FLOW REGIME IDENTIFICATION IN NATURAL CIRCULATION PHENOMENON USING RELAP5 CODE

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ABSTRACT

There has been a crescent interest in the scientific community in the study of natural circulation phenomenon. New generation of compact nuclear reactors uses the natural circulation of the fluid as a system of cooling and of residual heat removal in case of accident or shutdown. The objective of this paper is to compare the flow patterns of experimental data and numerical simulation for the natural circulation phenomenon in two-phase flow regime. An experimental circuit built with glass tubes is used for the experiments. Thus, it allows the thermal hydraulic phenomena visualization. There is an electric heater as the heat source, a heat exchanger as the heat sink and an expansion tank to accommodate fluid density excursions. The circuit instrumentation consists of thermocouples and pressure meters to better keep track of the flow and heat transfer phenomena. Data acquisition is performed through a computer interface developed with LABVIEW. The characteristic of the regime is identified using photography techniques. Numerical modeling and simulation is done with the thermal hydraulic code RELAP5, which is widely used for this purpose. This numerical simulation is capable to reproduce the flow regimes which are present in the circuit for the natural circulation phenomenon. Comparison between experimental and numerical simulation is presented in this work.

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]. There are also some conceptual designs using the natural circulation where the components and systems have been simplified by eliminating pumped recirculation systems and pumped emergency core cooling systems [2]

A theoretical and experimental research project is under development at *Instituto de Pesquisas Energéticas e Nucleares* (*IPEN-CNEN/SP*). The objective is to understand the complex phenomena involving the instabilities in two-phase flow in a natural circulation circuit.

This study started at the *Departamento de Engenharia Química da Escola Politécnica (USP)*. Experiments concerning single and two-phase flow in natural circulation regime were performed by this team [3, 4 and 5]. This work is a follow-up of the one which was presented in [6]. Some new RELAP5 modeling assumptions were done so the calculated and experimental results showed much better agreement.

In the literature, several other natural circulation experiments, related to nuclear reactors, had also been carried out by different authors [7, 8, and 9].

EXPERIMENTAL FACILITY

The experimental facility, presented in the Fig. 1, has a heated section with a 75 mm cylindrical glass tube and two electrical heaters. The power applied is controlled in the range from 0 to 8,400 W. The cooler is all made from glass with 33 mm internal diameter, 610 mm high and two spiral 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 environment at the top end. At the bottom end, this tank is connected to the loop in order 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.

Heaters are installed inside a glass tube with 76.2 mm diameter, 880 mm high and 8 mm thick. There are two heaters of 4,200 W each. The power of the first one is fixed and for the second, a variac controls the heater power from 0 to 4200 W. The heating power is imposed through an alternate voltage controller.

Coil cooler is composed of two concentric spirals, primary water circuit flows inside the shell and refrigeration water inside the spirals.

Expansion tank is also glass made with 7 liters of volume, 1,270 mm high and 120 mm diameter. It is located at 700 mm above the upper horizontal section of the circuit. Its upper nozzle is opened to the environment. The lower nozzle is connected to the surge line which is connected to cold leg.

The temperatures are measured by type K thermocouples at fifteen distinct points, three on the tube wall external surface (TW1 to TW3) and twelve at the fluid bulk (T11 to T22). A pressure meter is positioned at the outlet of the heating section and a differential pressure meter is positioned at the bottom of the expansion tank for level indication. Signal conditioning and a data acquisition board hosted in a PC completes the data acquisition system.

Digital cameras are used to take pictures and record videos at the top of the heaters and entrance of the hot leg to register the flow pattern.

The positions of the circuit instrumentation can be seen in Fig. 1.

