2009 International Nuclear Atlantic Conference - INAC 2009
Rio de Janeiro,RJ, Brazil, September27 to October 2, 2009
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: **978-85-99141-03-8**

CAPACITANCE SENSOR FOR VOID FRACTION MEASUREMENT IN A NATURAL CIRCULATION REFRIGERATION CIRCUIT

Marcelo S. Rocha[1], Eduardo L. L. Cabral[1] and José R. Simões-Moreira[2]

[1] Instituto de Pesquisas Energéticas e Nucleares, IPEN - CNEN/SP
Centro de Engenharia Nuclear - CEN
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
msrocha@ipen.br, elcabral@ipen.br

[2]Escola Politécnica, Universidade de São Paulo - USP
Departamento de Engenharia Mecânica
Rua Prof. Mello Moraes, 2231
0550-900 São Paulo, SP
jrsimoes@usp.br

ABSTRACT

Natural circulation is widely used in nuclear reactors for residual heat refrigeration. In this work, a conductance probe is designed and constructed to measure the instantaneous bulk void fraction in a vertical tube section. This probe is installed in a natural circulation refrigeration loop designed to simulate a nuclear reactor primary refrigeration circuit. During the operation of the natural circulation loop several gas-liquid flow patterns are observed, including oscillatory flow. The instantaneous signal generated by the capacitance probe allows the calculation of the two-phase flow void fraction. The void fraction obtained by the probe will be compared with the theoretical void fraction calculated by the computational program RELAP5/MOD3.2.2 gama. The probe design and electronics, as well as the previous results obtained are presented and discussed.

1. INTRODUCTION

1.1 Natural Circulation Refrigeration Loop of IPEN

Natural circulation cooling loops have been important technique for boiling water reactors (BWRs) cooling design because your operational simplicity, safety, and maintenance reduction features [1, 2]. In natural circulation BWRs, a chimney is installed on the core to increase natural circulation flow rate. In order to achieve reliable cooling performances, the natural circulation BWRs have to be designed and operated to avoid two-phase instability caused by adiabatic flashing, which is induced by the pressure drop due to gravity head at low pressure.

Those natural circulation cooling loops operates governed by the interplay of inertia, buoyancy and friction forces. Belong decades it has been subject of many studies and related in technical works [1 - 4]. In the nuclear reactors, natural circulation loops are key to the residual heat removing in case of primary circuit fail. Many cases have been studied concerned the performance of natural circulation loops after the known accident of *Three Mile Island*. That accident showed that those kinds of refrigeration circuits are not well known. Another important fact is the necessity of human actuation in case of severe accidents.

Two-phase heat transfer process control, design, safety, and performance improvement require the knowledge of heat transfer coefficient and the void fraction. As can be proved by predicting methods the heat transfer coefficient is dependent on the void fraction distribution and flow regime. So far oscillatory heat transfer problem, the flow boiling, is affected by the influence of flow direction on the heat transfer coefficient and void fraction during fully developed nucleate boiling in the vertical channel.

According to studies on void fraction measurement, have been performed by means of many techniques in heated tubes with subcooled liquids [1-4], results show that the direction of the flow affect the void fraction considerably.

Regarding that, this project aims to know the natural circulation refrigeration loop operational behavior in similar but reduced scale conditions as it should operate in a real BWR. In this way, the void fraction sensor is a key to determine flow variables, flow patterns behind other parameters with minimum uncertainty, once many other variables are directly associated with void fraction.

A prototype of a natural circulation loop simulating small scale of the real phenomenon that occur in a BWR were designed and constructed in the laboratory of the Nuclear Engineering Center (CEN) of IPEN to test and visualization of all involved phenomena.

1.2 The Void fraction Sensor

Many void fraction measuring techniques have been extensively studied in last decades in connection with determining the void fraction and characterizing the two-phase flow structure and regime. Two-phase flow presents a fluctuating nature, so its identification relies on measurement techniques using a specific instrumentation. The development of instrumentation for the void fraction measurement is the keystone for the multidimensional multiphase flow modeling as well as for flow monitoring purposes. In this context, many techniques for measuring the void fraction have been developed, and their particular success depends on a specific application. Generally, their signal response is two-phase flow structure-dependent and can be designed to indicate void fraction values that are instantaneous or time-averaged, local or global.

