2009 International Nuclear Atlantic Conference - INAC 2009
Rio de Janeiro,RJ, Brazil, September27 to October 2, 2009
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: 978-85-99141-03-8

THERMAL HYDRAULIC PHENOMENOLOGY FOR THE HEATING PROCESS IN A NATURAL CIRCULATION FACILITY

Walmir M. Torres, Luiz A. Macedo, Roberto N. Mesquita, Paulo Henrique F. Masotti, Rosani Maria P. Libardi, Gaianê Sabundjian, Delvonei A. Andrade, Pedro Ernesto Umbehaun, Thadeu N. Conti, Mauro F. S. Filho, Gabriel R. Melo

Instituto de Pesquisas Energéticas e Nucleares IPEN/CNEN-SP
Centro de Engenharia Nuclear
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
wmtorres@ipen.br

ABSTRACT

This work describes thermal hydraulic phenomenology observed for the heating process in a natural circulation facility. Glass made circuit allows observations of the thermal hydraulic processes over several regions. Natural convection, natural circulation, nucleated sub-cooled, saturated boiling and some flow patterns such as, bubbly, slug and churn flow are observed and described. Facility heated and cooled parts are responsible for the natural circulation when in operation. An expansion tank accommodates the fluid density variations due to the temperature changes and void fraction. Instrumentation consists of thermocouples distributed along the circuit. Two differential pressure transducers are used for pressure and level measurements. Instrumentation signals and images are simultaneously acquired to help with phenomenon description. A CCD digital camera at a 250μs shutter speed is used for the images acquisition. Phenomenology described is based on a test under 1.1×10^5 W/m^2 of heat flux which corresponds to an electrical heater power of 7000 W and 0.0236 kg/s (85 l/h) of cooling flow rate.

1. INTRODUCTION

Heat transfer and fluid flow in single and two phases have been studied during decades in order to understand involved phenomenology, to improve the mathematical models used in systems and equipment design, and in accident analysis codes validation. RELAP5 is a well-known accident analysis code in the nuclear area and uses some of these models for its calculations. Computational Fluid Dynamic (CFD) codes also use these models. Special highlight have been given to heat transfer and fluid flow under natural convection and natural circulation conditions. Several thermal equipment and systems in the industry including nuclear applications, use these study results and models in their projects. Residual Heat Removal system and Emergency Core Cooling system are some examples.

2. EXPERIMENTAL FACILITY

Natural Circulation Facility in Nuclear Engineering Center at IPEN is an experimental circuit constructed to provide thermal hydraulic data and information about phenomenology involved under single and two phase natural circulation conditions [1]. Figures 1 and 2 show a schematic draw and a photo of this facility. It is a rectangular assembly (2600 mm height and 850 mm wide) made of borosilicate glass tubes temperature resistant of 38.1 mm internal diameter and 4.42 mm thickness. It has a heated section, also in glass tube of 76.2 mm internal diameter and 880 mm length, with two stainless steel cladding Ni-Cr alloy electric heaters in U form, connected in parallel and in series with an electric power supply. Heaters H1 and H2 are fed with 220VAC nominal voltage. H1 operates always at maximum power after turned on and has no adjustment and the electric power in the heater H2 is adjusted by a variac in the range of 0 to 100% supply level. Electric voltages applied to the heaters are periodically measured during the tests using a digital multimeter. Heaters external diameter is 8.5 mm and the U total length is 1200 mm. The cooled section consists of a heat exchanger/condenser, also in glass, with two internal spiral coils where secondary cooling water flows. Tap water is pumped from a 2 m^3 reservoir to the heat exchanger/condenser with the desired secondary cooling flow rate and is measured by two rotameters. Circuit has an expansion tank opened to atmosphere in order to accommodate fluid density changes due to the temperature and void fraction changes. This tank is connected to the circuit through a flexible tube at its lower region in order to prevent steam entrance. Approximately twelve liters of demineralized water are used to fill the circuit. Fifteen 1.5 mm K type (Chromel-Alumel) ungrounded thermocouples are distributed along the circuit to measure fluid and ambient temperatures. TEFLON sleeves were made to install these thermocouples between the glass tubes. Metallic connections with “O-rings” are also used to install the thermocouples along the circuit. Three K type thermocouples with exposed junction are attached on the wall of glass tube for measurements at the hot leg of the circuit. Two Validyne type differential pressure transducers P1 and P2 are used to measure relative pressure at the outlet of heaters and the water level in expansion tank. All instruments were calibrated in laboratory. Electric signals from instruments are sent to a Data Acquisition System assembled with SCXI series equipment from National Instruments. The photos presented in this work were acquired using a CCD digital camera at 250μs (1/4000 s) shutter speed. The same digital camera was used to produce a digital video (1/60 s) of the fluid flow and heat transfer phenomenology and other interesting phenomena at the upper part of the heaters.

