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ELECTRICAL NON-INTRUSIVE PROBES APPLIED TO THE MONITORING OF TWO-PHASE FLOWS THROUGH PIPES: A LITERATURE BASED REVIEW

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Abstract. *This paper discuss about types of electrical probes for measuring physical quantities related to multiphase flows: conductive, capacitive, impedance and inductance, regarding the complexity and factors inherent to such flows through pipes such as: operating conditions, flow patterns, physical characteristics of the materials to be transported, focusing on the volumetric concentration, which is defined as the ratio between the volume of one phase with total volume within the sensing section. Multiphase flows through pipes can be found in various technological areas. Electrical probes have the advantage of having low time of response, they are robust and simple to operate and does not require license and special care as X-rays or gamma. Basically, electrical sensors are composed of three parts: a source of excitation signal with a sensing section installed in the pipe with electrodes, cables and shielding it "feels" the flow, and electronic transducer circuit. Along the last decades, the interest on electrical probes has greatly increased, however, there are many technological challenges that still request for research investments, since its industrial use is still limited.*

Keywords: *Multiphase flow, Electrical sensors, Electromagnetic sensors, Volume fraction.*

1. INTRODUCTION

The simultaneous flow of two or more immiscible components (solid, liquid or gaseous) through a pipeline or equipment generates a multiphase flow. This is a common occurrence in chemical, food, energy conversion, materials processing, and oil and gas industries. If only two components are present in the flow, it is, in special, called of two-phase flow, in which such one of two immiscible liquids as oil and water are also called of two-phase flow (Chisholm, 1983). They are mainly characterized by the spatial arrangement of each component along the pipeline, called of flow pattern or flow regime that depends on the fluid dynamics due to momentum, energy and mass transfer along the pipe (Taitel and Dukler, 1976; Grace *et al.*, 1976; Soo, 1995).

Two-phase flows occur in horizontal or inclined and vertical pipes even in upward or downward directions. They are classified in four types depending on the components combination (Crowe, 2005):

(a) liquid-liquid flow: it is primarily found in the oil production industry. One of reasons for studying this type of flow is the need for an efficient system of heavy oil transportation from the well to the platform, and the core flow technique is based on the injection of small volume of water with the oil, such that the lower viscous water flows is in the annular region in contact with the pipe's surface and the high vicious oil in the core (Bannwart, 2001);

(b) liquid-solid flow: the solid particulate is generally dispersed in a continuous liquid component. This type of flow occurs, for example, in oil well drilling operations by the transportation of the removed material though a pumping system. And also in transportation of materials such as gypsum, gravel, cement, mortar, iron ore, limestone and clay over long distances can be performed by liquid-solid flows (Rosa, 2012);

(c) gas-liquid flow: the movement of elongated gas bubbles in a liquid medium is an example of gas-liquid flow. This flow is common in oil production systems and can occur through the production column and along the pipeline connecting the well to the separator. Gas-liquid flows also occur in the power generation industry (nuclear, fossil and geothermal) in steam generators, condensers; in the natural gas transport pipelines, the presence of condensate, can generate an annular pattern where a condensate liquid layer flows flush to the wall and the high velocity gas in the core carrying small drops of condensate (Rosa, 2012);

(d) gas-solid flow: solid particulate dispersed in a continuous gas component is the most common type of gas-solid flow. This type of flow comprises pneumatic conveying and fluidized beds with large industrial application (Rosa, 2012). In pneumatic conveying, air flow is used for transportation of particulate matter, being examples of such materials the aluminum oxide, granular foods, clay, barite, bauxite, borax, calcium carbonate, calcium chloride, carbon black, cement, coffee (raw, roasted or ground), detergent, feldspar, carbon, flour, ash, fluorite, sand, broken glass, gypsum, iron oxide, magnesium limestone, powdered milk, peanut, PVC resin, salt, silica, ash, sodium sulfate, metal, sulfur, sugar, titanium dioxide and more (Heywood and Cheng, 1984).

