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FREQUENCY ANALYSIS FOR THE THERMAL HYDRAULIC CHARACTERIZATION OF A NATURAL CIRCULATION CIRCUIT

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ABSTRACT

This paper presents the Frequency Analysis studies of the pressure signals from an Experimental Natural Circulation Circuit during a heating process. The main objective is to identify the characteristic frequencies of this process using Fast Fourier Transform (FFT). Video images are used to associate these frequencies to the observed phenomenology in the circuit during the process. Sub-cooled and Saturated flow boiling, heaters vibrations, overall circuit vibrations, chugging and geysering were observed. Each phenomenon has its specific frequency associated. Some phenomena and their frequencies must be avoided or attenuated since they can cause damages to the natural circulation circuit and its components. Special operation procedures and devices can be developed to avoid these undesirable frequencies.

1. INTRODUCTION

Heat transfer and fluid flow in single and two-phase have been studied during decades in order to understand the involved phenomenology. The results of these studies improved the mathematical models used for systems and equipment designs and also in accident analysis codes validation in the nuclear area. 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 designs. Residual Heat Removal System and Emergency Core Cooling System are some examples. Due to the low head pumping provided by buoyance forces, systems operating with natural circulation are subjected to thermal-hydraulics-mechanical instabilities of different kind than systems operating in forced circulation. Many researchers have been studied these instabilities, their applications and consequences. In 1991, Wach [1] studied vibrations, noise and acoustic monitoring in German Light Water Reactors (LWR´s) using FFT and pattern recognition techniques. In 1995, Jiang et al. [2] studied the oscillations and instabilities during the start-up of a 5MW nuclear heating reactor. Geysering, flashing and low steam quality instabilities were described. In 2006, Villafuerte et al. [3] developed an online FFT monitoring system based on noise analysis for a BWR. An extensive review on flow instabilities in natural circulation boiling systems was presented in 2007 by Prasad et al. [4], where the thermal-hydraulic instabilities are classified in: static, dynamic and neutronic coupled. Oscillations in natural circulation systems were studied in 2009 by Lakshmanan and Pandey [5]. The frequency analyses of the mass flow rate time signals was performed using FFT for the Natural Circulation Test Facility (NCTF) and also with mass flow rate results from RELAP5 simulation related to a prototype of a Natural Circulation Boiling Water Reactor (NCBWR). This paper presents studies of Frequency Analysis for a heating process in an Experimental Natural Circulation Circuit (ENCC).

2. EXPERIMENTAL NATURAL CIRCULATION CIRCUIT (ENCC), DATA ACQUISITION SYSTEMS (DAS´s) AND IMAGE RESOURCES

The Experimental Natural Circulation Circuit (ENCC), in Nuclear Engineering Center at IPEN, was designed and constructed in glass to allow visualization, photographing and filming. It provides experimental data and information about the phenomenology occurring in single and two-phase flow natural circulation conditions [6].

ENCC is a rectangular assembly (2,600 mm height and 850 mm wide) made of borosilicate glass tubes of 38.1 mm internal diameter and 4.42 mm thickness. It has a heated section also made of glass tube of 76.2 mm internal diameter and 880 mm length. Inside of the heated section there are two U-form stainless steel cladding NiCr-alloy electric heaters (H1 and H2) fed by a 220 VAC electrical power supply. H1 has no adjustment on its electric power, while H2 can be adjusted by an auto transformer (Variac) in the range of 0 to 100% power. At the full power H1 and H2 provide nearly 8,400 W. Heaters have external diameter of 8.5 mm and the U total length of 1200 mm resulting in a total heat transfer area of 641 cm^2 and a maximum heat flux of 13.1 W/cm^2. The cooled section consists of a heat exchanger/condenser, also made of glass, with two internal coils where the cooling water flows. Tap water is pumped from a 2 m^3 tank to the heat exchanger/condenser with a desired cooling flow rate, which is controlled by valves and measured by two rotameters. There is also a vertical expansion tank opened to the atmosphere in order to support fluid density and void fraction changes due to the temperature. It has 108 mm internal diameter and near 800 mm height (7 liters capacity) and it 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 filling the circuit. Thirteen 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 and "O-rings" are used to install the thermocouples along the circuit. Three K type thermocouples with exposed junction are attached on the wall at the hot leg of the circuit for temperature measurements. Two Validyne differential pressure transducers P1 and P2 are used to measure relative pressure at the outlet of heated section and the water level in the expansion tank respectively. Figures 1 and 2 show a schematic draw and a photo of the experimental circuit.

All instruments were calibrated in laboratory and their electrical signals were sent to the ENCC Data Acquisition System (DAS-ENCC). DAS-ENCC was assembled with SCXI series components from National Instruments and LabVIEW 7.0 programming. It records the experimental data at each 12s or 0.083 Hz.

An additional Data Acquisition System (DAS–FFT), also using SCXI series components from National Instruments, was specially assembled for these Frequency Analysis studies in order to acquire the pressure signals from P1 at higher data rate acquisition 500 Hz (2ms).

The Frequency Analysis of these pressure signals were performed by MATLAB [7] with a FFT tool box and allows analysis of phenomena with frequencies up to 250 Hz.

The photos were acquired by a CCD digital camera at a shutter speed of 250μs (1/4000 s) and with a resolution of 3888 x 2592 pixels. Photos were taken above the heated section in a field of 100x100 mm. Another CCD digital camera was used to produce a digital video at a speed of 30 frames per second of the fluid flow and heat transfer phenomenology and other interesting phenomena at the upper part of the heaters. The photos of the phenomenology presented in this work were taken from digital video.

