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TWO –PHASE FLOW INSTABILITIES IN A NATURAL CIRCULATION RECTANGULAR LOOP

BELCHIOR Jr., A./ Centro Tecnológico da Marinha
em São Paulo (CTMSP)

BASTOS, J. L. F./Instituto de Pesquisas
Energéticas e Nucleares (IPEN/CNEN-SP)

SABUNDJIAN, G./ Instituto de Pesquisas
Energéticas e Nucleares (IPEN/CNEN-SP)

ANDRADE, D. A./ Instituto de Pesquisas
Energéticas e Nucleares (IPEN/CNEN-SP)

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ABSTRACT

This paper analyses the instabilities of a natural circulation square loop built at the University of São Paulo. The glass circuit has an electrical heater as the heat source and a coil cooler as the heat sink. An expansion tank is connected to the cold leg of the circuit to accommodate density variations of the coolant.

To provide additional information for the analysis, a model was developed with the RELAP5/MOD3.2 code. This procedure was adopted due to the lack of instrumentation. Some comments about the nodalization adopted are also presented.

INTRODUCTION

Natural circulation phenomenon is very important for the safety and design of nuclear reactors. Advanced reactors have been designed using passive safety systems based on natural circulation [1,2]. There are also some conceptual design using the natural circulation where the components and systems have been simplified by eliminating pumped recirculation systems and pumped emergency core cooling systems [3].

This paper treats the problem of two phase flow instabilities in a natural circulation rectangular loop. To understand this complex problem, an experimental loop was built with an electrical heater as the heat source and a coil cooler as the heat sink. Besides the experimental procedure, a theoretical model was developed using the RELAP5/MOD3.2.

Computational Code

The code RELAP5/MOD3.2 is a modified version of RELAP5/MOD3 [4], which was developed by the Idaho National Laboratory . This code was originally developed for the analysis of thermal hydraulic transients in Pressurized Water Reactors (PWR). RELAP5/MOD3.2 can model the primary and secondary cooling system of experimental facilities and of Nuclear Reactors with geometric details. The program uses the two fluid model and takes into account the mass, momentum and energy equations for the liquid and gaseous phases. One dimensional models are used to treat the fluid flow and the heat conduction at the structures. However this assumption is not assumed for the cross flow in the Plant core and for the flooding model which uses the bidimensional heat conduction in the neighborhoods of the rewetting region. The MOD3.2 version of RELAP5 counts on thermal hydraulic models, that includes in the original MOD3 version, the condensation model to simulate natural circulation transients.

The assessment of RELAP5/MOD3.2 with Natural Circulation Phenomena was presented and published by U.S. Nuclear Regulatory Commission, NUREG/IA-0144[5].

Experimental Facility and Procedures

To understand the complex phenomena involving the instabilities in a two-phase natural circulation system, an experimental loop was built at the University of São Paulo, EPUSP. Since the interest is a parametrical analysis, a small rectangular glass loop was designed with an electrical heat

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American Society of Mechanical Engineers source and a coil cooler. The main dimensions of the circuit as well as the thermocouple positions are indicated in Figure 1.

The heater is a 75 mm cylindrical glass tube with two electrical heaters. The power applied is controlled in the range of 0 to 7000 W. The cooler is all made in glass with 33 mm internal diameter, 610 mm high and 2 parallel coils. The coolant is tap water at ambient temperature. An expansion tank, acting as a PWR pressurizer, is partially filled with water and opened to the ambient at the top end. At the bot end it is connected to the loop to deal with the water specific volume changes. To prevent vapor admission to the expansion tank during two-phase flow experiments, the surge line is connected to the horizontal section of the cold leg.