The fluid dynamics of two-phase flows depends on the properties of the phases, diameter of the pipe and their position to gravity, length of the pipe, flow rates of each component, presence of the singularities and restrictions along the pipeline as valves, tees or bends and the surface roughness of the pipe (Chisholm, 1983; Crowe, 2005).

The study of techniques for monitoring and control of multiphase flows aims to reduce costs and to ensure energy economy. There are many measurement quantities related to those flows such as velocity, which in general is based on the technique of cross-correlation signals (dos Reis and Goldstein Jr., 2005; Gajewski, 2013), flow rate, volumetric concentration or fraction, film thickness, and spatial distribution of the phases or tomography (Heikkinen *et al*., 2006). The flow regime or pattern identification from the signals of these probes are also of interest (dos Reis and Goldstein Jr., 2008), which can bring security and efficiency to the transportation process. In addition, the measured data is useful for exploring the economic profitability of some industrial activity. Besides of flows in pipelines, processes involving equipment as evaporators, condensers, gas transportation lines or cooling systems of nuclear reactors also require monitoring (Pacheco *et al*., 2007). Being the volumetric concentration an important quantity related to these flows (Kendoush and Sarkis, 1995; Fukano, 1998), which is also called of holdup or void fraction and is defined as the ratio of the volume of one component by the total volume of the measurement pipe section (Chisholm, 1983).

Electrical probes get advantage of the distinct electrical properties of each components, which would be related to the magnitude of the electrical conductance (G), capacitance (C), inductance (L) or impedance (Z) in their sensors that, therefore, are related to the magnitude of the flow quantity to be measured. Basically, such probes are composed of two parts: a sensing section that “feels” the flow by the sensor (one or more electrodes or windings) and the electronic transducer that converts the signal from the sensor (dos Reis and Goldstein Jr, 2008) mostly to a suitable voltage signal level. There are also those based on microwave operating with frequencies of Giga-hertz (Al-Kizwini *et al.*, 2013; Jannier, 2013; Korostynska *et al*., 2014). All they are based on the Electromagnetic Theory, and the most of them uses a pipe section of non-conductive material in the sensing section, being currently available many commercial non-conductive composite materials with high strength (Nayyar, 2000).

Electrical probes have low time of response, they are robust with no moving parts, simple to handle and do not require licenses or special care as X-rays or gamma (Crowe, 2005). Their main disadvantages are the nonlinear response combined to its dependency on the spatial distribution of the components into the sensing section (Cantelli *et al*., 2011). Consequently, the suitable design of the sensor regarding the quantity of the flow to be measured is of primary importance to their performance (Corneliussen *et al.*, 2005).

The classification of electrical probes is also related to the invasiveness and intrusiveness of their sensors. A probe is invasive if its sensor has direct contact with the flowing materials, otherwise it is non-invasive, and it is intrusive if its sensor disturb the flow even getting or not direct contact with the flowing materials, otherwise it is non-intrusive (Bertani *et al.*, 2010; Powell, 2008). Both characteristics are important for choosing the wright probe.

Due to the complexity and variety of multiphase flows even of two-phase flows, and concerning the purpose of monitoring such flows, the development of an electric probe will depend on an individualized project. Therefore, despite of their advantages, electrical probes are still few used in industrial environments, since there are many challenges that require research investments, being many of them raised from the fact that electrical phenomena are related to the occurrence of three-dimensional “soft fields” (electric or magnetic) through the matter.

This work is aimed to present, based on the literature, non-intrusive electrical probes regarding factors related to their performance as operating conditions, characteristics of material to be transported and the physical quantities to be measured, focusing on the volumetric concentration.

