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EXPERIMENTAL STUDY OF NATURAL CIRCULATION CIRCUIT

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ABSTRACT

This work presents an experimental study about fluid flows behavior in natural circulation, under conditions of single-phase flow. The experiment was performed through experimental thermal-hydraulic circuit built at IEN. This test equipment has performance similar to passive system of residual heat removal present in Advanced Pressurized Water Reactors (APWR). This experimental study aims to observing and analyzing the natural circulation phenomenon, using this experimental circuit that was dimensioned and built based on concepts of similarity and scale. This philosophy allows the analysis of natural circulation behavior in single-phase flow conditions proportionally to the functioning real conditions of a nuclear reactor. The experiment was performed through procedures to initialization of hydraulic feeding of primary and secondary circuits and electrical energizing of resistors installed inside heater. Power controller has availability to adjust values of electrical power to feeding resistors, in order to portray several conditions of energy decay of nuclear reactor in a steady state. Data acquisition system allows the measurement and monitoring of the evolution of the temperature in various points through thermocouples installed in strategic points along hydraulic circuit. The behavior of the natural circulation phenomenon was monitored by graphical interface on computer screen, showing the temperature evolutions of measuring points and results stored in digital spreadsheets. The results stored in digital spreadsheets allowed the getting of data to graphic construction and discussion about natural circulation phenomenon. Finally, the calculus of Reynolds number allowed the establishment for a correlation of friction in function of geometric scales of length, heights and cross section of tubing, considering a natural circulation flow throughout in the region of hot leg.

1. INTRODUCTION

This experiment was carried out at the Experimental Thermal-hydraulic Laboratory (ETL), installed on the Nuclear Engineering Institute (IEN), as depicted in Fig.1. This experimental apparatus was used to perform experiment in a natural circulation circuit, based on concepts of similarity in height and volume reduced scales, being proportional to real installation with a 1:10 scale. Hydraulic circuit is composed by one closed primary loop and opened secondary loop. The thermo-hydraulic circuit, seen in cited figure, shows in first plane, heater, heat exchanger and expansion tank.

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This experiment is supported by basic concept of the natural circulation that consists a transfer from the thermal energy generated by heat source, through natural convection, to fluid. The heated fluid flows to a heat exchanger due to temperature variations, pressure and phases. After this cooling process, the fluid returns by gravity to heater system. This cycle repeats during all until establishment of heat exchange equilibrium in stationary regime. Natural circulation is resulting from occurrences of fluid density differences and elevation between heat source and heat exchanger.

Figure 1. General view of the Experimental Thermal-hydraulic Laboratory (ETL).

The heat source of circuit represents the heat dissipated by electrical resistors, through Joule effect, that is transformed in thermal energy. This heat generation, translates in reduced scale, the thermal power generated in stages of shutdown or failure, the power decay of nuclear reactions inside vessel of APWR.

Heat exchanger is used to remove heat added to the liquid by natural convection. This system consists of circulation of heated fluid through the tubing, in primary side of the hydraulic circuit. This fluid is involved by fluid flowing at room temperature in secondary side. Thus, there is an heat exchange through the heated fluid that furnishes heat to the fluid at room temperature.

Expansion tank is used to allow the fluid volume expansion caused by temperature increase. This technical reserve has like objective avoid over pressure in tubing of hydraulic circuit. The increase of fluid level in the expansion tank, translates the volume inventory the hydraulic circuit, which was expanded due to the heat transferred to the fluid.

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2. LITERATURE REVIEW

A study in thermal-hydraulics loop in reduced scales, built at IEN, was performed by [2], similar to Pressurized Water Reactor (PWR) passive heat removal system, to obtain typical natural circulation two-phase flow data and to validate numerical models. The experimental tests were performed in single and two-phase flows which were made to begin the validation of model.

Natural Convection Circuit (CCN) was studied by [3] and [1] aiming at obtaining typical natural circulation two-phase flow data, verifying the degree of similarity between CCN and passive heat removal system of a full scale prototype like AP600.

