Flow Measurement and Instrumentation 47 (2016) 90–99

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 1: Hardware design and evaluation

Nikolas Libert [a], Rigoberto E.M. Morales [b], Marco Jose da Silva [a,*]

[a] Department of Electrical Engineering, Universidade Tecnologica Federal do Parana (UTFPR), Curitiba, Brazil
[b] Department of Mechanical Engineering, Universidade Tecnologica Federal do Parana (UTFPR), Curitiba, Brazil

ARTICLE INFO

*Article history:*
Received 15 December 2014
Received in revised form
12 September 2015
Accepted 29 December 2015
Available online 30 December 2015

*Keywords:*
Two-phase flow
Void fraction
Capacitive probe
Microcontroller
Capacitance measurement

ABSTRACT

Two-phase flows are commonly found in many industrial applications, such as oil and gas production. The monitoring of such flows is performed either in field applications or in pilot plant studies. In both cases, simple and robust measuring techniques are required. Capacitive probes have been applied for void fraction measurement in pipes in research and industry. However, capacitive measuring systems applied so far are tailored for specific applications and may not be easily adaptable. In addition, more and more soft-computing methods are applied for advanced data processing and parameter extraction which requires more computational power of sensor systems for online data processing. We develop a capacitive system provided with a microcontroller in which necessary routines for data processing may be embedded. System design is detailed explained and system's performance is evaluated, showing appropriate accuracy and time response for the investigation of two-phase flows.



## 1. Introduction

Two-phase flows can be defined as a mixture of two different substances in motion. The phases are immiscible substances, so that between them there are one or more interfaces or discontinuities [1]. This type of flow is commonly found in industrial activities [2]. The flows of gas–liquid type are the most commonly found. The study of these flows is essential for optimization and cost reduction of engineering projects. It is common that these studies are based on the observation of flows generated in a controlled environment. In these cases there is a need for use of test pilot plants, where existing situations in the industry are recreated and parameters of interest connected with the flow are recorded by sensors. The measurement systems used in industry not always have the flexibility required for operation in experimental benches. In that sense, besides having an important role in the control and monitoring of industrial processes where the multiphase flows occur, the multiphase flow measurement systems are essential for research purposes in the development and more importantly the validation of mathematical models and prediction tools.

One of the most important parameters in two-phase flow characterization is the void fraction, as this is decisive in the pressure drop, heat exchange, and the flow pattern form [3]. This parameter can be interpreted as the gas volume fraction in a mixture at a given instant of time [4], although there are more stringent definitions [5]. There are various void fraction measurement techniques, among which we cite the ones based in ultrasound, x-rays, γ-rays, microwaves, optical methods, and electrical impedance.

Ultrasonic meters measure the void fraction based on differences in the module of elasticity and density of phases of the flow. The operation of this type of sensor is limited to void fractions below 20% [6]. In addition, the gas phase must be dispersed in a continuous liquid phase so that the waves do not reflect fully before entering the flow [7]. Meters based in x-ray [8–10] and γ-ray [11–14] have no limitations regarding the range of measurement, but require special safety care due to the use of ionizing radiation. The energy of the γ rays is usually higher, allowing easier penetration in tubes with large diameter or thickness [15]. However, they are generated by radioisotopes, which are restricted in some countries, whereas x-rays can be generated by tungsten filaments [13]. Microwave sensors operate with frequencies in the range of 300 MHz to 300 GHz and can be of resonant cavity [16,17] or transmission [18]. The response of the sensors varies with salinity [19] and with the flow pattern [20]. The non-intrusive optical measurement systems require transparent pipes and are limited to low void fractions [21,22], being mostly based on reflection or attenuation of light through the flow. The punctual void fraction [23,24] can be measured by optical intrusive probes. Furthermore, the use of high speed cameras [25] and image processing algorithms [26] are also part of the optical techniques.

* Corresponding author.
*E-mail address:* mdasilva@utfpr.edu.br (M.J. da Silva).

http://dx.doi.org/10.1016/j.flowmeasinst.2015.12.009

Finally, one can mention the impedance sensors, classified as capacitive [27] or resistive (sensitive to phase permittivity or conductivity, respectively). Resistive sensors need to be in contact with the flow and do not work for non-conductive continuous phases [28–31]. Capacitive sensors can be non-intrusive [32], but their operation is compromised when the continuous phase conductivity is too high. The main disadvantage of the impedance sensors is the variation of its response with the flow standard (same for microwave-based sensors). Nevertheless, due to its low cost and high speed measurement [22], together with the γ ray sensors, they are the most used in commercial instruments [13].

In this paper, we describe the design and evaluation of a new capacitive measurement system for void fraction determination in two-phase gas–liquid flow. The system is designed with a 32bits ARM microcontroller which can be used for embedded soft computing purposes, i.e. the system may be programmed so that we do not require a computer controlling the system, as usual in previous systems.

## 2. Theoretical background

Impedance sensors can be used for measuring the void fraction when there are differences between the permittivity or conductivity of the phases in a flow [22]. Depending on the format of the electrodes used and the physical characteristics of the phases, the permittivity or conductivity can be dominant in the measurement [27], allowing the impedance sensors to be classified respectively into two categories: capacitive or resistive. For most fluids, the conductivity has increased variation with temperature than permittivity, causing the capacitive sensors to have better thermal stability [33]. In addition, in resistive sensors the electrodes must be in contact with the flow, whereas the capacitive sensors can be mounted in a non-invasive and non-intrusive way.