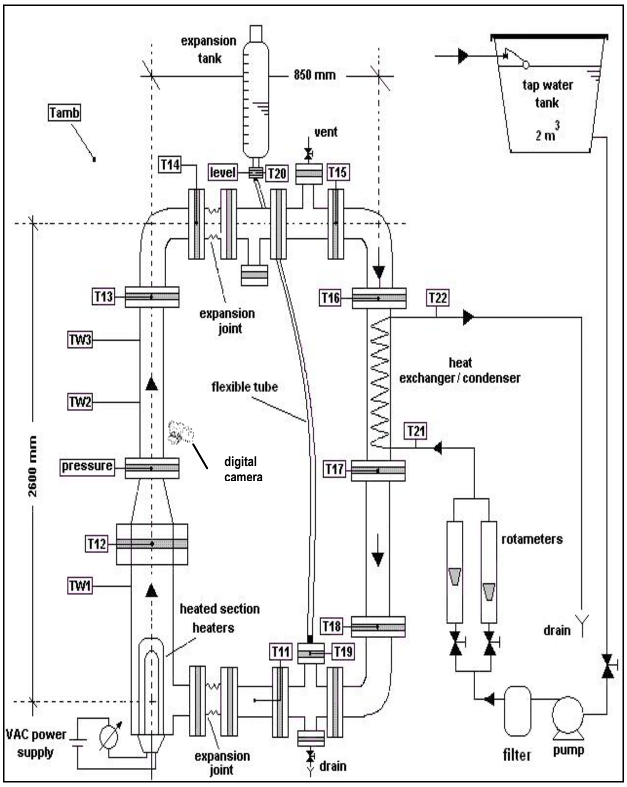


Figure 1: Natural circulation circuit diagram.

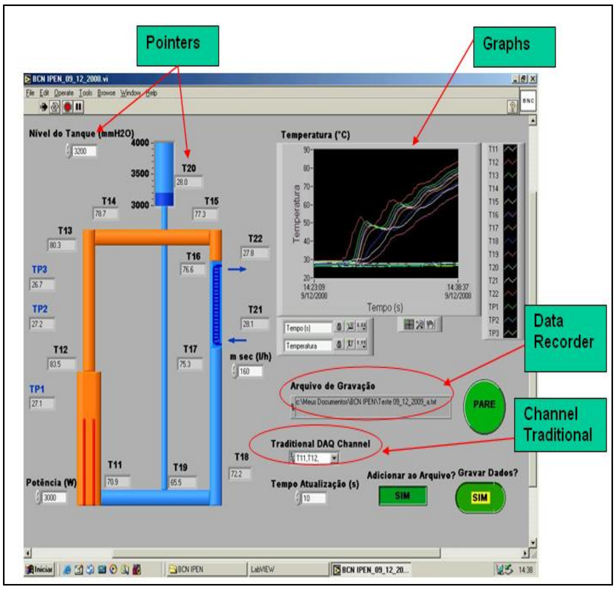
Data acquisition system is supplied by National Instruments. It consists of two signal conditioner modules, two terminal blocks and an acquisition PCMCIA card installed into a notebook computer. LabView [10] is used to create an interface, through which all the configuration is done.

Temperature data listed below are registered at a sampling rate of approximately 7 seconds:

a) six at the hot leg;
b) four at the cold leg;
c) two, inlet/outlet of the cooling water;
d) three on the external tube walls to estimate heat losses;

The secondary flow rates were measured by rotameters.

The details of the data acquisition system based on LabView are presented in Fig. 2.



Nível do Tanque (mmH2O) 3200
T20 28.0
T14 78.7
T15 77.3
T13 80.3
T22 27.8
T16 76.6
TP3 26.7
TP2 27.2
T21 28.1
T12 83.5
T17 75.3
m sec (l/h) 160
TP1 27.1
Arquivo de Gravação c:\Meus Documentos\BCN IPEN\Teste 09_12_2009_a.txt
Traditional DAQ Channel T11,T12,
T11 70.9
T19 65.5
T18 72.2
Potência (W) 3000
Tempo Atualização (s) 10
Adicionar ao Arquivo? SIM
Gravar Dados? SIM

Figure 2: Software interface.

