SUBCOOLED BOILING DETECTION USING PRESSURE TRANSDUCERS SIGNALS SPECTRAL ANALYSIS

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ABSTRACT.

The experimental technique used for detection of subcooled boiling through analysis of the fluctuation contained in pressure transducers signals is presented. This work was partly conducted at the Institut für Kerntechnik und zertörungsfreie Prüfverfahren von Hannover (IKPH, Germany) in a thermohydraulic circuit with one electrically heated rod with annular geometry test section. A second test section was constructed and it will be operated at the Instituto de Pesquisas Energéticas e Nucleares (IPEN, Brazil), is set with a test section containing a 3x3 rods square matrix configuration. Piezoresistive pressure sensors are used for subcooled boiling detection and spectral analysis/signal correlation techniques are applied. Parameters influencing subcooled boiling and its effect were studied. Results from the first experimental setup and a description of the second are presented.

INTRODUCTION.

The optimization of heat exchangers, steam generators, nuclear cores has the common objectives of minimizing flaws occurrence with increasing thermal efficiency and power densities thus reducing costs. These equipments are extensively used in process and power plants and increasing efficiency and durability will certainly represent an important capital and energy saving for the modern industry.

The subcooled boiling represents an important heat transfer regimen for thermal designs for it allows high heat flux rates in stable condition with moderate superheating of the surface. However, reliable heat transfer coefficients and induced vibration limiting criterias are required. Techniques for the monitoring and diagnosis of the equipments operating in such a condition is also needed.

Several factors affecting the subcooled boiling regimen can be mentioned: fluid pressure, velocity distribution, subcooled temperature, heated surface finishing and wetting characteristics. Due to the heat flux value, the heated surface generates vapor bubles in nucleation centers before the bulk temperature reaches saturation condition. These bubles grow, detach and condense in the subcooled fluid near the surface. The condensation occurs in a very short time (ms), generating, during the bubles implosion, pressure pulses and an increasing turbulence in the boundary layer. Both mechanisms tend to increase heat transfer to the bulk reducing temperature gradients.

Bubles implosion with the resulting pressure pulses are accompanied sometimes by acoustic noise and structural vibration. These three phenomena can be detected by the use of dynamic sensors (accelerometers, high frequency probes, piezoresistive pressure sensors and inductive displacement transducers) and spectral analysis and correlation of their signals (crosscorrelation, power spectrum densities and coherence).

SINGLE ROD EXPERIMENTAL SETUP.

A diagram of the experimental circuit used for the one rod test section is shown in Fig. 1. This experimental circuit was assembled and run at IKPH. This circuit can be divided into two parts: (A) is the feedwater section and (B) is the test section. Part (A) is constituted by a centrifuge pump, two air cooled heat exchangers, a pressurizer, a deairator, control valves, two bypasses and an air circulator. Part (B) is composed by the test section, the electrical supply and the sensors with their electronic processing system.

The test section (Fig. 2) has a lower entrance plenum and an upper exit plenum, both made with aluminum. The main test channel is composed by several policarbonate parts totalling 680 mm active lenght with 20 mm internal diameter with components for sensors positioning and flow visualization. The central heated rod has 11.5 mm diameter and an active lenght of 680 mm simulating PWR fuel rod. The heating is indirect controled by a variable direct current 20 kva transformer. The test section is connected to the feedwater section by flexible pipes to eliminate vibration transfer from the feedwater circuit which might affect subcooled boiling induced vibration. To avoid corrosion and deposits and to improve reproducibility, demineralized water was used.

DATA ACQUISITION AND PROCESSING.

To control and monitoring of the circuit during the experiments, the following operational parameters are measured: fluid temperature at the entrance and the exit of the test section, voltage and current through the heated rod and the flow rate through the test section.

The detection of subcooled boiling ocurrence is done by measuring the pressure fluctuations at selected points along the channel. In order to separate other sources of vibration and to get better monitoring of boiling, some additional dynamic sensors are positioned to measure absolute displacement of the rod and test section acceleration.

Figure 3 shows in a schematic drawing, the signals that are being measured. The pressure fluctuations are obtained with four pressure minitransducers type Kulite XTM-190-50. Two of these pressure sensors named P2X and P2Y are installed in the middle (half lenght) of the section oriented 90 degree apart defining the X and Y directions. The other two sensors are oriented in the X direction but one (P3X) is installed 100 mm above and another one (P1X) is installed 100 mm below. The heated rod displacement is measured using two inductive displacement sensors type Reutlinger WSG-69 positioned in the middle plane (D2X and D2Y), 90 degrees apart in the X and Y directions. To measure the vibration of the entire test section, a triaxial accelerometer type Kulite TGY-600-100 is used and placed at the outer surface on the half lenght plane (A2X-Y-Z).

