SIMPLE TECHNIQUE TO COMPENSATE THE EFFECT OF LIQUID CONDUCTIVITY VARIATIONS ON RESPONSE OF CONDUCTIVE PROBES

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Abstract. *Conductive probes have been widely used for measuring the liquid film thickness in gas-liquid two-phase flows. It is based on the measurement of the effective liquid conductance between two or more electrodes. However, the electrical conductivity of liquid depends on temperature and concentration of dissolved salts and gasses. This dependency can deteriorate the performance of the measurement system, since is not possible to prevent some variations with time in the most of practical applications. Therefore, in this work, a new simple and effective compensation technique of liquid conductivity variations on the response of conductive probes is presented, which isn't dependent of the measurement system response that can be linear or non-linear. Although the proposed technique is simple of implementation with only a gain control by an adjustable resistor, a suitable construction of the probe and design of the transducer circuit is also important. A measurement system with a parallel-wire probe and a transducer circuit was built and tested, and the new compensation technique was evaluated by using water-salt solutions with different concentration of dissolved chloride of sodium.*

Keywords*: Conductive Probe, Electrical Properties, Conductivity Compensation, Gas-liquid Flow.*

1. INTRODUCTION

Conductive probes have been widely used for measuring the liquid film thickness in gas-liquid flows (Brown *et al*, 1978, Hewitt, 1982, Choi and No, 1995, and Cook and Behnia, 1997), since those flows are commonly encountered in several industrial processes.

The sensing principle is based on the electrical conductance between two or more electrodes that are immersed in the gas-liquid flow. The electrical resistance depends almost only on the ionic liquid, since its electrical conductivity is up to 1,000 times greater than that one of the gas.

The conductive technique relatively easy to be implemented, however, special care is required on the construction of the measurement section, calibration and use. Several authors reported about conductive probes, which they classified as flush-wire, parallel-wire and flush-mounted probe (Koskie *et al*, 1989, Kang and Kim, 1992, Choi and No, 1995, Shi and Kocamustafaogullari, 1994, Lacy and Dukler, 1994). By using parallel wires, alternatively its operation principle can be also based on the capacitance instead of conductance between two parallel-wires (Fagundes Netto *et al,* 1999), however, they must be isolated electrically with PVC or other non-conductive material to avoid the conductance component in parallel with capacitive reactance, which will request a more complex transducer circuit. However, this electrical insulation increases drastically the wires' diameter affecting the probe's performance.

The electrical conductivity of the liquid can vary with the amount of dissolved gasses and the impurities dissolved in the liquid such as mineral salts, and on the temperature of the flow. Therefore, a compensation technique is required, since it is complicated to prevent any variations of liquid conductivity with time. Koskie *et al* (1989) proposed a compensation technique that uses a reference probe that measure the liquid conductivity located in the single-phase liquid supply line in their experimental apparatus, therefore they calculated a scaled signal by dividing the voltages from the measurement probe by those ones from the reference probe. However, the main disadvantage of this technique is a significant increase on the system complexity and cost. Alternatively, Wong *et al* (1996) proposed an electronic compensation technique which uses a variable resistor in series with the probe, and compensation is obtained by adjusting the output signal on a reference condition of liquid film thickness. However, although this technique is simple of implementation and use, it isn't attractive for practical applications, since a polynomial non-linear fit based on calibration data is required, which are obtained previously from tests with different aqueous solutions.

This paper presents a new compensation technique on conductive probe's performance due to variations of the liquid conductivity, which overcome the mentioned problems: (i) it is simple of implementation, (ii) any additional information from calibration data isn't necessary, and (iii) it doesn't depend on the probe's response which should be linear or non-linear. Furthermore, the proposed technique represents an alternative for compensating other probes based on different principles for measuring thickness of liquid films as well as holdup such as capacitive.

