electrodes and a measurement chamber, delimited by two plastic walls.

(relative permittivity of 4). The fluid under test is placed in the cavity between the walls. This kind of sensor can be represented by the equivalent circuits of Fig. 2b and c. The difference between the circuits is the inclusion of the resistor R_f, which is necessary for conductive fluids. The capacitances C_w and C_f arise respectively from the wall and the fluid in the measurement cell. The nodes A and B between C_w and C_f (Fig. 2c) are equivalent to the dashed lines A and B of Fig. 2a. As the fluid capacitance C_f is proportional to its permittivity, if one takes two capacitance measurements with different fluids (air and water, for example), the capacitance C_w of the wall can be easily calculated [13].

Although this electrical model is widely used [6], [14–16], it is only an approximation [17] that does not hold for inhomogeneous fluids, as shows the example of Fig. 3. We did a simulation of the same measurement cell in a situation in which only 50% of its chamber was filled with non-conductive water. Fig. 3 shows the equipotential surfaces when 1 V is applied between the electrodes. It is evident that there is not any equipotential surface equivalent to the ones denoted by the lines A and B of Fig. 2a (passing exactly in the wall-fluid interface). Therefore, there will be no more an equivalent capacitance C_w that exactly matches the wall region and modeling the electrodes by an association of resistors and capacitors will lead to errors. We have chosen to model the electrodes by their admittance values, which were obtained by FEM for the specific frequency of 5 MHz (if the use of an equivalent circuit was possible, the advantage would be the validity of the model for every frequency).

3. FEM simulations

In this section we describe the FEM simulations for the characterization of the sensor. Its electrical response was evaluated for the following flow patterns: stratified, dispersed bubbles and anular. We employed the electroquasistatic field model and found the admittance of the electrodes for different void fraction values.

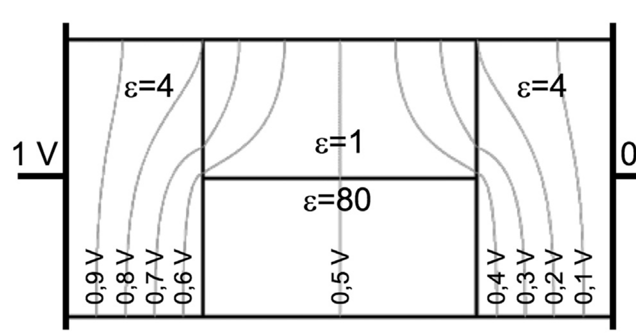

Fig. 3. Simplified measurement cell filled with water and air. Equipotential lines are shown when a 1 V potential is applied between the electrodes.