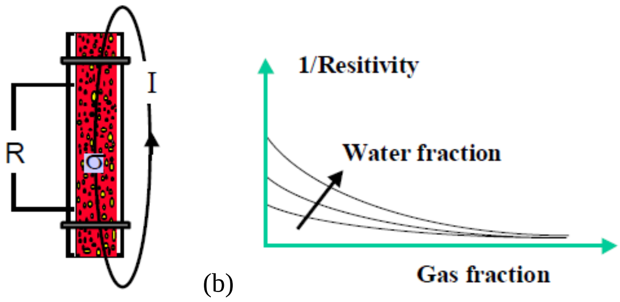
2. ELECTRICAL NON-INTRUSIVE PROBES APPLIED TO TWO-PHASE FLOWS FOR MEASURING THE VOLUMETRIC CONCENTRATION

The choice the type of probe should take into account, firstly, the electrical properties of each component of the two-phase flow, being, in general, as greater the difference between them as higher the sensitivity. Among such electrical properties, there are: the relative permittivity, ε_r, which is a quantity that affects the electric field, and in the case of water is about 80, about 1.0 for gases and 4.0 for mineral oils and many particulate materials in industry; the electrical conductivity σ, defined as the inverse of the resistivity, which is related to the ability of materials to conduct electrical current, which for tap water the conductivity is between 50 and 80 mS/m (Lentech, 2014), being very low to gases, oils and industrial particulate materials; and the magnetic relative permeability, μ_r, related to the crossing magnetic field through the matter, on which the water, for example, has a magnetic permeability 0.999992 (Griffith, 1999) near to the air and to other industrial non-magnetic materials. Water is one of the most common fluids in industrial plants.

The design of the sensor is of fundamental importance on the performance of the probe, as well as on the sensitivity of the whole measurement system (Bertani *et al.*, 2010), and also noise control by shielding and grounding techniques.

2.1 Conductance Probes (G)

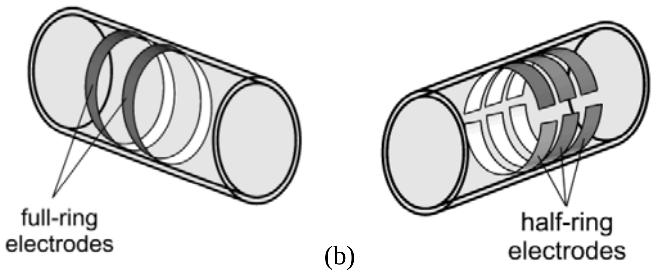
In Fig. 1, the principle of conductive or electrical resistance probe is based on applying a known potential difference V (or current, I) to generate an electric current I (or voltage V) that cross the flow within the sensing section (Ismail *et al*., 2005). Therefore, if the current I is measured (or voltage drop V), the electrical resistance R can be calculated from the 2º Ohm's Law (Corneliussen *et al*., 2005). The system response will be dependent on the conductivity or resistivity of each component, and on the path through the flow that can contain bubbles or regions of one or another component more or less conductive, on the geometric configuration and the arrangement of the electrodes in relation to the flow, and on the occurrence of oxidation or residue deposition on the surfaces along the time. Therefore, even R or I (or V) would be related to the volumetric concentration by adopting a suitable calibration strategy.



(a) (b)

Figure 1. Conductive probe's sketch in (a), and its response in (b) (Corneliussen *et al*., 2005)

Regarding the geometrical configurations of the non-intrusive sensor, the most commonly used are complete or half rings as shown in Fig. 2. In this type of probe, the electrodes will be always invasive.



(a) (b)

Figure 2. Non-intrusive electrode's configurations: two full-rings in (a); and three half-rings in (b) (da Silva, 2008).