2. CONSIDERATIONS ON CONSTRUCTION OF THE CONDUCTIVE PROBE

Some care on the construction of a conductive probe is important to the effectiveness of the proposed compensation technique. Hence, in this work, one type of conductive probe was considered as a case of study, while a similar analysis

can be done for other types. Figure 1(a) and 1(b) show a typical scheme of a conductive probe with two parallel-wires frequently used typically with horizontal air-water two-phase piping flows. This probe is built with two thin parallel wires stretched through the liquid layer perpendicularly to the inner pipe wall. The wires are fixed in a dielectric material at the wall, and they are kept under tension and stretched from outside the flow. The parallel G_x and C_x represent the electrical conductance and the electrical capacitance which impose the total impedance between the wires.

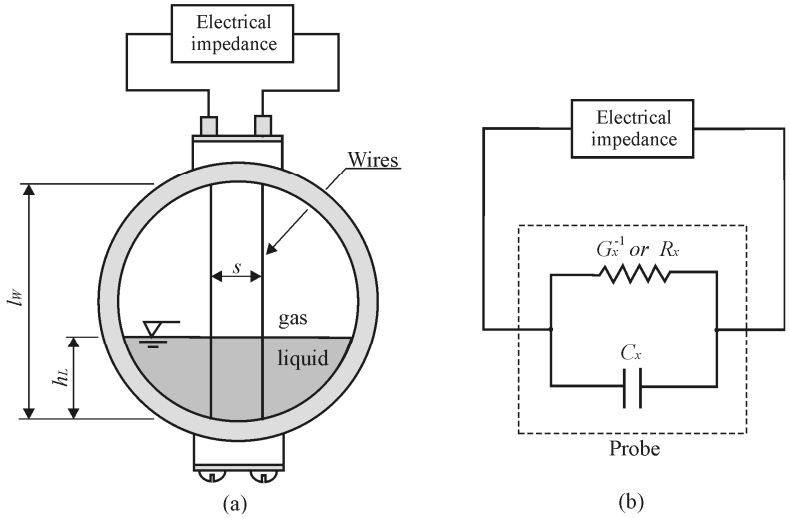


Figure 1. Parallel-wire probe: (a) probe for piping flows; (b) equivalent electrical circuit

The capacitive reactance due to C_x must be much larger than G_x^{-1} or R_x in conductive probes (the inverse of G_x represents the electrical resistance R_x). Moreover, values of R_x depend on several parameters such as the length l_w and diameter d of wires, space between them s, electrical conductivity of the wires' material σ_w, wet length or liquid layer thickness h_L, electrical conductivity of the liquid σ_L and of the gas σ_G, the surface condition of the wires that is represented by S_w, and on the presence of undesired effects due to the fluid flow represented by φ discussed in next paragraph. Therefore, R_x can be expressed in a general way as in Eq. (1).

$$R_x = f\left(l_w, d, s, \sigma_w, h_L, \sigma_L, \sigma_G, S_w, \varphi\right) \tag{1}$$

Parameters l_w, d, s and σ_w in Eq. (1) are determined during the probe's construction. While l_w depends of the requested measurement range, and d and s are chosen to avoid undesired effects from the fluid flow: (i) small waves generation in the gas-liquid interface due to the wires themselves; (ii) the viscous wake region behind the wires can capture some small gas bubbles; (iii) some liquid attachment between the wires can occurs along the gas layer, which occurs due to surface tension in the gas-liquid-solid interface. These effects cause distortion on the probe's response, specially (ii) and (iii) which alter the effective conductance of the medium around the wires. Consequently, while the diameter d must be as small as possible (0.1 mm or less) to limit undesired effects due to the flow, the mechanical resistance of wires must resist the efforts due to the flow, the distance between the wires s must be larger to avoid liquid attachment of liquid on the wires along the gas layer, it must also allow to measure instantaneous liquid layer thickness at some point, since the interface is usually disturbed by complex waves. Additionally, the measurement range of the probe is along the central region far away from the pipe's wall. Under a best condition, φ is disregarded in Eq. (1).

The wires' material, which σ_w is dependent, they were built with gold, platinum, platinum-rhodium, chromel, stainless steel and other metals as described in literature. Gold has electrical conductivity of about $4.16 \times 10^7\ \Omega^{-1}.m^{-1}$ at 20°C, platinum about 4.4 times lower, platinum-rhodium 8.0 times lower, chromel 7.0 times lower, and stainless steel about 180.0 times lower than gold (Lide, 1994). Therefore, one must consider that the probe's response becomes non-linear when the electrical resistance between the wires isn't much larger than that of the wires themselves (Koskie *et al*, 1989), which also depends of l_w and d.