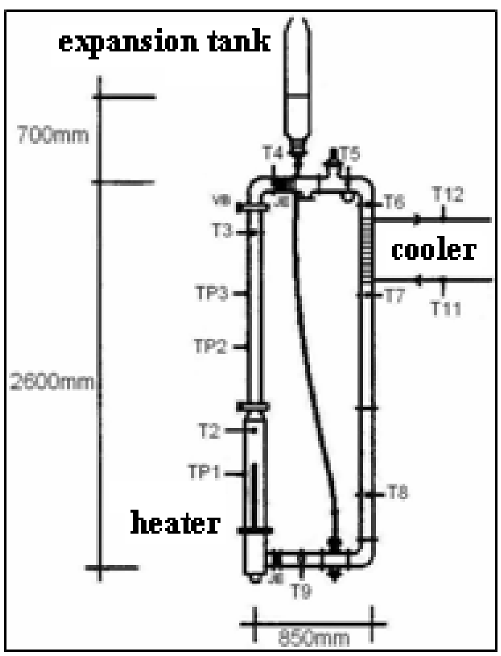


Figure 1. Schematic draw of the natural circulation facility.

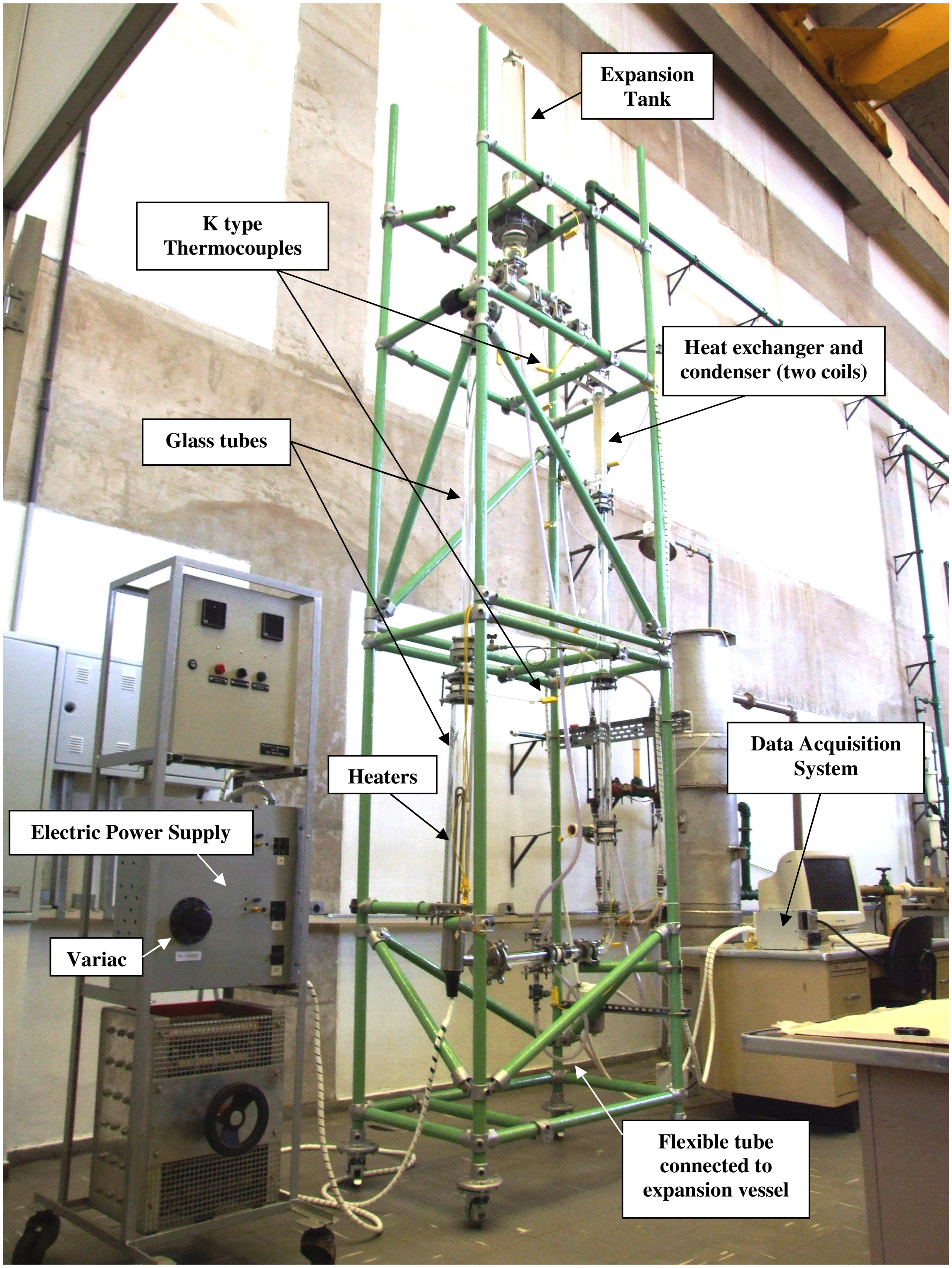


Figure 2. Natural circulation facility.

3. TEST CONDITIONS

Heating and cooling test conditions were chosen in order to obtain several heat transfer conditions and fluid flow patterns in single and two-phase along the circuit. Phenomenology described in this work is based on a heat flux of 1.1 x 10^5 W/m^2 (11 W/cm^2) on electrical heaters, corresponding to approximately 7000 W total electric power. Heaters H1 and H2 were set at respectively 100% and 85% power level. The secondary cooling flow rate was set 0.0236 kg/s (85 liters/hour).

3.1 Heat transfer in single-phase flow

Initially, the Data Acquisition System was turned on and its parameters were chosen before to start the data recording process. After that, the pump was turned on and the secondary cooling flow rate is set at the heat exchanger/condenser for the desired value and measured by rotameters. Pump and rotameters are not shown in the Fig. 1 and 2. This procedure avoids potential lack of cooling and possible occurrence of thermal shock in the circuit. Thermal hydraulic phenomenology observed is described as follow.

Immediately after the electric power is turned on with 7000 W at the heaters (1.1x10^5 W/m^2), convection lines are observed near the heaters in the initially stagnant liquid. Hot fluid flows up at the central region of the tube and cold fluid flows down near the tube wall. This is a characteristic behavior of natural convection phenomenon in **pool boiling processes** [2].

