THERMAL HYDRAULIC PHENOMENOLOGY IN A NATURAL CIRCULATION CIRCUIT

Walmir M. Torres (*), Luiz A. Macedo, Roberto N. Mesquita, Paulo Henrique F. Masotti, Gaianê Sabundjian, Delvonei A. Andrade, Pedro Ernesto Umbehaun

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 and presents the thermal hydraulic phenomenology observed during a heating process in the Experimental Natural Circulation Circuit (ENCC). This circuit, basically all glass made, permits the visualization of the processes over all its regions. The instrumentation of the experimental circuit consists of thermocouples and differential pressure transducers for relative pressure and level measurements. A data acquisition system was used to record the temperature and pressure data, and a digital camera was used to capture photos and video images presented in this work. It was observed, during the test, natural convection, natural circulation, pool boiling, nucleated sub-cooled and saturated flow boiling, and some two-phase flow patterns such as, bubbly, slug, and churn flow which are presented in this paper. It was also observed mechanical vibrations of the electrical heaters induced by steam bubbles production and collapsing in the boiling process, and heaters thermal deformations. This experimental circuit is easy to operate and to modify for further instruments, and permits the development of several works in boiling and condensation field.

INTRODUCTION

Heat transfer and fluid flow in single and two-phase have been studied during decades in order to understand the involved phenomenology, and to improve the mathematical models used for systems and equipment design, and also 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 models in their projects. Residual Heat Removal system and Emergency Core Cooling system are some examples.

EXPERIMENTAL NATURAL CIRCULATION CIRCUIT (ENCC)

The Experimental Natural Circulation Circuit (ENCC), in Nuclear Engineering Center at IPEN [1], was constructed to provide thermal hydraulic data and information about the phenomenology that occurs in single and two-phase natural circulation conditions. Figures 1 and 2 show a schematic draw and a photo of this experimental circuit. It is a rectangular assembly (2600 mm height and 850 mm wide) made of temperature resistant borosilicate glass tubes 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 (H1 and H2) connected to a 220 VAC electrical power supply. H1 operates always at maximum power after turned on and has no adjustment on its power. The electric power in the heater H2 can be adjusted by an auto transformer (Variac) in the range of 0 to 100%. When both heaters operate at full power they provide nearly 8400W. The electrical voltages supplied to the heaters are periodically measured during the tests using a digital multimeter. Heaters have external diameter of 8.5 mm and the U total length of 1200 mm. The cooled section consists of a heat exchanger/condenser, also glass made, with two internal coils where secondary cooling water flows. Tap water is pumped from a 2 m^3 tank to the heat exchanger/condenser with the desired secondary cooling flow rate, which is measured by two rotameters. ENCC also has an expansion tank opened to the atmosphere in order to accommodate fluid density changes due to the temperature and void fraction changes. This tank is connected to the circuit by a flexible tube at its lower region in order to avoid steam entrance. Nearly twelve liters of demineralized water are used to fill the circuit. Thirdteen 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 temperature measurements at the hot part 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 the expansion tank. All these instruments were calibrated in laboratory and their electrical signals are sent to a Data Acquisition System assembled with SCXI series equipment from National Instruments and LabView 7.0 programming. The photos presented in this work were acquired by 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.

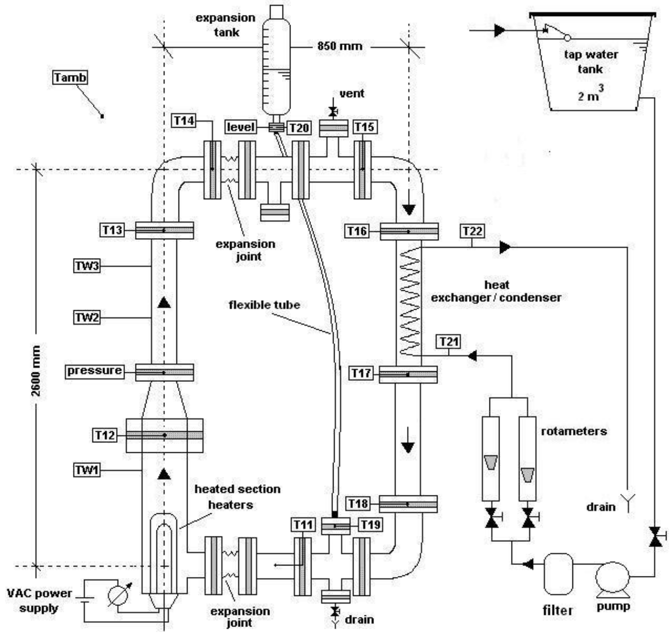


Figure 1. Experimental Natural Circulation Circut (ENCC).