In Eq. (1) the surface condition of the wires represented by S_w is constant if material of high resistance to oxidation is used, which avoids a variable rust layer on the metallic surface of the wires. Moreover, in Eq. (1), the electric conductivity of the liquid σ_L is many times greater than of the gas and, therefore, σ_G can be also disregarded in Eq. (1) as discussed before.

Consequently, while l_w, d, s, σ_w and S_w are constant due to the probe's construction while φ and σ_G can be disregarded. Therefore, R_x depends of only of h_L and σ_L which are independent. Furthermore, R_x can be expressed as in Eq. (2) by applying the Method of Separating Variables (Kreyszig, 1999).

$$R_x(h_L,\sigma_L) = F(h_L)G(\sigma_L) \tag{2}$$

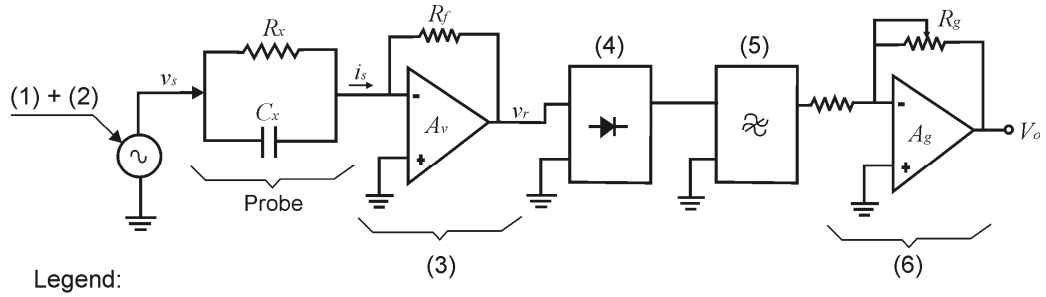
$F(h_L)^{-1}$ is linear if all above considerations about *d, s,* σ_w, S_w, F and σ_G in Eq. (1) are valid, since the electrons' flow between parallel wires will occur identically along the length at central region of the wires (measurement range), which is distant from the pipe's wall. Due to σ_L in Eq. (2), $G(h_L)$is also function of other parameters such as the temperature T and the concentration of dissolved salts and gasses in the liquid Γas in Eq. (3).

$$\sigma_L = g(T, \Gamma) \tag{3}$$

In this work, gold with 99.99% of purity was chosen for wires due to its high chemical stability, low electrical resistivity and high ductility, since diameter as small as 98 μm was obtained from a higher one of 1.0 mm directly by cold extrusion. Additionally, in Fig. 1, the geometric parameters of probe were d = 98 μm, $l_w = D$ = 34.0 mm, where D is the internal diameter of a Plexiglas pipe section of about 300 mm of length, and s = 2.0 mm. The probe's section was similar to that of Choi and No (1995).

3. ELECTRONIC TRANSDUCER AND COMPENSATION TECHNIQUE

Some care must be also taken on the design of the electronic transducer. In literature, two similar architectures of the electronic transducer circuit were presented by Koskie *et al* (1989) and Choi and No (1995) with the following six blocks shown in Fig. 2: (1) source of A.C. carrier signal, (2) buffer connected to the first parallel-wire, (3) current to voltage converter connected to the second wire, (4) full-wave precision rectifier, (5) active low-pass filter that together with the rectifier converts linearly the A.C. signal to D.C, and (6) output amplifier to range the output signal. Therefore, the carrier sinusoidal signal v_s from (1) and (2) is applied to the probe R_x and C_x, and current i_s is converted to v_r in (3), then v_r is rectified in (4), filtered in (5) and amplified in (6) to V_o at the D.C. output.



