2013 International Nuclear Atlantic Conference - INAC 2013
Recife, PE, Brazil, November 24-29, 2013
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
***ISBN*: 978-85-99141-05-2**

FLOW VISUALIZATION OF BUBBLE BEHAVIOR UNDER TWO-PHASE NATURAL CIRCULATION FLOW CONDITIONS USING HIGH SPEED DIGITAL CAMERA

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ABSTRACT

The present work aims at identifying flow patterns and measuring interfacial parameters in two-phase natural circulation by using visualization technique with high-speed digital camera. The experiments were conducted in the Natural Circulation Circuit (CCN), installed at Nuclear Engineering Institute/CNEN. The thermo-hydraulic circuit comprises heater, heat exchanger, expansion tank, the pressure relief valve and pipes to interconnect the components. A glass tube is installed at the midpoint of the riser connected to the heater outlet. The natural circulation circuit is complemented by acquisition system of values of temperatures, flow and graphic interface. The instrumentation has thermocouples, volumetric flow meter, rotameter and high-speed digital camera. The experimental study is performed through analysis of information from measurements of temperatures at strategic points along the hydraulic circuit, besides natural circulation flow rates. The comparisons between analytical and experimental values are validated by viewing, recording and processing of the images for the flows patterns. Variables involved in the process of identification of flow regimes, dimensionless parameters, the phase velocity of the flow, initial boiling point, the phenomenon of "flashing" pre-slug flow type were obtained experimentally.

1. INTRODUCTION

The natural circulation is of great interest in the nuclear reactor thermal-hydraulics. Many studies concerning the passive heat removal of a nuclear reactor by natural circulation have been carried out, in order to understand the physical phenomena and to develop methods of simulating the thermal-hydraulic behavior in a passive reactor cooling mode, [26,16,7,23,14,25,9]. Theoretical models for prediction of natural circulation two-phase flow parameters have been developed, and although these models have the ability to predict important flow parameters such as the pressure gradient, average phase velocities and void fractions, they are not capable to predict the flow structure itself. Moreover, the flow structure evolution may differ from that of forced convection flow [19,22,24].

The experimental measurement of two-phase natural circulation flow parameter requires appropriate techniques. The main requirement of a measurement technique to be successful for a two-phase flow is to have a high degree of spatial resolution, because the flow varies considerably over the cross section. In the last decades an extraordinary development has been made in visualization techniques and systems. Today, digital visualization systems are inherently capable to manipulate image data to extract more information than ever. The visualization technique have been used in many applications, such as machine vision, military systems, information and telecommunication, medical diagnostics, chemical and nuclear engineering. In the experimental research of two-phase natural circulation flow, the non-intrusive digital high-speed visualization technique has become a powerful tool, mainly when combined with other two-phase flow measurement techniques, such as temperature and flow rate measurements. It can provide valuable information on the void fraction, flow pattern, gas and liquid velocity, and bubble length and velocity by individual bubble tracking.

2. LITERATURE REVIEW

A research work of residual heat removal by natural circulation of scale in power plants with the loss of coolant, was presented by [13], using air coolers, passive coolant system injection and expansion of primary coolant. The results of experiments can be shown with graphics of sudden increase of temperature, coefficient of reactivity, reactor power, initial power of reactor and pressure. The behavioral studies of experimental facilities can be supported by the theory of scales and similarities.

[10] studied experimentally and numerically the natural circulation behavior of a liquid region confined in a rectangular parallelepiped cavity equipped with a heater and a cooler, in order to investigate the passive safety performance of an innovative marine nuclear reactor. The temperature and natural circulation flow were visualized by a liquid-crystal suspension method that enabled the authors to observe the local natural convection around the heater and the cooler, global natural circulation in the cavity, and thermal stratification. [15] used a glass transparent loop, designed according to scaling criteria, in order to simulate the two-phase natural circulation flow and various effects that occur in a hot-leg-U-bend, as part of the study of a small-break loss-of-coolant accident in a light-water reactor. [5] studied the correlation between two-phase flow pattern and thermal hydraulic behavior of a natural circulation loop, employing dynamic flow visualization techniques. Transient flow patterns in the loop were recorded by means of two cameras (CCD and video), and processed using image processing techniques. The time evolution data of loop flow rate, pressure, fluid temperature and flow patterns could be compared on the same time basis to explore the detailed interactions between flow patterns and other thermo-hydraulic properties. Pointed out that dynamic variation of flow pattern and flashing effect play important roles for two-phase flow in a low pressure natural circulation loop.