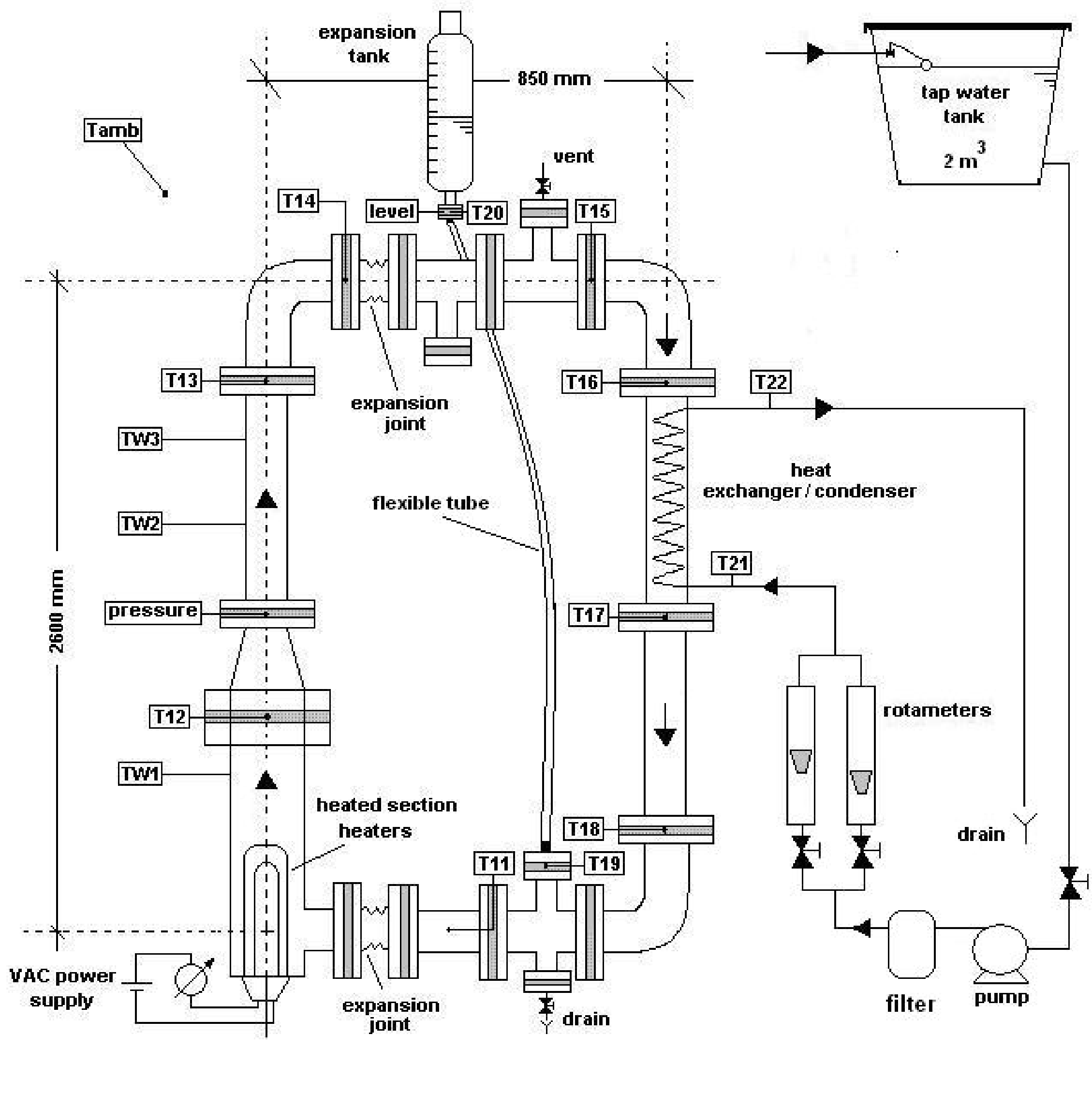

Figure 1. Experimental Natural Circulation Circuit (ENCC).

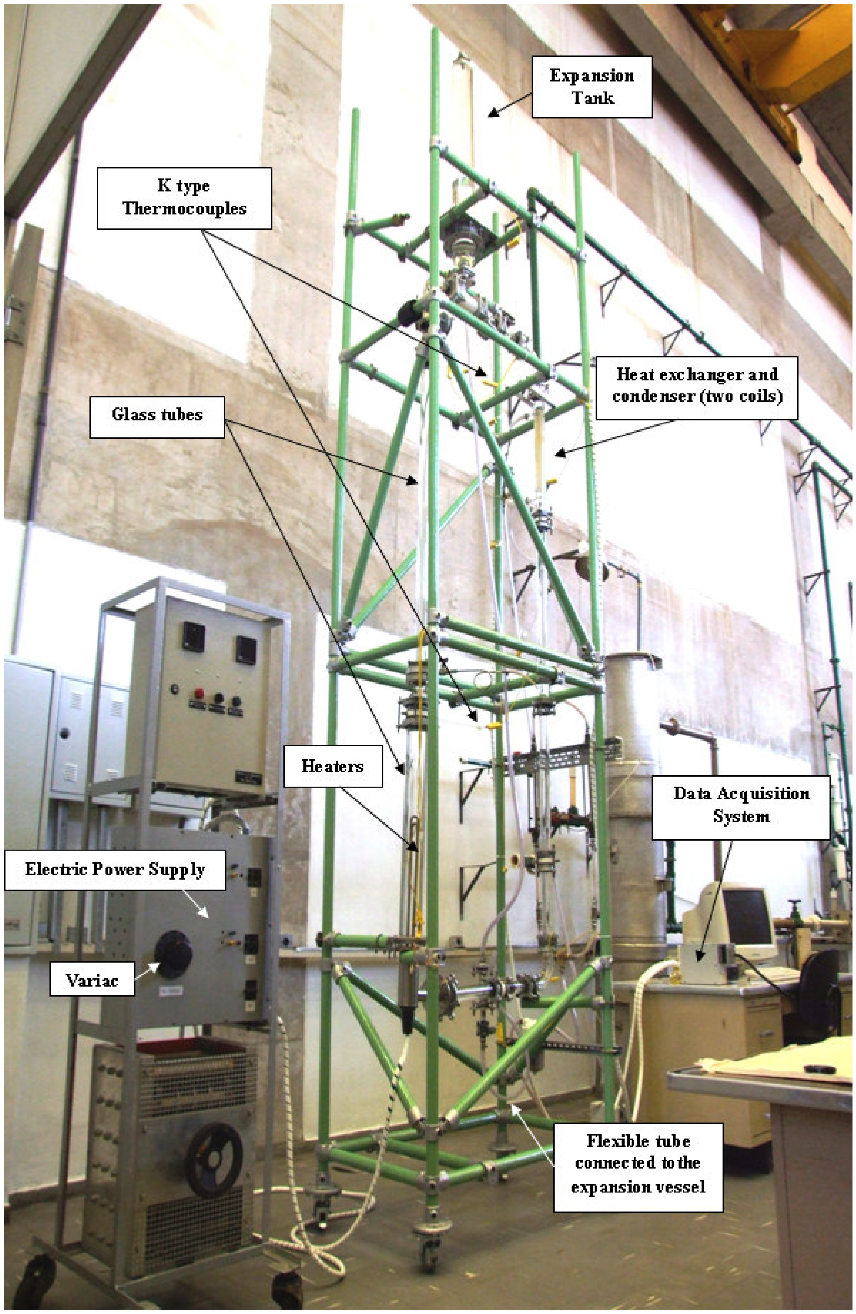

Figure 2. Experimental Natural Circulation Circuit (ENCC).