METHODOLOGY

The methodology used in this work consisted of experimental and theoretical studies. The RELAP5 code [12] was used for the numerical simulation of the natural circulation circuit to be assessed against experimental results.

RELAP5 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 can model the primary and secondary cooling system of experimental facilities and of Nuclear Reactors with geometric details. The program uses the two fluid models and takes into account the mass, momentum and energy equations for the liquid and gaseous phases. RELAP5 also has two additional equations to deal with noncondensable gases and soluble boron. One-dimensional models are used to treat the fluid flow and the heat conduction at the structures, but in some special cases such as the cross flow in the reactor core and the rewetting region in flooding model, two-dimensional models are used.

The RELAP5 code is capable to identify the fifteen different flow patterns which are presented in Tab. 1, each one associated to an integer number. Those numbers are stored in the RELAP5 code output file to specify the flow regime time behavior for each control volume during the transient simulation.

Table 1: Flow regime number (RELAP5 output).

Flow regime	Number
High mixing bubbly	1
High mixing bubbly/mist transition	2
High mixing mist	3
Bubbly	4
Slug	5
Annular mist	6
Mist pre-CHF	7
Inverted annular	8
Inverted slug	9
Mist	10
Mist post-CHF	11
Horizontal stratified	12
Vertical stratified	13
Level tracking	14
Jet junction	15

EXPERIMENT

An experiment starts with the primary circuit filled with demineralized water at rest and the heater off. The initial fluid temperature is completely homogeneous and equal to the ambient temperature all along the loop. The secondary side coil cooler flow rate and inlet temperature are established to constant values and then the heaters are turned on, supplying also, a constant heating power. The facility starts its heating up process that, depending on the combination of heating power and cooling flow rate, should evolve to a stable one-phase flow or to an unstable two-phase flow. When higher heating power and lower cooling flow rate are set up, two-phase flow is obtained.

Experiments showed that two-phase oscillation only started after the upper part of the hot leg had become completely filled with gas, so the hot leg water flow was interrupted, highly decreasing the transport of the heat from the heater to the cooler. This flow is reestablished when a vigorous two-phase flow start so the produced steam entrain some liquid from the heater to the cooler, increasing the heat removal. This increase in the heat removal cools down the circuit to the one phase flow again at the beginning of a new cycle.

In the Fig. 3, some photos of the two-phase flow patterns observed in the circuit are presented.

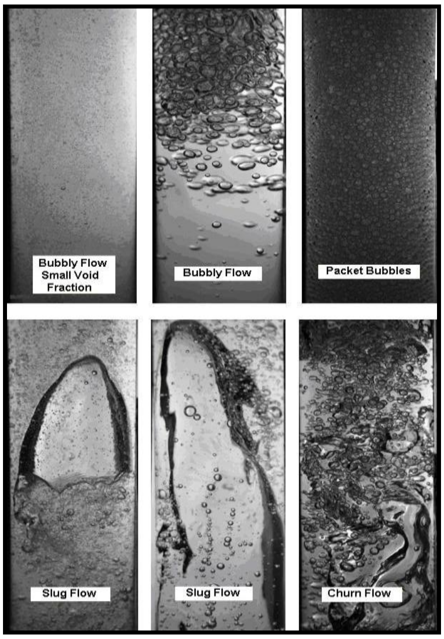


Figure 3: Two-phase flow patterns.

In order to be compared against RELAP5 calculated results, a typical unstable two-phase flow experiment was chosen. The operational conditions of this experiment are presented in Tab. 2.

Table 2: Operational condition of the experiment.

Two-phase flow conditions
Total power : 7,500 W
Cooling Water: 100 l/h
Initial temperature: 20 °C
Ambient temperature: 21 °C

THEORETICAL SIMULATION

To simulate the thermal hydraulic behavior of the circuit, a RELAP5 nodalization was developed using PIPE and BRANCH components to represent the hydrodynamics of the circuit and heat structures to represent the heater, the coil cooler and the heat losses to the environment. It is almost the same nodalization used in a previous work [6] plus some new assumption trying to better capture the experimentally observed flow patterns and measured values.

