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EXPERIMENTAL STUDY OF TWO-PHASE NATURAL CIRCULATION CIRCUIT

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Abstract. *This paper reports an experimental study on the behavior of fluid flow in natural circulation under single- and two-phase flow conditions. The natural circulation circuit was designed based on concepts of similarity and scale in proportion to the actual operating conditions of a nuclear reactor. This test equipment has similar performance to the passive system for removal of residual heat presents in Advanced Pressurized Water Reactors (APWR). The experiment was carried out by supplying water to primary and secondary circuits, as well as electrical power resistors installed inside the heater. Power controller has available to ajsut the values for supply of electrical power resistors, in order to simulate conditions of decay of power from the nuclear reactor in steady state. Data acquisition system allows the measurement and control of the temperature at different points by means of thermocouples installed at several points along the circuit. The behavior of the phenomenon of natural circulation was monitored by a software with graphical interface, showing the evolution of temperature measurement points and the results stored in digital format spreadsheets. Besides, the natural circulation flow rate was measured by a flowmeter installed on the hot leg. A flow visualization technique was used the for identifying vertical flow regimes of two-phase natural circulation. Finally, the Reynolds Number was calculated for the establishment of a friction factor correlation dependent on the scale geometrical length, height and diameter of the pipe.*

Keywords*: natural circulation, residual heat removal, scaled installation, single-phase flow, two-phase flow.*

1. INTRODUCTION

The phenomenon of natural circulation has high relevance in studies and projects of advanced nuclear reactors, in order to increase safety in nuclear installations. The application of natural circulation concept in passive system of residual heat removal arises as an innovator element that is capable to enable the autonomous operation in cooling the reactor core in shut-down conditions or accident.

A study of similar installation in geometric scale was developed by Kocamustafaogullari (1984), 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

The equations of energy and momentum were studied by Zvirim (1981a), for evaluating of heat exchange involving the couplings between hydraulics phenomena and thermodynamic, in the presence of phase change. Besides, the behavior of natural circulation loop in parallel circuits was studied by Zvirim (1981b), using analytical and experimental research so as to identify the behavior of the phenomenon under conditions of single- and two-phase flows.

A summary of the state-of-the-art scaling analysis involving facility design and test conditions for Advanced Plant Experiment (APEX) was presented by Reyes and Hochreiter (1998), beyond the accurate geometric representation of AP600 nuclear steam supply system to development of the computer codes.

An example of study on similarities in volumetric scale was developed by Kawanishi et al. (1991), 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.

Kirouac et al. (1999) developed studies to indicate suitable instrumentation to be applied in measuring two phase flow vertical. High-speed camera was used to visualize coalescence, bubble size and flow patterns Image processing allowed the calculation of the drag force, the speed of upward flow, void fraction, besides liquid and gas velocities. The techniques that were used could be checked for relevant validations.

An installation similar to the study of power scale was developed Subkii et al. (2003), 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 and 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.

Liu et al. (2005) performed an experimental study for investigation of flow-induced of chain of bubbles in ascendent movement, for visualization and image processing. Image of figures with oscillatory motion of bubbles were showed. The low viscosity of the fluid was cited like cause of the phenomenon. The upward movement of bubbles causes induction which is called the false turbulence. The process of capturing bubbles was applied to identification of the trajectories and velocities of bubbles that are positioned in relation to the axis of reference. The work was important for identification of velocity fields in the liquid.

The behavior of a system for heat removal in an emergency (EHRs) was investigated by Santini et al. (2010), using a closed circuit under natural circulation of two-phase flow in order to characterize the system, using parameters of temperature, flow and pressure.

This paper presents an experimental study on the behavior of a natural circulation circuit under conditions of single- and two-phase flows.

2. EXPERIMENTAL PROCEDURES

2.1 Circuit description

. The experiment was carried out by using an two-phase natural circulation circuit installed at the Institute of Nuclear Engineering (IEN/CNEN), as shown in Fig.1. The experimental facility was designed based on the works of Botelho (2002a) e Botelho (2002b), 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.

Figure 1. Partial view of the Laboratory of Experimental Thermo-hydraulic (LTE).