[20,21] investigated experimentally and numerically the geysering phenomena, one possible instability type that may occur in ABWR reactors cooled by natural circulation only. [11] presented an experimental three-dimensional reconstruction and visualization of stationary and transient flashing flow in a vertical pipe. The experimental measurements were performed by means of wire-mesh sensors. Steam bubbles complete three-dimensional reconstruction were performed by taking into account the bubble velocity, then allowing

the flow pattern visualization. Moreover the bubble size distributions were obtained both in stationary and transient conditions. [12] studied flow patterns associated with phase transients and static instabilities, using a visualization technique applied on a two-phase natural circulation loop. The visualization was combined with temperature measurements in order to estimate the instability cyclic period and to detect a flow transition pattern. Finally the authors implemented a fuzzy inference algorithm that allowed a two-phase pattern classification system based on the image flow processing.

The theoretical and experimental studies of natural circulation phenomenon with experiments using single-phase and two-phase flow, was performed by [17], in the similar conditions to circuit of residual heat removal of nuclear reactors. The experiments were performed using the energy variation inside heater and flow variation of cooling water of secondary system to the computational model validation RELAP5. The thermal-hydraulic analysis presented the results of the simulations supposing both the single-phase flow like also two-phase through graphs of temperature evolution to compare with the experimentally obtained data beyond in terms of mass flow of primary and secondary systems and void fraction in heater and in expansion tank.

Theoretical and experimental studies of the natural circulation phenomenon with single-phase and two-phase flows, was presented by [18], for validation of RELAP5 computational model in the continuation of the research project of natural circulation. The results of the simulations are presented through graphs of temperature evolution and experimental data of heater output, experimental data of heat exchanger output (single-phase), considering both flows types, single-phase and two-phase. The mass flow of primary system (RELAP5) and the evolution of void fraction of the secondary cooling (RELAP5) are also presented.

The study of experimental research on natural circulation phenomenon was performed by [6] using experimental loop was built based on the concepts of scale and used the two-phase flow (water and nitrogen) for better separation of phenomena hydrodynamic, in it noted the importance and the great influence of parameters such as friction and geometry of hydraulic loop in the results. Such results of experiments include the measurements of void distribution on the patterns hot leg and flows. The tests were performed in several conditions, being very important for data extrapolation to real installations. The results included graphs of superficial velocity of gas and liquid and friction coefficient.

This paper reports experimental results of a visualization technique tests carried out on the Nuclear Engineering Institute's Natural Circulation Loop. A high-speed digital camera was employed in combination with temperature and flow rate measurements, allowing to acquire data of liquid superficial velocity and bubble velocity for a particular electric power applied on the loop heater. Nowadays, a test program has been performed using the Natural Circulation Loop in order to obtain a series of experimental data to evaluate the operational conditions, instrumentation and data acquisition and control system performance. The second objective of this program is to contribute to the development of non-conventional measurement techniques and instrumentation to be applied in future APWR passive heat removal systems research.

3. EXPERIMENTAL PROCEDURES

3.1. Circuit description

The experiment was carried out by using an two-phase natural circulation circuit installed at the Institute of Nuclear Engineering (IEN/CNEN). A general view and a schematic of the Natural Circulation Loop are shown in in Fig. 1. The experimental facility was designed based on the works of [1,2,3,8], taking into account relations of similarity and scale, compared to the circuit of residual heat removal of Advanced Pressurized Water Reactors. The volume scale is 1 : 96. The height scale is 1 : 10. It is a one-tenth height scale, atmospheric pressure model designed to meet the single and two-phase flow similarity criteria to a typical prototype APWR full scale passive residual heat removal system. The main parts of the loop are a primary system, instrumentation, data acquisition and control system.

The primary system was comprised by a cylindrical vessel with downcomer, a core barrel housing electrically heated rods, upper plenum and lower plenum, interconnected with a shell seven-tubes heat exchanger by hot/cold pipe legs. The hot leg was formed by two flanged pipes 0.302 m long made of stainless steel with an inner diameter of 0.0234 m, and a tube 0.302 m long transparent boron-silicate glass with the same inner diameter. A vertical pipe connected the cold leg of the loop to an expansion tank which absorbed the loop fluid volume changes, and a safety valve was installed to protect it against overpressure. The heat exchanger represents a prototype Passive Reactor Heat Removal Heat Exchanger (PRHR-HX) with the primary fluid flowing inside the seven tubes. The primary system is thermally insulated from the ambient air by a 1 inch layer of glass wool. The hot/cold pipe legs internal diameters were chosen meeting the similarity criterion for the global friction number. Due to the local area reduction of an electromagnetic flowmeter, with a diameter of half approximately of the cold leg diameter, besides its measuring function it also contributed to meet the global friction number similarity criterion.

The power for electrically heated rods was controlled from a rack featured with one AC/DC transformer, current shunt, power multipliers and other electronic devices. The data acquisition and control system were provided with instrumentation in order to acquire flow, power and temperature data. All the signal outputs from the instrumentation were received, processed and recorded in this system which had included one industrial standard PXI computer with a software package, signal amplifiers/conditioners, switching panels, A/D converters, and display.