The data acquisition system is based on a HP21MX computer which receives the signals recorded analogically on tape. Before being recorded the signals are amplified to a maximum range of 1.5 volts and filtered to the frequency range of interest which is 10 to 600 Hz.

The signal processing by Fast Fourier Transform (FFT) is also performed in the computer. The calculation of the Power Spectrum Density, Cross Correlations and Coherence are performed by a special program named FOURI.

EXPERIMENTAL RESULTS.

As mentioned above, the subcooled boiling regimen is characterized by the bubbles implosion in the bulk subcooled temperature fluid flow resulting in pressure pulses. Therefore, subcooled boiling can be detected and analyzed by measuring the pressure pulses. The frequency and amplitude of these pulses are functions of the subcooled inlet temperature and local subcooled temperature, the flow channel geometry, pressure, heated surface finishing, the average fluid velocity and the heat flux rate.

A set of experimental runs was performed at fixed pressure of 1.2 bar, varying the heat flux, average velocity and degree of subcooling (saturation temperature - entrance temperature).

Figure 4. presents a set of power spectrum density and their correspondent time signals for the P2X pressure sensor for fixed heat flux of 55 W/cm^2, surface finishing of 4 micrometer, average channel velocity of 1.5 m/s. Several degrees of subcooling ranging from 77.5 °C to 14.0 °C was changed in steps. The first run with a degree of subcooling of 77.5 °C represents no-heating condition and is a reference signal for all sensors since all noise are generated only by the circuit rather than by boiling phenomena. At this reference condition one can identify two peaks in Figure 4.a at 48 Hz and 140 Hz with maximum amplitude of 2 mbars which are induced by the centrifuge pump operation and standing wave resonance respectively.

Reducing the degree of subcooling by setps of 5 °C each up to 43 °C and with the electric power turned on to generate a heat flux of 55 W/cm^2, the power spectrum density (Figure 4.b) presents an increase of four order of magnitude in Db of noise amplitude in the frequency range between 200 and 500 Hz. This increase in the noise level in the pressure sensors signals is associated with the **onset of subcooled boiling** when small bubbles are formed at the surface, detached and condensed nearby without showing however a fixed periodic behaviour.

The degree of subcooling was further decreased by steps of 0.5 °C at each run. When the subcooling reaches 32 °C (Figure 4.c), a threshold is reached which separates a non-periodic bubbles condensation pulses regimen from a **periodic pulses regimen** with characteristic frequencies. This can be correlated to the presence of a two well developed peaks in the P2X pressure sensor power spectrum curve at 116 Hz and at 232 Hz, being the fundamental and the first multiple frequency values respectively. At this condition one can also observe a slight reduction in the average level of the power spectrum of pressure pulses signals which is associated with the increase in average energy carried away by the bubbles rather than being transformed in pressure pulses. The periodic behaviour of the pressure pulses can also be observed in the time domain curve of the signal where a oscilating amplitude starts to be formed. At this point, both the heated rod as well as the structure are excited by the condensation pulses which can be seen by performing coherence calculation between the displacement sensor D2X and P2X power spectrums and between the triaxial accelerometer A2(X,Y,Z) and P2X power spectrums. The coherence at the frequencies where the peaks occur are high as shown in Figure 5.

Further decreasing the subcooling in 0.5 °C steps, the periodic behaviour of the pulses is more evidenced by increasing amplitude of the power spectrum peaks at changing frequencies. At a subcooling of 26.0 °C, the Figure 4.d shows a sharp increase in amplitude both in time domain and in frequency domain which is caused by the superposition of the fundamental frequency of condensation pulses with the first fundamental vibration mode of the heated rod resulting in a **resonance condition.**

Figure 6 presents under resonance condition the power spectrums and amplitudes in time domain in X direction for the pressure sensor P2X as well as for the displacement sensor D2X and for the accelerometer A2X. From these curves, one can determine the fundamental vibration frequency (78 Hz) and its second and third harmonics. Theses vibrations produce relative displacements of the heated rod of 0.05 mm, pressure pulses of the order of 0.15 bar and accelerations of the entire test section of about 0.04 g.

Reducing the subcooling to 14 °C, Figure 4.e shows the P2X power spectrum without significant condensation pulses at any frequency except to a small pulse at the 31.25 Hz. In the time domain, the signal looses its periodic behaviour and the amplitudes return to the level of no boiling condition. This fact can be explained as the beginning of nucleate boiling regimen and **departure from subcooled boiling** where most bubbles combine together forming larger bubbles which have energy enough to be carried away rather than being condensed locally transfering energy as pressure pulses.

Figure 7 summarizes the changes in the condensation pulses frequency at the P2X sensor for different degrees of subcooling at fixed heat flux of 55 W/cm^2, average velocity of 1.5 m/s and surface finishing of 4.0 micrometer. One can observe a common peak at 10 Hz for all power spectrums which has a relatively high amplitude and it is associated to low frequency movement of the heated rod due to thermal expantion/contraction.