The circuit is composed by heater, heat exchanger, expansion tank and water feeding, as depicted in Fig.2. The heater is formed by 52 resistors, which allows the generation of a maximum electrical power of 1530 W, where each resistor is installed inside a steel pipe. Tubing set of resistors immersed in water and is installed inside a steel cylinder of internal diameter 0.20 m and 1.10 m in height. The region on the bottom of the heater which is located with a drop of 0.10 m is called the lower plenum. The flow region, with the entry route of the heater to the lower plenum, measuring 0.61 m in length, is called down-comer. The heat exchanger is constructed of seven steel pipes in triangular arrangement with 0.60 m high and 0.031 m internal diameter. The heater and heat exchanger are connected by pipe with the same inner diameter of 23 mm, known as the hot leg and cold leg, which are integral parts of the primary side of the hydraulic circuit. The cooling water circulation in the secondary side of the heat exchanger is at environment temperature.

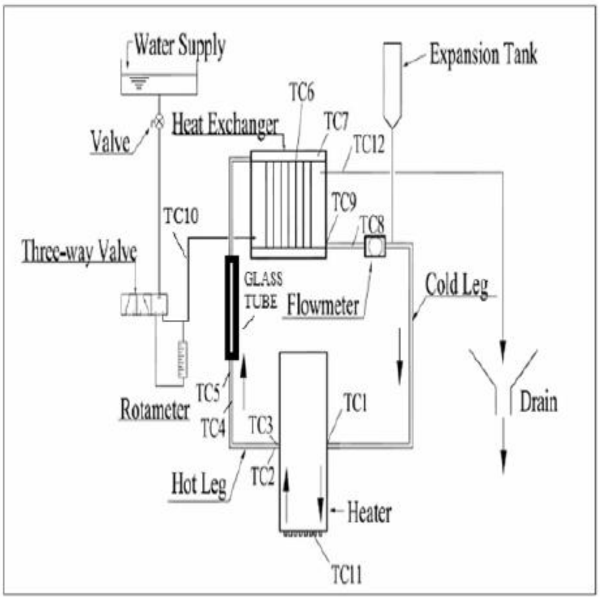


Figure 2. Diagram of the natural circulation circuit.

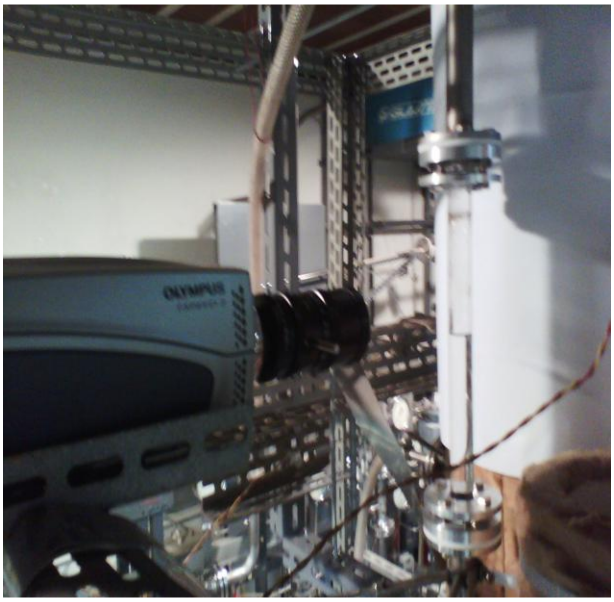


Figure 3. Details of glass tube and camera.

The flow may be adjusted by the flow-meter in the range 0 to 25 l / h. A power controller is used to adjust the values of the electric power supply to the heater resistors located in the range 0 to 1600 W. A data acquisition system allows temperature measurement by means of thermocouples installed along the circuit, and measuring natural circulation flow, via an electromagnetic flow-meter.

The expansion column, installed at the entrance of the heater allows expansion of the water heated by the resistors to a tank located at its end where there is a pressure relief valve. Expansion tank is built with a steel cylinder 0.20 m internal diameter and serves as a pressure controller and is partially filled with distilled water and having a pressure relief valve installed at the upper end.