Legend:

(1) Source of A.C. carrier signal - oscillator
(2) Buffer of current
(3) Current to voltage converter
(4) Full-wave precision rectifier
(5) Active low-pass filter
(6) Output D. C. amplifier

Figure 2. Bocks diagram of the transducer circuit

When choosing the frequency of v_s, two aspects can interfere on response of the probe: (i) the electrical resistance of an ionic fluid is a strong function of the frequency of the applied signal, therefore, Brown *et al* (1978) determined that a carrier frequency in excess of 50 kHz is optimal; (ii) the capacitive reactance between the wires must be as high as possible, consequently, the frequency f must be as low as possible. For that reason, a prototype of the electronic circuit was built to operate with f = 50 kHz. Moreover, some experimental measurements showed that, when the probe's prototype was full filled with water that presents a dielectric permittivity about 80 times than of air, the capacitance between the wires C_x didn't exceeded 0.8 pF. Therefore, the capacitive reactance with the 50 kHz carrier signal was 3.98 MΩ, which was about 265 times larger than 15 kΩ measured for R_x.

The transfer function of the transducer of Fig. 2 can be represented by Eq. (4), where v_{sp} is the peak electrical voltage of v_s and A_g is the gain of the output amplifier adjusted through R_g. R_x was substituted by Eq. (2) in the right side of it.

$$V_o = \frac{2\,v_{sp}\,A_g}{\pi}\frac{R_f}{R_x} = \frac{2\,v_{sp}\,A_g}{\pi}\frac{R_f}{F(h_L)G(\sigma_L)} \tag{4}$$

The main idea of the compensation technique due to liquid conductivity variations is adjust R_f in order to compensate effects of $G(h_L)$ on V_o. R_f is an adjustable resistor (potentiometer) as shown in the circuit of Fig. 3, and Eq. (4) can be modified by including a representing the setting variable of R_f with $0 \le a \le 1$. Therefore, V_o in Eq. (4) is desired to be only function of h_L, consequently Eq. (5) can be obtained.

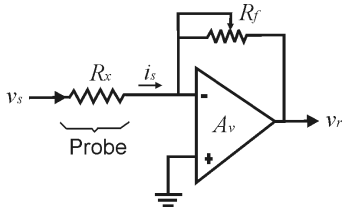


Figure 3. Resistive probe and current to voltage converter

$$\frac{a\,R_f}{F(h_L)G(\sigma_L)} = \frac{R_f}{F(h_L)} \tag{5}$$

Equation (5) has a unique solution given by Eq. (6), which means that a must be set equal to $G(h_L)$, and thus it is only function of σ_L or of T and Γ from Eq. (3).

$$a = G(\sigma_L) \tag{6}$$

Once $F(h_L)$ is obtained by calibration, some suitable state reference of liquid layer thickness, designed by h_{Lref}, must be chosen by the user, which produces the voltage $V_{o,ref}$ at output of the transducer circuit, and compensation is done by adjusting V_o to $V_{o,ref}$ when a different situation of σ_L from that of calibration is observed, which also can be verified on the reference state.

Wong *et al* (1996) proposed an alternative compensation technique with an adjustable resistor R_e in series with the probe R_x while R_f is fixed, as shown in Fig. 4. In this case, the transfer function of the transducer of Fig. 2 is given by Eq. (7).

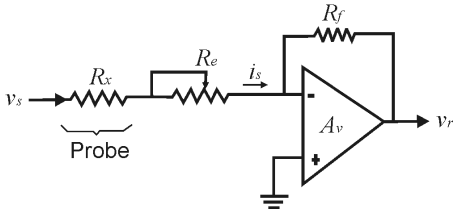


Figure 4. Circuit proposed by Wong *et al* (1996)

$$V_o = \frac{2\,v_{sp}\,A_g}{\pi}\frac{R_f}{R_x + a\,R_e} = \frac{2\,v_{sp}\,A_g}{\pi}\frac{R_f}{F(h_L)G(\sigma_L) + a\,R_e} \tag{7}$$

However, a similar analysis of that of Eq. (5) shows that V_o in Eq. (7) cannot be only a function of h_L by setting a of R_e, since, a is dependent of both h_L and σ_L in Eq. (8) and the compensation technique should be not effective.