Several electrode arrangements to capacitive sensors have already been developed [34], among which may be mentioned the ring, concave plates, and helical electrodes. Chun and Sung [32] compared the sensitivity of the ring electrodes and the concave plates electrodes. The axial way that the electric field takes in the ring electrodes causes the response to be more linear. However, the radial distribution of the field is not uniform and sensitivity at the core of the flow is lower [35]. Both types of electrodes have responses that depend upon the flow pattern. Helical electrodes were developed with the goal of reducing such dependence [13]. Ye et. al [36] studied the homogeneity of the electric field in this type of electrode, which has as its main drawback the reduced spatial resolution [37]. According to [38], the concave plates electrode has the greatest sensibility.

Regardless of the type of used electrode, it is important that it is provided by a shielding so that phenomena external to the pipe do not interfere in the measurements. The shielding must be grounded and kept at a minimum distance from the measurement electrode [39]. In this work we used a capacitive sensor with concave plate electrodes and some of their characteristics are presented below.

### 2.1. Stray capacitances

Fig. 1a depicts the cross section of a concave plate electrode set. Electrodes A and B must be placed around the pipe where the flow to be investigated takes place. The equivalent capacitance $C_{AB}$ results from the two fluids inside of the pipe and the pipe wall itself, which should be made of a non-conductive material. As the fluids are assumed to have different dielectric constants, the amount of each phase can be inferred from measured values of $C_{AB}$. Ye et. al [36] show it is possible to compensate the effect of the pipe wall

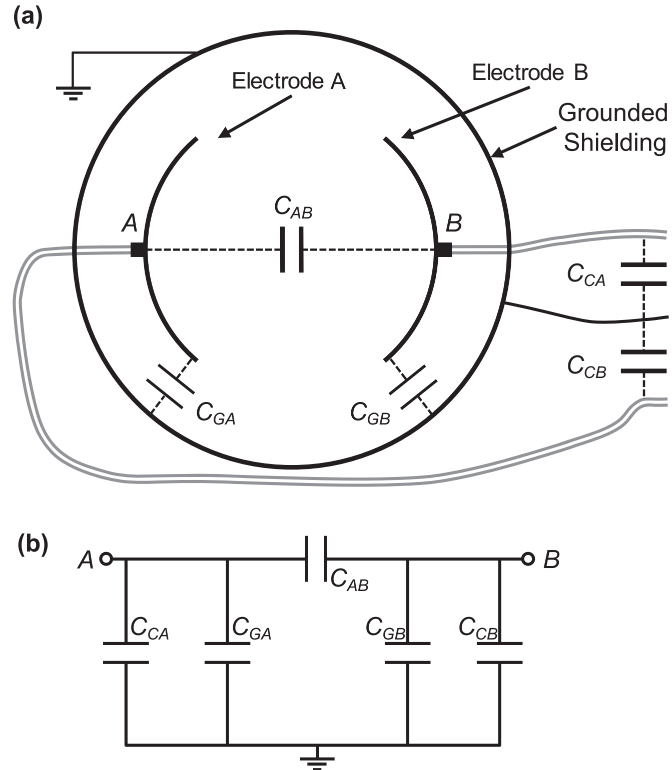


**Fig. 1.** Representation of a concave plate electrode with the stray capacitances (a) and an equivalent circuit (b).

on the measured value $C_{AB}$. In Fig. 1a two pairs of stray capacitances are also represented: $C_{CA}$ and $C_{CB}$, from the cables connected to the electrodes; and $C_{GA}$ and $C_{GB}$, which are the capacitances between the measurement electrodes and the grounded shielding. In Fig. 1b an equivalent circuit of the electrodes set can be seen.

It is common that the capacitance $C_{AB}$ has values in a range between 0.1–10 pF. The stray capacitance of a coaxial cable can easily exceed this range of values – cables with 100 pF/m are commonly used. Thus, it is essential to use measurement circuits immune to stray capacitances in order to properly obtain $C_{AB}$.

Huang et al. [40] compared four types of circuits for capacitance measurement: resonant, oscillatory, AC bridge, and charge/discharge circuits. The last two can be considered immune to stray capacitances and were reviewed by Yang [41]. A difficulty in charge/discharge circuits is the charge injection error arising out of the use of analog switches. In addition, when flow phases do not have neglected conductivity, the sensor cannot be considered purely capacitive and the capacitor $C_{AB}$ in Fig. 1b must be replaced by its equivalent impedance. In this condition the charge/discharge circuit will not function correctly. In this work, an AC bridge circuit was used, which is detailed in next section.

### 2.2. AC based circuit

A typical AC-based circuit is shown in Fig. 2a. For an ideal operational amplifier [42], the output $V_o$ shall be given by $V_o = -V_i \cdot Z_F / Z_X$. Thus, for known values of $Z_F$ and $V_i$, impedance $Z_X$ can be determined. A more practical application of this same circuit is given in Fig. 2b, in which we included the voltage source output impedance $Z_S$ and replaced $Z_X$ by the electrodes equivalent circuit. All the stray capacitances of Fig. 1b were grouped to make viewing easier, and are represented by impedances $Z_{SA}$ and $Z_{SB}$. The impedance $Z_{AB}$ reflects the flow behavior and is the parameter to be monitored.

If one applies at the input of the circuit in Fig. 2b, sequentially,