In order to examine the axial dependence of the condensation pulses, the power spectrum and amplitudes in time and frequency domain of the P2X, P2Y and P1X pressure sensors are shown in Figure 8 for the resonance condition, i.e. average velocity of 1.5 m/s, heat flux of 55 W/cm^2 and a degree of subcooling of 26 °C. It is interesting to notice that there is a perfect **synchronization** in frequencies between all curves for every sensor either in X direction as well as in the Y direction. Although there is an axial distance of 100 mm between the P2X and P2Y sensors and that there is also a temperature difference of about 1.6 °C between the two positions which would result in a predicted frequency shift of 10 Hz using Figure 7, this does not happen and we still have a perfect synchronization among the condensation pulses frequencies for every sensor.

In another set of experimental condition, with subcooling of 18.5 °C, average velocity of 1.5 m/s and heat flux at 55 W/cm^2, the synchronization of the pressure pulses is also present as seen in Figure 9. The fundamental frequency is 43 Hz corresponding to the entire test section natural frequency which is another resonance condition and the regimen is near the **departure of subcooling regimen.**

The pulses synchronization, the changes in frequency and amplitude in the pressure pulses signals can found some phenomenological basis in the studies from Griffith & Wallis (1960), Bergles & Rohsenow (1964) and Bucher (1979). They have shown that for a constant heat flux and average water velocity, the bubbles size increases with decreasing subcooling at the inlet. From the onset of subcooled boiling, this phenomena induces an increasing condensation rate with bubbles implosions. With further increasing bubble dimension however, the condensation rate is decreased resulting in lesser implosions and therefore less energy is transformed into pressure pulses reducing the pressure signals amplitudes.

There is a range of subcooling at the inlet which produce a condensation rate such that the resulting implosions generate energy in the form of pressure waves strong enough to liberate bubbles in the vicinity from their nucleation sites and to implode them causing the observed syncrhonization for the signals at different posiitions in a sort of chain reaction. There is a limiting value for the subcooling where the bubbles size reach a dimension such that the condensation rate is so reduced that the implosion rate is so low and the pressure pulses energy is no longer enough to keep the chain reaction (syncrhonization). At this point we are probably near the end of the subcooled boiling regimen approaching the nucleate boiling regimen.

3X3 RODS SQUARE MATRIX TEST SECTION.

In order to extend the experimental capabilities to analyze the effects on subcooled boiling with parallel heated rods, a new circuit and test section named Apollo was designed and constructed at IPEN, São Paulo. This experimental facility is already operational and the experiments should be initiated soon. The circuit is typical for this type of application and its main operational characteristics are: pressures ranging from atmospheric up to 1.5 bar, maximum heat flux up to 200 W/cm^2 and maximum total demineralized water flow rate of 20 m^3/hr . The circuit control system allows fine control of the inlet temperature, heat flux and flow rate.

The body of the test section is made of aluminum with two policarbonate windows for visualization. Three flanged sections are assembled to contain the heated rods. The bottom (inlet chamber) and top sections (outlet chamber) are designed to homogenize and to orient the velocity distribution. The heated rods are arranged in a 3x3 square matrix configuration with two PWR reator type spacer grids spaced 600 mm apart. The rods are heated electrically indirectally with external diameter of 10 mm and active lenght of 600 mm. The cladding is made of stainless steel 316.

To measure displacements, two Bently & Nevada eddy current type sensors are employed, to monitor the test section vibration, two Bruel & Kjaer accelerometers are used. To detect pressure pulses, four piezoelectric Kulite minitransducers were installed. Twenty type K Omega thermocouples were installed to map the temperature distribution and to detect mixing. Besides these sensors, high frequency probes for bubble counting were also assembled. A National DAQ board with Labwindow software will be used for data acquisition and analysis will be done with MATLAB 5.

CONCLUSIONS.

The main objective of this work is to develop and demonstrate the feasibility of monitoring and detecting the subcooled boiling regimen using pressure transducers and spectral analysis of their signals. The experimental set up and conditions used allows us to conclude that under these conditions, the selected set of sensors and analysis tools is capable of detecting from the **onset** of subcooled boiling through the entire regimen up to the **departure** from subcooled boiling. Three important phenomena were observed:

1) There is a range of thermohydraulic parameters in which one can observe **characteristic periodic pressure pulses** which frequencies and amplitudes are functions of the flow conditions.

2) These periodic pressure pulses can induce vibration upon the heated rod and when there is a superposition of either the rod fundamental vibration frequency or its upper harmonics with the pressure pulses frequencies, **resonance** occur inducing high displacements and stresses. This condition should be avoided during design phase.

3) Under some conditions these pressure pulses are not strongly position dependent since there is a propagation of pressure waves from a given position inducing other sites to liberate bubbles with subsequent collapse generating **synchronized pulses** with same frequencies over a range of axial positions.