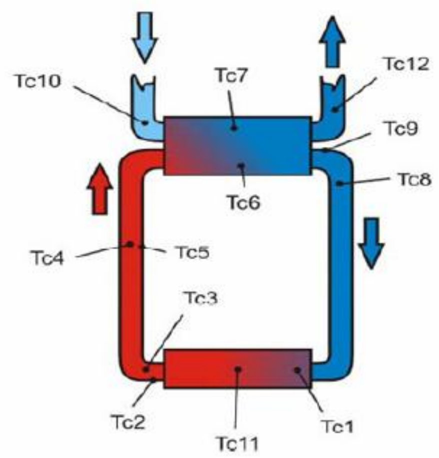


Figure 4. Schematic diagram of primary loop and secondary loop.

2.2 Temperature measurement by thermocouples

Measurements of temperatures in thermo-hydraulic circuit were performed with twelve thermocouples, as depicted in Fig 4, as a function of temperature measurement regions of fluid and wall. Thermocouple 1 (TC1) measures the temperature of fluid in the down-comer. Thermocouple 2 (TC2) measures the temperature of wall in the region corresponding to the heater output and input of the hot leg. Thermocouple 3 (TC3) measures the temperature of fluid in the region corresponding to the heater output and input of the hot leg. Thermocouple 4 (TC4) measures the temperature of fluid in the region corresponding to one third the length of the hot leg. Thermocouple 5 (TC5) measures the temperature of the wall in the region corresponding to one third the length of the hot leg. Thermocouple 6 (TC6) measures the temperature of the primary fluid, which circulates in the pipe inside the heat exchanger. Thermocouple 7 (TC7) measures the temperature of the pipe wall inside the heat exchanger corresponding to the temperature at the interface between the outer pipe wall of the primary fluid and the secondary fluid near the pipe wall. Thermocouple 8 (TC8) measures the temperature of the primary fluid in the region corresponding to the output of the heat exchanger and inlet to the cold leg. Thermocouple 9 (TC9) measures the temperature of the wall in the region corresponding to the output of the heat exchanger and inlet to the cold leg.

The hydraulic diagram, as depicted in Fig.4, includes the primary loop and secondary loop, besides the positions of measurements points, along the flow excursion. The temperature values are also showed in LabView supervisory.

2.3 Technique of flow visualization

Another technique used corresponds to the flow visualization for identification of flow regime, and measurement of flow parameters. This stage is in course and consists of an image acquisition system that is composed by a high-speed camera, software for image acquisition and diagnostic, personal computer and Ethernet network. The camera is of digital type high-speed polychromatic model Speed 2, manufacturer Olympus and is positioned in front of the glass tubing, as shown in Fig.3. The interconnection of the camera with the personal computer is performed via an Ethernet network cable (according to the defined IP) to software for processing and diagnostic image, code i-SPEED 3 Software Suite, manufacturer Olympus. Image acquisition can be performed in the range 0 to 33,000 frames per second in condition of low resolution and in the range 0 to 1000 frames per second with high resolution. To improve the image was positioned a contrast element on the back of the glass tubing. In addition, were added reflectors for lighting the room to improve the illumination of the object using lamps 250 and 1000W.

The image acquisition was performed in preliminary tests in order to determine the best settings for the object distance, choice of lenses, setting focus and improving the level of illumination. The experiments will take account the preset time to carry out the film to permit the identification of flow conditions along time.

2.4 Measurement of natural circulation flow rate

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 8 shows the evolution curve of natural circulation flow versus time that was built using Grapher software, starting from the data retrieved of electronic spreadsheet.

3. RESULTS

The points showed in graphics correspond to: (y-axis) heater inlet; (a) heater oulet; (b) 1/3 hot leg; (c) heat exchanger inlet; (d) heat exchanger outlet; (e) down comer inlet; (f) plenum inlet.

The graph, as depicted in Fig.5, corresponds to the temperature measurements along the circuit corresponding to the experiment carried out with application of the value of power of 400 W and secondary cooling flow of 15 l/h. The points correspond to: (y axis) heater inlet; (a) heater oulet; (b) 1/3 hot leg; (c) heat exchanger inlet; (d) heat exchanger outlet; (e) down comer inlet; (f) plenum inlet.