A study of similar installation in geometric scale was developed by [6] who performed thermal-hydraulic simulations based on concepts of similarity using a 1:2 scale and an experimental circuit with four loops. One of the simulations has used the equations of the continuity, momentum and energy taking into consideration the average area for single-phase flow conditions. The other simulation used the drift-flux model with temporal average in short time and average sectional area for two-phase flow conditions. The equations and the one-dimensional models were used in the simulations adequately. Numerical calculations were performed to meet the similarity requirement and scaling criteria for the natural circulation under mentioned conditions.

An example of study on similarities in volumetric scale was developed by [5] who presented experimental studies of the volume scale installation in order to identify the behavior in a loss of coolant accident in cold leg of a PWR. The control of heat due to the decay of energy in reactor was run with performances in flow and steam generator, thereby acting in the thermal-hydraulic behavior in natural circulation and cooling of condensation. Tests with varying pressure on secondary system to temperature control of core to verify the influence of concentration of liquid refrigerant in steam generator were performed. The results of experiments can be showed with graphics of pressure, flow, void fraction, temperature, natural circulation flow, heat removal and heat transfer coefficient.

A research work of residual heat removal by natural circulation of scale in power plants with the loss of coolant, was presented by [7], 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.

The study of experimental research on natural circulation phenomenon was performed by [4] 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.

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A summary of the state-of-the-art scaling analysis involving facility design and test conditions for Advanced Plant Experiment (APEX), was presented by [8], beyond the accurate geometric representation of AP600 nuclear steam supply system to development of the computer codes.

A theoretical and experimental study in single-phase loop of natural circulation with non-uniform diameters was presented by [12], where was observed the influence of Reynolds number and Grashof number as well as mass flow. The experiments took into consideration the turbulent and laminar flows. Comparisons of experimental data with the correlations were satisfactory performance. The complement of the experimental method to investigate the flow of natural circulation happened to continuous models using dimensionless parameters. The results of the experiments were visualized with graphs of Reynolds number versus Grashof number and Reynolds number versus number of Stanton.

An installation similar to the study of power scale was developed [11] who presented an experimental study of transport phenomena in the generation of the thermal-hydraulic instabilities present in the natural circulation flow of Boiling Water Reactors (BWR) reactors, especially in the start-up of the operation. The study was accomplished in experimental natural circulation loop with two parallel channels and the expansion tank assembly. The main objective was mapping the thermal-hydraulic stability in the reactor operation start in order to prevent the effects of these instabilities. The studies involved single-phase flow, the occurrence of geysering, hydrostatic oscillations fluctuations, density wave oscillation, transitory oscillation. The results of the experiments with graphs of the average flow, velocity, pressure, velocity-time, density wave, transient oscillation, average velocity, oscillation period, pressure drop and fluctuation of hydrostatic heights.

The theoretical and experimental studies of natural circulation phenomenon with experiments using single-phase and two-phase flow, was performed by [9], 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 [10], 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.

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3. EXPERIMENTAL PROCEDURES

3.1. Circuit description

The thermo-hydraulic circuit is composed by heater, heat exchanger, expansion tank and water feeding, as depicted in Fig.2. Heater is composed by fifty-two resistors elements, downcomer and plenum. Each resistor is installed inside a steel tube and immersed in water. Tube set is mounted inside a steel cylinder with 0.20 m of internal diameter and 1.0984 m of total height. Downcomer is located inside heater, its height is 0.61 m. Plenum is located in inferior part of heater, its height is 0.10 m. Heat exchanger is constructed with seven steel tubes of 0.031 m of internal diameter with triangular arrangement, with 0.60 m of height. The cooling water of secondary side of heat exchanger is at laboratory temperature and the flow can be adjusted in the range of 0-25 l/h. Heater and heat exchanger are linked by tubes in primary side of hydraulic circuit. These linking tubes are known as hot leg and cold leg. Both tubes have the same diameter. One tube installed in heat exchanger output allows the expanded volume to rise during the heating period towards expansion tank installed in superior part of circuit. Expansion tank is constructed with a steel cylinder with 0.20 m of internal diameter and acts as a pressure controller, being partially filled with distilled water and a pressure relief valve is installed at top end.