After a few seconds the fluid near the heaters wall become superheated and small bubbles are produced at nucleation sites along the heaters wall. Produced bubbles are condensed almost immediately by cold fluid in a process known as **subcooled pool boiling** [2]**.** The fluid bulk temperature is below saturation condition while the fluid temperature near the heaters wall is in saturation condition (see Fig 4a).

Mechanical deformations were observed on the heaters due to difference of temperatures between heaters and fluid (see Fig 4a). Mechanical vibrations of large amplitude are also observed at the heaters [2, 5 and 8]. Sub-cooled boiling process is responsible for these vibrations. The bubbles condensing and formation process on the heaters produces pressure pulses in the fluid which on its turn induce vibrations on the heaters. Differential pressure transducer P1 at outlet of heated region measures these pressure pulses which propagate along the circuit (see Fig.3).

Fluid temperature increase at the heated region of the circuit and an unbalancing of hydrostatic forces between heated and cooled regions is responsible for starting an effective fluid flow around the circuit known as **natural circulation**. The cold fluid in the cold leg enters at heaters and decreases the temperatures in this region, according to Fig. 3. The boiling process goes on and **subcooled flow boiling** [1] in natural circulation is the dominant phenomenon (see Fig. 4b).

In the collapsing process, some bubbles blow-up and produce a large amount of micro bubbles which are carried by fluid flow. These micro bubbles do not collapse immediately in the sub-cooled fluid because they have small heat transfer area. They condensate when flow through the hot leg happens. This two-phase flow can be classified as bubbly flow with small void fraction.