All of the power and temperature instruments were calibrated to reference standards and they were checked prior to the tests. The estimated temperature and power uncertainties are, respectively, 2.4 Celsius grad and 0.83 percent.

An Endress+Hauser model H15 Promag 50 electromagnetic flow meter is used for the measurement of natural circulation flow rate. The measured values by volumetric flow meter were sent to the data acquisition system of PXI system and transformed in electronic spreadsheet via processing by LabView.

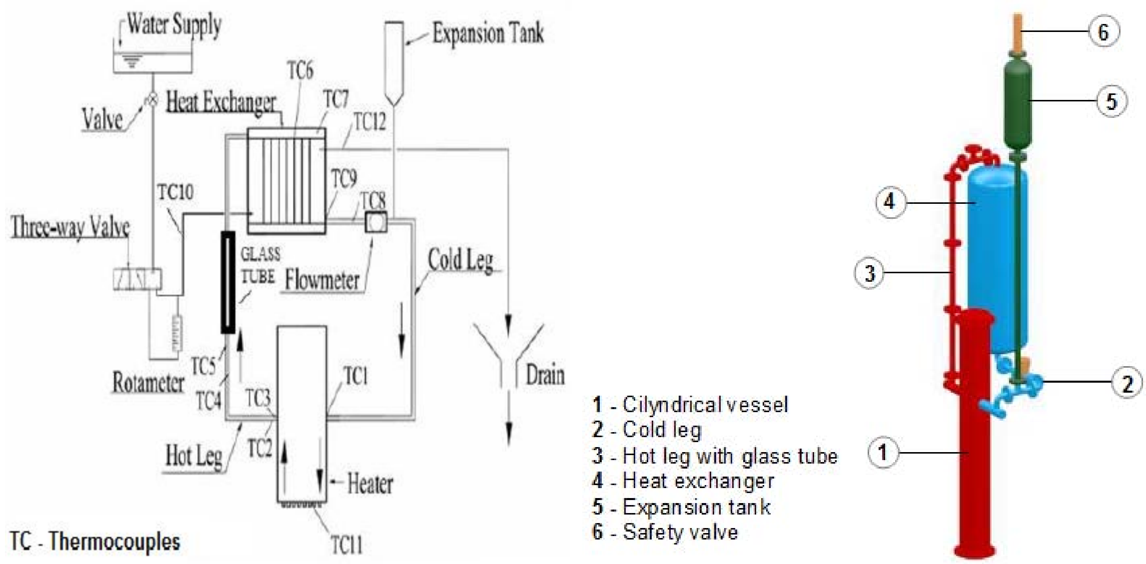


Figure 1: Schematic of natural circulation circuit and points of measurements through thermocouples.

3.2. Visualization system

The visualization system was formed by a colour high-speed digital camera equipped with a CMOS chip sensor (maximum resolution 800 x 600 pixels), zoom lenses, an acquisition and image analysis program, and a computer. Tripods and mounting devices completed the system that has capacity to record sequences of images from 60 to $33,000$ frames per second. Complete control of the camera operating system including frame rate triggering, adjustment image resolutions and shutter speed was facilitated through the personal computer. The camera professional zoom objective could be focused at distances shorter than 1.0 m. The lightning system included a light projector placed in front of and above the transparent glass tube. The position was important for preventing shadowing and reflections, and for ensuring good image quality. For each frame rate only a set of predetermined resolution was available. Higher resolutions (pixels per frame) result in longer recording times and fewer video images in internal camera memory, so that a compromise between frame speed and resolution has to be found. The frame speed of 60 frames per second was found to be sufficient for the measurements and was used in all experiments reported in this paper. The camera was manually started and stopped recording. The sequence of images displayed on the computer monitor could be stored in a computer file, retrieved and replayed to analyze the flow motion sequence in detail. The set of discrete pictures were saved as a series of colour AVI images with a resolution of 800 x 600 pixels. The information on the bubbly flow within the pipe was obtained by processing about 920 frames.

3.3. Measurements and comments

The experiment provided the acquisition of temperature values at the points defined in Fig. 1. However, for the analysis of flow regimes were only considered the temperature values in the hot and cold legs. This difference in temperature becomes important to study the energy balance between the transfer of heat through the heater and the removal of heat by the heat exchanger. The experimental apparatus, the type scalled provides greater accuracy for studies regarding the effects of hydro-dynamic variables.