Assuming that, despite all degasification efforts, the circuit still had some air dissolved in the water. A simple calculation showed that if there were 25 mg of air per 1 kg of water in the circuit, the complete dissociation of this gas, which usually happen near water saturation temperature, should be enough, at 1bar, to fill almost 20% of the horizontal part of the hot leg at 20 °C and to block it completely when heated over 95 °C.

The RELAP5 does not treat the solubility of non-condensable in water, so any amount air can only be represented trough void fraction since the gas is always considered dissociated from the liquid. An initial 20% void fraction in the horizontal upper part of the hot leg was considered plus an artificial mean for transporting the soluble air from the outlet of the cooler to the inlet of the heater was implemented.

RELAP5 components and nodalization and are presented in Tab. 3 and Fig. 4.

Table 3: Nodalization components.

Component	Comp. number	Comp. type
Heater (outlet junction)	100 110	pipe sngljun
Hot Leg	120	pipe
(inlet junction) Primary Cooler (outlet junction)	130 140 150	sngljun pipe sngljun
Cold Leg	160 170 175	pipe branch branch
Surge Line	180	pipe
Expansion Tank	185 190 210	branch branch branch
Secondary Cooler	220	pipe
Cooling Water (inlet)	230 240	tmdpvol tmdpjun
Cooling Water (outlet)	250 260	sngljun tmdpvol
Artificial air transport	99 155	branch tmdpjun
Containment	500	tmdpvol

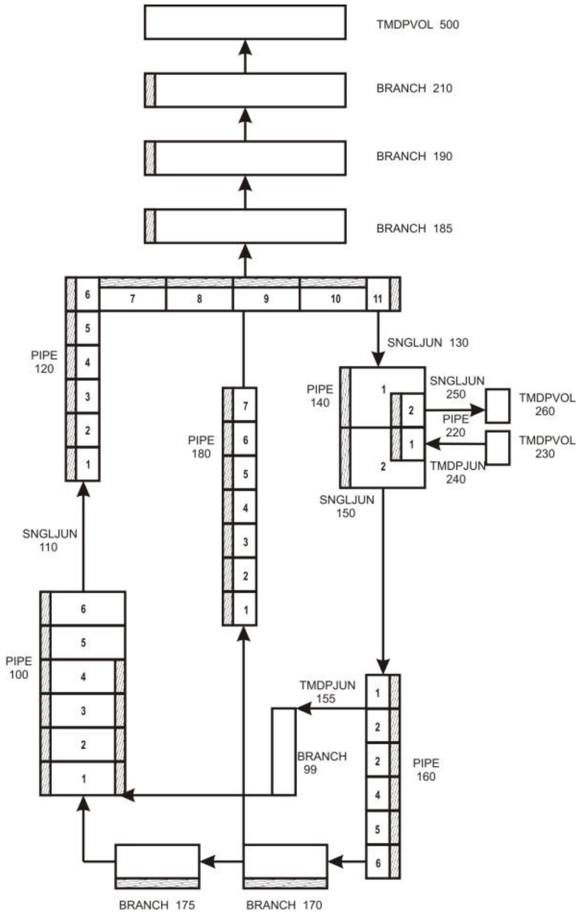


Figure 4: RELAP5 – Facility nodalization.

RESULTS

In this work a two-phase flow case was studied for a power of 7.5 kW and 100 l/hr cooling flow rate. Figures 5 to 10 summarize the obtained results. The first four figures present the comparison of measured and calculated values and the last three present only calculated values. All of them present a detailed zoom covering the same three cycle period.

Fluid temperature at the inlet and outlet of the heaters are presented in Fig. 5 and 6 respectively. These points correspond to T11 and T12 thermocouple presented in Fig. 1. The temperature oscillation period were very well predicted by RELAP5 while oscillation amplitude for the outlet of the heater was underestimated.

