

A RELAP5 STUDY TO IDENTIFY FLOW REGIME IN NATURAL CIRCULATION PHENOMENON

Gaianê Sabundjian¹, Walmir M. Torres¹, Luiz A. Macedo¹, Roberto N. Mesquita¹,
Delvonei A. Andrade¹, Pedro E. Umbehaun¹, Thadeu N. Conti¹, Paulo H. F. Masotti¹,
Antonio Belchior Junior¹ and Gabriel Angelo¹

¹Instituto de Pesquisas Energéticas e Nucleares (IPEN/CNEN-SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP

gdjian@ipen.br; delvonei@ig.com.br; umbehaun@ipen.br; wmtorres@ipen.br; tnconti@ipen.br
rnavarro@ipen.br; lamacedo@ipen.br; pmasotti@ipen.br; abelchior@ipen.br; gabriel.angelos@gmail.com

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 some of 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.

1. 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, 5 and 6]. Other experiments were carried out by different authors as found in the literature [7, 8, and 9].

The circuit 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.

The heating power is imposed through an alternate voltage controller, variac. The temperatures are measured in 15 points, three on the tubes surface and the others inside the tubes, Fig.1. Type K thermocouples are used and a pressure meter is positioned at the heating section top. Signal conditioning and a data acquisition board hosted in a PC completes the data acquisition system.

Heaters are installed inside a glass tube with 76.2 mm diameter, 880 mm high and 8 mm thick, Fig. 1. 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.

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 positions of the thermocouples can be seen in Fig. 1.

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, Fig. 1.

The secondary flow rates were measured by rotameters.