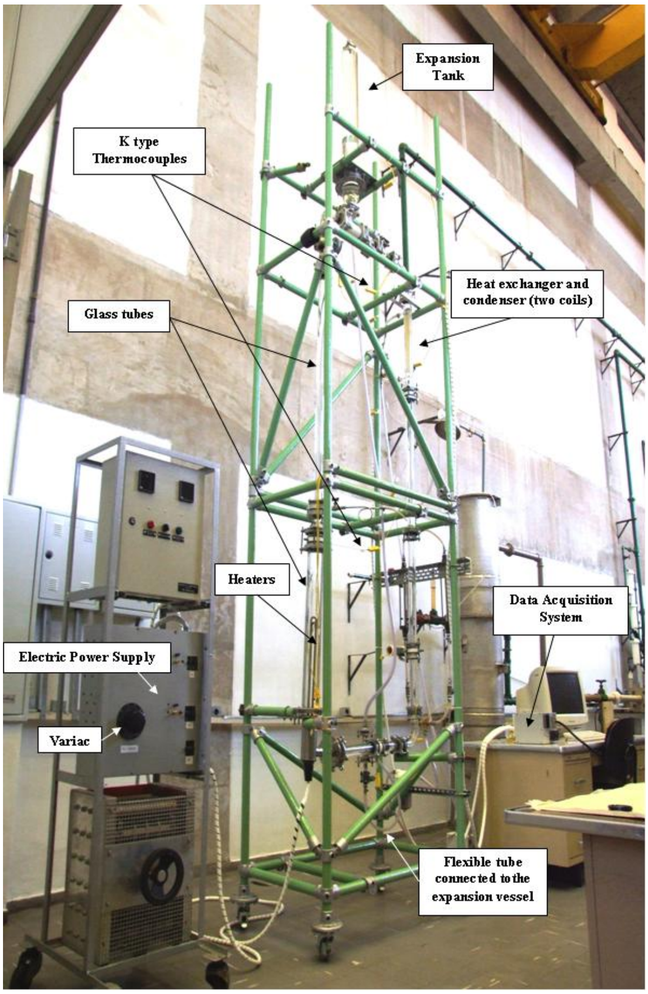


Figure 2. Experimental Natural Circulation Circut (ENCC).

TEST CONDITIONS AND OPERATION PROCEDURES

Based on previous experience, the heating and cooling test conditions were chosen in order to produce several heat transfer conditions and fluid flow patterns in single and two-phase along the circuit. The phenomenology described in this work refers to an average heat flux of 1.05 x 10^5 W/m^2 (10.5W/cm^2) on the electrical heaters, corresponding to approximately 6700W total electrical power. H1 and H2 were set respectively at 100% (4000W) and 65% (2700W). The secondary cooling flow rate was set 0.0236 kg/s (85 liters/hour).

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. This procedure avoids the potential lack of cooling in the heat exchanger/condenser and the occurrence of thermal shock in the circuit. Thermal hydraulic phenomenology observed is described as follow.

Heat transfer in single-phase flow

After the electrical power at the heaters is turned on with 6700W (1.1x10^5W/m^2), convection lines were 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 the **pool boiling processes** [2].

In a few seconds the fluid near the heaters walls became superheated and small bubbles were produced at nucleation sites. These bubbles were condensed almost instantaneously by adjacent cold fluid in a process known as **subcooled pool boiling** [2]**.** At this point, the fluid bulk temperature was below saturation condition while the fluid temperature near the heaters wall is in saturation condition. Also, at this time, there is no net flow rate around the circuit (see Fig 4a).

Temporary thermal-mechanical deformations were observed on the heaters due to the internal difference of temperatures between inside the heaters and the external cold fluid. (see Fig 4a). The heaters return to their original positions when they are turned off.

Mechanical vibrations of large amplitude were also observed at the heaters [2, 5 and 8]. Sub-cooled boiling process is responsible for these vibrations. The bubbles production and condensation processes on the heaters produce pressure pulses in the fluid which induce vibrations on the heaters when in their natural frequency.

The fluid temperature increases 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 that was in the cold leg of the circuit enters at the heaters region 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).

During the bubbles 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 will condensate while flowing up along the hot leg of the circuit. This two-phase flow can be classified as bubbly flow with very small void fraction.