$$\frac{R_f}{F(h_L)G(\sigma_L) + a\,R_e} = \frac{R_f}{F(h_L)} \quad \rightarrow \quad a = \frac{F(h_L)}{R_e}\left[1 - G(\sigma_L)\right] \tag{8}$$

4. STATIC CALIBRATION AND EVALUATION OF THE COMPENSATION TECHNIQUE

The static performance of the probe system was evaluated using the apparatus shown schematically in Fig. 5. It is composed of a horizontal tube plugged in both extremities and divided in two parts: a test section with two PVC joints where the probe is installed, and a fixed section with a micrometer with two liquid taps on the bottom of the tube. The test section can be rotated through the nylon joint with o-rings for general study of gas-liquid instrumentation for

horizontal piping flows. The base has four screws that allowed adjusting its horizontal level. The micrometer with a range from 25 to 50 mm, and a minor scale division equals to 0.01 mm, is used to measure the liquid film thickness. Reis and Goldstein Jr (2005a) used the same calibration apparatus for studying capacitive non-intrusive probes. Output voltages V_o were measured with a Hewlett and Packard multimeter model HP 4284A.

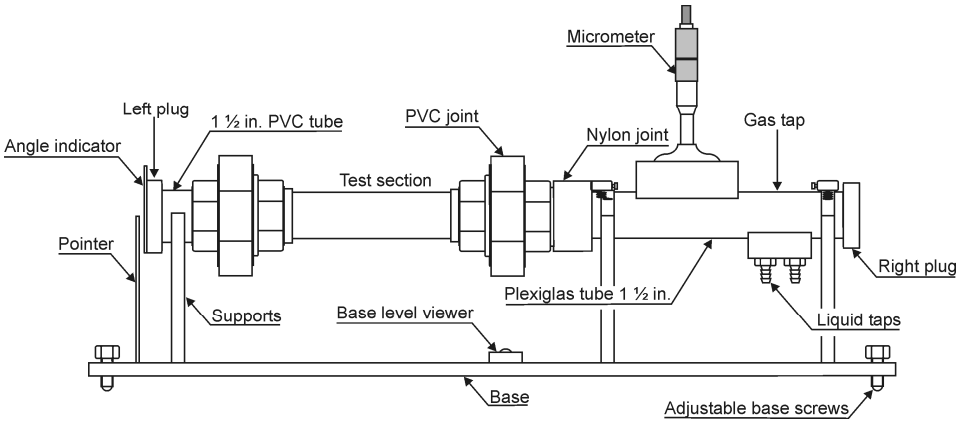


Figure 5. Static calibration device

The calibration curve of the probe is shown in Figs. 6, where h_L/D is the non-dimensional liquid layer thickness. It was registered 18 calibration points (9 from bottom to the top of range, and the 9 from the top to bottom), and the uncertainties were estimated equal to ±1.576% of FS or ±0.535 mm with a confidence interval of 95% from a linear regression of data, and the reference state chosen as pipe full filled of water with $V_{o,ref}$ = 4.6569 V at 22.6°C. One should note that reference state must be chosen on some easy-to-set condition of liquid layer thickness, since compensation procedure will always be executed on this reference state.