The graphic of the Reynolds number versus time, is depicted in Fig.7. The variable values were corrected over time in function of the density variation due to the temperature measurements through hydraulic loop. Note excepting the tube diameter of hot leg all variables were being modified in function of the density variation over time. The graphic of the natural circulation flow versus time, is depicted in Fig.8. To realize the experiments were applied the amount of power of 1100 W and secondary cooling flow of 5 l/h.

The graph, as depicted in Fig.6, corresponds to the experiment carried out with application of the amount of power of 800 W and secondary cooling flow of 15 l/h. The curves represent the flow stabilization tendency due to the heat exchange equilibrium in hydraulic circuit.

Fig.9 shows images of bubbles moving along the riser. Figs. 9(a) and Fig. 9(b) correspond to visualization in time interval from 22500 to 24000 s, while Fig. 9(c) corresponds to visualization in time interval from 24000 to 25000 s.

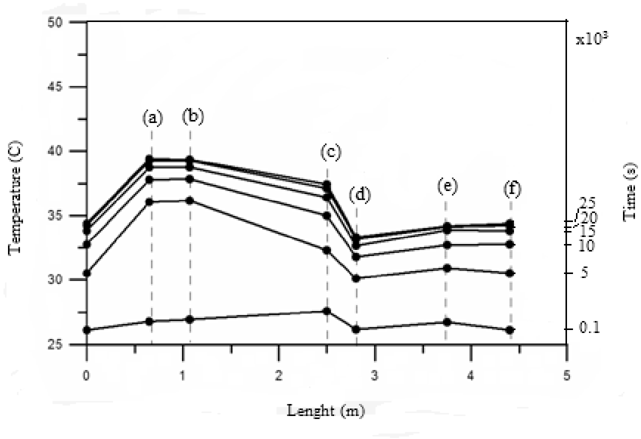


Figure 5. Temperature evolution along the natural circulation circuit for power level P = 400W.

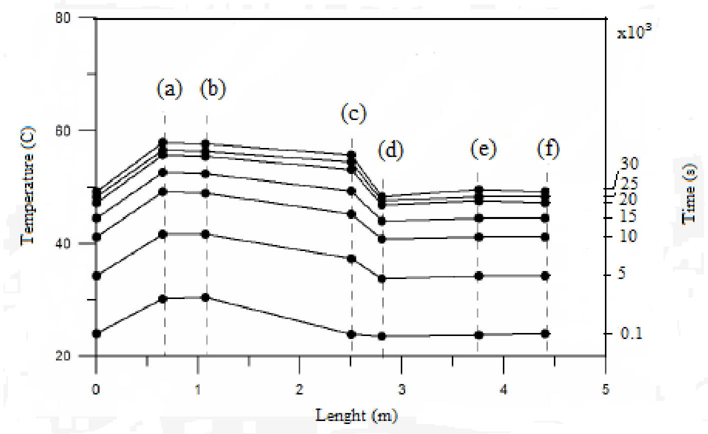


Figure 6. Temperature evolution along the natural circulation circuit for power level P = 800W.

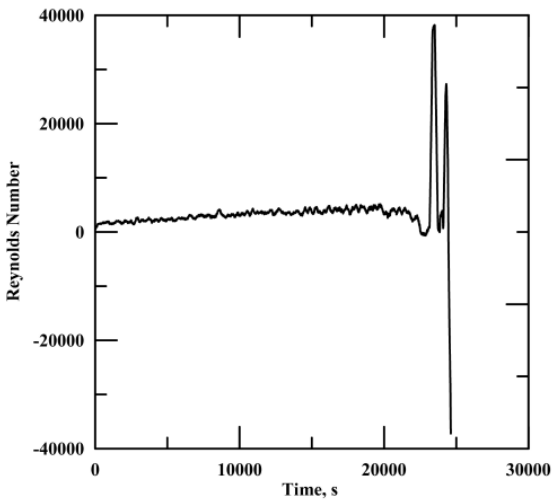


Figure 7. Reynolds Number as a function of time.