One widely used technique for void fraction measurement is based on the measurement of the two-phase electrical impedance, the working principle of which relies on taking the advantage of the difference in electrical impedance of each one of the two phases. Many different sensor configurations have been devised and can be grouped into two major categories: namely, invasive to the flow or non-invasive. Many studies have been carried out using invasive probes mainly for obtaining the local void fraction distribution and the phase interfacial area, using, for instance, an impedance or optical sensor type.

Other probe arrangements have been conceived in a flush configuration mounted with the pipe wall, which gives them the clear advantage that they do not disturb the two-phase flow distribution. These latter sensor types consist of examples of noninvasive ones. Among those, the impedance probe method is the simplest and probably the cheapest of all techniques.

Specific processes with intense heat transfer demand more accurate and reliable instrumentation for their best quality production, once the most fluids electrical impedances are strongly dependant on temperature.

Simple impedance probes formed by a wall flush mounted pair of electrodes have been used along with flow data statistical processing for both vertical as well as horizontal gas-liquid flow [5–8]. This simple configuration is known to be accurate to indicate the average void fraction as long as the void fraction is cross-section uniformly distributed. However, investigations show that a non-uniform cross-section void fraction distribution changes the instantaneous signal, giving rise to erroneous indication of the actual average void fraction.

Therefore, for a two-phase flow system in which the void fraction may be not uniformly distributed over the cross-section, such as some fluidized bed reactors flows and inclined and horizontal stratified flows, that kind of a simple pair of electrodes is not recommended. The two-phase mixture impedance technique can be basically divided in two other types: the resistive and the capacitive impedance technique.

As a proposed solution, a single pair of electrodes sensor is required to eliminate the misreading due to that void fraction non-uniform distribution problem. Later, other studies were carried out in connection with the determination of instantaneous signal response to void fraction wave propagation.

Electrical impedance tomography is a modern technique that has brought some considerable advances and demonstrates a two-phase flow reconstruction principle based on signals of many flush mounted electrodes.

The electrical impedance measurement technique can also be applied to the liquid-liquid mixture for mass content determination [7-8]. The authors obtained a transference function of the mean electrical conductivity of different ethanol and gasoline blends at several temperatures. The technique developed in this work aims to investigate the influence of the volumetric void fraction distribution over a cross-section analyzing the exiting signal from two impedance probes. Two eight-electrode sensors and their electronic circuits were built.

Next, the two sensors were mounted in a vertical tube for void fraction measurements. Besides measuring void fraction, a sensor signal processing investigation was also carried out in order to obtain other relevant flow parameters, such as Taylor bubble propagation velocity and length and flow regime identification. To achieve these goals, statistical tools were used, including auto- and cross-correlation (AC & CC) and power density function (PDF).

The capacitance technique can be applied to numerous applications and its success is associated to the electrodes geometry and flow direction. The specific literature presents many studies in which it is clear the dependency of the system characteristics and the probe geometry and measurement technique. So, the first step for an experimental study of impedance sensor for void fraction measurement is the choice of the best sensor type, geometry and measurement technique for the system characteristics. Some capacitive sensors geometry is presented in Fig. 2 as most useful by scientific works presented in literature.

From the three main techniques for measuring mean phase content--radioactive absorption and scattering, direct volume measurement by quick-closing valves and impedance measurements only the latter is relatively easy to use in a rotating system.

For water-steam flow, an increase in temperature from 25 to 50°C doubles the conductivity, whereas the relative permittivity decreases by only 15%. Moreover, the relative permittivity of the water is not affected by a change of ionic concentration. Drift can be reduced by operating at sufficiently high frequency to give domination by capacitance.

Another important issue on capacitance sensors response influence is the guard electrode presence, electrodes dimensions, and fluid temperature. For small diameters tubes sensitivity is an important issue, so electrodes dimensions influences directly on sensors response. Innumerous works in literature presents different correlations for two-phase flow measurement using capacitance probes but the physical parameters and flow conditions are so sparse to compare them.