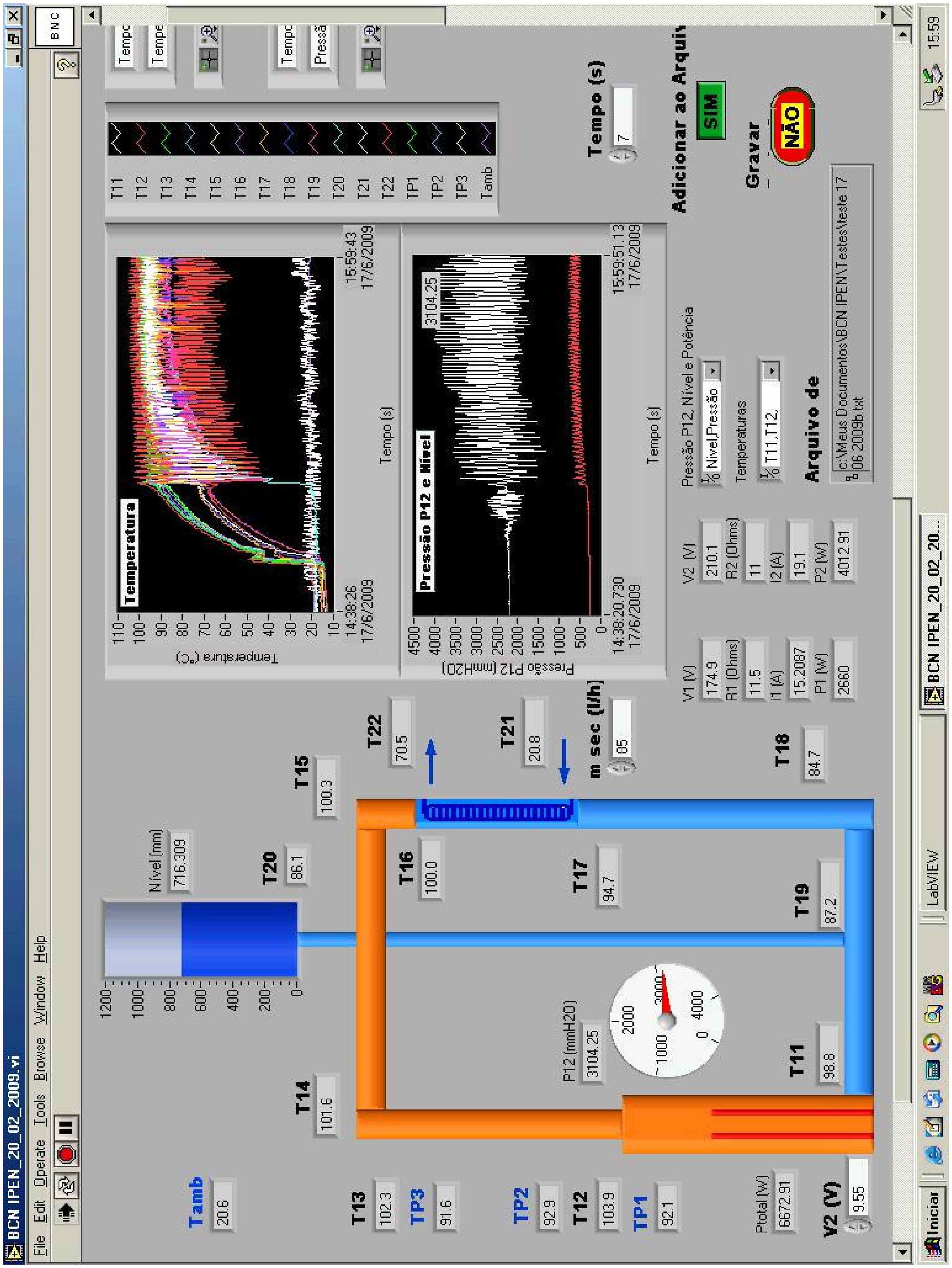
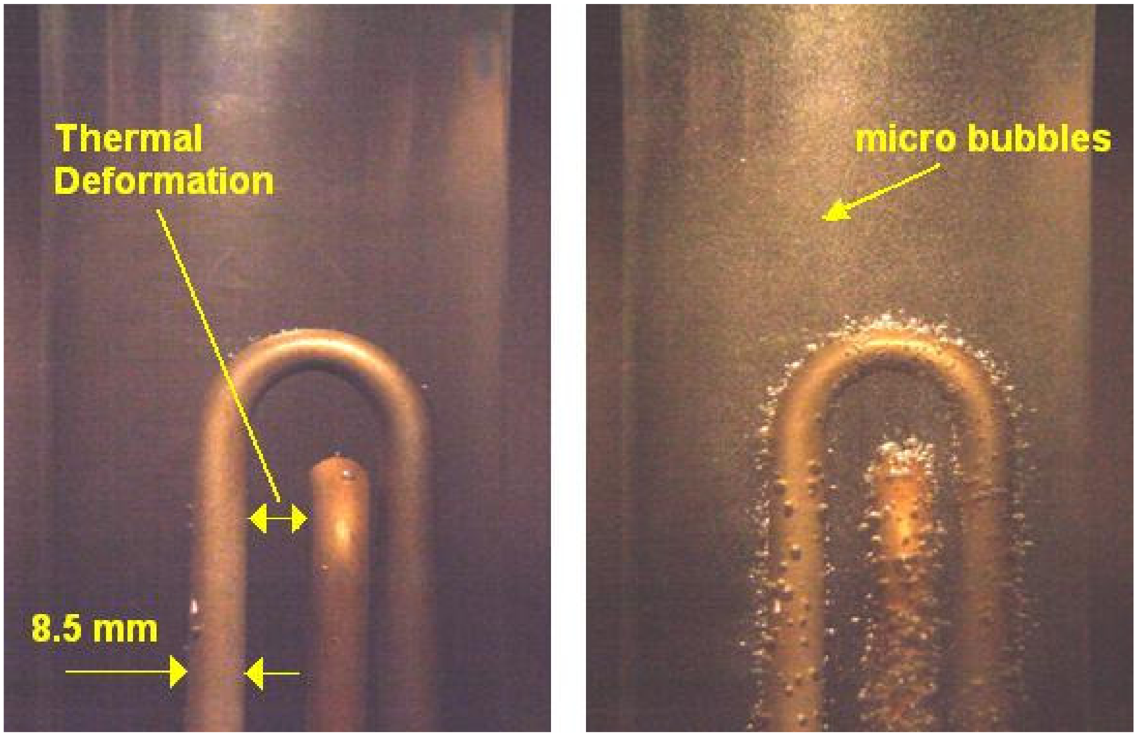