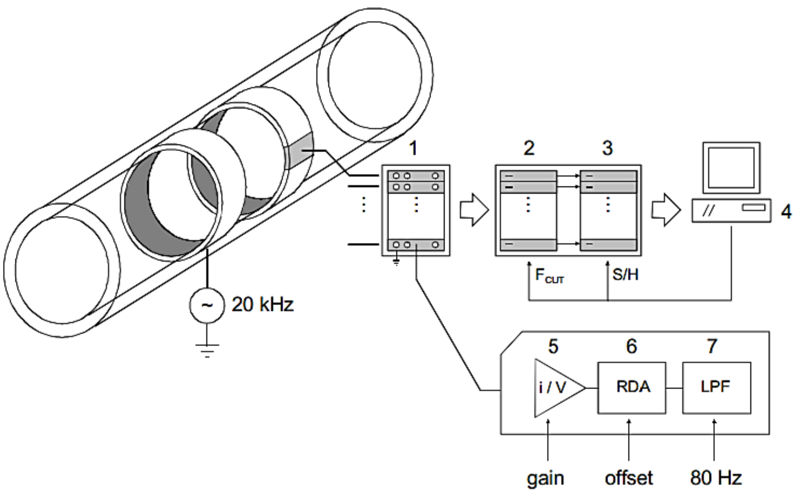


Figure 3. Conductive probe with segmented sensing electrode (Klein and Seleguim Jr., 2004)

A schematic of a probe with ring electrodes is show in Fig. 3, which was proposed by Klein and Seleghim Jr. (2004). One of the electrodes, called of source or excitation electrode, is a full-ring connected to a voltage source with a fixed frequency of 20 kHz. The other electrode is the sensor and is segmented in 16 parts that are switched to acquire data for one measurement frame, being each part connected to an individual transducer circuit (1) with a current to voltage converter (5) , an offset adjust circuit (6) and a Butterworth low-pass filter with 80 Hz cutoff frequency (7). The other block are the anti-aliasing filter (2), the data acquisition sample and hold circuit (3), and the microcomputer (4). The data on each frame was used to obtain images related to the flow by using a computational algorithm.

Conductive probes have the advantage of operate with low signal excitation frequencies, which can become of lower complexity the shielding and grounding strategies on transducer circuit design, connectors, cables, etc.

2.2 Capacitance Probes (C)

A simple diagram of a capacitive electric probe with electrodes mounted externally on vertical pipe is shown in Fig. 4. In Fig. 4 (a), the pipe is made of non-conducting material so that the electric field can cross its wall (and the flow) from the source electrode (red) where a fixed voltage signal is applied, generating an electrical current related to the magnitude of the flow quantity to be measured on the sensing electrode (blue) to be measured (dos Reis and Cunha, 2014). The system response will depend on the electrical permittivity of each component, and on the path through the flow containing bubbles or regions of one or another component more or less capacitive, the geometric configuration and the arrangement of the electrodes (concave in this case) in relation to the flow.

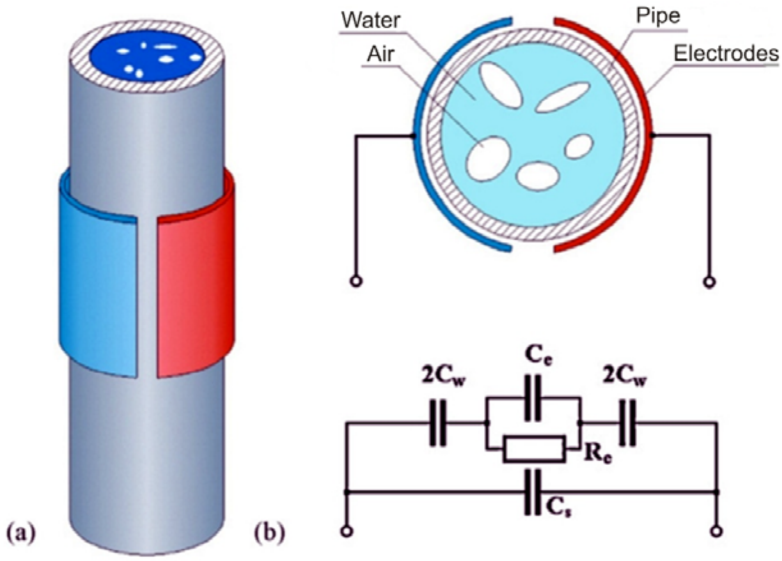


Figura 4. Capacitive sensor in (a), cut view of the sensor and its equivalent circuit in (b) (dos Reis and Cunha, 2014)