The present type of sensor operates based on the dissimilarity of electrical properties of the liquid and vapor demineralized water. According to the operational frequency of the signal applied between the electrodes along with the knowledge of the electrical properties of the fluids, the average dominating impedance of the two-phase mixture filling in the cross-section may be either resistive, capacitive, or both. The sensor analyzed in this study operates in the capacitive range. The elementary electrical model of the sensor and the measuring system that operates without electrolysis near electrodes surfaces can be compared to a parallel RC circuit.

A parallel RC analysis shows in a simple way that, for the resistive operating range, it is possible to associate the overall two-phase mixture resistance with the corresponding electrical average conductivity, as follows:

Fluid capacitance is strongly temperature-dependent. To get around this problem, a common technique is to work with a dimensionless capacitance rather than the absolute value so that the temperature influence is diminished, if not eliminated. Although the use of dimensionless capacitance use, another mathematical correction must be applied to the sensor signals guaranteeing the less temperature effect influence as possible. The dimensionless capacitance is the ratio between the actual two-phase water-steam capacitance at the same temperature. By taking regular water electrical properties (dielectric), one can estimate the operating frequency of the applied signal, which results in a range, for capacitive impedance measurement, of $f > 1$ MHz.

2. EXPERMENTAL FACILITY

2.1 Natural Circulation Refrigeration Loop

The natural circulation loop is formed by glass Pyrex tubes of 38 mm internal diameter, 2.6 m height, with an upward vertical pipe where a heat source section 4.5 kW electrical resistance is located, and a vertical downward pipe where a spiral heat exchanger removes part of the total heat. The capacitance sensor for void fraction measurement is located at the vertical upward pipe above the heating section as can be seen in Fig. 1.

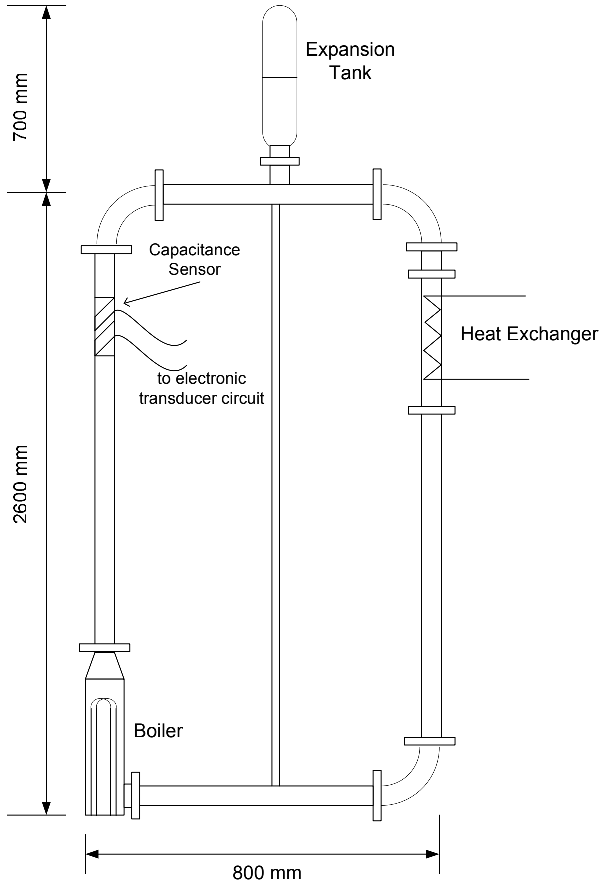


Figure 1. Schematics of natural circulation loop.

The expansion tank absorbs the flow density and pressure variation, and it is connected to the inferior section point. The superior expansion tank nozzle keep opened to atmosphere permitting the circuit run at atmosphere pressure. Al the circuit is not thermally insulated permitting the visualization of all circuit sections.

The boiler section is an electrical resistance is controlled by a voltage controller that makes the power control from zero to about 4.5 kWe. Temperatures are measured in 16 points along the circuit, and T type thermocouples have been used. There are two points of surface temperature measurement and 14 points of internal flow temperature measurement. There are two points of pressure measurement made by piezoelectric transducers. All data are acquired by a 32 channels acquisition data system. Before, the secondary flow from heat exchanger is monitored by two points of temperature and flow measurement.