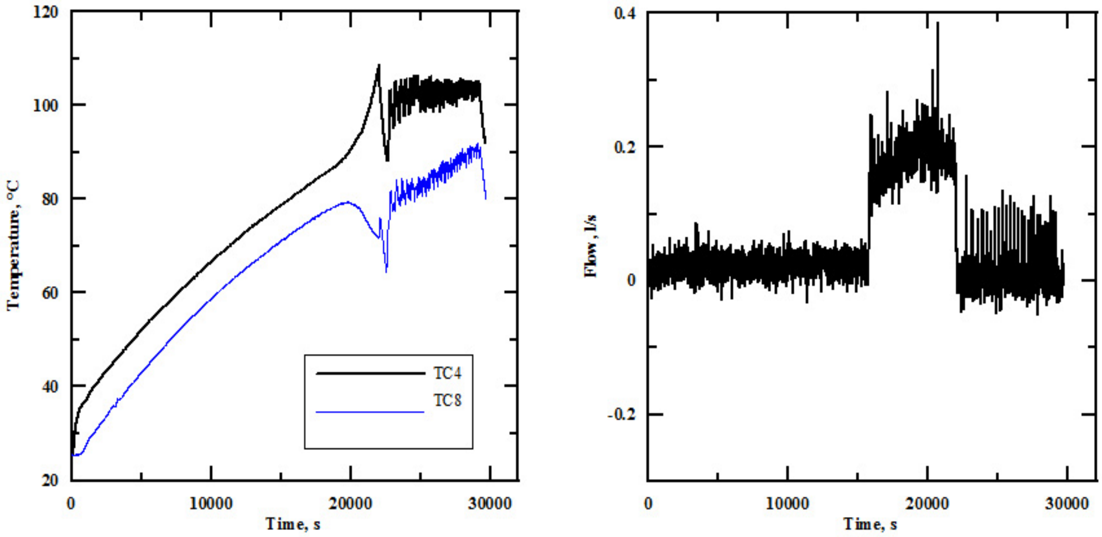


Figure 2: (a) Temperatures measurements between TC4 and TC8, (b) Natural circulation flow measurement.

4. RESULTS

The analysis of the experiment can be divided into three stages, as shown Fig. 2. The first stage corresponds to the region of the graph with the evolution of temperature in hot and cold legs, occurs in a linear way, characterizing the single-phase flow. The second stage corresponds to the formation of nucleate boiling regime and formation of micro-bubbles dispersed, characterizing the single-phase to two-phase transition. The third stage is set to the beginning of the two-phase system with the rise of type flow regimes slug and churn.

4.1. Single-phase flow analysis

To perform the analysis of the flow pattern and calculate the dimensionless parameter was taken into account the temperature difference between the hot and cold legs, as seen in Fig. 3, and also considering the time interval 0-15000 s, where this difference remains approximately constant. it was adopted a steady difference close to 9 Celsius grad. The informations were extracted from [1,2,3]. As the expansion coefficient of the water is small and the average and the reference densities are close to the usual value. The percentage difference between the experimental values and analytical values was estimated to be 1.6 percent. The hydraulic resistance (HR) of the natural circulation circuit was obtained with the value of $1.7257 \times 10^8 m^{-4}$. The natural circulation flow ($\dot{m}$) was calculated with the value of 0.02455 Kg/s. The Number of Friction (NF) was calculated with the value of 3826.

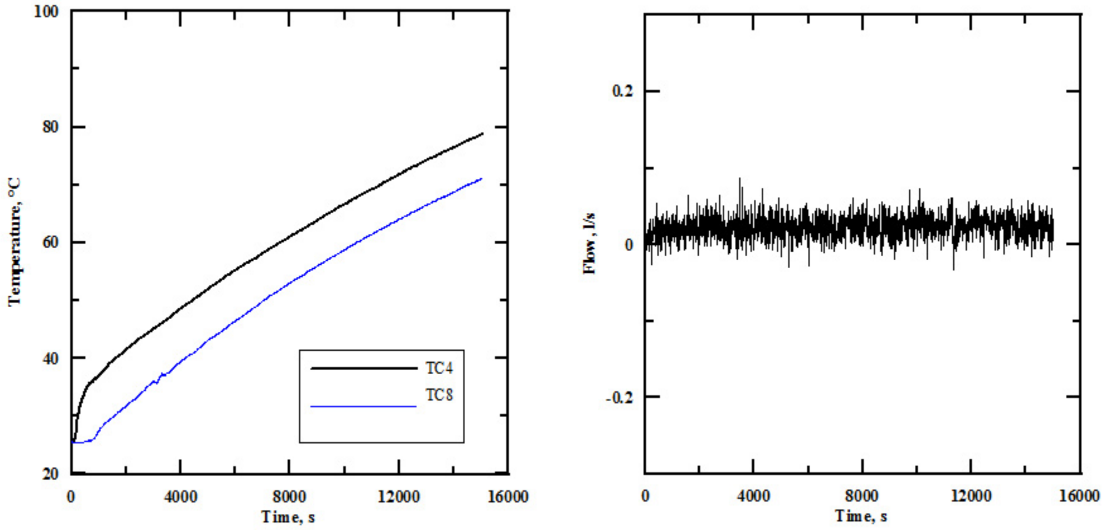


Figure 3: (a) Temperatures in Single-phase flow pattern and (b) Single-phase natural circulation flow.