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

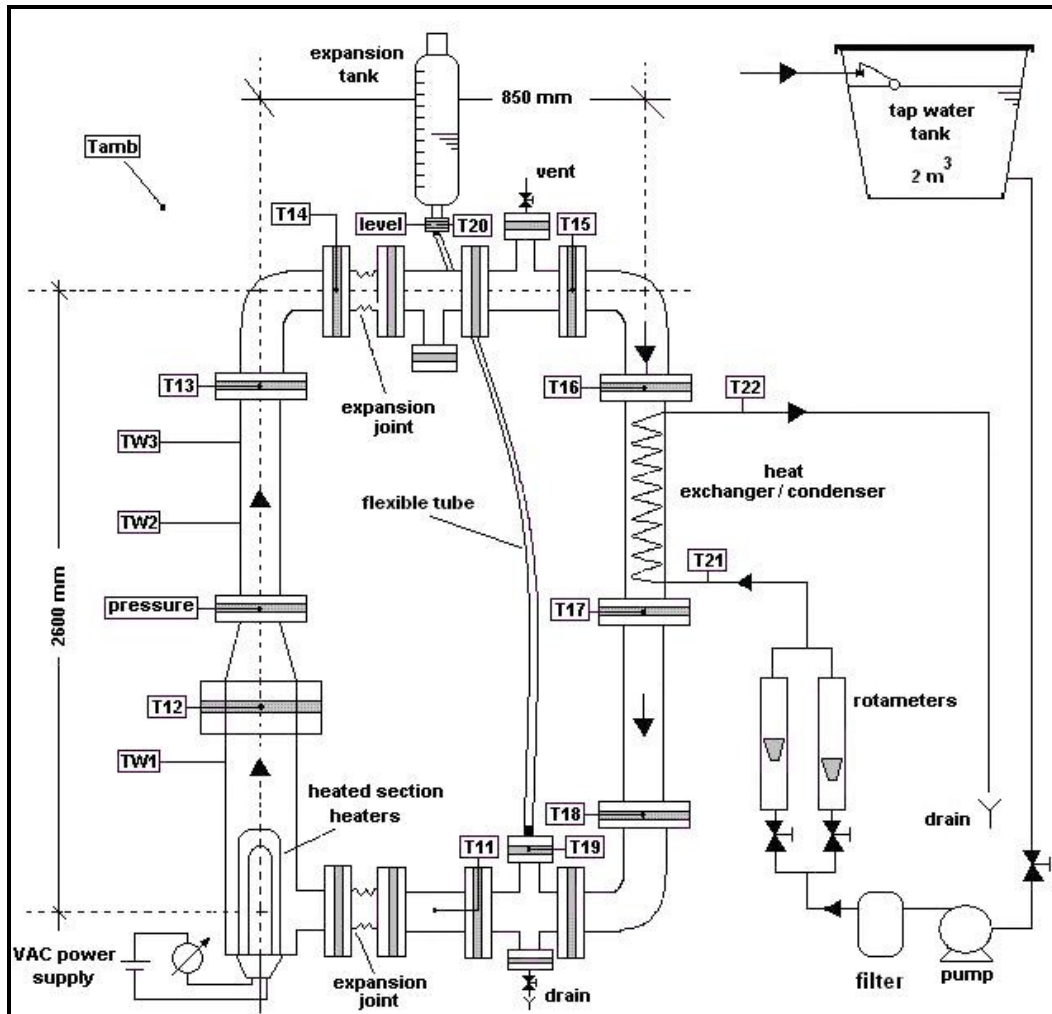


Figure 1. Natural circulation circuit diagram

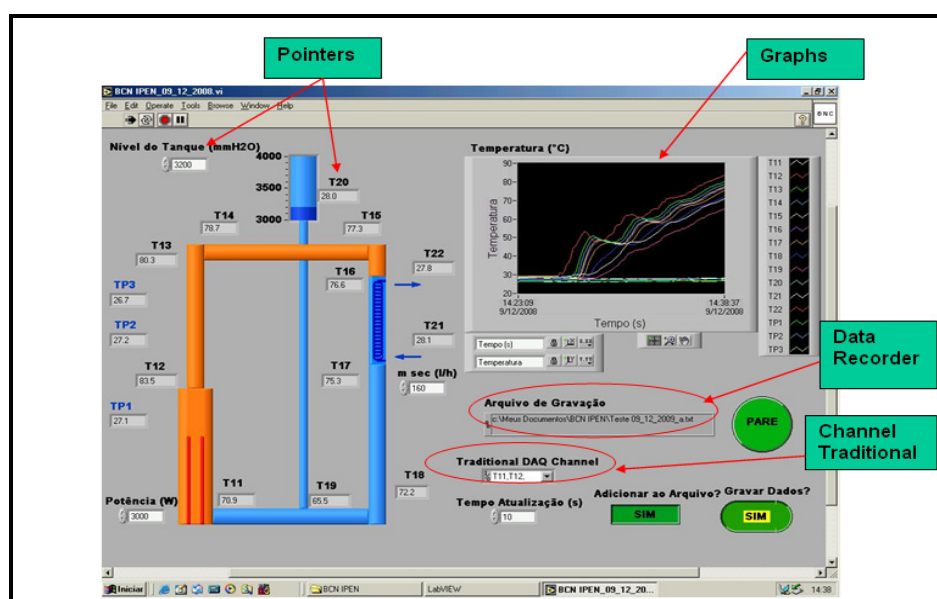


Figure 2. Software interface

2. METHODOLOGY

The methodology used in this work consisted of experimental and theoretical studies. RELAP5 code [11] was used to simulate the natural circulation circuit.

The experiment started with the primary circuit filled with water at rest and the heater off. The fluid temperature was completely homogeneous and equal to the ambient temperature all along the loop. The heater was turned on with a constant heating power. The secondary flow rate and the inlet temperature at the coil cooler were also kept constant. The experiment was done only to 7,500 W of power, two-phase flow study.

Figure 3 presents photos of the two-phase flow patterns in the circuit.