2.1. Experimental Test Conditions and Measurements

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 natural circulation along the circuit. The heating condition was set at 5,500 W, H1 100% (4,000 W) and H2 37.5% (1,500 W). The secondary cooling flow rate was set at 0.0278 kg/s (100 liters/hour). Figure 3 shows the inlet (T11) and outlet (T12) temperatures at heated section. Figure 4 shows the pressure at the outlet heated section (P1) and level at the expansion tank (P2). Results presented in the Fig. 3 and 4 were obtained with 12s sample rate by DAS-ENCC. Figure 5 shows P1 at a 2ms sample rate by DAS-FFT at each 130 s resulting in files with 65000 points. It was obtained 40 files with $2.6\text{x}10^6$ points. There are gaps of near 7 s in time between two adjacent measurements for reset the data acquisition system.

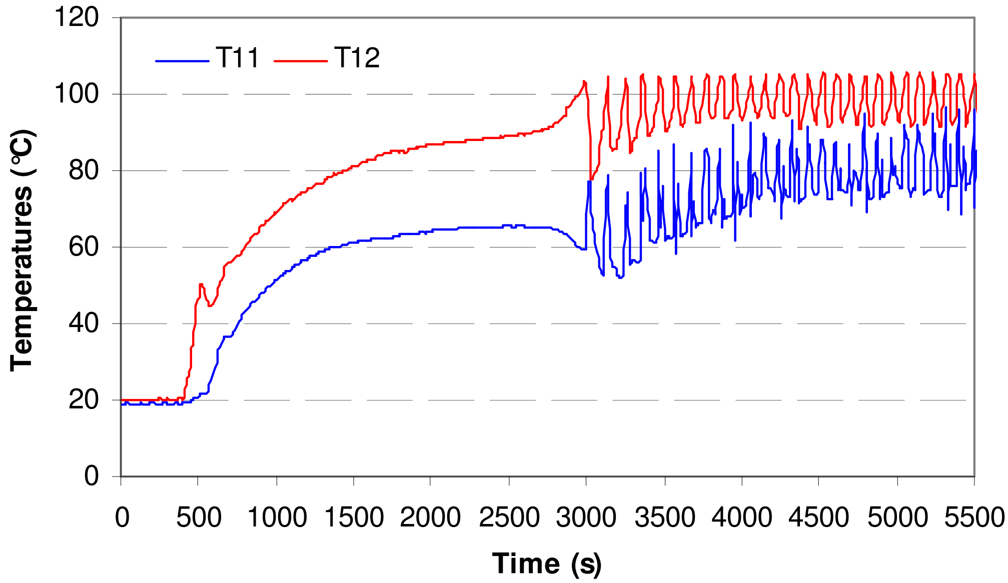

Figure 3. Temperatures T11 and T12 (12s sample rate – 0.083Hz).

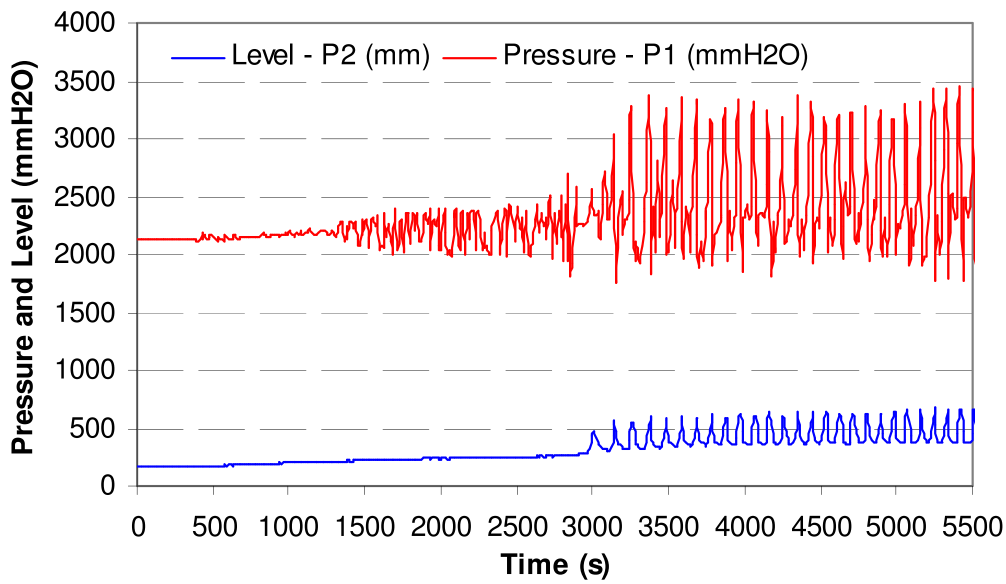

Figure 4. Pressure P1 and level P2 (12s sample rate – 0.083Hz).

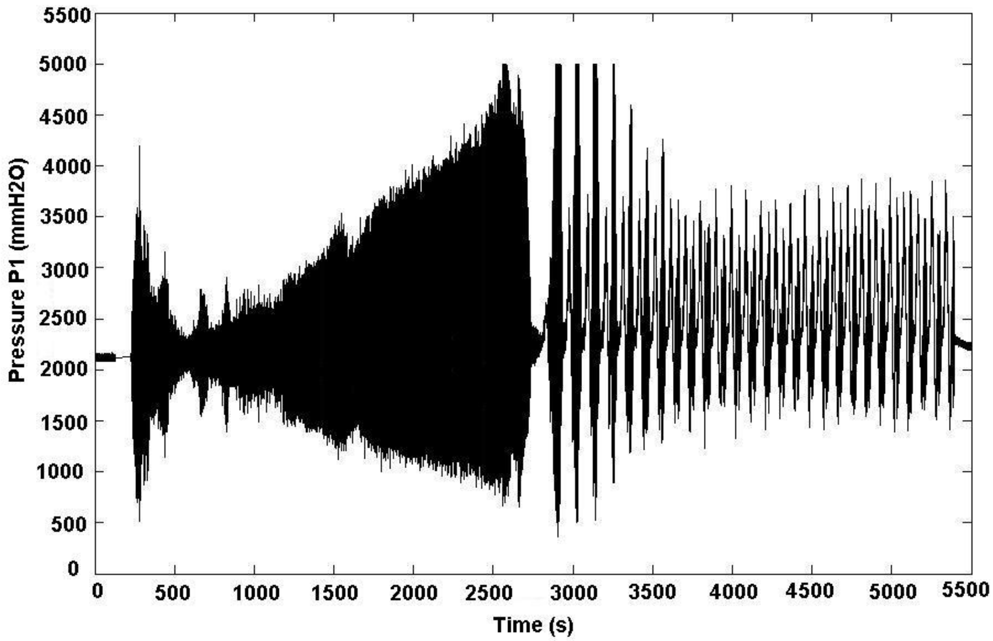

Figure 5. Pressure P1 (2ms sample rate – 500 Hz).