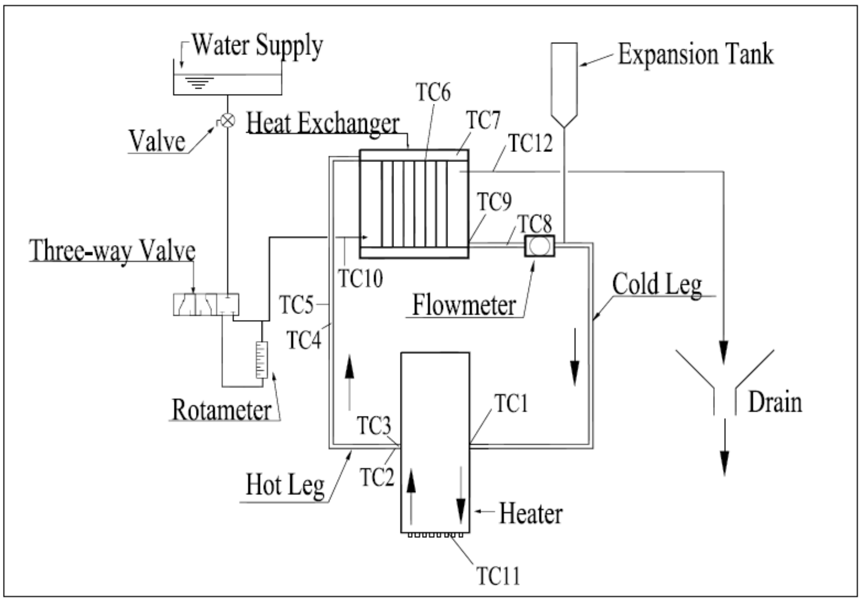

Figure 2. Schematic of natural circulation circuit and points of measurements through thermocouples.

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The set of data acquisition system is composed by a load controller, thermocouples, a signal amplifier, a data acquisition module and a computer. The load controller allows maintaining the electrical power in constant value, furnishing electrical current to electrical resistors inside heater. The level of electrical power can be adjusted in the range of 0-1400 W, through of control module installed on computer. The power supply is furnished to load controller in low voltage 220 V, three-phase, 60 Hz. Thermocouples are positioned throughout hydraulic circuit and furnish the measurement signal in millivolts to amplifier module.

Signal amplifier sends the output signal to data acquisition module to transform the analogical signal to digital signal to be processed by computer. Computer allows the visualization of temperature values through the graphic interface. Computer graphic interface has all the necessary controls to handle the system data and to allow the visualization of temperature and natural circulation flow display.

Thermocouple 1 (TC1) is positioned in heater input, this point is also known as cold leg output near to down comer. Thermocouple 2 (TC2) is positioned in hot leg input (fluid) to allow measuring the fluid temperature. Thermocouple 3 (TC3) is also positioned in hot leg input (wall) to allow measuring the tube wall temperature. Thermocouple 4 (TC4) is positioned in the medium point of hot leg (fluid) to allow measuring the fluid temperature. Thermocouple 5 (TC5) is positioned in the medium point of hot leg (wall) to allow measuring the tube wall temperature. Thermocouple 6 (TC6) is positioned in heat exchanger input (wall) to allow the measurement of the tube wall temperature. Thermocouple 7 (TC7) is positioned in heat exchanger input (fluid) to allow measuring the primary fluid temperature. Thermocouple 8 (TC8) is positioned in cold leg input to allow the measurement of the fluid temperature. Thermocouple 9 (TC9) is positioned in cold leg input (wall) to allow measuring the tube wall temperature. Thermocouple 10 (TC10) is positioned in heat exchanger input (fluid) to allow the measurement of the fluid temperature of secondary cooling loop. Thermocouple 11 (TC11) is positioned to allow measuring the inferior plenum temperature. Thermocouple 12 (TC12) is positioned in heat exchanger output to allow measuring the fluid temperature of secondary cooling loop. These points are located as depicted in Fig.2.