Figure 3. Data Acquisition System front panel – temperatures, pressure and level.



(a) **(b)**

Figure 4. Subcooled pool boiling (a) and Subcooled flow boiling (b)

3.2 Heat transfer in two-phase flow

Fluid temperature along the circuit increases and also the number of nucleation sites on heaters wall. Therefore, the bubble condensation and production rate also increases. There is an specific condition in this bubbles formation and collapse process where a resonance occurs and the tube seems to emit light. The difference between water and steam light refraction indexes is responsible by this phenomenon.

Steam production increases on heaters producing larger bubbles which flow along the hot leg. Some of these bubbles do not collapse and accumulate at horizontal upper region of the circuit. Consequently, the water level in the expansion tank increases.

Saturation temperature of the fluid is reached in the hot leg and this heat transfer process is known as **saturated flow boiling** [2], (Fig. 5). Several patterns are observed, such as: bubbly flow with large void fraction, slug flow and churn flow. Steam amount in horizontal upper region increases drastically from churn flow condition and decreases the flow along the circuit. This induces an increase in expansion tank water level with a higher rate. In a next phase an unbalance of forces occurs between hot and cold legs. Steam in the upper part is expelled to the heat exchanger/condenser, where it is partially condensed. Herewith, the water level in the expansion tank decreases. The fluid in the cold leg flows to the heaters region and decreases drastically the temperature in a short time period. The steam production goes on with the continuous electric power supply and a new thermal and two-phase flow cycle begins. This cyclic behavior of temperatures, pressure and water level has a defined frequency of 0.022 Hz (period = 46s) as shown in the Fig. 6 and 7.