In order to perform the frequency analysis, the time signal pressure (see Fig. 5) was divided in five periods, according to Table 2. These periods were chosen for different flow regimes in the ENCC. The first period corresponds to the no power on electrical heaters and no cooling flow rate. The second and third periods are related to single-phase flow (sub-cooled flow) and the fourth corresponds to a transition between single and two-phase saturated flow. The fifth is associated to two-phase saturated flow.

Table 2. Periods of pressure signals P1 for frequency analysis

Period	1	2	3	4	5
Time (s)	0 - 130	320 - 740	850 - 2650	3050 - 3750	4050 - 5200

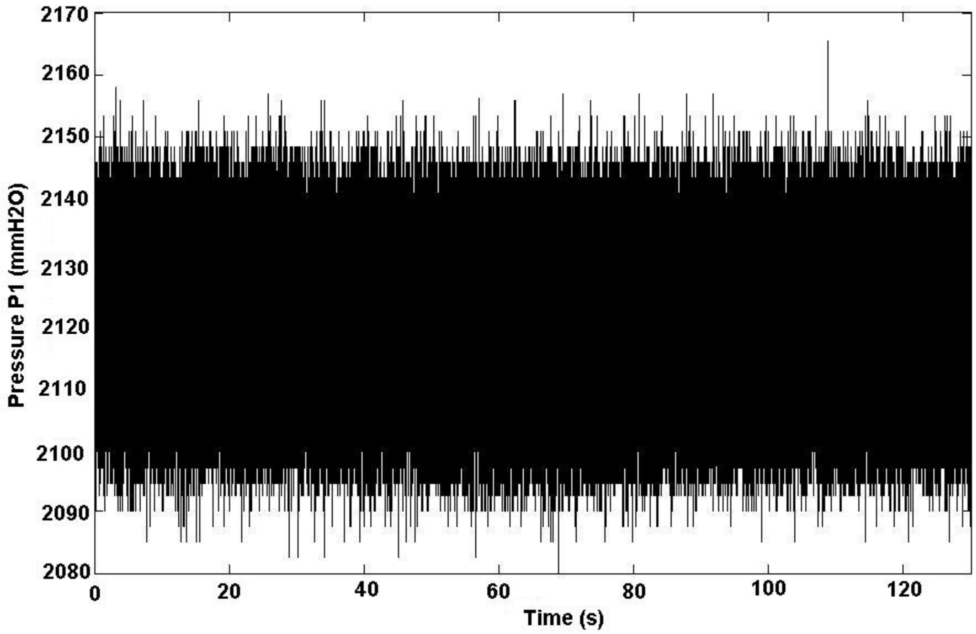

Figure 6. Pressure P1 (period 1).

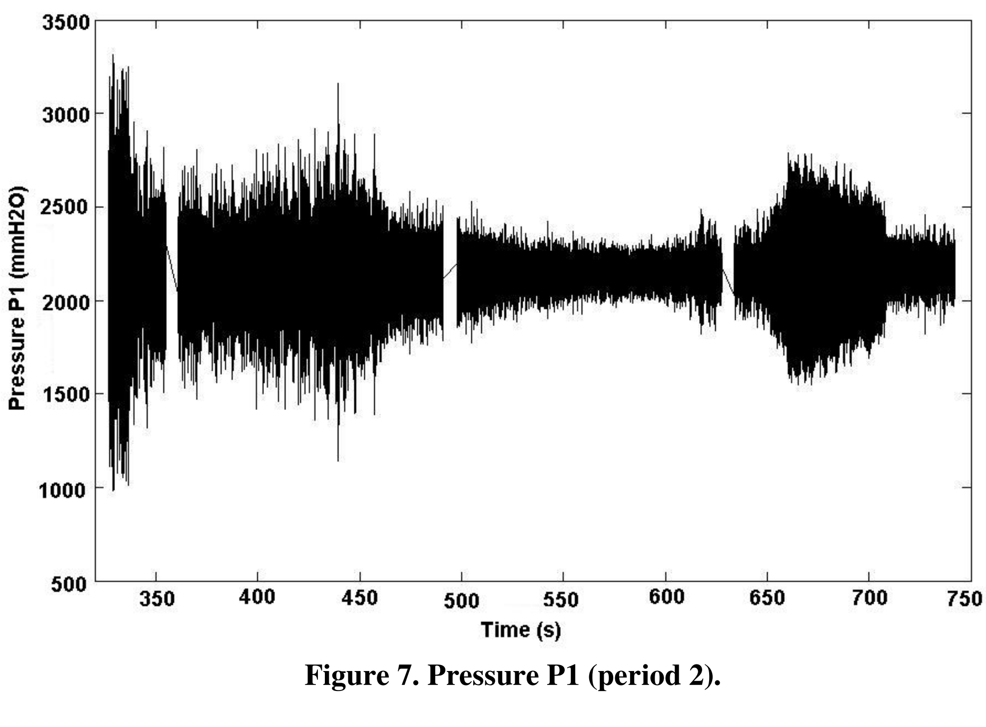

Figure 7. Pressure P1 (period 2).

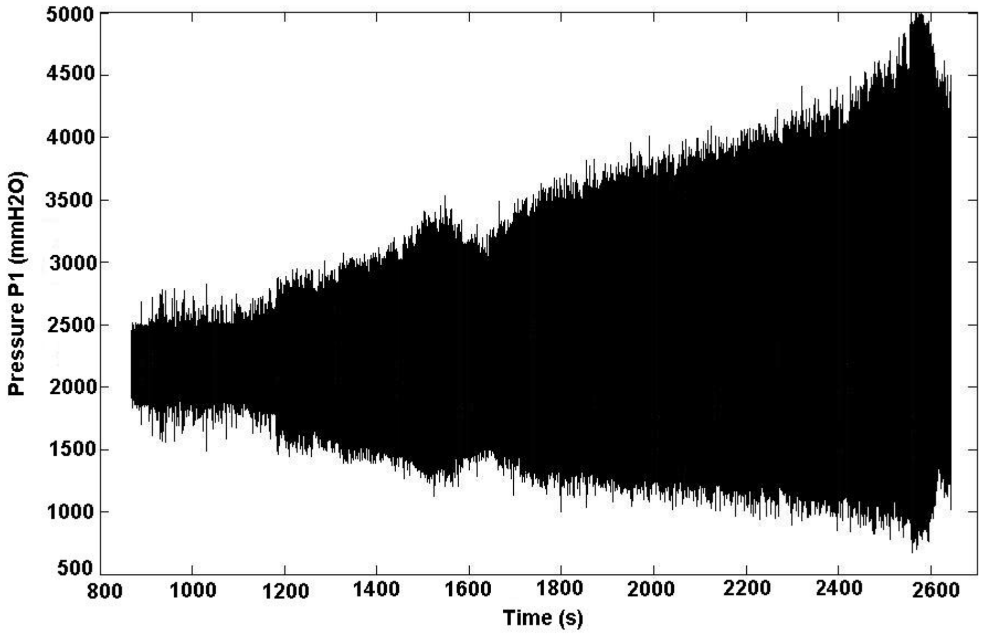

Figure 8. Pressure P1 (period 3).