3.2. Measurements and comments

The temperature variations between TC1 and TC3 allow calculating the heat furnished by convection to fluid by heat dissipation through electrical resistors that show the temperatures measurements in the input and output of heater, as depicted in Fig.3. The temperature variations between TC4 and TC5 allow identifying the heat transmission through tubing material, that show the temperatures in the medium point of hot leg (fluid and tube wall), as depicted in Fig.4.

The temperature variations between TC8 and TC9 allow identifying the heat transmission through tubing material, that show the temperatures in the output of heat exchanger, as depicted in Fig.5. The temperature variations between TC3 and TC4 allow identifying the heat loss by conduction and convection in the flow path, that show the temperatures in the medium point of hot leg and in the output of heater, as depicted in Fig.6.

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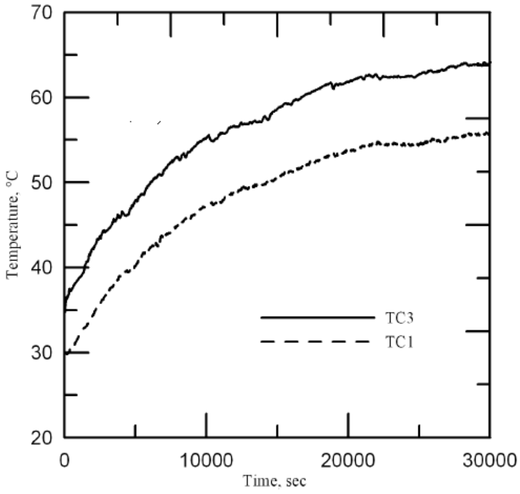

Figure 3. Input and output tempera tures of heater.

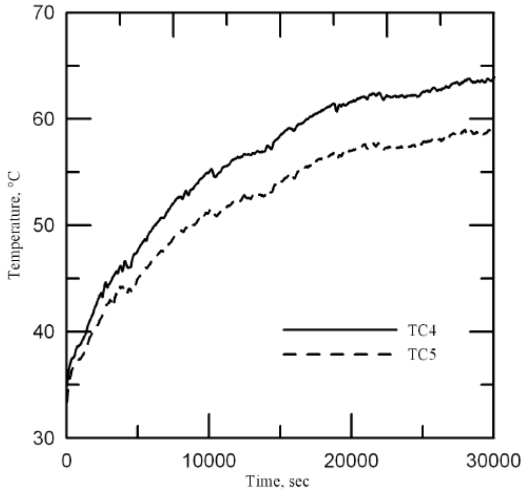

Figure 4. Temperatures in medium point, fluid and tube wall in hot leg.

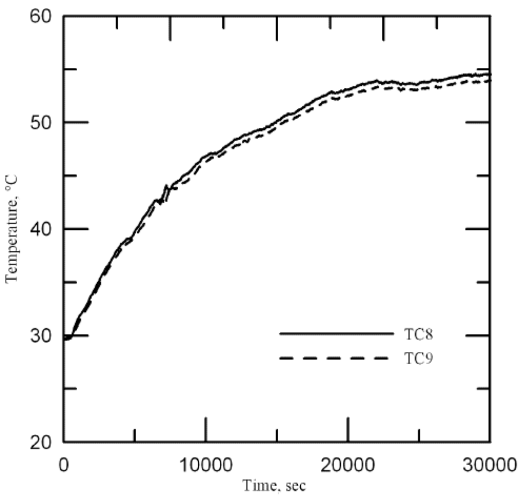

Figure 5. Output temperature in heat exchanger, fluid and tube wall.

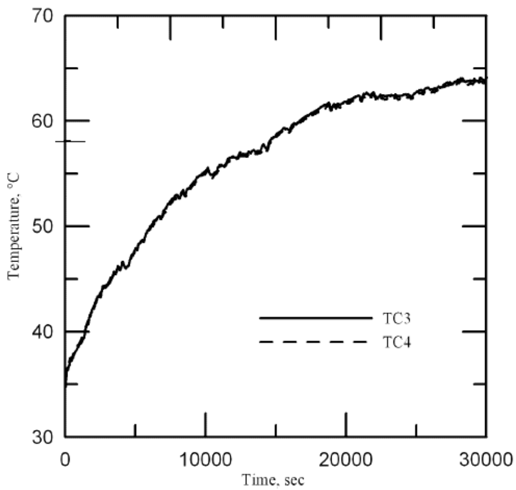

Figure 6. Temperatures in the medium point of hot leg and heater output.