2.2 Void Faction Measurement

In this study a capacitance sensor with a phase-sensitive detector, operating at a frequency of 1 MHz, is used,as can be seen in Fig. 2. A copper tape coating is wound around the tube which has an i.d. of 38 mm. Electrode 1 makes three complete revolutions around the tube, electrode 2 only two. The pitch of the helix is πD, hence the active length of the sensor is $2\pi D$ (~ 4 dia). The shield electrodes fix stray capacitance and make an analytical approach of the helical cross-capacitor possible. The guard electrodes are connected electrically to the two shield electrodes. Special dual cables with characteristic capacitance of about nano-Faradays are used to connect the electronic circuit to the shield electrodes. This arrangement permits a capacitance measurement independently of the length of the coaxial leads and external fields.

The actual volumetric void fraction will be measured by two different techniques, which is going to be considered the calibration standards within this project scope. For the natural circulation circuit where the capacitance sensor is mounted, the void fraction range varies from 0 to about 60%, as revealed by the simulation results from RELAP5 [2]. Two techniques are going to be considered as the actual average volumetric void fraction measurement: the first one is the gravimetric method (GM), because the liquid at rest, resulting in a small pressure column oscillation, provide accurate measurements and furnishing small measurement uncertainties (less than 5% according o literature).

The second standard technique is based on the use of existing well posed prediction theoretical models for a vertical column two-phase flow. Using the RELAP5 prediction model for two-phase flow prediction of a specific well known situation (bubbly flow for example) in which the GM method permits a good void fraction measurement to compare, and extrapolate it for higher void fraction two-phase flow conditions.

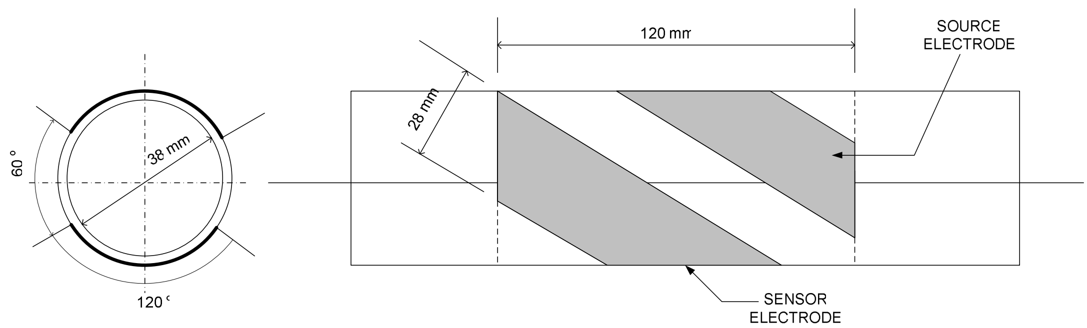
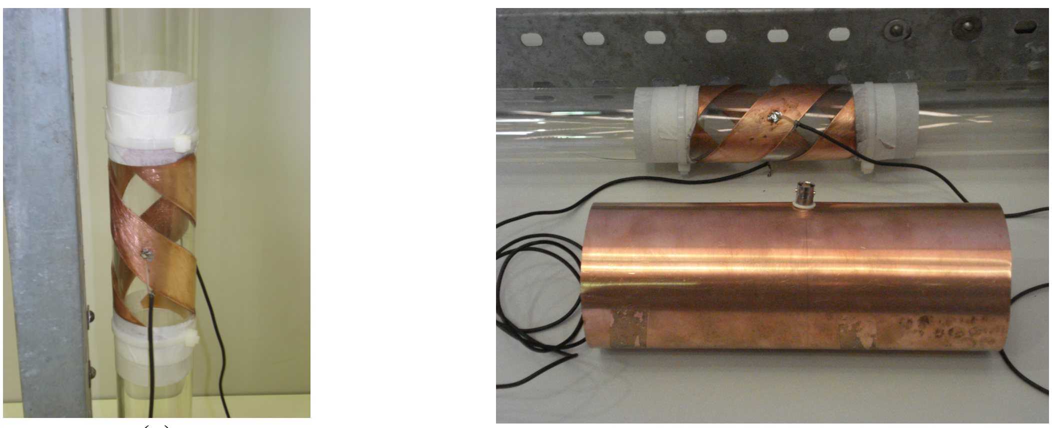


Figure 2. Capacitance sensor dimensions.



(a) (b)

Figure 3. Capacitance sensor assembled on a vertical test section (a), and sensor with electromagnetic insulator.