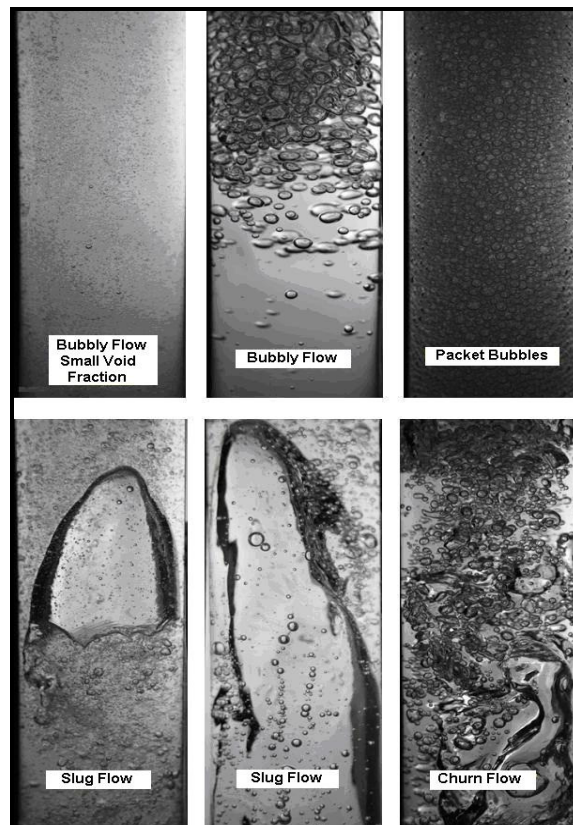


Figure 3. Two-phase flow patterns

3. EXPERIMENTAL AND THEORETICAL SIMULATION

To simulate the thermal hydraulic behavior of the circuit, a nodalization [12] was developed using PIPE and BRANCH components to represent all the circuit. At the beginning, all the volumes were filled with water except that one representing the upper part of expansion tank, which had also some air. Heat losses to the environment were also considered.

Experiments showed that two-phase oscillation only started when the upper part of the hot leg became completely filled with vapor. The saturation temperature is considered as the

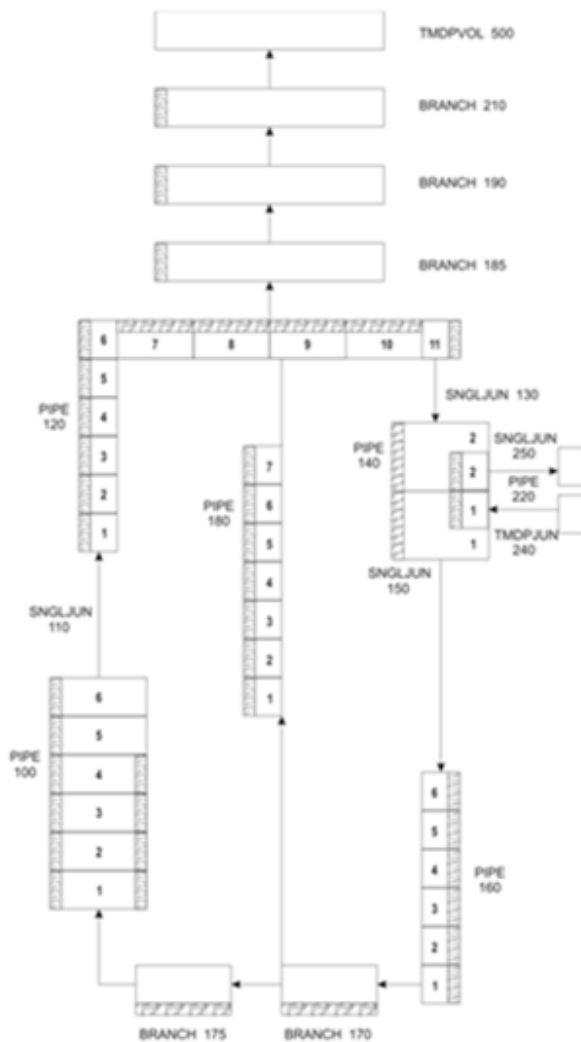
temperature to the change from liquid to vapor phase, in the pressure of the circuit, disregarding the presence of non-condensable gases. Table 1 presents two-phase flow operational conditions.

Table 1. Operational condition of the experiment

Two-phase flow conditions
Total power: 7,500 W
Cooling Water: 0.0233 kg/s
Initial Temperature: 20 °C
Environment Temperature: 21 °C

RELAP5 nodalization and components are presented in Figure 4 and Table 2, respectively.

Table 2. Nodalization components



COMPONENT	COMPONENT NUMBER	COMPONENT TYPE
Heater	100	PIPE
Hot Leg	120	PIPE
Primary Cooler (outlet)	140	PIPE
Cold Leg	150	SINGLJUN
	160	PIPE
	170	BRANCH
Surge Line	175	BRANCH
	180	PIPE
Expansion Tank	185	BRANCH
	190	BRANCH
	210	BRANCH
Secondary Cooler	220	PIPE
Cooling Water (inlet)	230	TMDPVOL
	240	TMDPJUN
Cooling Water (outlet)	250	SINGLJUN
	260	TMDPVOL
Containment	500	TMDPVOL

Figure 4. RELAP5 – Facility nodalization

The RELAP5 code is capable to reproduce the flow patterns presented in Table 3. Flow regimes are described in the RELAP5 output through numbers according to Table 3.