Further experiments will be carried out using a 3x3 bundled square matrix heated rods to extend the conclusions of this present work to a more realistic equipment situation. However, from the present results, we are optimistics that such a setup is capable of monitoring and diagnosis heat transfer equipments (heat exchangers and nuclear cores) to be designed and operated under a subcooled boiling regimen enhancing heat transfer performance. Steam generators could also be monitored for the occurence of boiling induced vibration under resonance condition reducing the probability of vibration induced flaws.

REFERENCES.

1) Bergles, A.E. and Rohsenow, W.M., "The Determination of Forced-Convection Surface Boiling Heat Transfer", Transactions ASME, series C, 86, 1964.

2) Bucher, B., "Beitrag zum Siedebeginn beim Unterkühlten Sieden mit Zwangskonvektion", Promotionsarbeit, Hannover Universität, Hannover, 1979.

3) Griffith, P. and Wallis, J.D., "The Role of Surface Conditions in Nucleate Boiling", Chemical Engineering Symposium series, no. 30, 1960.

4) Martens, V., "Untersuchung der Schwingunsanregung von Wärmetauscherrohren durch Mantelseiteges Unterkühltes Sieden", Promotionsarbeit, Hannover Universität, Hannover, 1987.

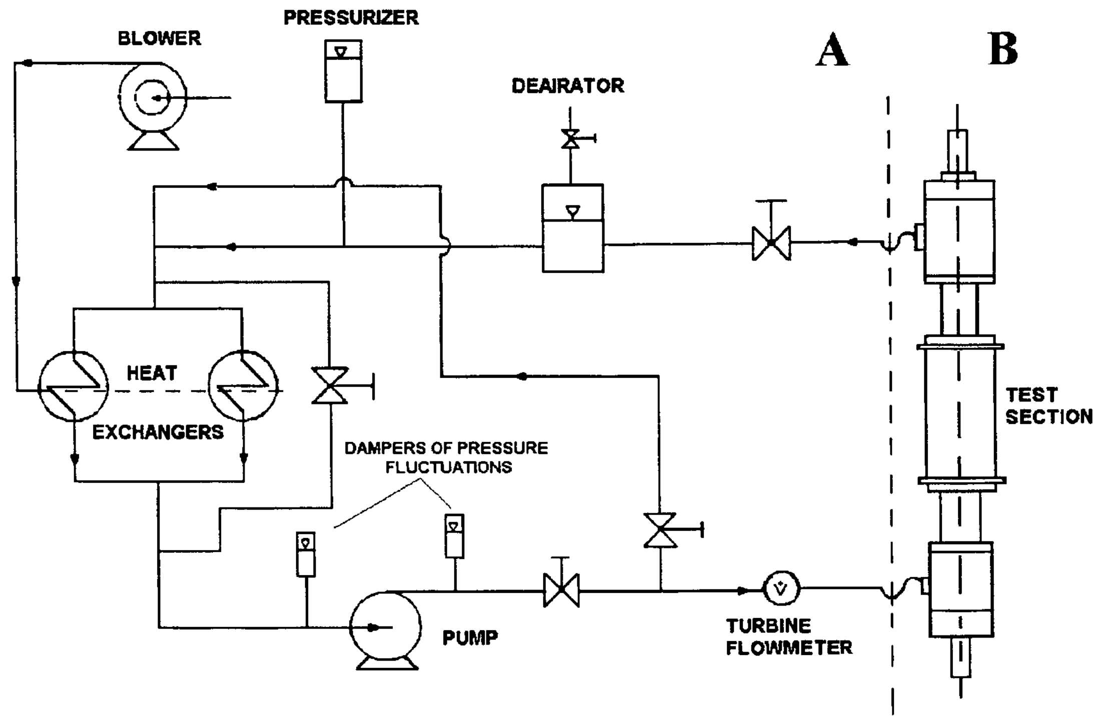


Figure 1. - Experimental Loop for Subcooled Boiling - Flow Diagram.

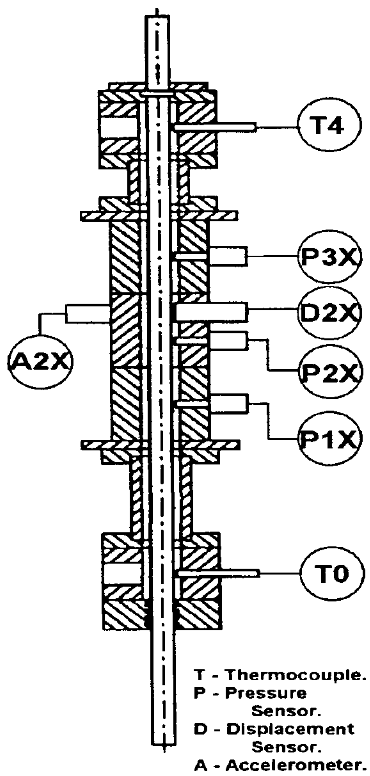


Figure 2. - Single Heated Rod AnnularTest Section.