2.3 Electronic Circuit

An electronic circuit was designed and constructed to make the capacitance signal transduction to an outlet signal (V_0) varying from 0 to 5V DC, corresponding to the void fraction variation from 0 to 100%.

As can be seen in Fig. 4, the electronic circuit consist of a signal generator which furnish a sinusoidal wave, 5 Vpp/1MHz signal that modules a current source producing a (V_S) 5 Vpp/1 MHz, 3 mA signal that is applied to the dual helical electrodes capacitance sensor. The two-phase mixture capacitance (C_X) variation into the vertical tube produces a signal that is amplified, rectified and filtered to a 100 Hz signal (V_0) that, finally, is amplified and adjusted to be measured by a data acquisition system. The electronic circuit module is connected to the capacitance sensor by coaxial cables with low capacitance (C_{S1} and C_{S2}). The resistive impedance parcel (R_X) can be disregarded, once for high frequencies the resistance is to low to be accounted.

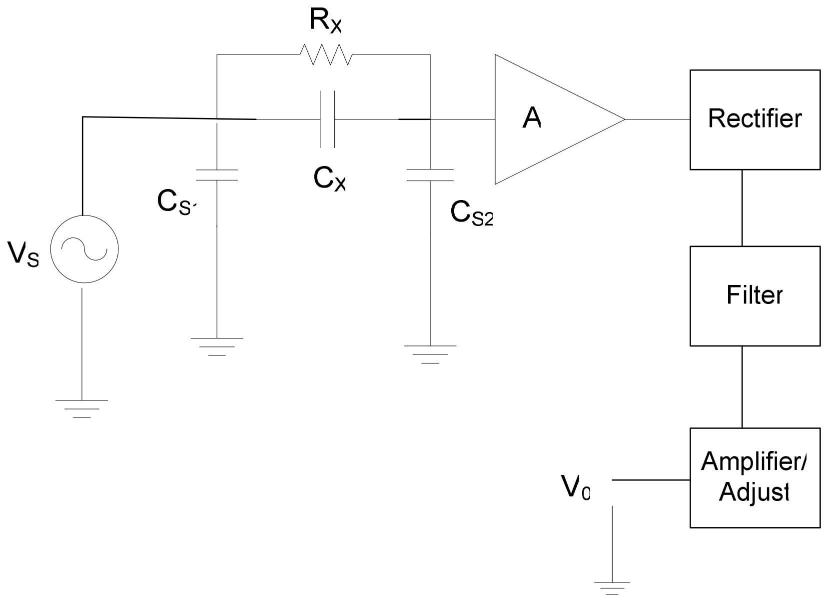


Figure 4. Electronic circuit diagram.

3. CAPACITANCE SENSOR MODEL

3.1 The capacitance sensor electrical model

There are many works in which the capacitance sensor was modeled, and some analytical solutions were obtained for specific flow conditions.
Geraets and Borst (1988) [4] shows that, for a simplified electrode configuration compound of two concave flush mounted electrodes, the capacitance and electric field distribution can be calculated by Laplace equation in a cylindrical coordinates as follows:

$$\frac{\partial^2 V}{\partial r^2}+\frac{1}{r}\frac{\partial V}{\partial r}+\frac{1}{r^2}\frac{\partial^2 V}{\partial \phi^2}+\frac{\partial^2 V}{\partial z^2}=0 \tag{1}$$

where, V is the potential distribution, r is the radial direction coordinate, z is the axial direction coordinate, and ϕ is the circumferential direction coordinate.

After a series of mathematical, geometric and boundary conditions applications, the final analytical solution for the eq. (1) is:

$$V(r,\xi)=\frac{\xi V_0}{\pi}+\frac{2V_0}{\pi}\sum_{n=1}^{\infty}\frac{\sin(n\xi)\cos(n\xi)I_n\left(\frac{nr}{pR}\right)}{nI_n\left(\frac{n}{p}\right)} \tag{2}$$

where, $\xi = \phi$ - z / pR, R is a half of the inner diameter. The pitch parameter p is equal to the ratio of the pitch of the helix (s) and the circumference ($2\pi R$), $p = s / 2\pi R$. The parameter I_n is a modified Bessel function of the first order, and n is an integer. The internal cross-capacitance per unit length (C') can be written as:

$$C'=\frac{2\varepsilon_0\varepsilon_r}{\pi}\left\{\ln\frac{\sin\left[\frac{(\phi_1+\phi_2)}{2}\right]}{\sin\left[\frac{(\phi_2-\phi_1)}{2}\right]}+\sum_{n=1}^{\infty}\frac{2\sin(n\phi_1)\sin(n\phi_2)I_{n+1}\left(\frac{n}{p}\right)}{pnI_n\left(\frac{n}{p}\right)}\right\} \tag{3}$$

where, ε_0, and ε_r are the free space permittivity and the relative permittivity of the internal mixture flow.

3.2 Flow temperature effect on sensor signal

One of the main characteristics of the natural circulation refrigeration circuit is the flow temperature variation during all heat dynamic cycle observed. The electrical properties changing along the cycle must be evaluated, so the sensor's outlet signal will change too.

The two-phase mixture temperature variation is one of the critical parameter that influences the capacitance changing ($C_X = f(T)$). As a consequence the outlet signal (V_0) from electronic transducer circuit will varies as the flow temperature and void fraction varies too ($V_0 = f$ (T)).

A complete description on how temperature influences the outlet signal (V_0) can be seen in [9]. According to the authors, the outlet signal is influenced by flow temperature variation for a two helical electrodes as shown in section 2, by:

$$V_0 = V - a[1-\alpha(T_0)][\varepsilon_L(T)-\varepsilon_L(T_0)] \tag{4}$$

where V_0 is the sensor outlet signal for a calibration temperature T_0, V is the sensor outlet signal for a temperature T, α is the void fraction, a is the voltage derivative to the temperature

dV/dT, and ε_L is the liquid relative permittivity. The calibration tests where carried out in a certain temperature T_0 = 20 °C, and the total heat cycle varies from 20 °C to 100 °C.

Accordingly, the liquid relative permittivity variation ($d\varepsilon_L/dT$) variation with temperature is many times higher than vapor relative permittivity variation ($d\varepsilon_V/dT$), so this is the motive that it is not regarded in this formulation.

Preliminary tests carried out with the capacitance sensor show the outlet signal variation with the dielectric constant changing with temperature, as is shown in Table 1. Three lectures were carried out for each temperature level from 20 °C to 45 °C maintaining water in the liquid phase. To verify the vapor capacitance correspondent value of V0, lectures were obtained for at he water vapor phase in which temperature was 70 °C. So, the minimum and the maximum outlet signal values were obtained with some intermediary liquid phase capacitance values.

Table 1. Liquid capacitance and outlet signal variation with temperature.

Temperature (*°C*)	Capacitance (*pF*)	V_{0_1} (*V*)	V_{0_2} (*V*)	V_{0_3} (*V*)	V_{0_4} (*V*)
20	1,2	1,264	1,208	1,228	1,215
25	1,32	1,306	1,313	1,297	1,325
30	1,54	1,68	1,614	1,584	1,567
35	1,73	1,726	1,784	1,696	1,711
40	2,06	2,135	1,973	1,984	2,044
45	2,458	2,297	2,317	2,265	2,371
70*	4,623	4,588	4,642	4,596	4,634

As one can see in Fig. 5, the outlet signal variation with temperature is not a linear function temperature, and a third order polynomial curve fit can express those variations with reasonable error.

In Fig. 6, its possible to observe the capacitance variation with water temperature variation. As commented before, the capacitance is largely influenced by temperature as proved here. The capacitance signals were obtained with a LRC decade with 0.1 pF of resolution. The capacitance lecture was made after instrument and temperature stabilization, which occurred after 20 minutes generally.

The curve fit obtained shows a second order function modeling the water capacitance variation with liquid temperature variation.