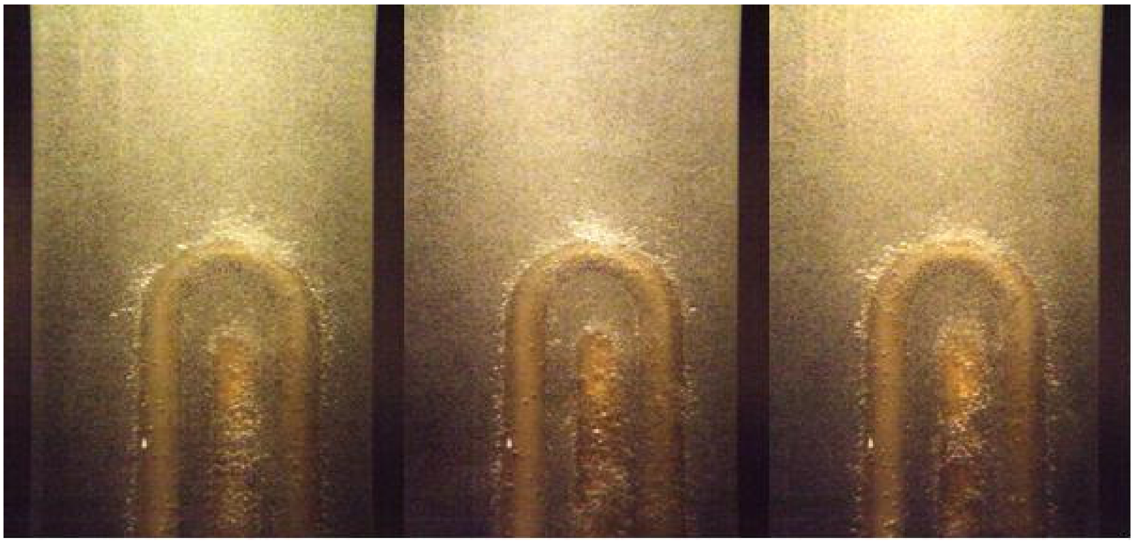


Figure 5. Saturated flow boiling images.

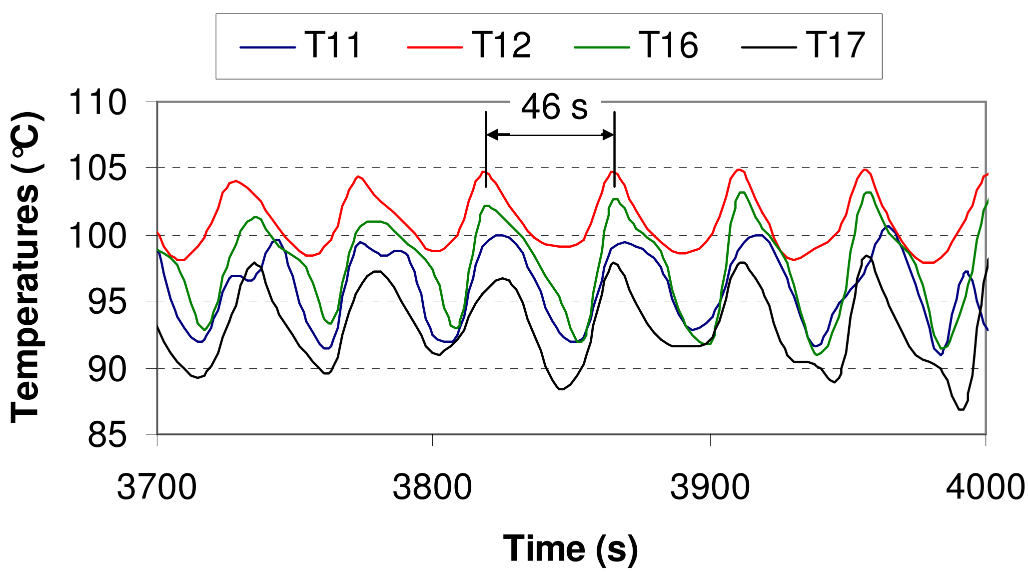


Figure 6. Temperatures behavior in steady state conditions.