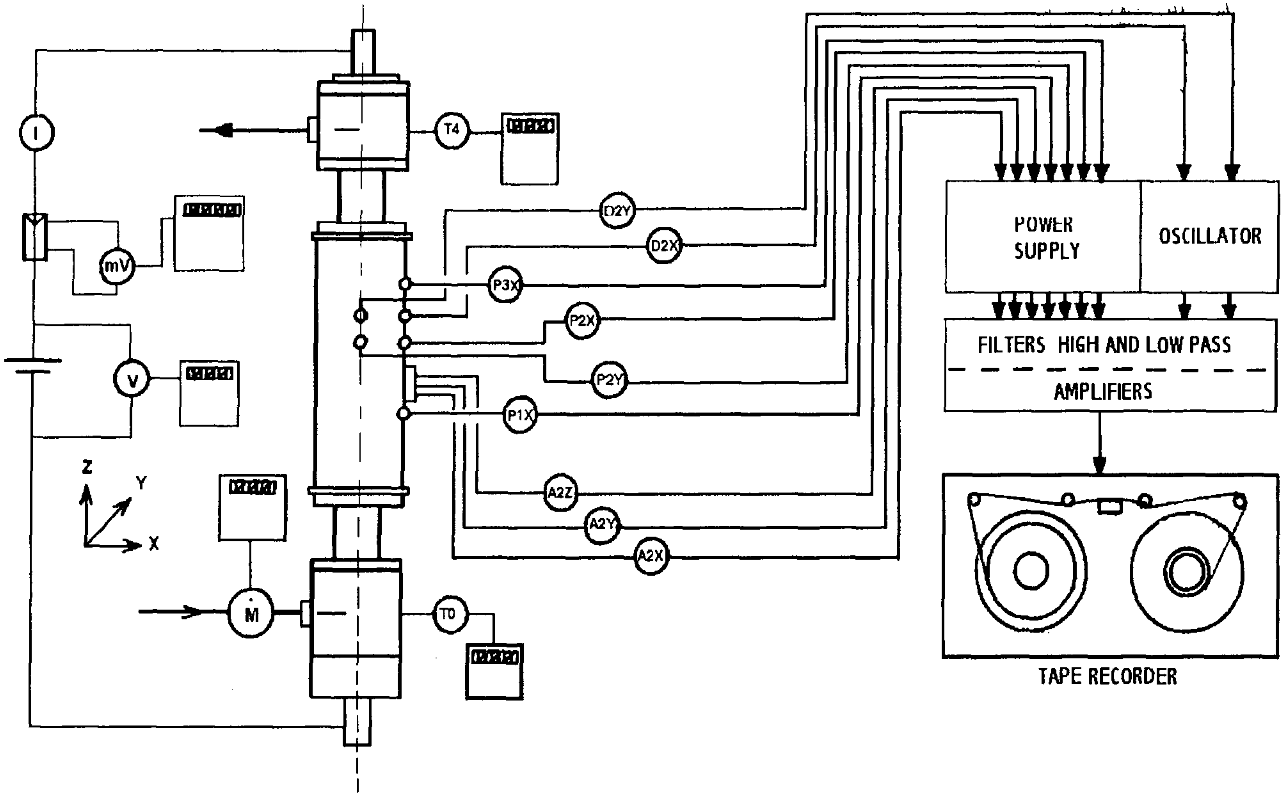
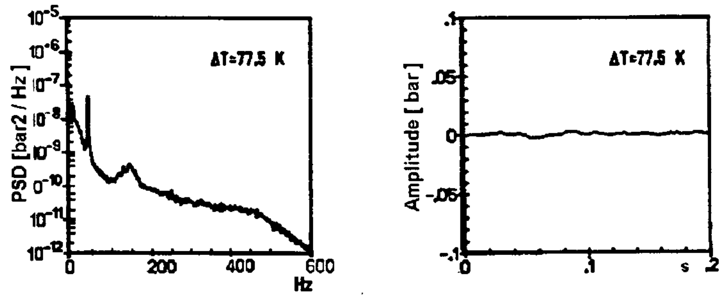
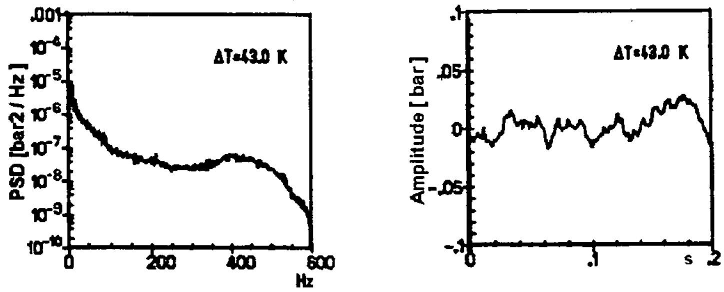