Those results were obtained with a preliminary electronic circuit developed to verify the total capacitance range and outlet signal rage variation with temperature variation. A new accurate electronic circuit has been developed to capacitance measurement improvement

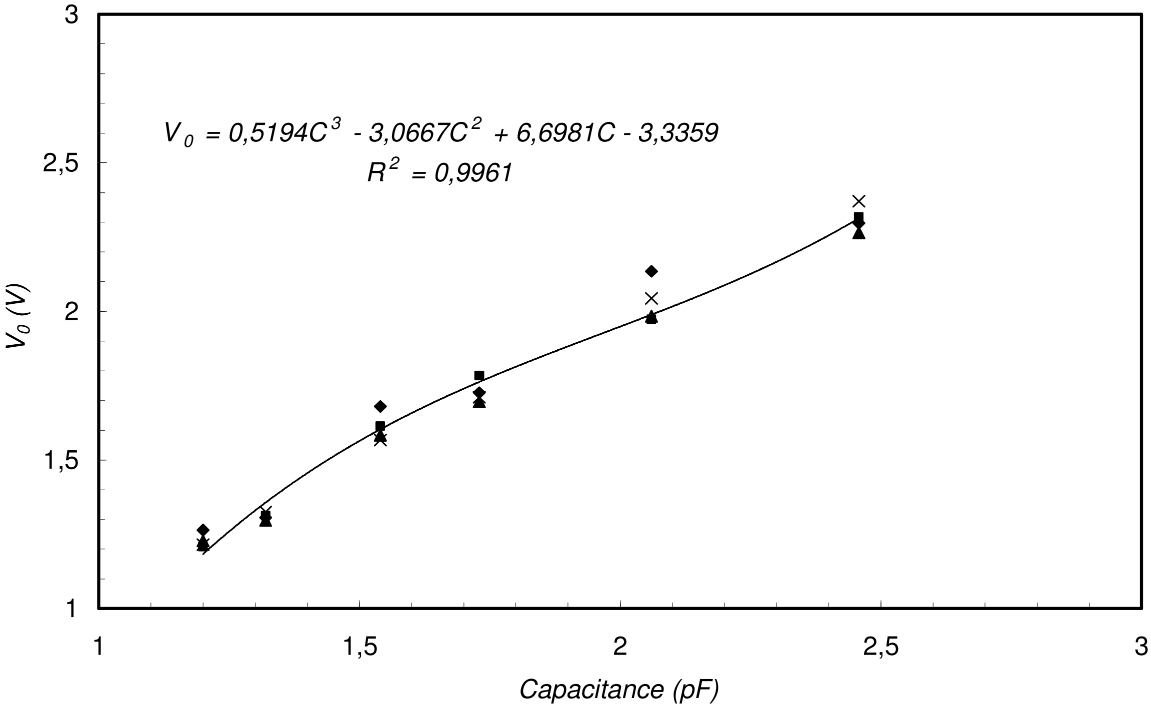


Figure 5. Capacitance sensor outlet signal variation with temperature.