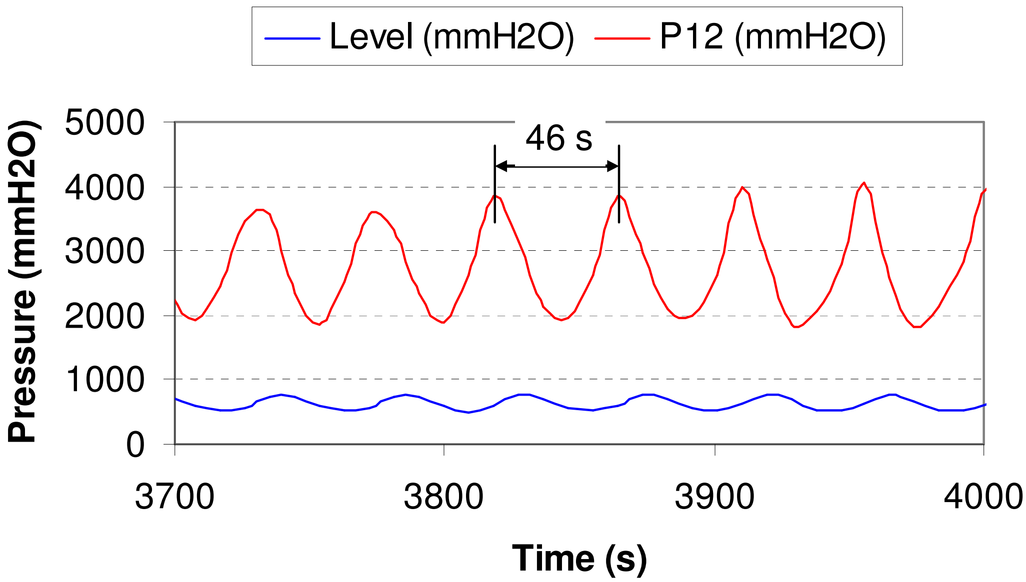


Figure 7. Pressure and water level behavior in the steady state conditions.

3.3 Two-phase flow patterns

Some two-phase flow patterns were observed along the circuit during the heating process, such as: bubbly flow with low and high void fractions, packed bubbles flow, slug flow and churn flow [2-7]. These two-phase flow patterns were photographed and are shown in Fig. 8.

4. CONCLUSIONS

Experimental Facility allows one and two phase natural circulation controlled experiments. It is constructed in glass and enables the visualization of thermal heat transfer and fluid flow phenomenology. Observed phenomena for the facility heating process is presented in this work in a resumed form. Experimental conditions were choosen in order to obtain two phase natural circulation flow. Several two phase patterns were observed and presented in this work. This Experimental Facility has been improved to also be used on different training in thermal hydraulic courses.

Other phenomena are also visualized such as: mechanical thermal deformation and induced mechanical vibrations at the heaters by subcooled and saturated boiling processes. These phenomena were recorded in photos and videos by a CCD digital camera.

As future works, sound and pressure signals analysis will be performed to correlate mechanical vibrations with sub cooled and saturated boiling processes. A WebLab will be developed for thermal hydraulic distance learning applications.