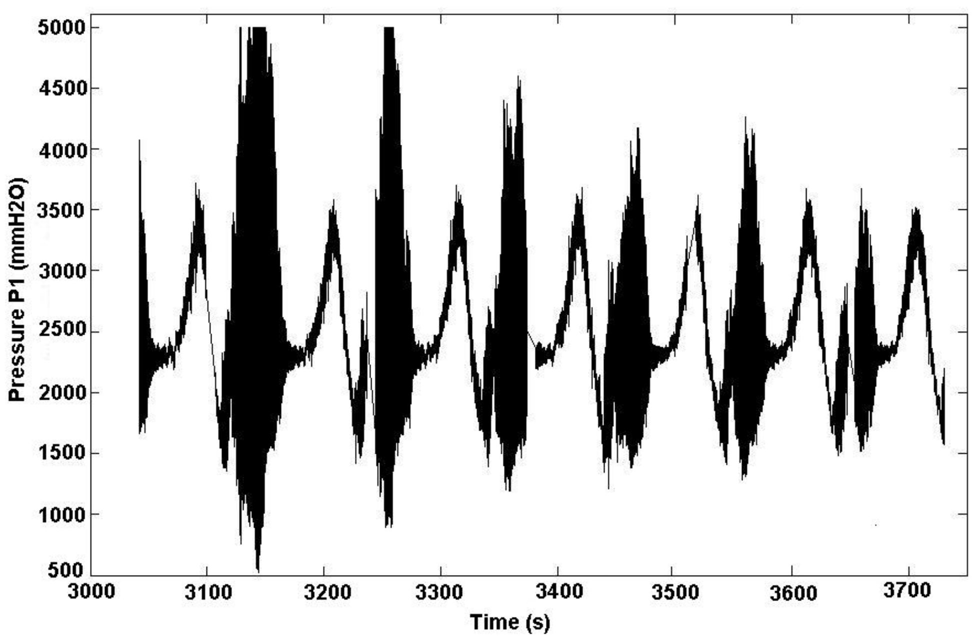

Figure 9. Pressure P1 (period 4).

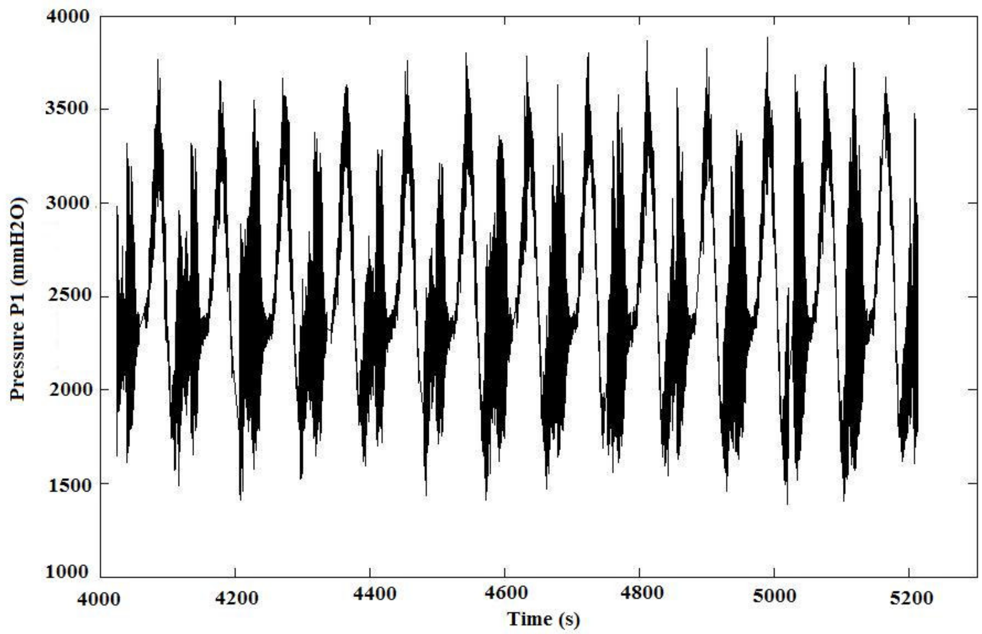

Figure 10. Pressure P1 (period 5).

2.2. Frequency Analysis

The frequency analyses were performed by MATLAB with a FFT tool box using the Hanning filter. The Power Spectrum Density (PSD) for the five periods is presented in the Figures 11-15. Figure 11 shows a peak frequency in 48 Hz corresponding to DAS-FFT data acquisition system since only it was working during this period. Figure 12 shows a peak frequency in 19 Hz and its harmonic frequencies in 38 Hz and 57 Hz, and also a peak frequency in 59 Hz. The phenomena responsible for theses frequencies were not identified and needs to be investigated. Heater vibrations were observed in the period 2. An investigation on video frames indicated a vibration frequency of 10 Hz (see Fig. 17). This frequency does not appear in PSD plot. Figure 13 shows a peak frequency in 15 Hz and its harmonics frequencies in 30 Hz and 45 Hz. This phenomenon was identified and corresponds to a process of production and condensation of bubbles on heating surface. Figure 16 shows a sequence of frames with their respective times through is possible to calculate the frequency of 15 Hz. Figures 14 and 15 show a peak frequency in 68 Hz. This frequency is associated to cooling pumping process and also appears in the Fig. 12 and 13. The phenomenon responsible for the peak frequency in 6 Hz showed in Fig 14 and 15 was not identified yet and need to be investigated. The oscillatory behavior showed in Fig. 9 and 10 have very low frequencies, near 10 mHz and do not appear in PSD plots. This behavior is due to geysering and chugging in the circuit.

