CS 7906451

ZJE - 181 1978

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ABSTRACT

The report deals with the method based on the measuring and evaluation of acoustic signal emitted at subcooled boiling of water and with the possibilities of applying this method to boiling process diagnostics on experimental water loops and pressurized water reactors.

Introduction

One of the most important factors influencing the degree of heat rating of PWR fuel elements is the crisis of boiling. The crisis of boiling is a phenomenon in the course of which a reasonable deterioration of heat removal from the fuel element occurs. This can lead to a melting of fuel element or of its coating. Therefore it is very important for the development of PWRs to master this phenomenon. The investigation of boiling process diagnostic methods is a tool to solve this problem. Such methods can be applied in experimental research and also for reactor core diagnostics during reactor operation. This report deals with the method of boiling process diagnostics based on the measuring of acoustic energy emitted during the boiling of the water.

Boiling process

Let us suppose that a heating element is placed in channel through which flows water. The course of heat flow vs. temperature gradient between the heat-exchange surface and water is shown (Fig. 1).

Point A corresponds to the saturation point. Between the points A and B is the region of bubble boiling. At isolated points of heat-exchange surface called the active centres arise steam bubbles; they separate from the surface and cease to exist in the subcooled area. The area between points B and C is the area of crisis of boiling i. e. the area of balancing between bubble and plane boiling. In the point C begins plane boiling area. Heat exchange between heat-exchange surface and water goes through a film of steam.

Bubble boiling in PWR core can be considered as a stage preceding the emergency situation and the beginning of film boiling is the emergency situation which is to be immediately removed. From the viewpoint of economy and safety, - the development of boiling detection system appears to be important. This system should detect boiling in reactor core as soon as in its bubble phase, it should check its trend and reliably detect the beginning of the crisis of boiling.

The origin of acoustic emission during boiling

In subcooled boiling the acoustic energy is emitted through pressure pulsations during growth, collapse and volume oscillations of steam bubbles or during volume changes within the steam film in the neighbourhood of heat-exchange surface.

In subcooled boiling the temperature of water is below the saturation point with the exception of a thin layer close to the heat-exchange surface. Steam bubble arising on heat-exchange surface is, after reaching a certain radius, separated from the surface by the effect of dynamic forces of flow of liquid. In subcooled area the bubble collapses. As a dominant phenomenon in the whole process of growth and collapse of a bubble can be considered the last phase of bubble collapse /1/. In this time the rest of bubble contents is compressed and a short intensive pressure pulse is emitted. The higher the subcooling, the faster is the collapse and higher frequency components appear in frequency spectrum (over 100 kHz at higher degrees of subcooling).

Steam bubbles arise in separated points of heat exchange surface (the so called active centres). When the bubble leaves the active centre a new bubble begins to rise. The signal from one active centre is therefore a sequence of pressure impulses. The amplitude, width and period of occurrence are random variables and therefore this sequence appears to be an impulse random process. However, because of a great number of active centres on the heat-exchange surface, the resulting signal is a continuous random process. With the increase of heat flow the number of active centres increases. It means that the number of acoustic sources increases and total intensity of acoustic signal increases too. When the whole surface is densely covered with steam bubbles the bubbles join into greater formations and their volume changes. So a smaller number of macro sources of acoustic signals is produced. This is characteristic for the changeover from bubble to film boiling.

The sensor of acoustić emission signal

The acoustic emission signal can be measured by piezoelectric transducer located either direct in water or at the end of waveguide submerged in water. Acoustic emission can be measured either in a wide frequency range or in a narrow frequency band at resonance frequency of the transducer. This frequency should be selected out of the range of disturbing noise.

Experimental results

Experiments in water tank

The goal of these experiments was to verify the sensitivity of acoustic emission method for the detection of boiling and to find out the frequency spectrum of acoustic emission signal under ideal conditions without any influence of disturbing acoustical noise.

Experiments were realized in an open water tank. Sizes of tank: length 100 cm, width 70 cm, height 80 cm. Resistance wire of a length of 5 cm and diameter 0,5 mm located in the centre of the tank was used as a heating element. Acoustic emission signal was measured by a hydrophone located 10 cm under the heating element. The installation is shown in fig. 2. On a pipe made of an isolation material through which are led the power supply wires for the heating element is fitted a nozzle for the restriction of water circulation around the heating element. It enables that after switching on heating current the boiling proceeds from the stage of subcooled boiling to the stage of boiling close to the saturation point.