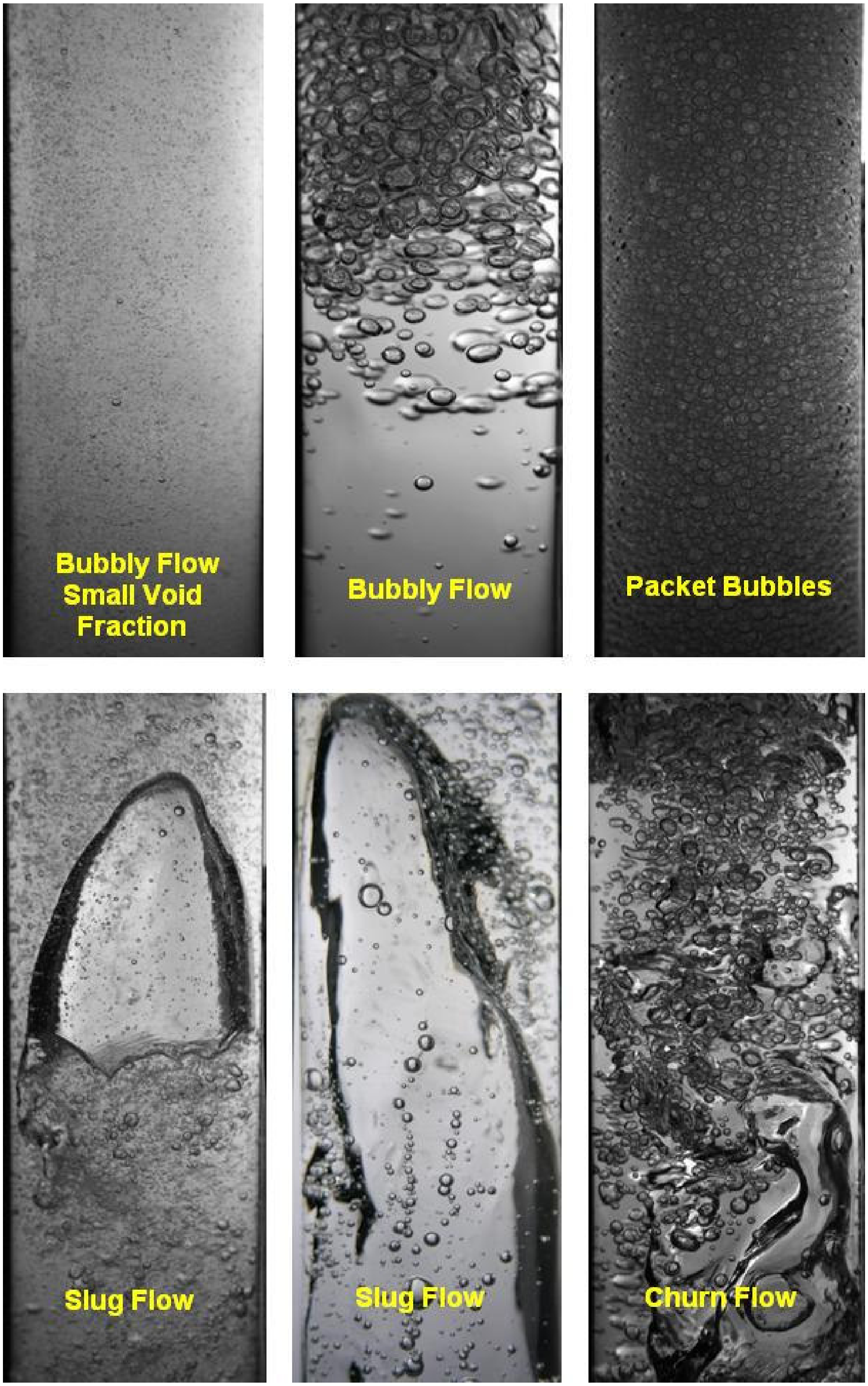


Figure 8. Two-phase flow patterns.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Departamento de Engenharia Química da Escola Politécnica da USP by lending the Experimental Facility and financial support by the Instituto de Pesquisas Energéticas e Nucleares – IPEN.

REFERENCES

1. G. Sabundjian, D. A. Andrade, P. E. Umbehaun, W. M. Torres, A. J. A. Castro, F. A. Braz Filho, E. M. Borges, A. Belchior Jr., R. T. V. Rocha, O. L. A. Damy, E. Torres, Relap5 Simulation for One and Two-Phase Natural Circulation Phenomenon*, Proceedings of International Nuclear Atlantic Conference – INAC 2007*, Santos, São Paulo, Brazil, September 30 to October 5, 2007.
2. L. S. Tong, *Boiling Heat Transfer and Two-Phase Flow*, John Wiley & Sons, INC., New York, USA (1965).
3. J. G. Collier, J. R. Thome, *Convective Boiling and Condensation*, Clarendon Press, Oxford, UK (1996).
4. G. B. Wallis, *One-Dimensional Two-Phase Flow,* McGraw Hill Book Company, New York, USA (1969).
5. A. E. Bergles, J. G. Collier, J. M. Delhaye, G. F. Hewitt, F. Mayinger, *Two-Phase Flow and Heat Transfer in the Power and Process Industries,* Hemisphere Publishing Corporation, Washington, USA (1981).
6. D. Butterworth, G. F. Hewitt, *Two-Phase Flow and Heat Transfer,* Oxford University Press, Oxford, UK (1977).
7. J. J. Ginoux, *Two-Phase Flows and Heat Transfer with Application to Nuclear Reactor Design Problems*, Hemisphere Publishing Corporation, Washington, USA (1978).
8. A. E. Bergles, S. Ishigai, *Two-Phase Flow Dynamics*, Hemisphere Publishing Corporation, Washington, USA (1981).