4.2. Single-phase / Two-phase flow transition analysis

The temperature drop observed in the cold leg was due to the flow of cold water from the expansion tank, toward the midpoint between the cold leg and downcomer entrance. The temperature rise in the hot leg, coupled to the occurrence of low flow, as detailed Fig. 4, caused a flow of natural circulation between the volume of cold water present in the expansion tank and cold leg, resulting in cooling of this region of hydraulic circuit. The temperature of the water in the expansion tank, in turn, increased due to the upward flow of natural circulation of the cold leg to the expansion tank.

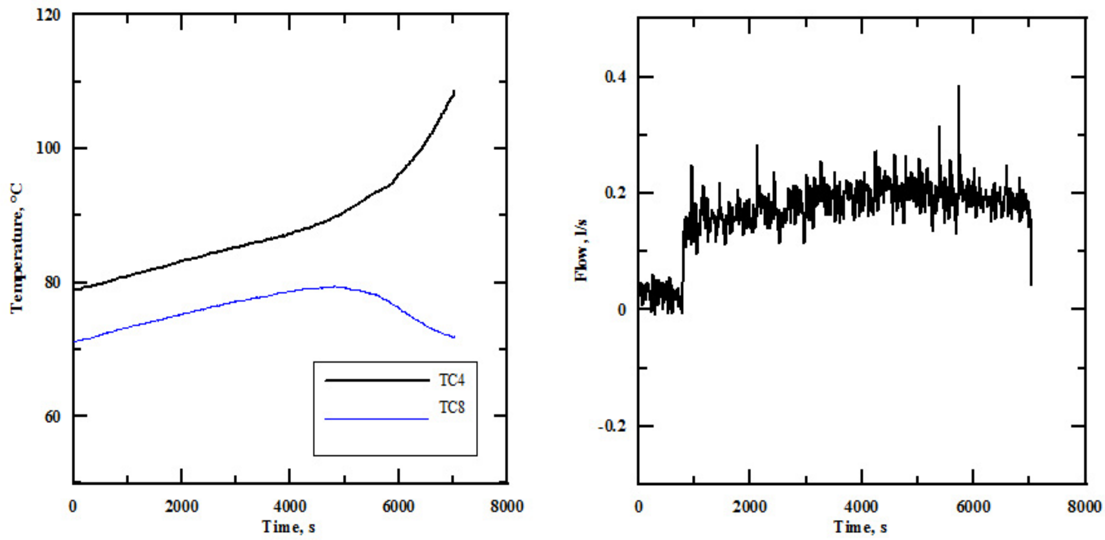


Figure 4: (a) Single-phase / Two-phase flow transition and (b) Natural circulation flow transition.

Typical images of the natural circulation flow taken with the high-speed camera are presented in Fig. 5, where the flow regimes can be identified in transition region, respectively, as: (a) single-phase flow, (b) finely dispersed bubble flow, and (c) slug flow. The heating power was 1100 W and the flow was moving upwards.

The histogram shown in Fig. 5 summarises the average bubble velocity measurements. It could be seen that the majority of bubble velocity was situated in an interval of 0.10 m/s to 0.16 m/s. Furthermore, based on frames recorded by the high-speed digital camera it was possible to identify two types of bubble according to bubble shape: small spherical and spherical cap as could be seen, respectively, in (b) and (c) as shown in this same figure.

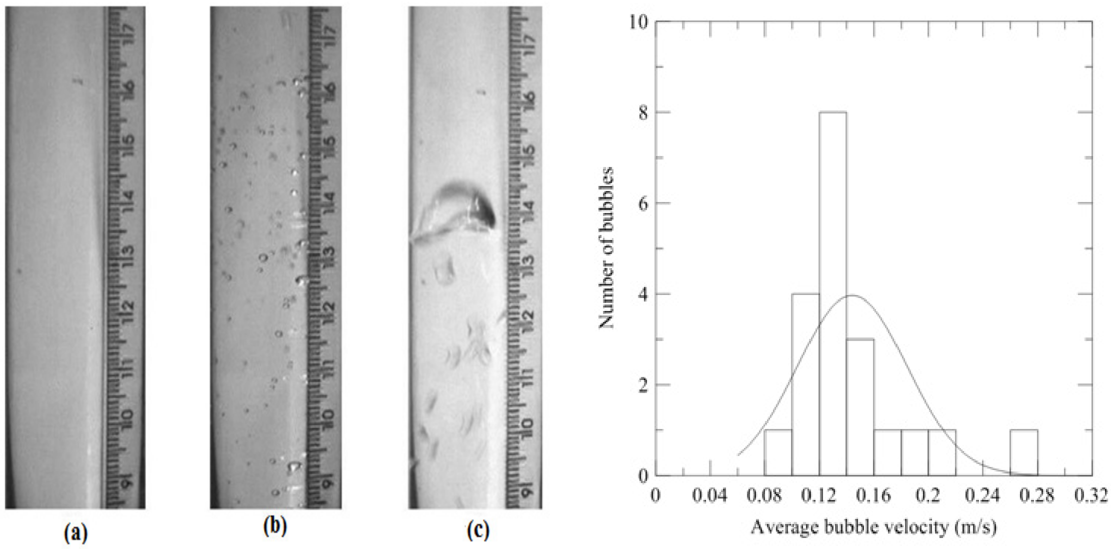


Figure 5: (a)Images of flow regimes transition and (b) Histogram of average bubble velocity.