The proposed equivalent circuit of the sensor is shown in Fig. 4 (b), where C_w is the capacitance through dielectric pipe wall, therefore, it occurs on both sides of the sensor; C_s is due to the cable and connections; and C_e and R_e are the capacitance and electrical resistance related to the two-phase flow (Demori *et al*., 2010; dos Reis and Cunha, 2014).

Various non-intrusive configurations of electrodes are possible (Sami *et al*, 1980; Kendoush and Sarkis., 1995): parallel plates, concave, double ring, unidirectional and duplex, each one having its own sensing characteristics. According to dos Reis and Cunha (2014), concave, double ring, unidirectional configurations are mostly used in practical situations, having, in general, concave electrodes the higher sensitivity and the most linear response, however, is highly dependent on the spatial distribution of the components within the sensor, in turn, the double ring has greater immunity to the spatial distribution of the phases, however, it has low sensitivity and linearity of response, and the double helix has near to double ring characteristics. When designing the electrodes, one must regard the flow regime to be monitored and flow quantity to be measured (Li *et al*., 2013).

The most widely used architecture capacitance transducer circuit is based on the method called AC, whose advantage is its high signal to noise ratio, linearity and high sensitivity. It was first proposed by Mariolli *et al*. (1993).

2.3 Impedance Probes (Z)

The method based on the electrical impedance (Z) have been developed since 40 years ago. It depends on both the capacitive reactance relative to the global capacitance (C) and on the parallel global conductance (G) in the sensor, therefore, on the permittivity and conductivity of each component of the flow (Falcone *et al*., 2009).

The measurement strategy is similar to conductance and capacitance probes. A sinusoidal voltage signal V of given amplitude and frequency is applied to an electrode while the other remains at virtual ground condition at 0 V or even it can be comprised to the metallic pipe wall itself, and the resulting electric current through the impedance Z_x that is measured by A, or even the voltage drop V_1 though Z_x that performs as a voltage divider with R as shown in Fig. 5. Such circuit allows to measure the phase shift and amplitude of the real and imaginary parts of the resulting current in relation to the reference V (Heikkinen *et al.*, 2006; Bertani *et al.*, 2010). Another strategy is based on the application of a step type voltage signal and measurement of the resulting signal current along the time (da Silva, 2008).

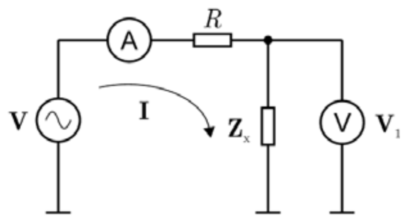
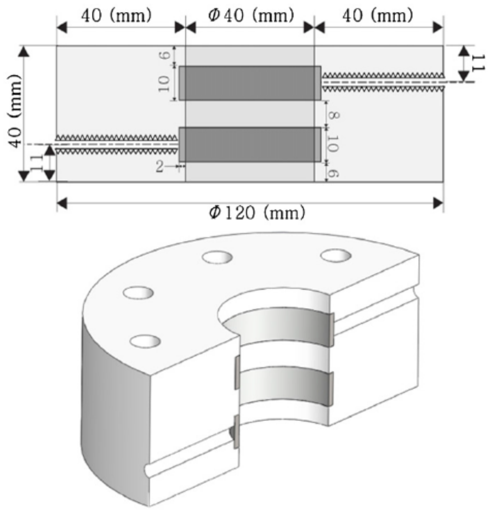


Figura 5. Measuring method for determining the impedance (da Silva, 2008)

For impedance non-intrusive probes, the electrodes usually are ring-shaped as shown in Fig. 2. Accordingly, Ko *et al*. (2013) reported on an electrical impedance sensor for small diameter pipes, which is shown in Fig. 6 with the cut view of the sensing section in (a) and the sensor view in (b). One must notice that impedance sensor are always invasive as the conductive ones.