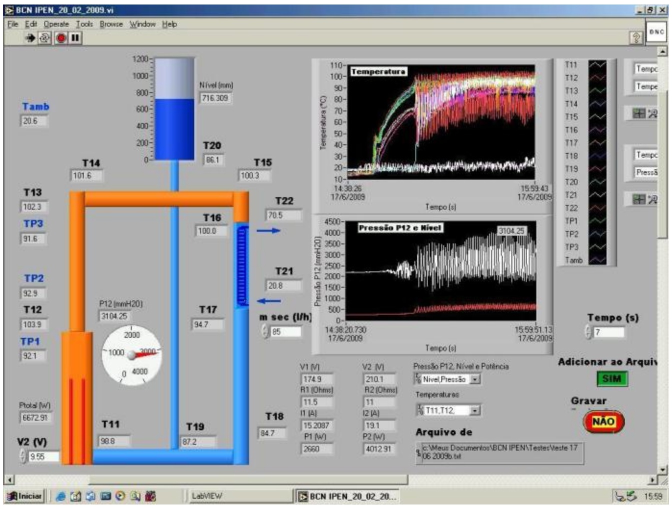
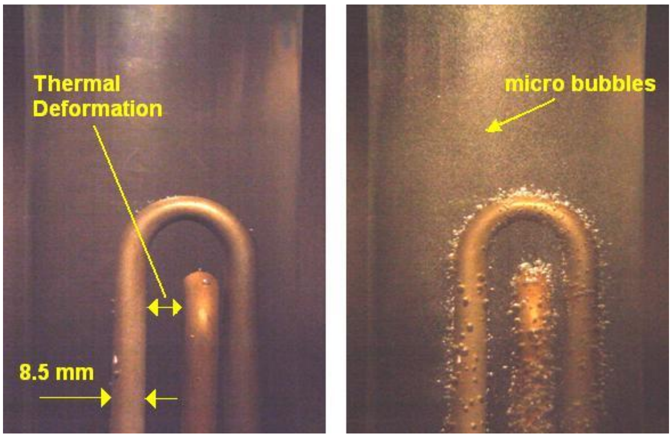


Figure 3. Temperature, pressure and level behavior. Data Acquisition System front panel.



(a) (b)

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

Heat transfer in two-phase flow

The fluid temperature along the circuit increases and also the number of nucleation sites on heaters walls. Therefore, the bubble production and condensation rates also increase. There is a specific condition in these bubbles production and condensation processes where a kind of 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 and larger bubbles are produced, which flow along the hot leg. Part 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 two-phase flow patterns are observed, such as: bubbly flow with large void fraction, slug flow and churn flow. The steam amount in horizontal upper region increases drastically from churn flow condition and the net flow rate along the circuit decreases. This induces an increase in the expansion tank water level. In a next phase an unbalance of forces occurs between hot and cold legs and then the steam in the upper part of the circuit is expelled to the heat exchanger/condenser, where it is partially condensed. Hence, the water level in the expansion tank decreases. The fluid that was 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 electrical power supply and a new thermal and two-phase flow cycle begins. This cyclic behavior of temperatures, pressure and water level has a well defined frequency of 0.022 Hz (period=46s) for these specific heating and cooling test conditions, as shown in the Fig. 6 and 7. Other heating and cooling conditions will also produce cyclic behavior in a different frequency.

Figure 5. Saturated flow boiling.

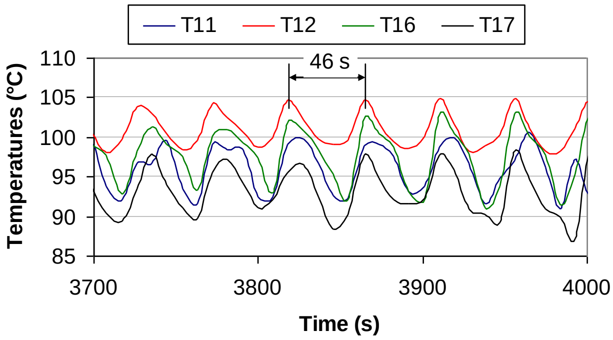


Figure 6. Cyclic temperatures behaviors in steady state two-phase flow condition

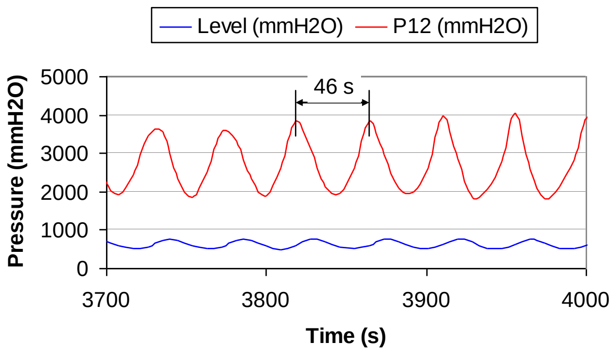


Figure 7. Cyclic pressure and water level behaviors in the steady state two-phase flow conditions.