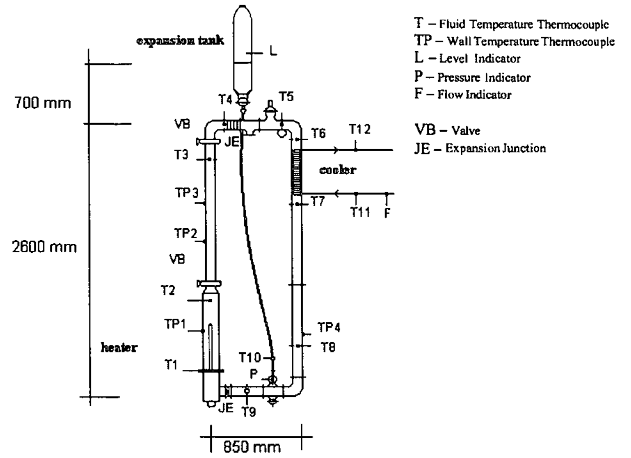

Figure 1 – Schematic View of the Loop

The data listed below is registered at a sampling rate of approximately 5 seconds:

- six temperature indications at the hot leg;
- four temperature indications at the cold leg;
- one temperature indication at the surge line;
- two temperature indications, inlet/outlet of the cooling water;
- one flow rate indication of the cooling water and
- three temperature indications of the external tube walls to estimate heat losses.

The heating power is calculated by measuring the electric current and the tension. A digital multimeter (3 1/2 digits) was used. The uncertainty at the electric power is two percent of the calculated value. The temperature measuring system, consisting of type T thermocouples, signal conditioning and data acquisition boards hosted in a PC, has a global uncertainty estimated in 0.5 °C.

The experiment starts with the primary circuit filled with water at rest and the heater turned off. The fluid temperature is completely homogeneous and equal to the ambient temperature all along the loop. The heater is turned on with a constant heating power. The flow rate and the inlet temperature at the coil cooler are also kept constant. This procedure is repeated for different power levels and flow rates at the coil cooler.

For low power levels, there is no phase change and, after a damped oscillatory initial behavior, a stationary flow regime is established. For higher power levels the same one phase oscillatory flow pattern is observed at the beginning, followed by a two-phase oscillatory regime.

Figure 2 shows the behavior of the hot leg, cold leg and coil cooler outlet temperatures for one-phase flow experiments.

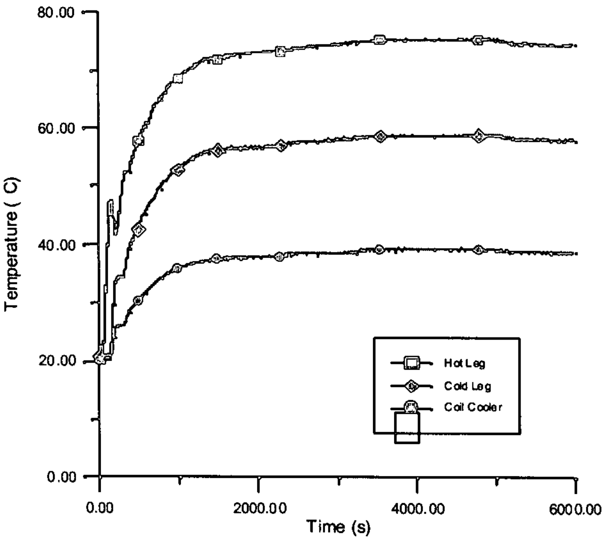

Figure 2 – Temperature Evolution for One-Phase Flow Experiment

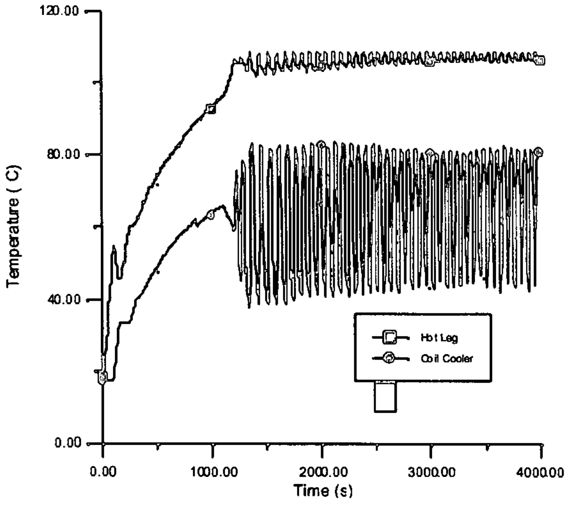

Figure 3 – Temperature Evolution for Two-Phase Flow Experiment

Figure 3 presents a typical temperature evolution for the hot leg and coil cooler outlet temperatures for two-phase flow experiments. The cycles, observed at the experiment, have a well defined amplitude and a periodicity of approximately 60 seconds. Analyzing the behavior of the hot leg, a cycle can be divided in three stages: incubation, expulsion and a refill period.