Fig. 6 illustrates the mechanism of the oscillations: in (a) the water heated by the electric resistances bundle flows in single-phase regime only; at (b) boiling starts when the water temperature exceeds the local saturation temperature; in (c) the vapour bubbles coalesced and accumulated in the upper plenum blocking the flow and inducing a flow reversal in the flowmeter coming from the expansion tank; an increase in the flow rate breaks the vapour bubble and water could fill in the upper plenum forcing the bubbles out, (d). Then the process is repeated periodically. This figure also shows the measured liquid flow rates as a function of time for 1100 W heating operational condition. Oscillations could be observed to start-up in flow rate curve when the experimental run time exceeded a certain value. Based on visual observations together with this curve, a possible explanation for that behaviour is the so-called "natural circulation oscillation" already described in literature.

4.3. Two-phase flow analysis

The graphics shown in Fig. 7 identifying the cyclic behavior of both the temperature as the flow over time. The time related to this cycle was identified by images acquisition, as shown in Fig. 8. Upon reaching maximum value of temperature in the hot leg, the

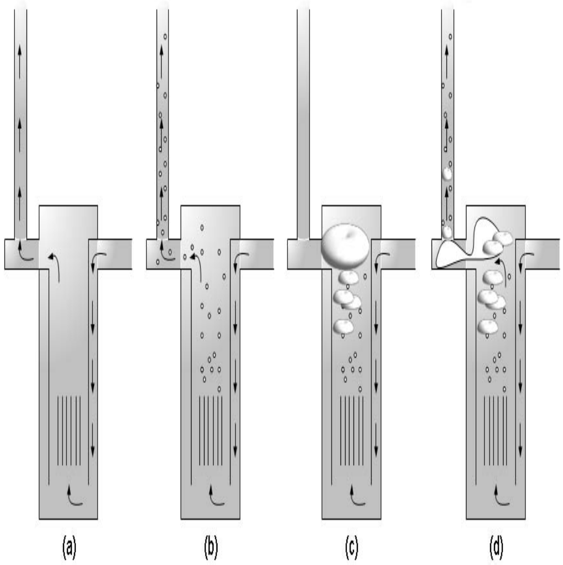


Figure 6: Illustration of the natural circulation oscillation process.

flow occurs through several patterns until a period of damping in this cycle, leaving no bubbles until new cycle start again.

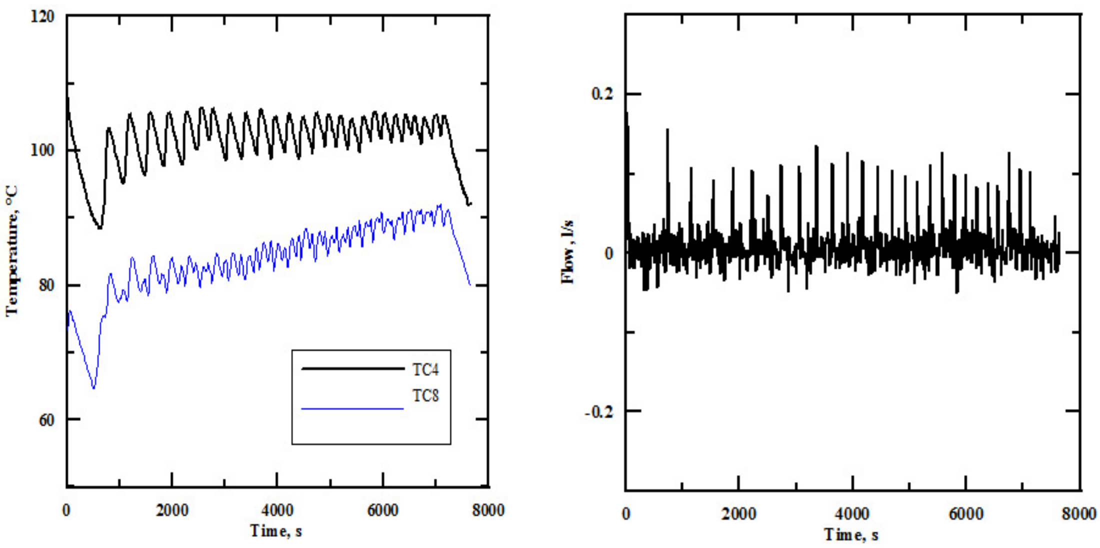


Figure 7: (a) Temperatures in Two-phase flow pattern and (b) Two-phase natural circulation flow.