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.

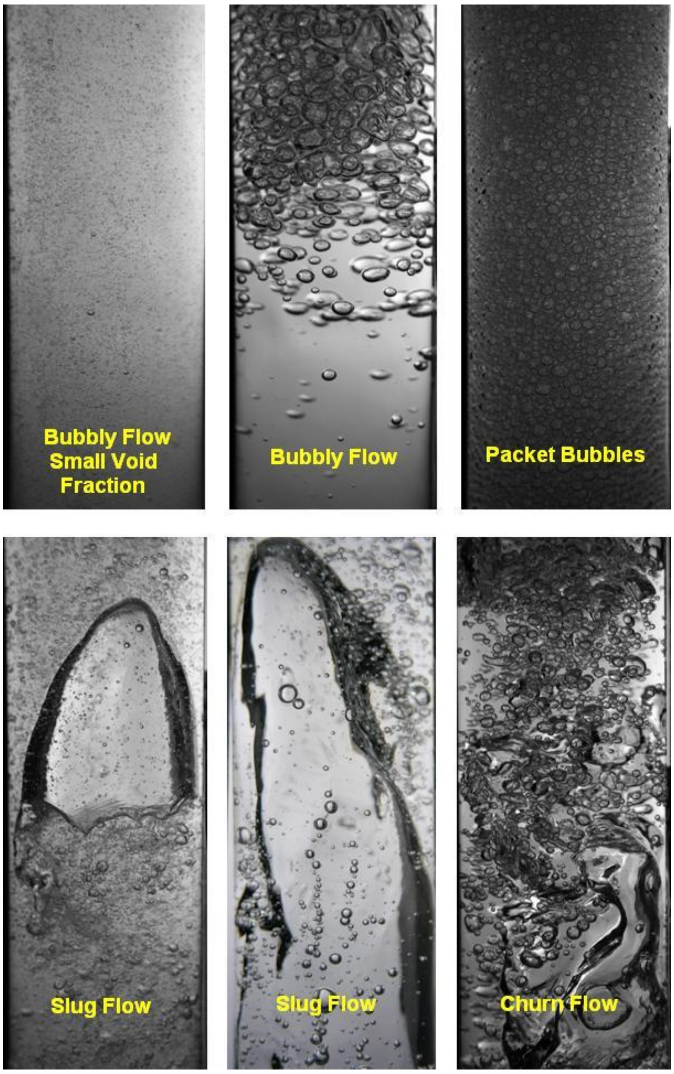


Figure 8. Two-phase flow patterns

CONCLUSIONS

ENCC allows to perform one and two phase natural circulation controlled tests. It is constructed in glass and enables the visualization of thermal heat transfer and fluid flow phenomenology. The phenomenology observed during a heating process is presented in this work in a resumed form. The test conditions were choosen in order to obtain two phase natural circulation flow. Several two phase patterns were observed and presented in this work. Also, this experimental circuit has been improved to be used as a tool in thermal hydraulic courses.

Other phenomena are also visualized such as: thermal-mechanical deformation of the heaters, and induced mechanical vibrations of 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 subcooled and saturated boiling processes. Accelerometrs can also be assembled to the experimental circuit in order to study mechanical vibrations. A WebLab will be developed for thermal hydraulic distance learning applications. Void fraction measurements using software of images analysis

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.

REFERÊNCIAS

[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 e J.G. Thome, Convective boiling amd Condensation, Oxford Science Press, New York, 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).

THERMAL HYDRAULIC PHENOMENOLOGY IN A NATURAL CIRCULATION CIRCUIT

Walmir M. Torres (*), Luiz A. Macedo, Roberto N. Mesquita, Paulo Henrique F. Masotti, Gaianê Sabundjian, Delvonei A. Andrade, Pedro Ernesto Umbehaun

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 and presents the thermal hydraulic phenomenology observed during a heating process in the Experimental Natural Circulation Circuit (ENCC). This circuit, basically all glass made, permits the visualization of the processes over all its regions. The instrumentation of the experimental circuit consists of thermocouples and differential pressure transducers for relative pressure and level measurements. A data acquisition system was used to record the temperature and pressure data, and a digital camera was used to capture photos and video images presented in this work. It was observed, during the test, natural convection, natural circulation, pool boiling, nucleated sub-cooled and saturated flow boiling, and some two-phase flow patterns such as, bubbly, slug, and churn flow which are presented in this paper. It was also observed mechanical vibrations of the electrical heaters induced by steam bubbles production and collapsing in the boiling process, and heaters thermal deformations. This experimental circuit is easy to operate and to modify for further instruments, and permits the development of several works in boiling and condensation field.