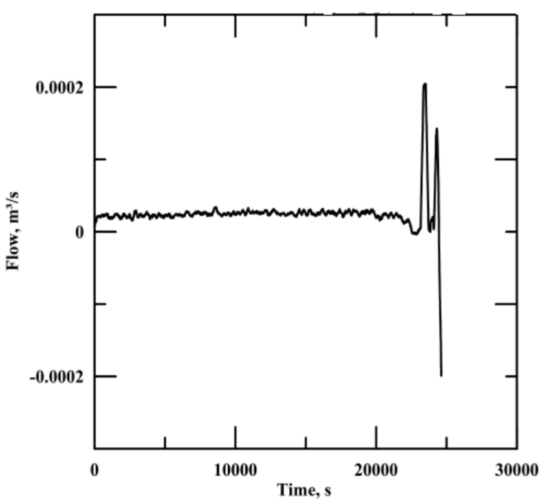
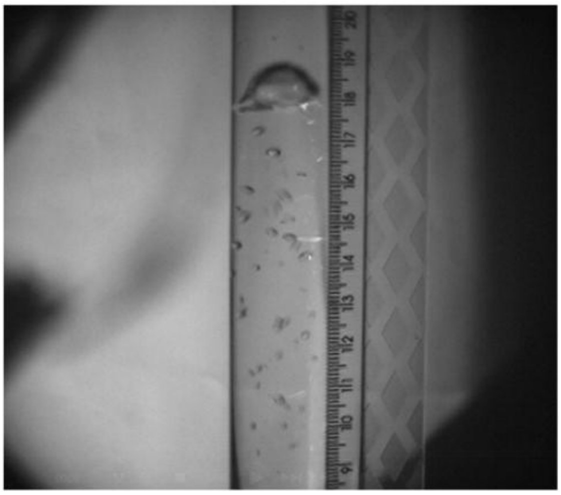
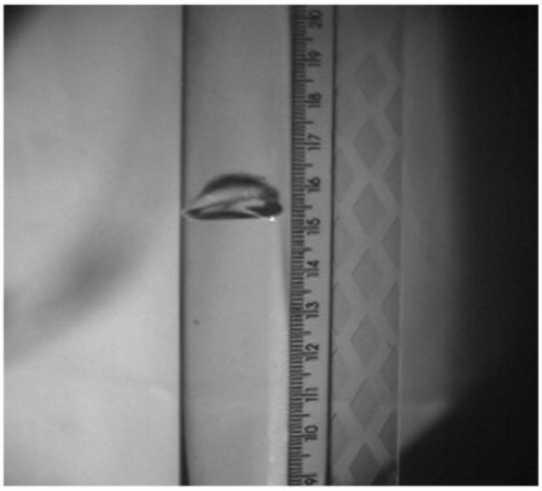


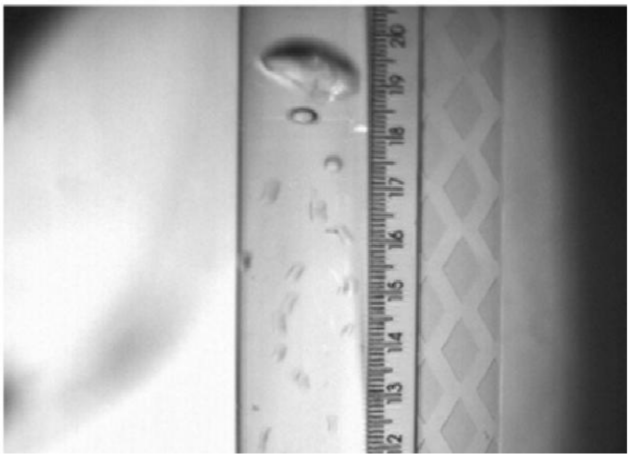
Figure 8. Natural circulation flow rate as a function of time.



(a).



(b)



(c)

Figure 9. Image of the bubbles.

4. 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 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 Reynolds number allows concluding that the natural circulation flow has a transitory behavior between the laminar and turbulent regimes. The images allowed identifying the behavior of flow natural circulation compared with two-phase natural circulation along the hot leg (riser).

5. ACKNOWLEDGMENTS

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