At the incubation period (approximately 10 seconds) there is no net flow at the loop. The vapor bubbles, generated at the heater, merge at the contraction, creating a slug flow at the vertical part of the hot leg. During this period, the vapor remains at the upper horizontal leg of the loop drying this part of the circuit. At this period, the pressure of the circuit grows slightly expulsing the liquid from the cold leg to the expansion tank. A thermocouple at the heater inlet shows the gradual rise of the liquid temperature.

As more and more vapor is generated at the heater, the slug flow is replaced by a churn flow with the expulsion of liquid, entrained by the vapor, to the cold leg through the coil cooler. This period characterizes the expulsion period. During this period, the expansion tank water level rises, consequently, augmenting a little more the pressure inside the circuit.

The difference of the hydrostatic head, from the hot and cold legs, increases creating a flow rate at the circuit replacing the hot water at the heater by cold water from the coil cooler. Then the vapor production at the heater decreases and the horizontal part of the hot leg is partially filled with water again. At this time a natural circulation flow, similar to one-phase flow, is established for a short period until two-phase flow process starts again.

Development of RELAP5 model

To simulate the thermal hydraulic behavior of the circuit a first model [6] was developed, using *PIPE* and *BRANCH* components to represent all the facility piping. The nodes used for this nodalization are about 0.3 m long. At the beginning, all the volumes were filled with water except that one representing the upper part of expansion tank, which has also some air. Heat losses to the environment were also considered.

This model was able to predict the behavior of the one-phase experiments tuning the heat losses to the environment but did not predict the two-phase flow oscillations that occurred with higher heat power dissipation. It was noted that in some experimental results, the two-phase flow oscillations started even when the highest liquid temperature in the facility was below the saturation. This suggests that some important details were missed or not well represented in the model. Figure 4 shows a comparison for the calculated and experimental temperatures for a two-phase flow experiment.

Looking more carefully to the model it was noted that two main points should be better represented: the natural convection inside pipes and the presence of non-condensable gases dissolved in the tap water used to fill the loop. The natural convection inside the surge line causes the heat up of the expansion tank that was not observed at the model. This explains why an additional heat loss had to be added to obtain a better agreement. To represent this convection, the surge line and the bottom part of the expansion tank were split in two parts, one to represent the up flow and other to represent the down flow. Two parallel pipes, with cross flow junctions, were used to represent the surge line. The same was done to the expansion tank. So that, the heat up of the tank was observed. In order to better represent the startup of the experiments, the same kind of nodalization was applied to the heaters and vertical region above them. When the heaters were turned on, a natural circulation was established inside the heater before it could be established along all the circuit.

Observing the experiments, it was noted that the two-phase oscillation only started when the upper part of the hot leg became completely full of gas and it usually happened at a temperature below the saturation temperature. The saturation temperature is considered as the temperature to the change from liquid to vapor phase, in the facility pressure, disregarding the presence of non-condensable gases. This indicates that this gas is a composition of pure vapor and non-condensable gases. Then air was added at the upper part of the hot leg to compensate the non-completely degassing of the circuit, so those two-phase oscillations were reproduced in the calculation

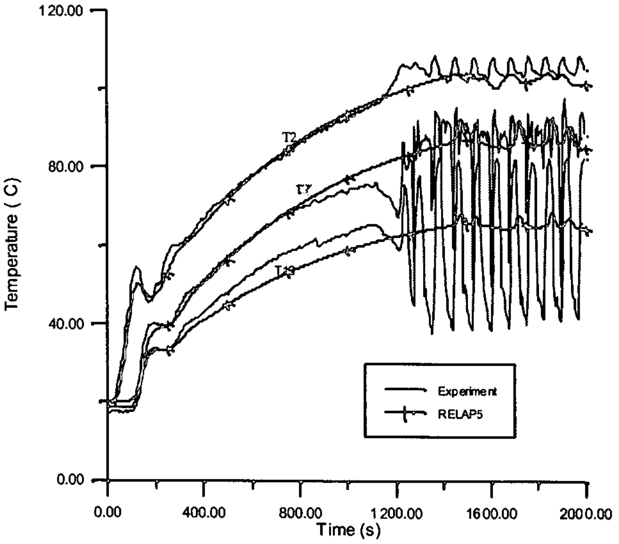

Figure 4 - Measured and calculated temperatures for the first nodalization attempted

The final nodalization is presented in Figure 5. Table 1 represents the components association between RELAP final nodalization and the facility.