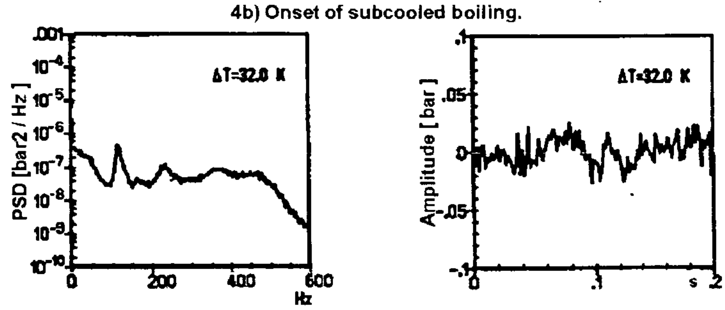
Figure 3. - Signal Acquisition and Analysis System - Block Diagram.



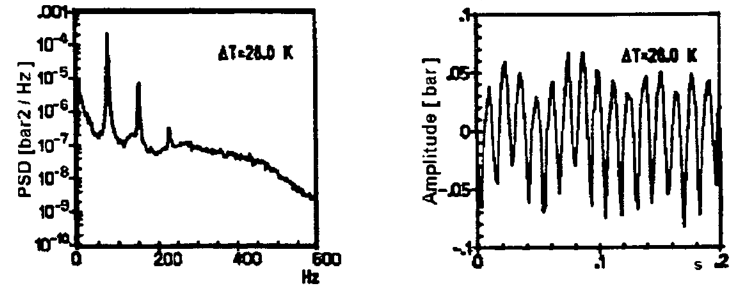
4a) No-heating condition.



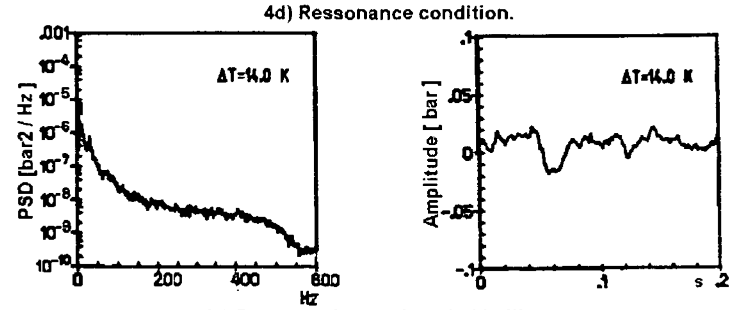
4b) Onset of subcooled boiling.



4c) Onset of characteristic pulses.



4d) Ressonance condition.



4e) Departure from subcooled boiling.

Figure 4. - Pressure Sensor P2X Signal in Time and Frequency Domain.