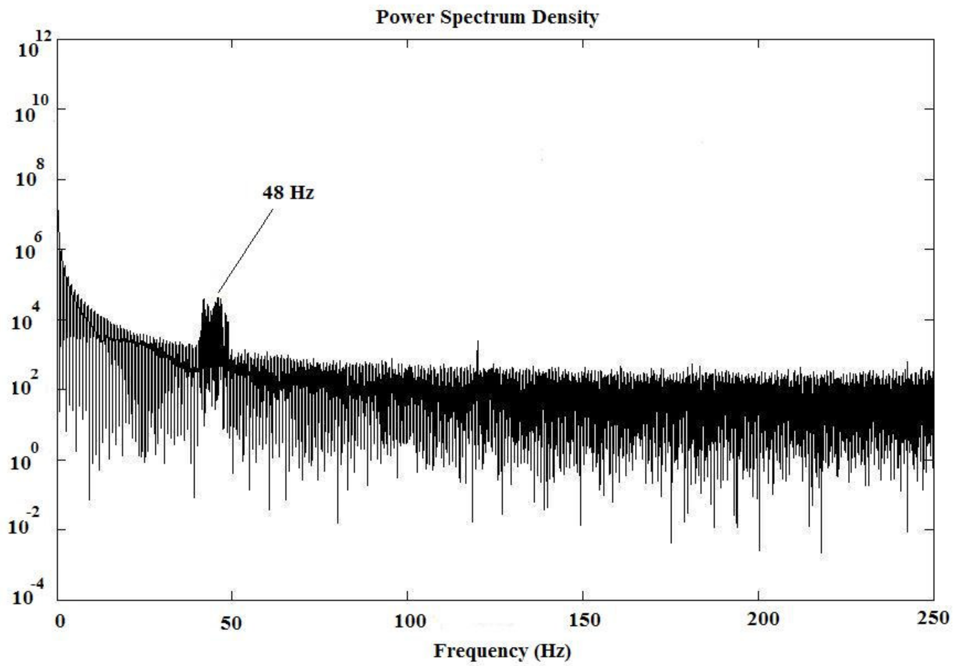

Figure 11. PSD for period 1.

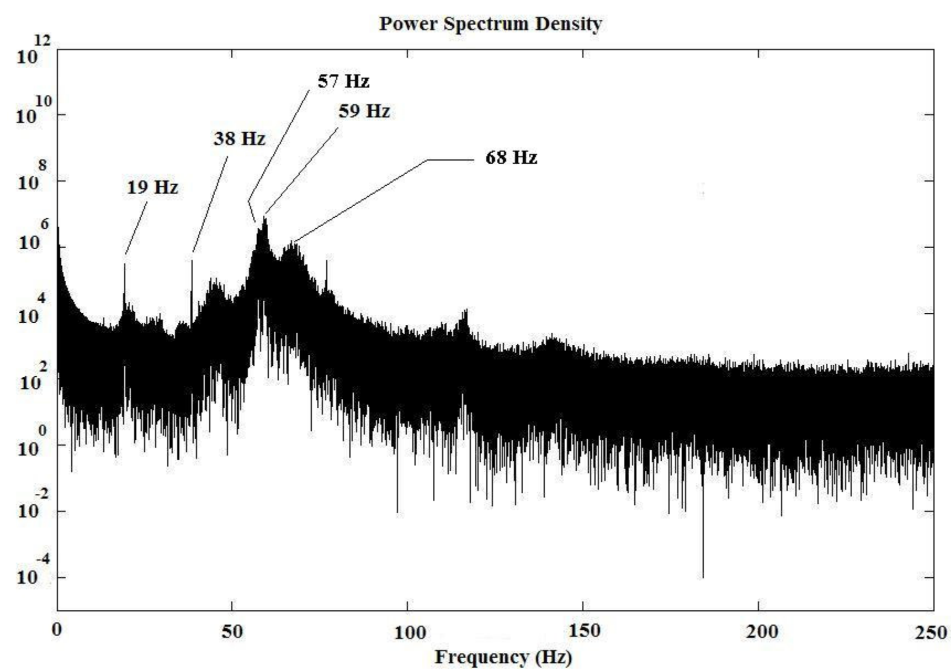

Figure 12. PSD for period 2.

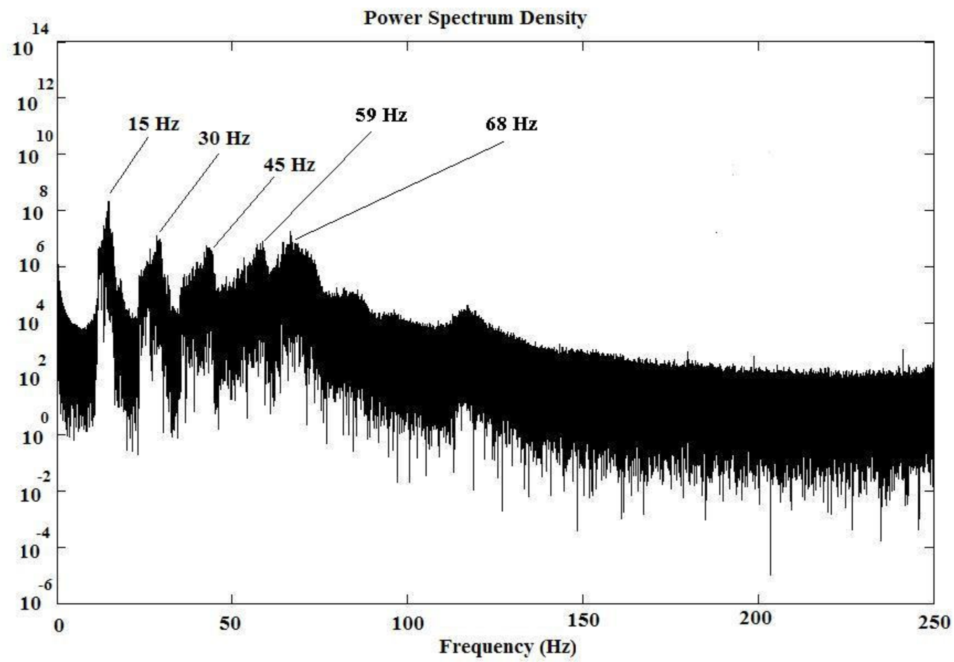

Figure 13. PSD for period 3.