The temperature variations between TC10 and TC12 allow identifying the heat removal in secondary cooling loop, that show the temperatures in the input and output of secondary cooling system, as depicted in Fig.7. The temperature variations between TC3 and TC2 allow identifying the heat transmission by tubing material, that show the temperatures in the output of heater, as depicted in Fig.8.

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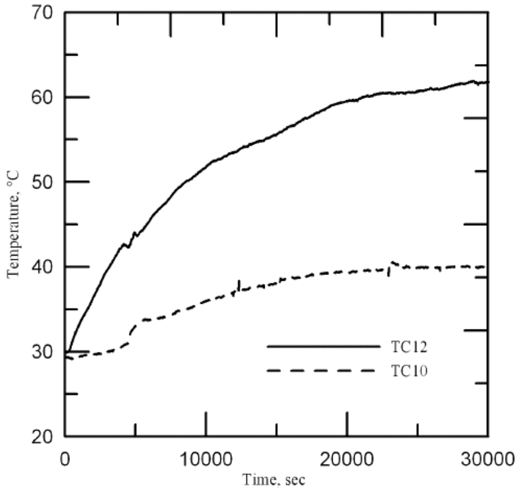

Figure 7. Input and output of secondary cooling system.

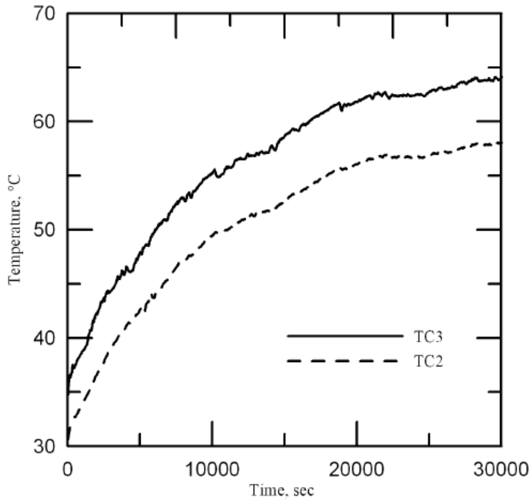

Figure 8. Temperatures of heater output, fluid and tube wall.

The temperature variations between TC4 and TC8 allow calculating the heat exchange between primary and secondary systems, that show the temperatures in the medium point of hot leg and in output of heat exchanger, as depicted in Fig.9. The temperature variations between TC7 and TC6 allow identifying the heat transmission through tubing material that show the temperatures of the fluid and tube wall in heat exchanger, as depicted in Fig.10.

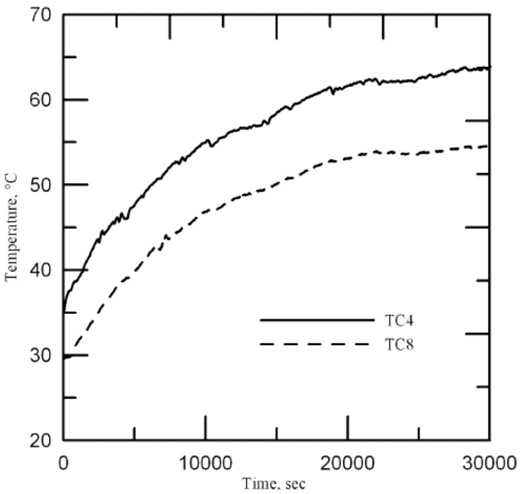

Figure 9. Temperatures in the middle hot leg and heat exchanger output.