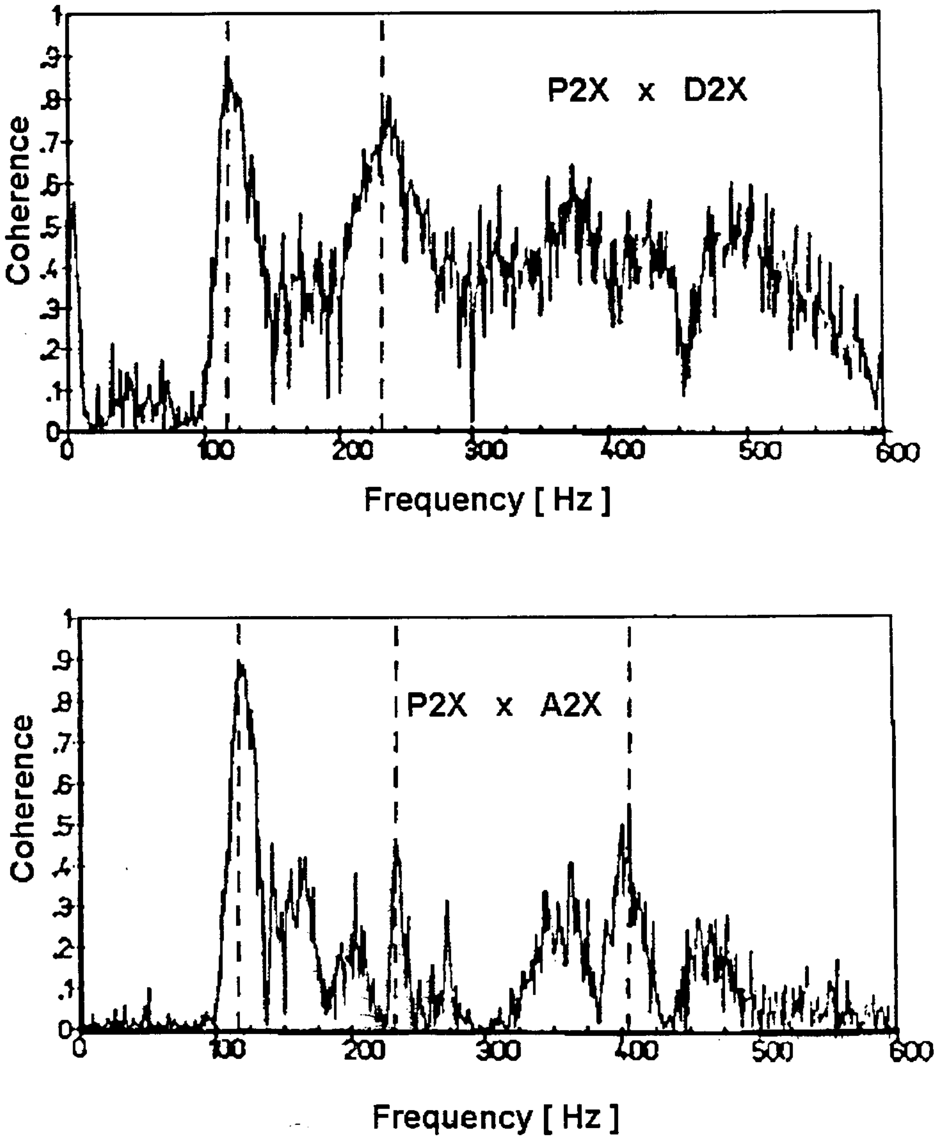


Figure 5. - Coherence between Pressure Sensor, Displacement Sensor and Accelerometer Signals (P2X, D2X, A2X) in 32 °C Subcooling.

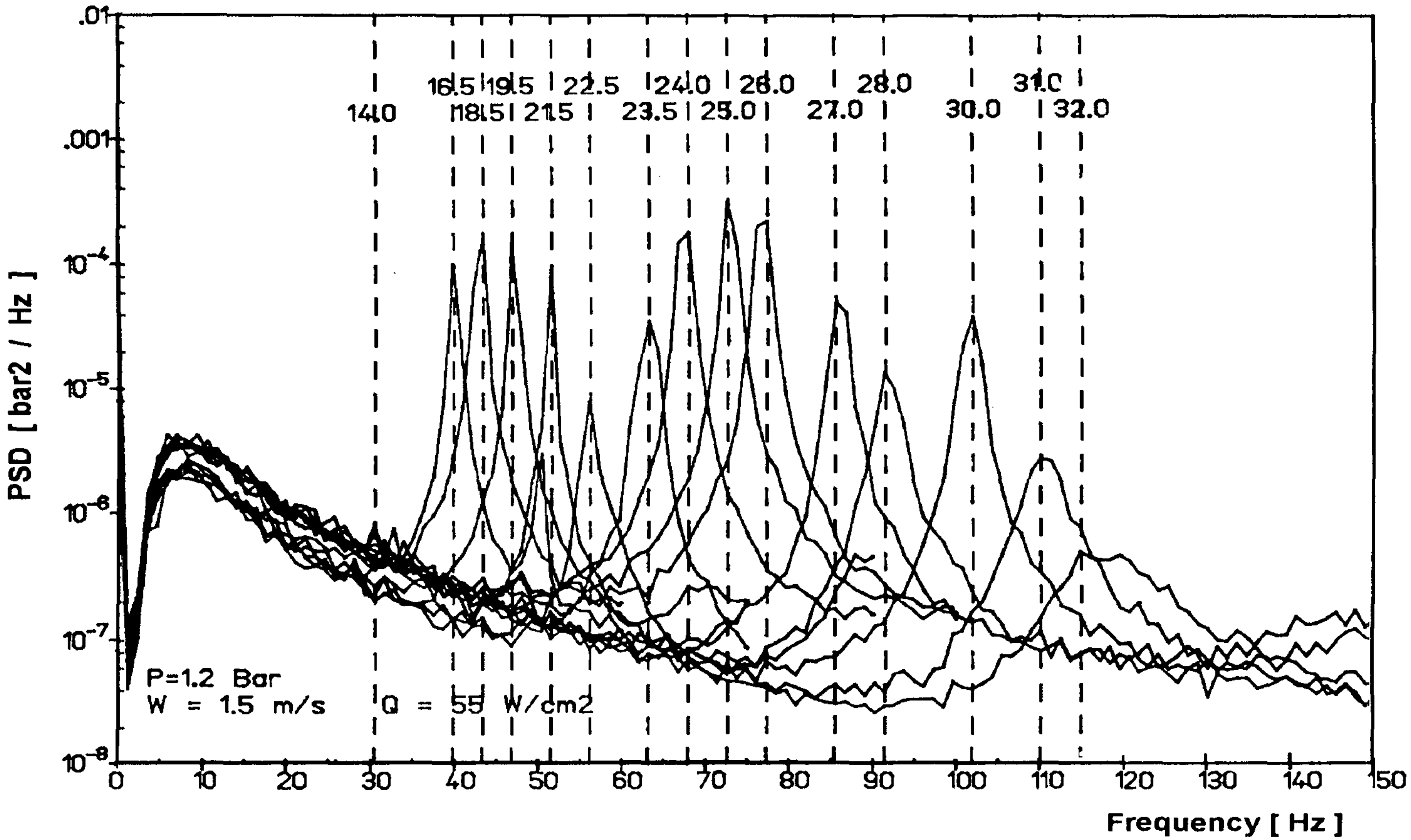


Figure 7. - P2X Pressure Sensor Power Spectrum Density as Function of Degree of Subcooling.