Table 3. 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

4. RESULTS

In this work only two-phase flow case was studied for a power of 7,500 W.

Figure 5 shows the comparison of measured and calculated temperature in the outlet of the heaters. This point corresponds to T12 thermocouple represented in Fig. 1. Figure 6 shows a region (4,600 to 4,700 s) where the void fraction reached the unity, reason for what the graphic zooms were drawn within all the figures.

Figures 6 and 7 show the void fraction and flow mass in the primary circuits, respectively, obtained of the RELAP5 simulation for two-phase flow.

Figure 8 illustrates the flow regimes described by RELAP5. For this simulation, output of RELAP5 captured only two flow regimes, Slug and Annular mist, number 5 and number 6, respectively, Table 3.

However, several flow regimes, each 49 s, are observed in the experiments, Fig. 9.

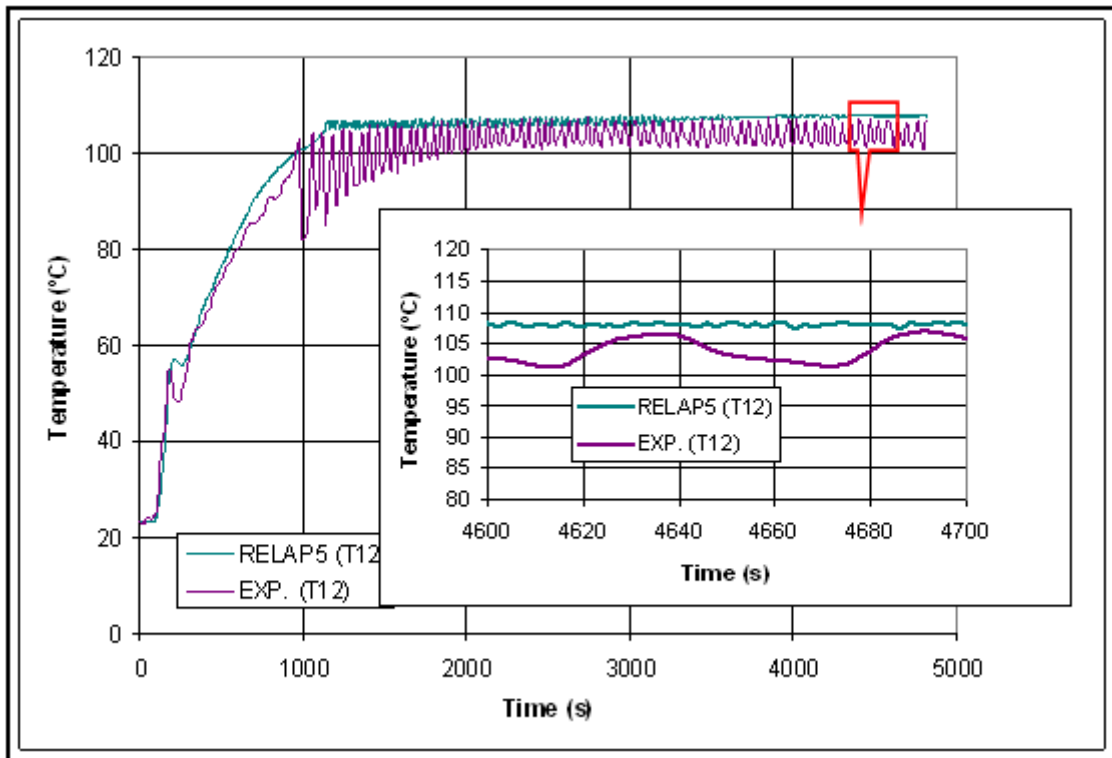


Figure 5. Temperature theoretical/experimental outlet of the heater (T12) in two-phase flow