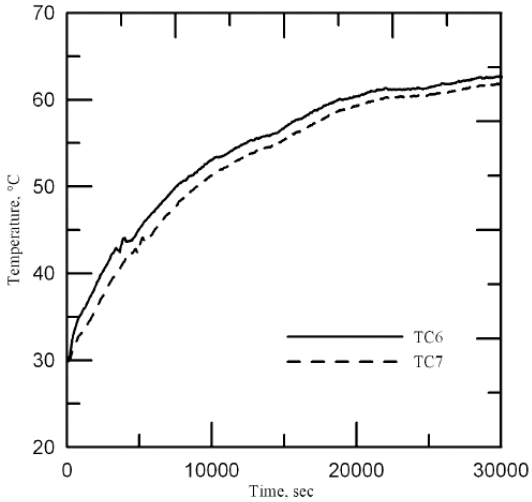

Figure 10. Temperatures in heat exchanger, fluid and tube wall.

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The temperature variations between TC1 and TC8 allow identifying the heat loss by conduction and convection in the flow path. The temperatures in heat exchanger output and heater input, as depicted in Fig.11. The temperature variations between TC10 and TC12, TC4 and TC8, TC6 and TC7, TC1 and TC3 allow identifying the stabilization tendency in heat exchange in several points of hydraulic loop, beyond the heat gain in heater with stabilization tendency over time, as depicted in Fig.12.

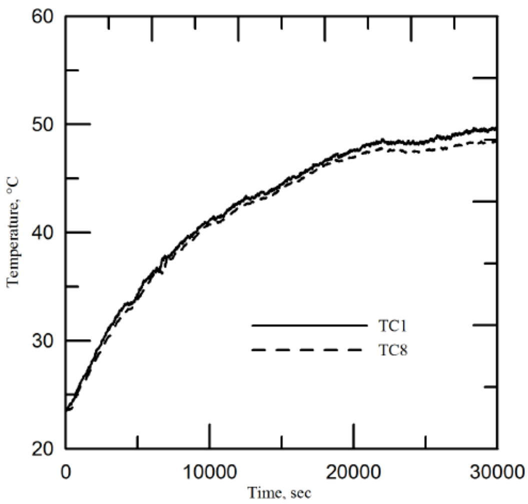

Figure 11. Temperatures in heater input and heat exchanger output.

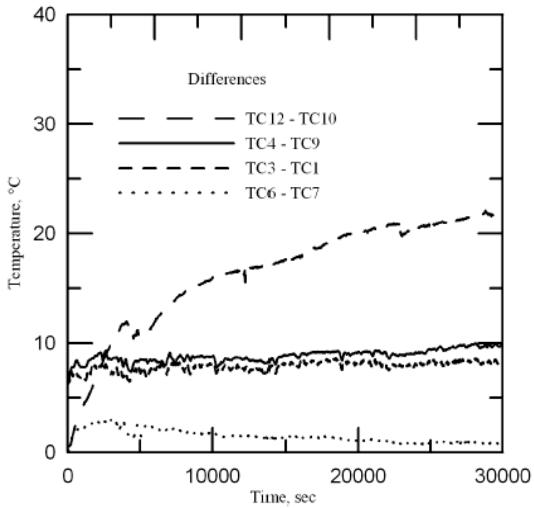

Figure 12. Temperatures differences between heater and heat exchanger.

The input values of variables to be adjusted in the process have been established for the execution of the experiment, adjusting load controller in relation to the electrical power supplied to heater as well as the adjust of rotameter to the flow of cooling water in secondary side of heat exchanger. The level of electrical power was adjusted with the constant value of 800 W, through of control module installed on computer. The flow of the cooling water of secondary side of heat exchanger was adjusted on point measuring also with constant value of 16 l/h.

The temperature in the laboratory at the beginning of the experiment was measured at 30^{o} C and the relative humidity at 65 %.

The excursion of the natural circulation flow temperatures in hydraulic loop over time is depicted in Fig.13. The curve represents the flow stabilization tendency due the heat exchange equilibrium in hydraulic circuit.

Most studies involving natural circulation present curves of temperatures, with oscillatory behavior from the beginning of the experiment, due to the two-phase flow. In this study the behavior does not follows this pattern due to flow be single-phase.