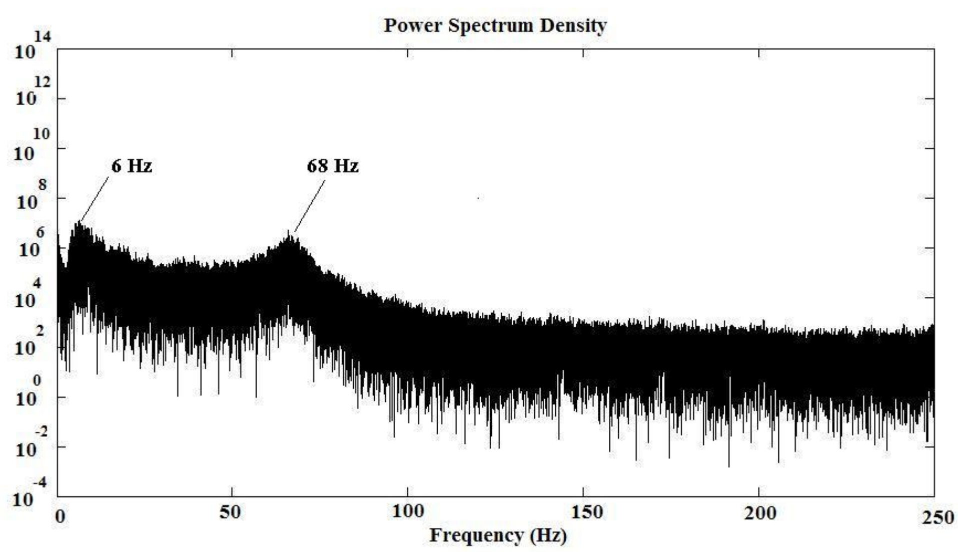

Figure 14. PSD for period 4.

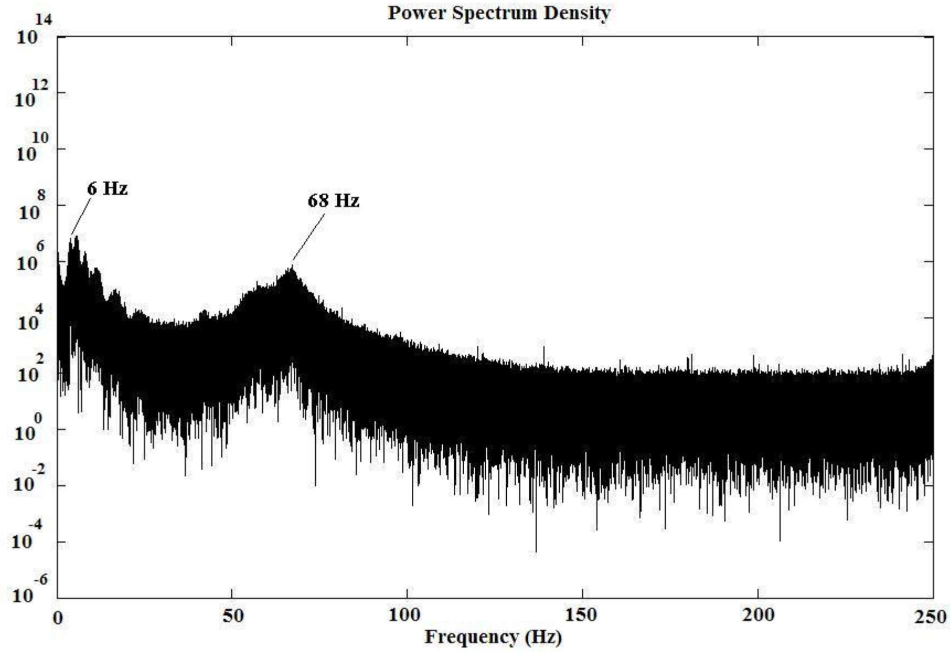

Figure 15. PSD for period 5.

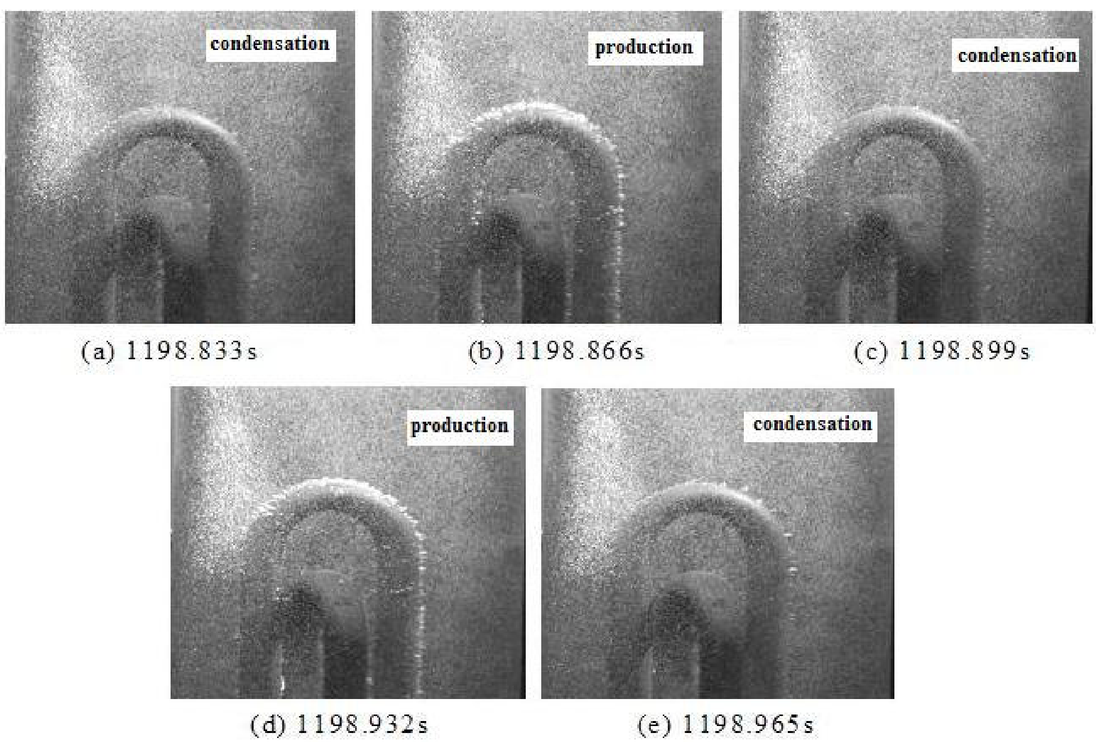

Figure 16. Sequence of frames with 2 cycles of Production and Condensation (15 Hz) cycle 1 (a, b and c) ; cycle 2 (c, d and e).