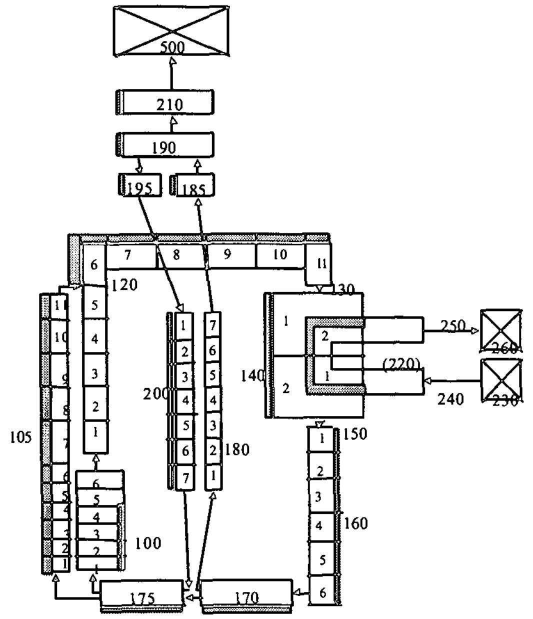

Figure 5 – RELAP5 MOD3.2 – Facility Nodalization

Table 1 – Nodalization of the Natural Circulation Experimental Facility: Hydraulic Regions and Code Component Correspondence

Component	Component Number	Component Type
Heater	100 105 (1-6)	PIPE PIPE
Hot Leg	105 (7-11) 120	PIPE PIPE
Primary Cooler	140	PIPE
Cold Leg	160 170 175	PIPE BRANCH BRANCH
Surge Line	180 200	PIPE PIPE
Expansion Tank	185 190 195 210	BRANCH BRANCH BRANCH BRANCH
Secondary Cooler	220	PIPE
Cooling Water (in)	230 240	TMDPVOL TMDPJUN
Cooling Water (out)	250 260	SNGLJUN TMDPVOL
Containment	500	TMDPVOL

Figure 6 shows the comparison of measured and calculated temperature for three points of the facility. These points correspond to T2, T7 and T12 Thermocouples represented in Figure 1. The main phenomena that take part of the two-phase flow natural circulation are very well represented by RELAP5 facility nodalization. Due to the good agreement for the calculated and measured values one could be sure to adopt this procedure.

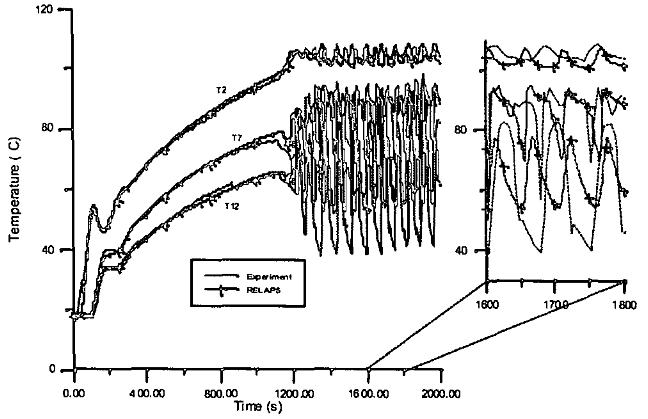

Figure 6 – Comparison for the measured and calculated temperatures

Two Phase Flow Instabilities Analysis

The experiment chosen for the analysis had the following operational conditions: heating power – 6500 W; cooling water temperature – 20 °C and flow rate – 1.4 l/min.

The heater was turned on and after 1200 s the two-phase instabilities started. This behavior is represented by Figure 6, Figure 7 and Figure 8.