The RELAP5 calculated circuit pressure was in good agreement with the experimental results as can be seen in Fig. 7. Probably the oscillatory behavior of the experimental results was lost due to the data acquisition period of 12 s.

Void formation in the circuit expels the liquid to the expansion tank. Figure 8 shows the level in the expansion tank while the Fig. 9 shows the heater outlet void fraction. Detailed zoom shows the increasing of the level as the void fraction increase.

Figure 10 illustrates the flow regimes identified by RELAP5 calculation. For this simulation, output of RELAP5 captured three alternately flow regimes during the oscillatory phase: Bubbly, Slug and Annular mist, corresponding respectively to number 4, 5 and number 6 from Table 1. These flow regimes were compared, through a visual identification, with the video recorded data.

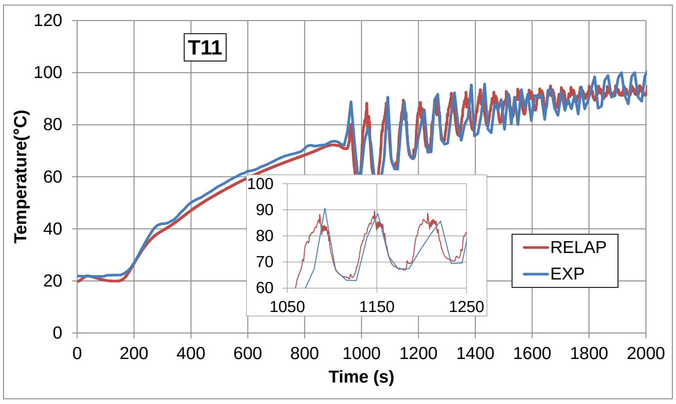


Figure 5: Temperature theoretical/experimental at the heater inlet (T11 position) in two-phase flow

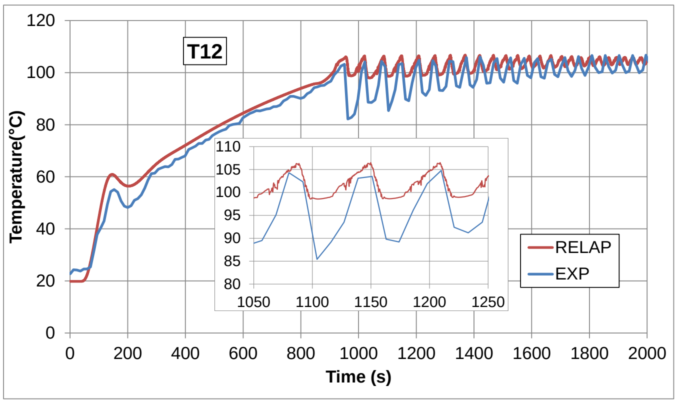


Figure 6: Temperature theoretical/experimental at the heater outlet (T12 position) in two-phase flow.

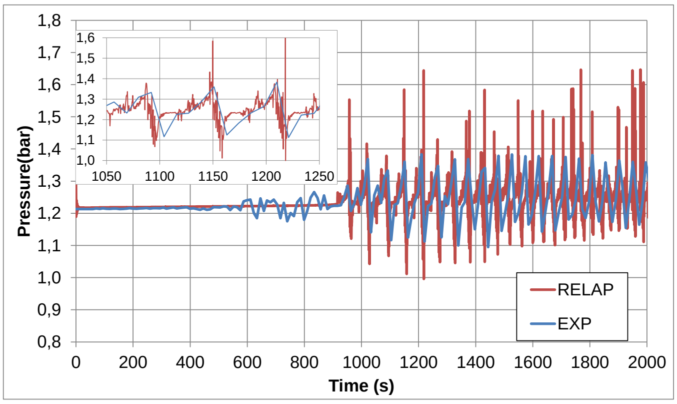


Figure 7: Pressure in the circuit primary side.