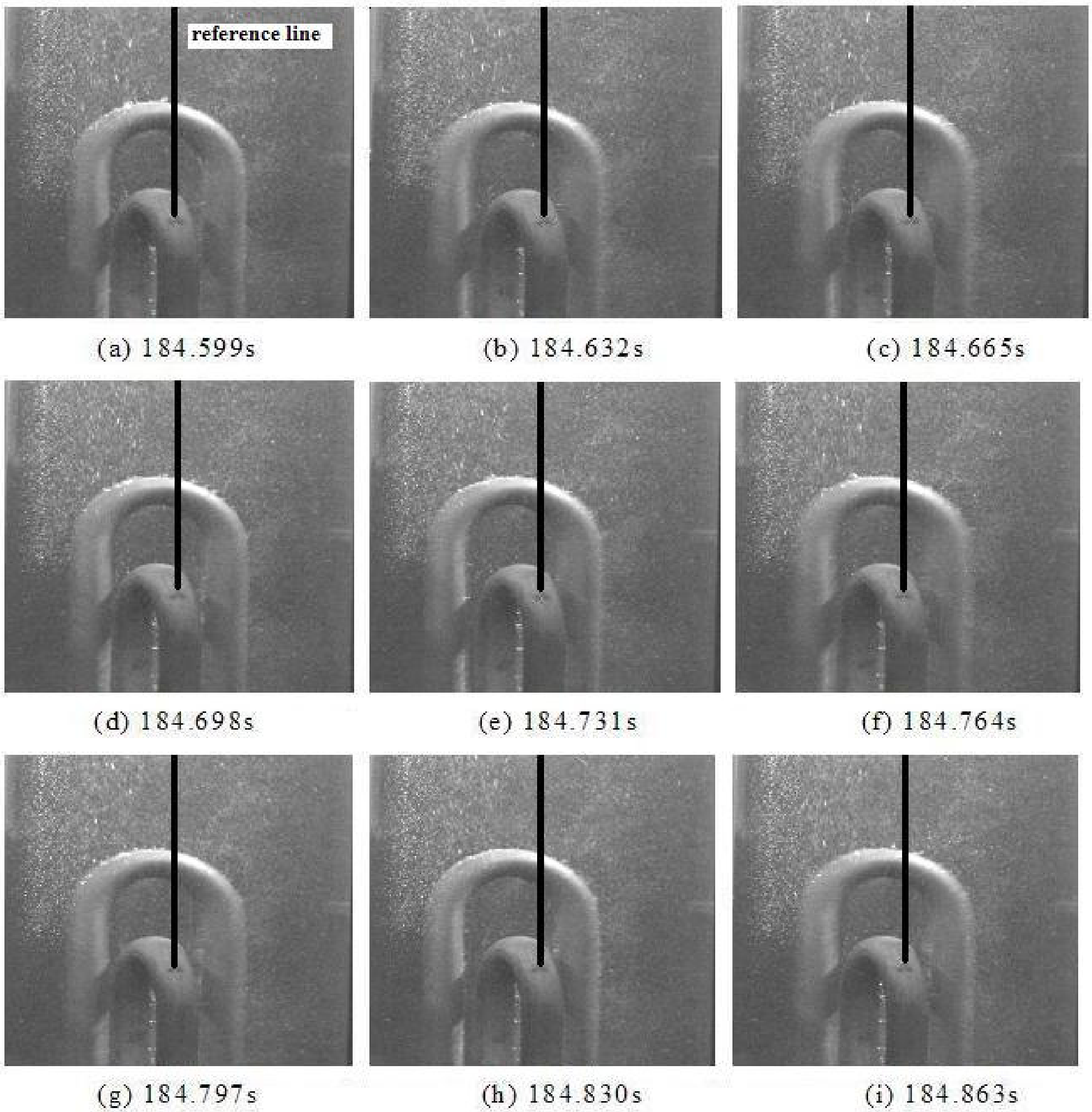

Figure 17. Sequence of frames with 2.67 cycles of heater vibration (10 Hz) cycle 1 (a, b, c and d) ; cycle 2 (d, e, f and g).

3. CONCLUSIONS

This work presents the Frequency Analyses studies of the pressure signal from the Experimental Natural Circulation Circuit (ENCC). The experimental test was carried out for a 5,500 W heating and a cooling flow rate of 0.028 kg/s. Two Data Acquisition Systems were used, one for ENCC with a data acquisition rate of 0.083 Hz (12s) and other only for pressure measurements with a acquisition rate of 500 Hz (0.002 s).

The 500 Hz signal pressure was divided in five periods along the time. Each period corresponds to a heat transfer regime and single and two-phase flow conditions during the heating transient. Frequency Analyses were performed for each period by Matlab using a FFT tool box with Hanning filter. The results were presented in Power Spectrum Density (PSD) plots.

It was identified a peak frequency in 48Hz corresponding to DAS-FFT in the PSD for the first period. In general, the PSD plots show a peak frequency in 68Hz due to the cooling flow pumping. This peak frequency disappears when the cooling pump is turned off. A peak frequency in 19Hz and its harmonic frequencies in 38 and 57Hz were observed in the PSD for the period 2. Another peak frequency in 59Hz was observed for the same period. The phenomenology corresponding to these peak frequencies were not identified yet and needs to be investigated deeply. Heater vibrations were also observed during the period 2. These vibrations are due to production and collapsing of the bubbles on the heater surface in sub-cooled heat transfer regime. This vibration frequency (10Hz) does not appear in the PSD plot and shows that the differential pressure transducer installed in that position of the circuit was not able to detect this phenomenon or it is inadequate. It must to be relocated or another kind of instrumentation must to be used. Posterior analyses of video frames showed a frequency heater vibration of 10Hz. In the period 3, it was observed a peak frequency in 15 Hz and its harmonic frequencies of 30 and 45 Hz. The related phenomenology was identified e corresponds to a strong production and collapsing of bubbles on the heater surface in nearly saturated boiling. Posterior analyses of video frames confirm this frequency of 15Hz. PSD's for the periods 4 and 5 showed a peak frequency in 6Hz. The phenomenology corresponding to this peak frequency was not identified and also needs to be investigated using additional instrumentation such as accelerometers for vibrations and microphones for audio analyses. It was observed low frequency vibrations of the circuit during the periods 4 and 5 due to two-phase flow and phase changing around the circuit that can be responsible by 6Hz peak frequency. The frequency of the cyclic behavior of the circuit in two-phase flow regime (periods 4 and 5) can be calculated from pressure x time plot without using FFT and is very low (10 mHz). This frequency does not appear in PSD for the periods 4 and 5. The studies will continue using additional instrumentation, high speed filming and photo camera and different analysis techniques for other heating and cooling conditions in Experimental Natural Circulation Circuit.

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