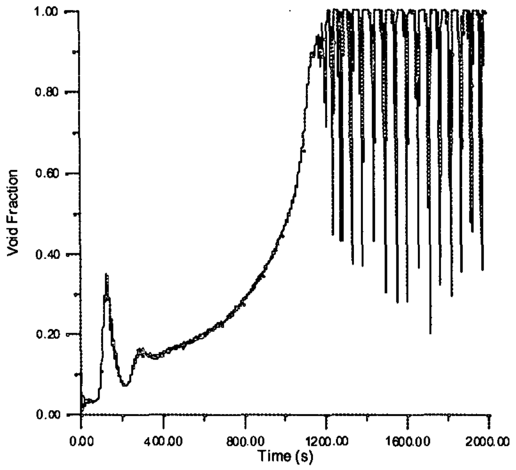

Figure 7 – Calculated Void Fraction at the Hot Leg Top

Figure 7 shows that the void fraction at the top of the hot leg increases as temperature becomes higher, Figure 6. This characteristic is due to the vapor and gas mixture expansion. A flow interruption is observed when the horizontal part of the hot leg is full of vapor, Figure 8.

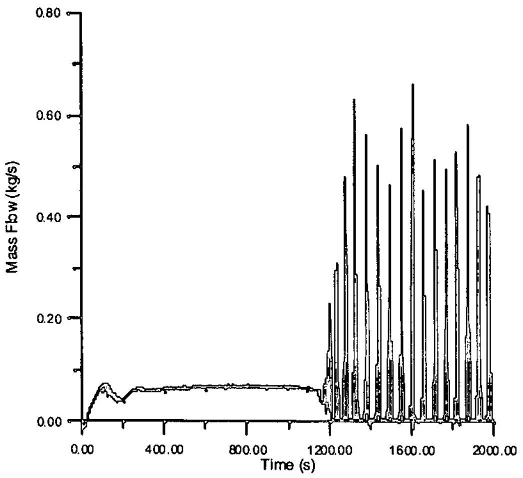

Figure 8 – Calculated Mass Flow Rate at the Hot Leg Top

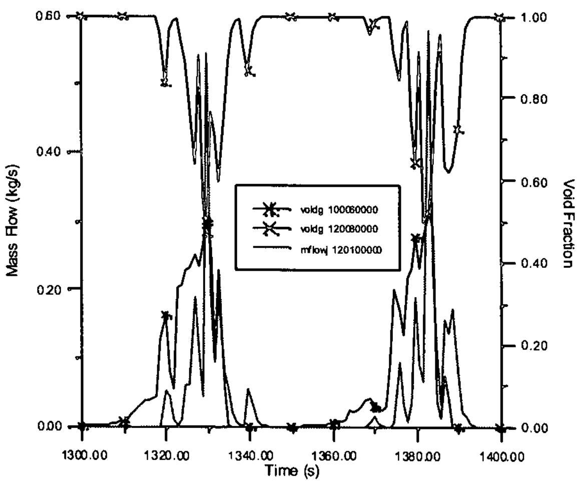

Figure 9 – Void Fraction and Mass Flow Rate at the Hot Leg Top during Two-Phase Flow Oscillation

A detailed view in a shorter period of time is presented in Figure 9. When the hot leg top is full of vapor (voidg 120080000 = 1.0), no significant flow is observed in the circuit. As the vapor quantity in the heater increases (voidg 100060000), liquid is entrained by the flowing up vapor in the hot leg toward the heat sink, illustrated by the hot leg mass flow rate (mflowj 120100000). Therefore, a liquid flow is established in the circuit, consequently, cold liquid goes to the heater, avoiding the vapor generation. Even with no vapor generation in the heater as the flow drive force, there are some seconds of one-phase flow until the horizontal hot leg part becomes full of vapor again.

Conclusions

In order to have a better understanding of the natural circulation phenomena in closed loops a glass square circuit was built with an electrical heater as the heat source and a coil cooler as the heat sink. Experiments were made in one and two-phase flows and special attention was dedicated to the analysis of the instabilities observed.

The RELAP5/MOD3.2 was used to simulate the thermal hydraulic behavior of the system. The results obtained provided additional information enabling a better understanding of the two-phase instabilities.

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