(a)

(b)

Figura 6. Impedance sensor of Ko *et al.* (2013): cut views in (a) and sensor view in (b)

Ko *et al.* (2013) used two electrodes ring type with a diameter of 40 mm in diameter, the length of the electrodes was 10 mm and the space between them was 8 mm, the electrodes were made of stainless steel of 2 mm thick mounted flush to the inner surface of a Teflon^{TM} sensing section.

Measurement systems based on up to 32 electrodes in the sensing section allow to get sufficient information for constitute an image of the component distribution within the measurement section, which should use different computational strategies and algorithms. When the sensor is predominantly conductive, the method is called Electrical Resistance Tomography (ERT) (Ma *et al.,* 2001), when it is predominantly capacitive is Tomography Electrical Capacitance (ECT) (Liu *et al.*, 2005), and when it is based on impedance, Electric Impedance Tomographyc (EIT) (Ismail *et al.*, 2005). Regarding the X-ray or magnetic resonance systems, these methods have the advantage of allowing to acquire up to 1,000 frames per second, making them more suitable for monitoring flows.

Even conductive, capacitive or impedance probes can suffer influence of capacitive or conductive axial couplings when operating with electrically conductive fluids (Demori *et al.*, 2010).

2.4 Inductance Electromagnetic Probes (L)

Probes based on electrical inductance measurement have been proposed since 90s. Basically, the flow components have distinct magnetic permeability, and the mixture content affect the inductance in a winding built around the pipe as shown in Fig. 7, which can be simple tapped coil (Kendoush and Sarkis, 1996) with two overlapped windings as an autotransformer (Kendoush *et al.,* 2000), where a part of the winding is excitation and another induction or even with two separate windings (Kai *et al*., 2012). In the case of simple coil, the electrical current is measured directly keeping the magnitude and frequency of the excitation voltage (function generator), while the induced voltage in the second winding is measured (meter or oscilloscope) in Fig. 7. In these probes, the pipe must be of non-magnetic material, since it could concentrate the magnetic field through the wall reducing the sensitivity of the probe. The probe of Kendoush and Sarkis (1996) in Fig. 7 used a pipe section of glass.

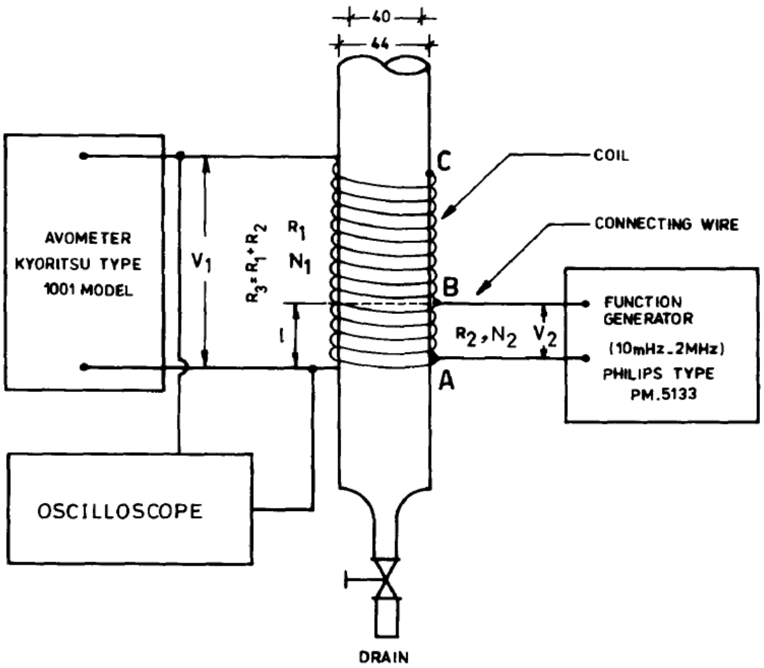


Figure 7. Inductance probe of Kendoush and Sarkis (1996)