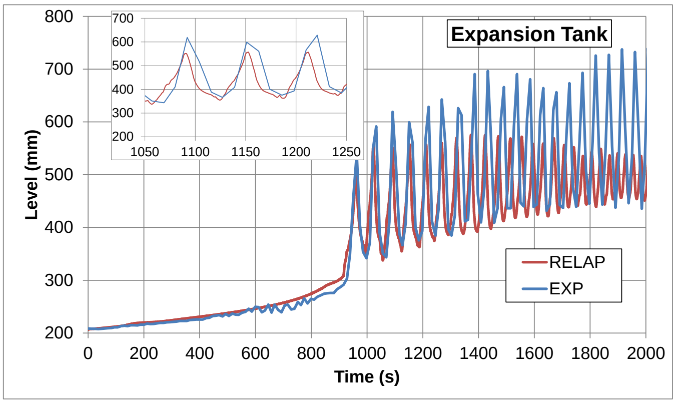


Figure 8: Water level theoretical/experimental in the expansion tank.

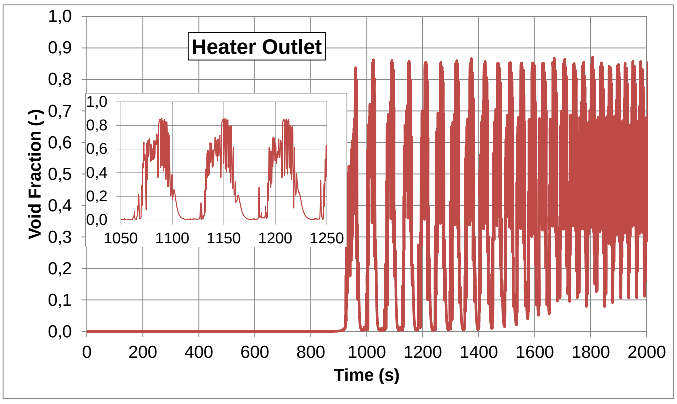


Figure 9: Calculated void fraction at the heater outlet (near T12 position) in two-phase flow.

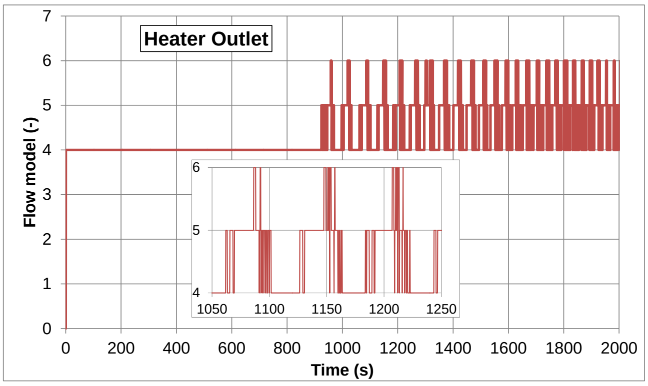


Figure 10: Calculated flow regimes at the heater outlet (near T12 position) in two-phase flow.

Figure 11 presents a sequence of images showing snapshots of the time evolution of the experimental flow pattern of a hot leg vertical section of 20 cm length. Each one was obtained from a frame of a video recorded during one cycle of the two phase flow oscillation. These snapshots are organized from left to right, from top to bottom. They were presented in the same sequence of occurrence but they were not chosen in a constant time interval since they only intend to show the flow pattern changes.

Figure 12 presents the RELAP5 calculated flow pattern during one cycle.

Both, theoretical and experimental results showed the same sequence of flow pattern:

1) bubbly flow
2) alternating bubbly flow / slug flow
3) slug flow
4) alternating slug flow / annular mist flow
5) alternating slug flow / annular mist flow / bubbly flow
6) alternating bubbly flow / slug flow
7) bubbly flow