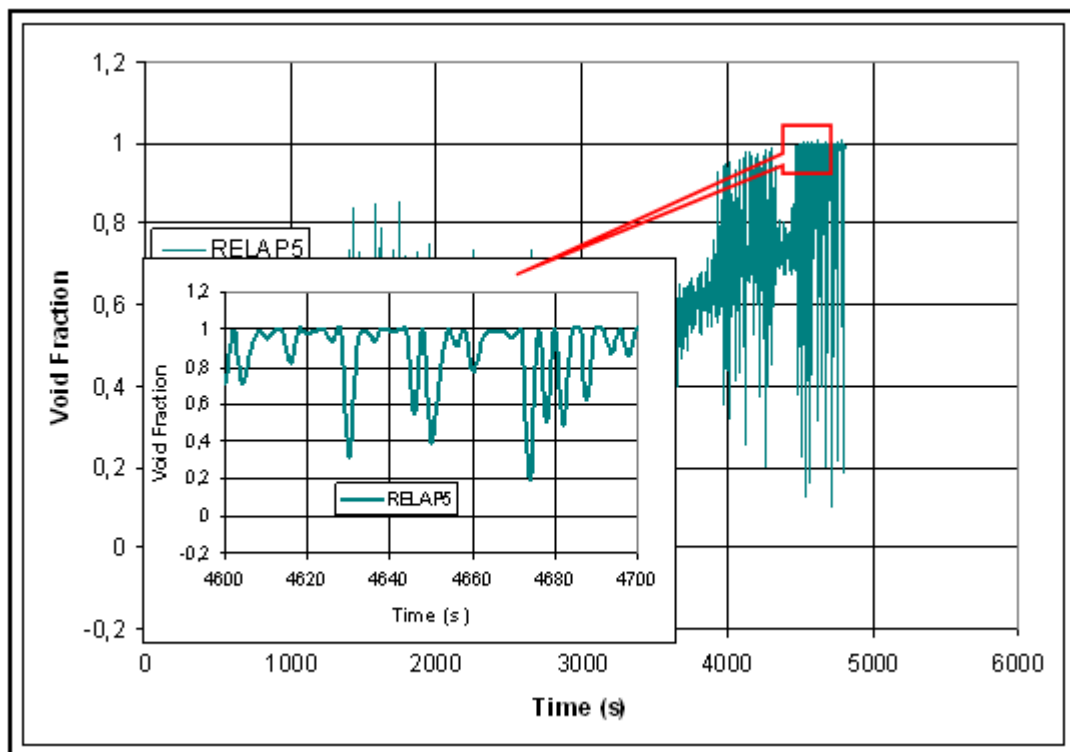


Figure 6. Void fraction in primary circuit in two-phase flow (RELAP5)