The experimental procedure for velocity measurement consisted in to superimpose a position reference on the frames stored in the computer files. It was a horizontal and a vertical line that intersect at a target providing X and Y co-ordinates. This feature could be enabled to determine the bubble position and bubble velocity, during the residence time of a bubble in front of the camera lens. The system was calibrated by measuring the physical distance between two points of interest on the rule and entering the distance between the set points in the system. The rule was calibrated by comparison with a standard vernier scale, and the length uncertainty was estimated to be the vernier uncertainty, namely

0.01 mm. The system then calculated the distance and velocity between any two points of interest on successive frames. All measurements were in two dimensions perpendicular to the camera. Images aquisition are shown in Fig. 8. It can be seen by the images, the following flow patterns types: (a) bubbly and slug-cap, (b) slug-plug, (c) slug-to-churn, (d) slug-cap / bubbly. In this Fig. 8 are shown acquired images by high-speed digital camera, which allow a narrow correlation with the graphic, as depicted in Fig. 9.

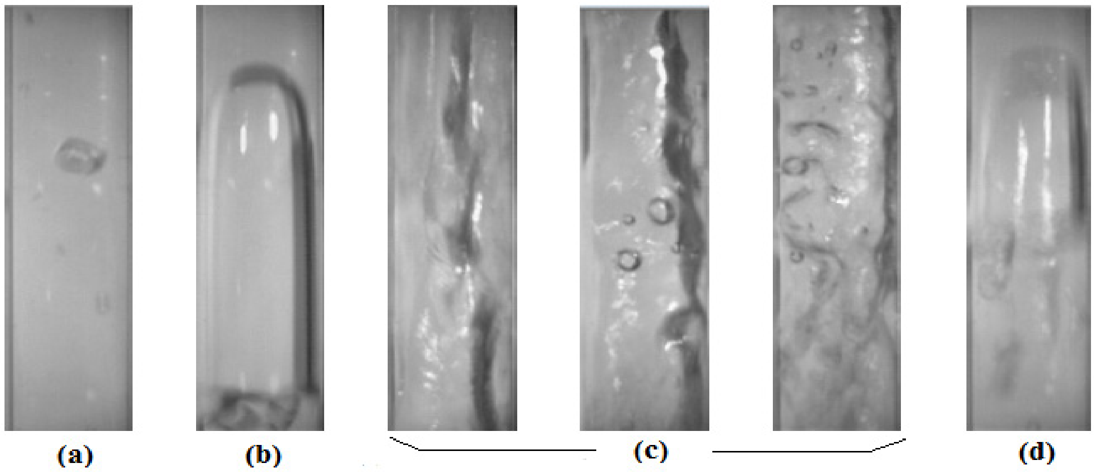


Figure 8: Two-phase flow regimes in natural circulation oscillation process.

The Fig. 9 summarises the bubble velocity measurements in function of time. It can be seen at initial moment of cycle, that the region identified as (a), presents in this interval of time of 1 to 16 seconds, a changing of flow regime begining from of bubbly flow type to Taylor-cap flow type, where the velocity varied of 0.3 to 0.5 m per second. In next moment, the region identified as (b), showed in the interval of time of 16 to 19 seconds, the flow regime to change from Taylor-cap flow type to slug-plug type, where the bubbles velocity varied of 0.6 to 1.3 m per second. The region identified as (c), shows in interval of time of 19 to 21 seconds, the transition of flow regime of slug flow type to churn flow type, where the bubbles velocity varies of 1.3 to 1.6 m per second. The final part of phase transition was characterized by churn flow type, being the maximum speed calculated to 2.8 meters per second, but by presenting high degree of uncertainty, due to the randomness, it was not shown this value in graphic. Finally, in region identified as (d), occurred the changing of flow regime, in other words, from the churn flow type to the slug flow type, in the interval of time from 21 to 27 seconds, with bubble velocity ranging from 1.1 to 0.3 meters per second. The end of cycle, the region is identified as (a), shows in interval of time from 27 to 30 seconds, the flow regime changed of the slug flow type to the bubbly flow type, where the bubbles velocity varied from 0.3 to 0.2 meters per second. The measurement total interval was defined in 58 seconds, according shooting time and number of frames and identi ed up to 30 seconds with occurrence de several flow regimes and the remainder of the time of about 28 seconds, without bubbles.