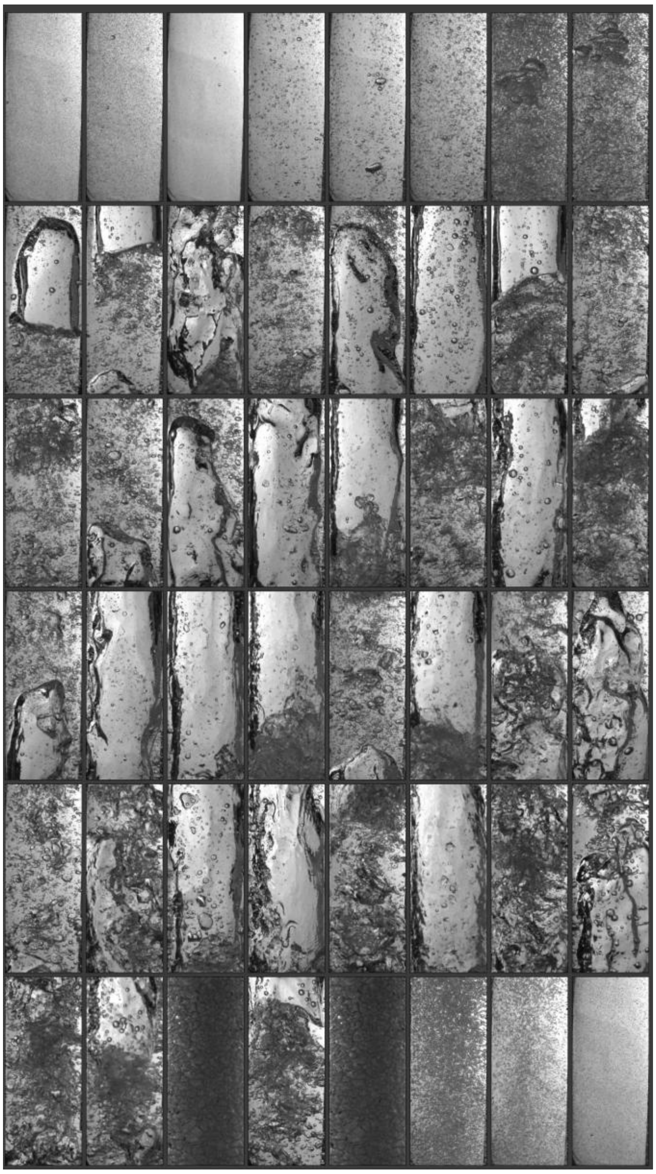


Figure 11: Images of the flow regimes at the of the heater outlet (near T12 position) in two-phase flow experiment.

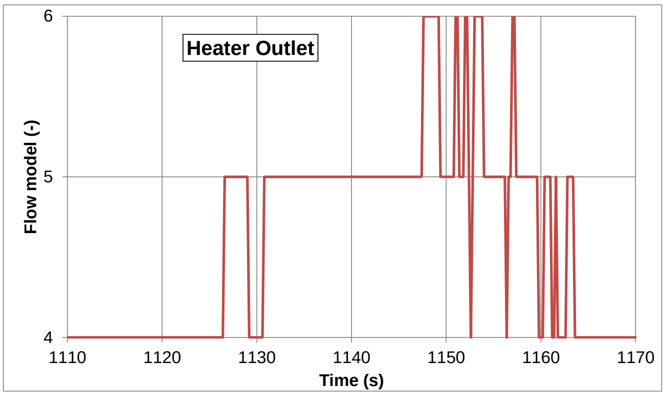


Figure 12: Calculated flow regimes at the heater outlet (near T12 position) in two-phase flow.

CONCLUSION

Experiments were performed in two-phase flow. It was also numerically simulated with RELAP5. The experimental/ theoretical comparison showed to be in a good agreement.

Additional experiments are programmed in order to register pressure and void fraction distribution and primary circuit flow. These measures will contribute to the better understanding of the one and two-phase natural circulation phenomena and also to provide data to validate numerical simulations.

Although RELAP5 model was able to identify all the flow regimes some further nodalization improvements are also necessary to capture the initial heating up phase of the transient and temperature oscillation amplitude. A more detailed nodalization will be developed in order to supply this gap.

ACKNOWLEDGMENTS

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