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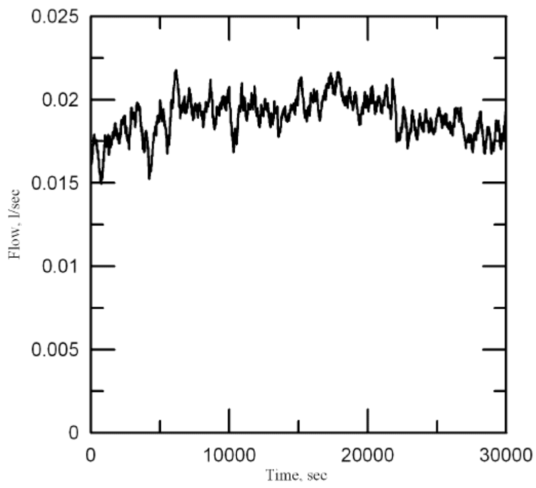

Figure 13. Excursion of the natural circulation flow in hot leg.

4. RESULTS

The graphic of the Reynolds number versus time, according to Fig.14, was elaborated using Eq.1. The values of the variables were corrected over time in function of the density variation due to the temperature measurements through hydraulic loop. Note that except the tube diameter of hot leg all variables were being modified in function of the density variation over time.

$$\mathrm{Re} = \frac{\rho . V . D}{\mu} \quad (1)$$

Nomenclature

ρ fluid density (kg/m^3)
V fluid velocity through the transversal section of hot leg tube (m/s)
D diameter of hot leg tube (m)
μ viscosity coefficient (kg/ms)

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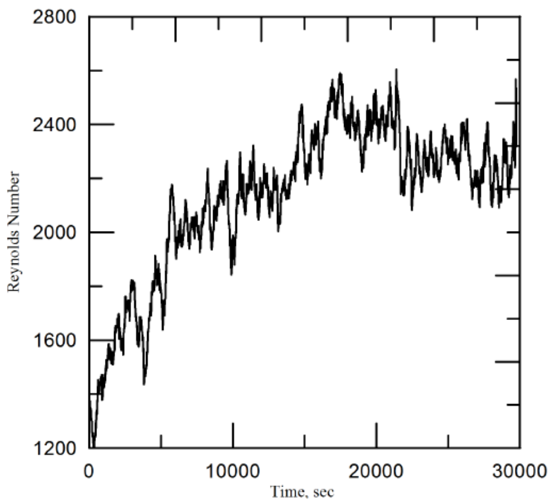

Figure 14. Reynolds number in hot leg tube.

The medium value of Reynolds number was elaborated using Eq.2, using medium values of all stored in the data spreadsheet. Note that the stabilization of the natural circulation flow maintains a slight correspondence with the stabilization of Reynolds number.

$$\mathrm{Re}_m = \frac{4}{\pi} \frac{Q_m}{D.\upsilon_m} \qquad (2)$$

Nomenclature

Q_m medium value of the natural circulation flow (m^3/s)

D diameter of hot leg tube (m)

υ_m medium value of the cinematic viscosity (m^2/s)

Re_m medium Reynolds number (dimensionless)

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Replacing the values bellow in Eq.2,

$Q_m = 0.000018859\ m^3/s$

$D = 0.023\ m$

$\upsilon_m = 0.47859 \ .\ 10^{-6}\ m^2/s$

$\pi = 3.1415926654$

$$Re_m = 2{,}181.41$$

5. CONCLUSIONS

The experiments contributed for the study of the behavior of the natural circulation phenomenon by using a low-cost small-sized thermal-hydraulic circuit based on the philosophy of height and volume proportionality and scaled similar circuit. The experiment had a positive contribution for the acquisition of important information on the phenomenon of natural circulation, as well as for the identification of real conditions of functioning in shut down or emergency of nuclear power plants from the performed experiments in similar conditions. The curves depicted in Fig.3 to 12 allowed calculating the heat loss by convection and conduction in the tubing, the heat exchange between primary and secondary systems and the furnished heat by heater to the fluid of experimental loop. The Reynolds number allows concluding that the natural circulation flow has a transitory behavior between the laminar and turbulent regimes.

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