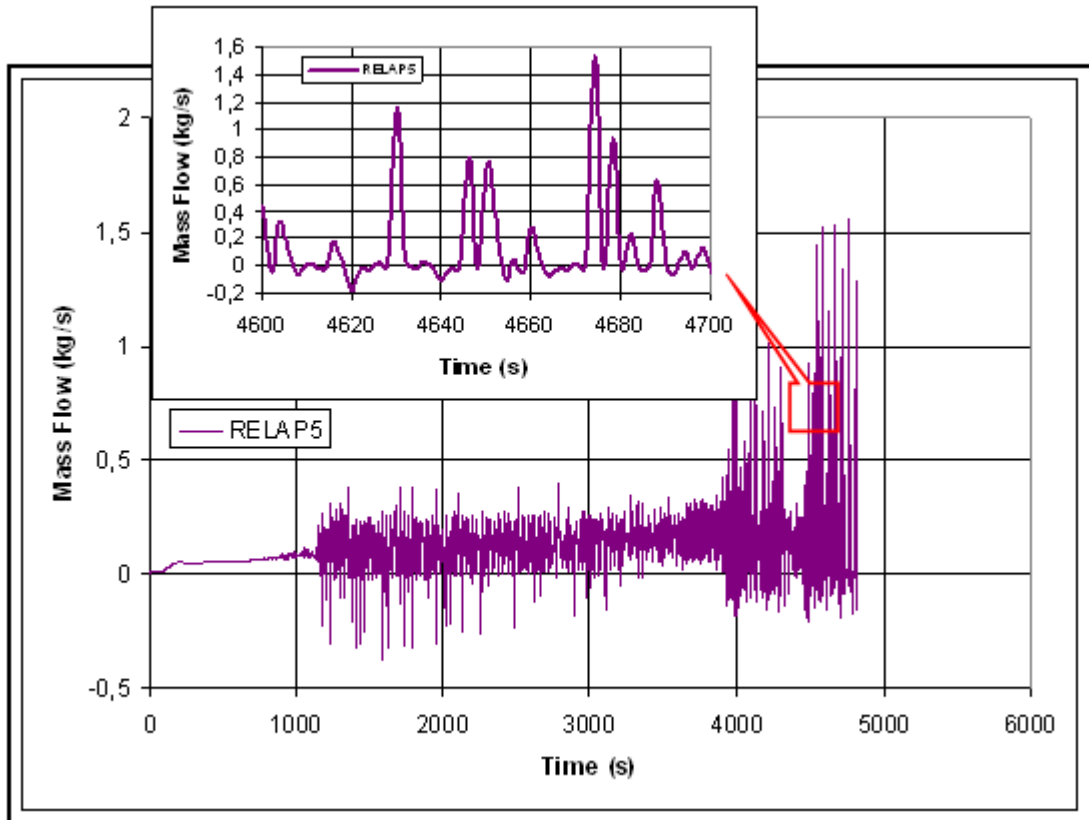


Figure 7. Flow mass in the primary circuit in two-phase flow (RELAP5).

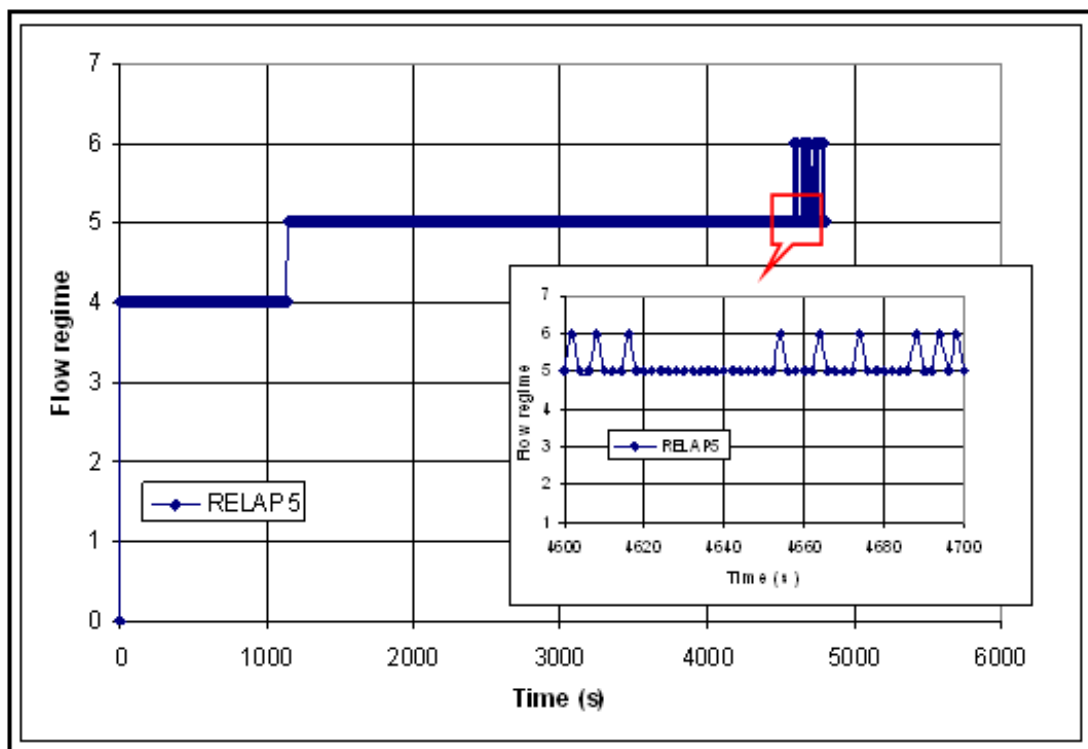


Figure 8. Flow regimes outlet of the heater (T12) in two-phase flow (RELAP5)