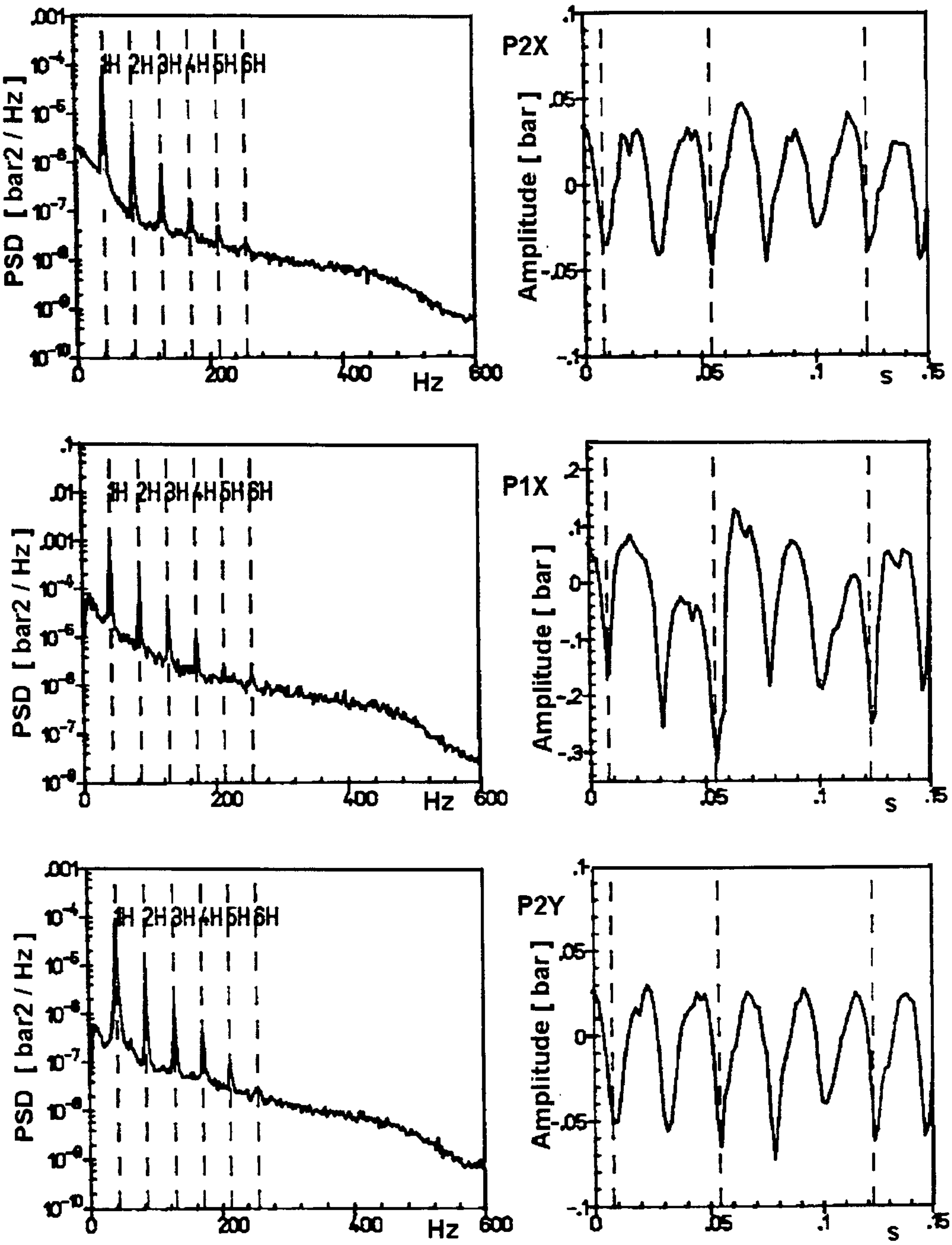


Figure 9. - Condensation Pressure Pulses Synchronization for Subcooling of 18.5 °C.

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TÍTULO DO TRABALHO:
Subcooled Boiling Detection using Pressure Transducers Signals Spectral Analysis

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Spectral analysis, Subcooled boiling detection

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