The acquisition of the temperature and flow, via Labview is performed at intervals of 10 seconds. For this reason, it was not possible to make a match, step by step, with values of time interval related to the velocity of bubbles. However, the range used for observation of the phenomenon corresponds with the visual identification of the flow

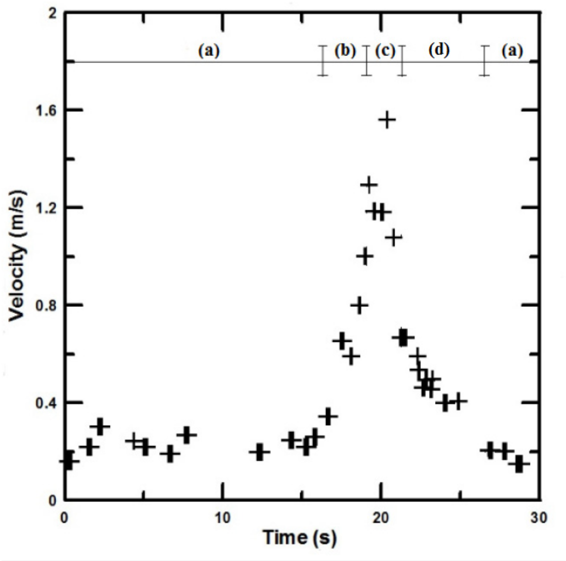
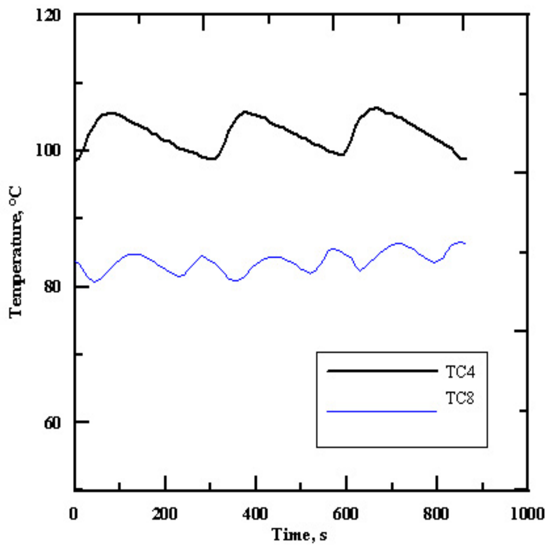


Figure 9: Bubble velocity x time.

regime and measurements performed as shown in Fig. 10. For this reason were drawn graphs of temperature and flow natural circulation, covering the time interval that allows adequate observation of the occurrence of cycles of flow patterns for the experiment



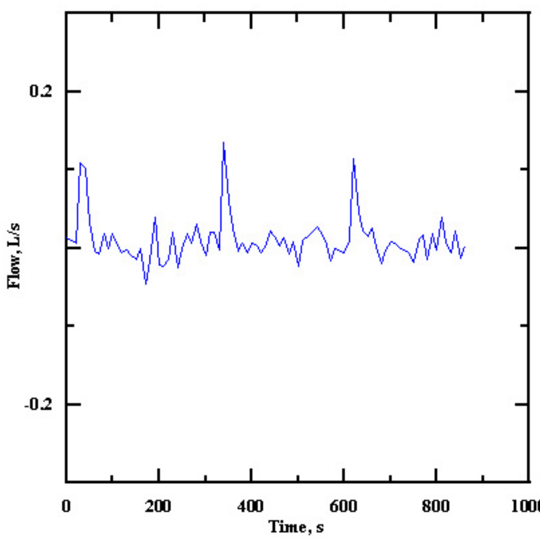


Figure 10: (a) Temperature variation cycles and (b) Natural circulation Flow variation cycles.

5. CONCLUSIONS

An experimental work was conducted to identify two-phase regimes in a natural circulation loop by using a visualization system formed mainly by a high-speed digital camera, an image analysis program and a computer. It can observe the correlation between the temperature evolution through the hot leg, in comparison with the flow rate and the bubbles velocity profile. The following conclusions could be deduced:

- The electromagnetic flowmeter placed at cold leg of the loop allowed to identify flow rate oscillations starting up when the experimental run time exceeded a certain value;

- The visualization system with a high-speed digital camera allowed characterizing the flow regimes. It was observed two regimes: finely dispersed bubble, slug flow and churn flow. The bubbles contained in finely dispersed flow were of small spherical type whereas in slug flow they were of spherical cap type;

- The visualization system was able to determine the bubble size and bubble velocity. The graphic of the bubble velocity distribution showed that the majority of bubbles was located in the region where the velocity was within an interval of 0.30 m/s to 1.60 m/s, as depicted in Fig. 9;

- Based on the results of flow rate measurements and the frames recorded by the high-speed digital camera it was possible to achieve an explanation for the flow oscillations, according the phenomenon called in literature as "natural circulation oscillation".

ACKNOWLEDGMENTS

Authors acknowledge the support provided by the staff of Nuclear Engineering Institute (IEN) and COPPE-Federal University of Rio de Janeiro to carrying out the different measurements. The authors also acknowledge gratefully the support of the CNPq and FAPERJ.

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