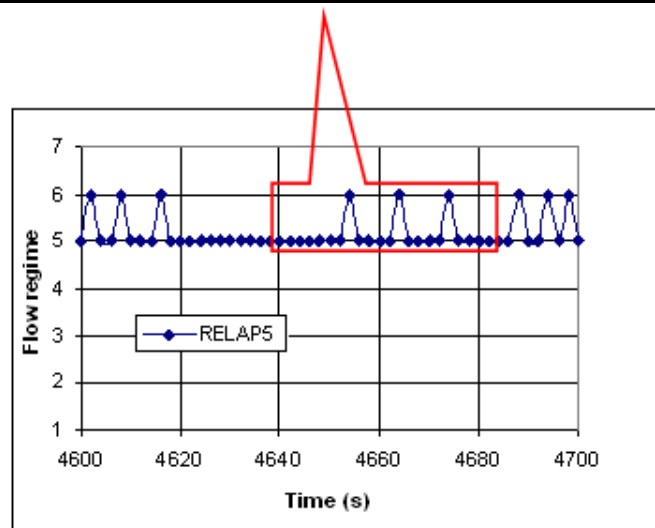
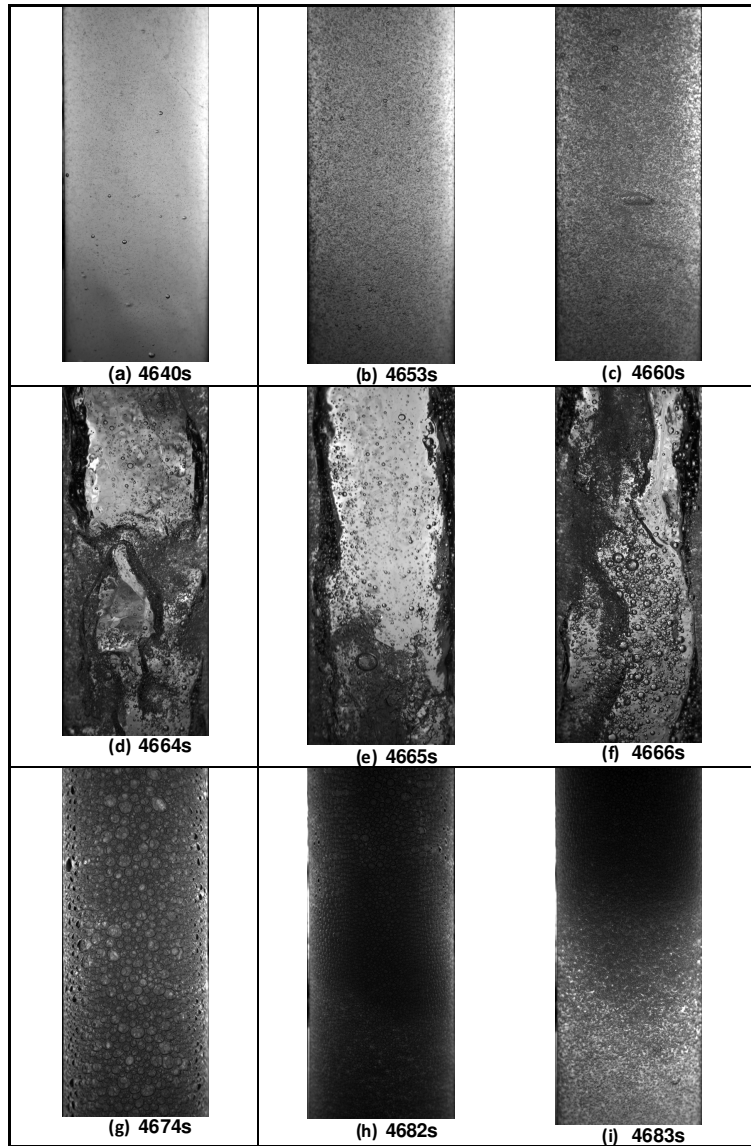


Figure 9. Flow regimes outlet of the heater (T12) in two-phase flow (experimental)

Table 4 shows the flow regimes described in the RELAP5 output and in the experimental results, in the times steps presented in Fig. 9.