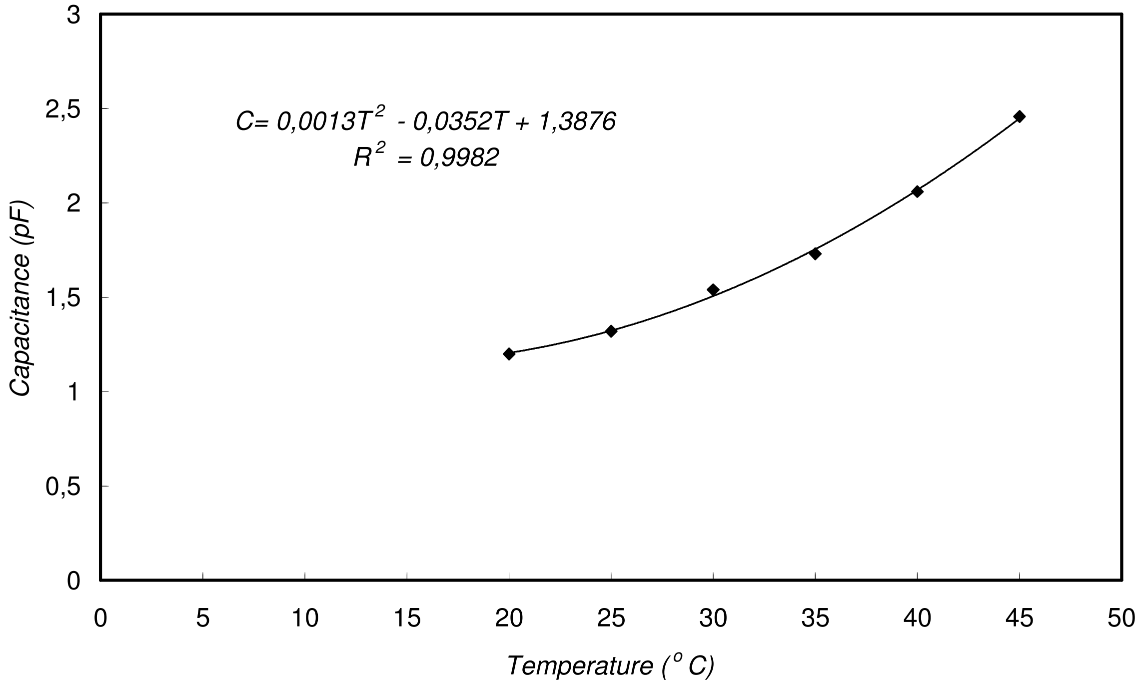


Figure 6. Water capacitance variation as a function of temperature.

4. CONCLUSIONS AND REMARKS

Present work shows the design, construction and preliminary tests of a capacitance sensor for void fraction measurement in a prototype of a natural circulation refrigeration loop designed to simulate a BWR refrigeration circuit.

The capacitance sensor has being designed to measure bulk void fraction on a vertical upward two-phase flow section, and previous results show that it has enough sensitivity to detect the void fraction with uncertainty level sufficient to compare results with the data obtained by simulations. Some parameters that have large influence over capacitance sensors results were considered and have been treated to avoid it. For a preliminary electronic circuit developed, the circuit outlet signal range was obtained with temperature variation, as well as the water capacitance variation range with temperature variation. Results shows non linear correlations for both outlet signal and capacitance signal variation with temperature.

Next research step consist on development of a new electronic circuit , sensor calibration and final tests that will permit comparisons with simulation data.

ACKNOWLEDGMENTS

The authors wish to acknowledge the CNPq (Brazilian Counsel for Research and Development) for the personal and research funding.

REFERENCES

1. Inada, F., Furuya, M., and Yasuo, A., "Thermo-hydraulic instability of Bowling natural circulation loop induced by flashing (analytical consideration)", *Nuclear Engineering and Design*, **Vol. 200**, pp. 187-199 (2000).
2. Furuya, M., Inada, F., and van der Hagen, T.H.J.J., "Flashing induced density wave oscillations in natural circulation BWR – mechanism of instability and stability map", *Nuclear Engineering and Design*, **Vol. 235**, pp. 1557-1569 (2005).
3. Hart J.E., "A new analysis of the closed loop thermosyhon", *Int. Journal of Heat and Mass Transfer*, **Vol. 27**, pp. 125-136 (1984).
4. Geraets, J.J.M., and Borst, J.C., "A capacitance sensor for two-phase void fraction measurement and flow pattern identification", *Int. Journal of Multiphase Flow*, **Vol. 14**, pp. 305-320 (1998).
5. Jaworek, A., Krupa, A., and Trela, M., "Capacitance sensor for void fraction measurement in water/steam flows", *Flow Measurement and Instrumentation*, **Vol. 15**, pp. 317-324 (2004).
6. Abouelwafa, M.S.A., and Kendall, E.J.M., "The use of capacitance sensors for phase percentage determination in multiphase pipelines", *IEEE Transactions Instrumentation Measurement*, **Vol. 29**, pp. 24-27 (1980).
7. Rocha, M.S., and Simões-Moreira, J.R., "Void fraction measurement and signal analysis from multiple-electrode impedance sensors", *Heat Transfer Engineering Journal*, **Vol.29**, pp. 924-935 (2008).
8. Rocha, M.S., and Simões-Moreira, J.R., "Comparision of RMS and PDF Signal Analyses from Multiple-Electrodes Impedance Sensors in Two-Phase Flow, *Proceeding of 1o*

Encontro Brasileiro Sobre Ebulição, Condensação e Escoamento Multifásico Líquido-Gás – EBECEM 2008, Florianópolis, April 28-29, **Vol. 1**, 8 p. (2008).
9. Dos Reis, E., and Goldstein Jr., L., “A procedure for correcting for the effect of fluid flow temperature variation on the response of capacitive void fraction meters”, *Flow Measurement and Instrumentation*, **Vol. 16**, pp. 267-274 (2005).