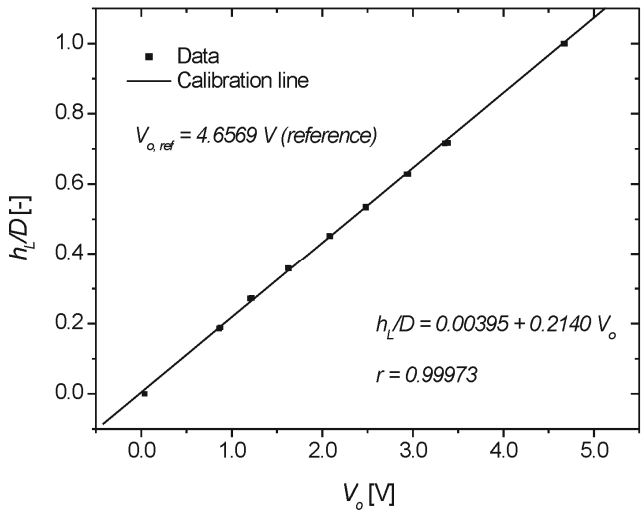


Figure 6. Calibration curves of probe with wires of ϕ98 μm

In order to confirm the efficiency of the proposed compensation technique, three different tests were made with common water from urban waterworks system. For each test, about 2 liters of water was sampled with different amounts of chlorite of sodium according to Wong *et al* (1996). Two samples were prepared with salt concentration of 0.098% and 0.196% in weight respectively, and any salt was dissolved in the third sample (only clear water). Soon after, the system response was registered for each sample using the apparatus shown in Fig. 5, and the same procedure for static calibration.

Figure 7 shows results obtained. For each water-salt solution with a different salt concentration, V_o was adjusted in the reference state when the pipe is full filled with water. Therefore, with clear water in the reference state, V_o = 4.6573 V and any adjustment in R_f of Fig. 3 was done, after that nine data points shown in Fig. 7 for clean water were obtained. Following, when 0.098% sample was tested on the reference state, V_o = 13.6431 V that was the saturation voltage of the transducer circuit, which had occurred at about h_L/D = 0.45. However, according to the compensation procedure discussed in item 3, it was adjusted to 4.6361 V though the resistor R_f, and then nine data points shown in Fig. 7 for

0.098% were also obtained. The same procedure was adopted for the 0.196% water, when V_o was increased to from 4.6061 V to 7.6182 V on the reference state of pipe full filled with water, and it was adjusted to 4.6463 V before registering data shown in Fig. 7 for 0.196%.

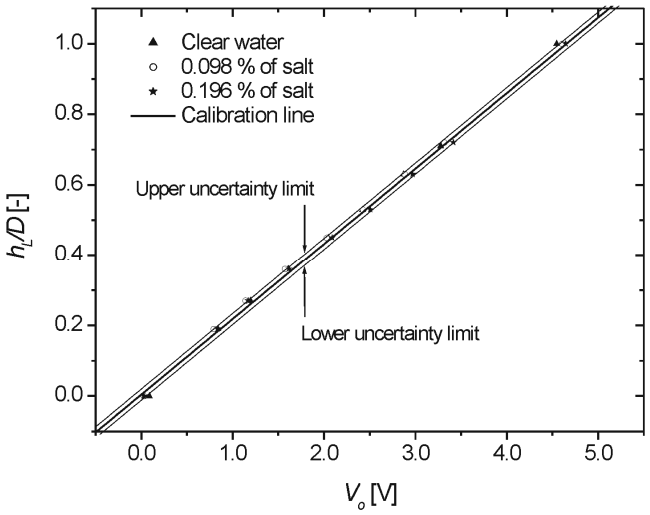


Figure 6. Compensation of the conductivity variations

Two additional lines in Fig. 7 delimit the lower and the upper range of uncertainties around the calibration line. From all of 3 x 9 = 27 data points, 24 of them were into the lower to upper range of uncertainties, representing 89% with the proposed compensation technique against 95% of the confidence interval of calibration.

5. CONCLUSION AND REMARKS

This paper presents a new compensation technique of effect of liquid conductivity variations on the performance of conductive probes. Although it is simple with only implementation of a gain control though an adjustable resistor in the transducer circuit, an appropriate construction of the probe's measurement section and design of the transducer circuit are also important.

Experimental data were obtained from a conductive parallel-wire probe for measurement of water layer thickness. Therefore, three water-salt solutions with conductivities were used in tests, and results shown a small difference of each set of data from the probe's calibration curve, confirming the proposed compensation technique as effective.

In several measurement systems of parameters related to gas-liquid flows, the probe's response can be represented by Eq. (2), having two separated functions: the probe's response from calibration; and another representing the dependence of some electrical properties of one of the flow components, in general the liquid. In these cases, the proposed technique can always be used. Therefore, it can represent an alternative from that of Reis and Goldstein Jr (2005b) for compensating variations of dielectric permittivity of liquid due to temperature in capacitive probes for measurement of holdup or thickness of liquid films.

6. ACKNOWLEDGEMENTS

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