Table 4. Flow regimes in the RELAP5 output and experimental results

TIME (s)	RELAP5 (flow regimes)	EXPERIMENTAL (flow regimes)
4640	Slug	Bubbly
4653	Annular mist	High mixing bubbly/mist transition
4660	Slug	High mixing bubbly/mist transition
4664	Annular mist	Churn
4665	Annular mist/Slug Transition	Annular
4666	Annular mist/Slug Transition	Churn
4674	Slug/Annular mist Transition	Froth
4682	Slug	Froth
4683	Slug	Froth/Bubbly Transition

5. CONCLUSIONS

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

Additional experiments are programmed in order to register pressure distribution, primary circuit flow, expansion tank temperature and level. These measures will contribute to the better understanding of the one and two-phase natural circulation phenomena.

Experimental measures of flow rate void fraction, pressure and level of the expansion tank will also be acquired to provide data to validate numerical simulations.

Although RELAP5 model was able to identify slug and annular mist flow regimes it was not able to identify all the regimes observed in the experiments. A more detailed nodalization, [13], will be developed in order to supply this gap.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support for this work by the University of São Paulo.

REFERENCES

1. M.E. Braaten and W. Shyy, “*Study of Pressure Correction Methods with Multigrid for Viscous Flow Calculations in Nonorthogonal Curvilinear Coordinates*”, Number Heat Transfer, vol. 11, pp. 417-442, (1987).
2. Y. Jaluria and K.E. Torrance, Computational Heat Transfer, Hemisphere, Washington, D.C., (1986).
3. Tema Especial de Termoidráulica do XI ENFIR – Grupo CTMSP, Poços de Caldas – MG, Brasil (1997).
4. G. Sabundjian, D. A. de Andrade, P. E. Umbehaun, W. M. Torres, A. Belchior Jr., A. J. A. de Castro, R. T. V. da Rocha, O. L. A. Damy, “*Simulação e Análise do Fenômeno de Circulação Natural Monofásica e Bifásica no Circuito Experimental Instalado na Engenharia Química POLI – USP, com o Código RELAP5*”, INAC2005, Santos (2005).
5. G. Sabundjian, D. A. de Andrade, P. E. Umbehaun, W. M. Torres, A. Belchior Jr., A. J. A. de Castro, R. T. V. da Rocha, O. L. A. Damy, E. Torres, “*Análise Experimental do Fenômeno de Circulação Natural*”, ENCIT 2006, Curitiba (2006).
6. G. Sabundjian, D. A. de Andrade, P. E. Umbehaun, W. M. Torres, A. J. A. de Castro, T. N. Conti, P. H. F. Masotti, R. N. de Mesquita, P. A. Paladino, F. A. Braz Filho, E. M. Borges, A. Belchior Jr., R. T. V. da Rocha e O. L. A. Damy, “*Análise Teórico e Experimental do Fenômeno de Circulação Natural*”, EBCEM2008, Florianópolis (2008).
7. A. Kaliatka, E. Uspuras, M. Vaisnoras and G. Krivoshein, “*Analysis of decay heat removal from RBMK-1500 reactor in decommissioning phases by natural circulation of water and air.*” Nuclear Engineering and Design 240 - 1242-1250 (2010).
8. H. Omar, N. Ghazi, F. Alhabit and A. Hainoum, “*Thermal Hydraulic analysis of Syrian MNSR research reactor using RELAP5/Mod3.2 code.*” Annals of nuclear Energy 37 - 572-581 (2010).
9. M. Azzoune, L. Mammou, M. H. Boulheouchat, T. Zidi, M. Y. Mokeddem, S. Belaid, A. Bousbia Salah, B. Meftah and A. Boumedien, “*NUR research reactor safety analysis study for long time natural convection (NC) operation mode.*” Nuclear Engineering and Design 240 - 823-831(2010).
10. LabView 7.0 Express, National Laboratory, USA (2003).
11. RELAP5/MOD3.2.2Gamma, NUREG/CR-5535, IDAHO LAB. SCIENTECH Inc., Idaho (1999).
12. E. M. Borges, F. A. Braz Filho, G. Sabundjian, “*Familiarização do programa computacional RELAP5*”. Relatório Técnico da Divisão de Energia Nuclear, IEAv, CTA, (2006).
13. S.P. Lakshmanan, M. Pamdey, P. P. Kumar, K. N. Iyer, “*Study of startup transients and power ramping of natural circulation boiling systems*”. Nuclear Engineering and Design 239, 1076-1083, (2009).