A variant of this method is shown in Fig. 8 with two coils installed around the perimeter of a non-conductive pipe. Differently of the sensor shown in Fig. 7, the magnetic field has the transverse direction to the pipe axis as predominant direction. This sensor was proposed by exciting eddy currents and used an “inclusion” body in the angle φ to evaluate the sensitivity and the effect of spatial distribution of materials on the performance of this sensor (Stawicki *et al.,* 2009).

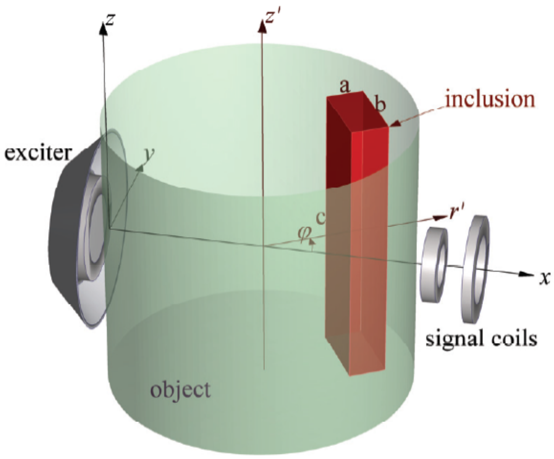


Figure 8. Measuring system: exciter, object with inclusion and receiver (Stawicki *et al.,* 2009)

In general, the magnetic permeability of non-magnetic materials commonly found in industrial environments such as gas, water or mineral oils is low close to the vacuum, therefore, this method has the great disadvantage since it imposes drastic limit on the sensor’s sensitivity. Consequently, those probes are suitable with ferromagnetic particulate (Kendoush *et al*., 2000) or liquid materials (Kuwahara and Yamaguchi, 2005).

More recently, the occurrence of eddy currents induced by magnetic fields into the mass of a conductive liquid component have been reported, which generate a secondary magnetic flux that affects the potential difference due to the primary magnetic flux through the sensor windings (Qu *et al*., 2013). Therefore, the measurement of the volume concentration in two-phase flows can be performed by regarding such effect of eddy currents into the sensing region of the flow. In this case, such method have been also explored in tomography systems, called of Magnetic Induction Tomography (MIT) (Wei and Soleimani, 2012; Xuan *et al.*, 2013).

3. FINAL CONSIDERATIONS

In this work, information from literature about electrical probes for measuring physical quantities related to multiphase flows was explored: conductive, capacitive, impedance and inductance, regarding the complexity and factors inherent to such flows through pipes such as: operating conditions, flow patterns, physical characteristics of the materials to be transported, focusing on the volumetric concentration.

Electrical probes get advantage of the distinct electrical properties of each components, being, in general, as greater the difference between them as higher their sensitivity. They have low time of response, they are robust with no moving parts, simple to handle and do not require licenses or special. However, their main disadvantages are the nonlinear response combined to its dependency on the spatial distribution of the components into the sensing section, since electrical phenomena are related to the occurrence of three-dimensional “soft fields” (electric or magnetic) through the matter, and the suitable design of the sensor must regard the quantity of the flow to be measured.

Electrical probes are still few used in industrial environments, since there are many challenges that require research investments. Even conductive, capacitive or impedance probes can suffer influence of capacitive or conductive axial couplings when operating with electrically conductive fluids, however, the study of inductance probes based on generation of eddy currents in the flow should be explored to avoid such effects, since the most of industrial liquids in multiphase flows are conductive.

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