Block scheme of the measuring equipment is shown in fig. 3. The RMS voltage-time dependence of the signal at the output of selected 1/3 - octave filter was measured. The experiment could be repeated under the same initial conditions because heating of the water in the tank was insignificant. The results could be averaged. By measuring over the whole spectrum the dependence of frequency spectrum vs. time was obtained. By this way the change of frequency spectrum vs. the degree of subcooling was detected. Fig. 4 shows the frequency spectrum measured immediately after switching on the heating current, and after 100 s. Signal level in dB is related to the noise level (here it is practically the electronic noise only).

The results of experiments show:

- Acoustical method is very sensitive under ideal conditions.
- Acoustic emission signal is a wide-band signal with its upper limit exceeding 100 kHz.
- With the increase of subcooling the intensity of acoustic signal increases at higher frequencies.

Experiments on water loop

The goal of these experiments was to find out the acoustic emission signal to noise ratio for non-idealized object. The experiments were realized on experimental water loop the maximum parameters of which are: temperature 330°C, pressure 17 MPa, water flow velocity in measuring section 7 m/s. The loop is a relatively complicated equipment and therefore the operation noise level is expected to be high. Measuring section of the loop is a pipe of inner diameter 14,5 mm and of length 3 m. In the centre of a pipe is an electrically heated element - the rod of circular cross-section with a diameter of 9 mm. The rod is in five points distanced by spacers.

Acoustic emission was measured by one piezoelectric transducer (type KD 10 of GDR production, resonance frequency 16 kHz) placed at the upper part of the heating rod outside of the loop. Heating rod serves as a waveguide (see fig. 5).

Block scheme of the measuring equipment is shown in fig. 6. In this experiment the spectrum of acoustic emission signal during the rise of heating current was measured.

The boiling changed from a stage without boiling to a highly developed boiling. The pressure and water flow velocity remained constant. Fig. 7 shows typical spectral curves. The peak at 16 kHz refers to resonance frequency of the transducer, the peak at 4 kHz is caused obviously by resonance frequenc of some mechanical element of the loop.

Fig. 7 shows that

- Acoustic emission signal to noise ratio remains considerable.
- In a developed boiling the increase of acoustic emission intensity is visible mainly at higher frequencies.
- In more developed boiling the emission increases also at lower frequencios.

Conclusions from both experiments:

- The intensity of acoustic emission signal is the measure of intensity of boiling.
- The information contained in the shape of the spectrum of signal is predominantly qualitative (the rise of first bubbles, clustering of bubbles into greater formations, etc.).

Therefore acoustic emission signal intensity and spectral curve character appear to be suitable featuros for boiling process dignostics.

The possibilities of measuring the acoustic emission signal in PWR core

PWR is a very complicated object with a high level of disturbing noise of acoustical nature. Let us analyze briefly the possibilities of measuring the acoustic emission signal arising from boiling in a reactor core.

From the acoustical viewpoint, the reactor core is very complicated. It is densely filled by fuel pins distanced by grids. Sound propagation through the water is therefore difficult.

Two ways of measuring the acoustic signal arising in reactor core exist. First, placing the transducer inside pressure vessel, second, using the waveguide to lead out the acoustic signal outside of pressure vessel. The first way imposes great pretensions on the design of the transducer (demanding working conditions) but the measurement is more sensitive than in the second case.

The insertion of acoustic transducer direct into the bundle of fuel pins is not possible. It is necessary to count with leading out the acoustic signal into the space above the core by the use of waveguide leading through the bundle of fuel elements. There is no problem to replace several fuel pins in the core by waveguides. Acoustic transducer can be fitted at the upper end of this waveguide. When no transducer allowed to working inside reactor vessel is available the waveguide must lead through the pressure bushing up to a space over the cover of reactor vessel. Design problems connected with it can be solved.

Acoustic emission signal evaluation

In PWR a great number of acoustic disturbing signals of a great intensity exists. It is mainly noise caused by the flow of water through reactor core and by vibrations of mechanical elements of the reactor. The useful signal (acoustic emission signal caused by boiling) must be measured against this background noise.

Further problem consists in a great influence of geometry of the object (which is in this case very complicated) on the acoustic signal accepted by the transducer. It is therefore very difficult to create sufficient physical or mathematical model describing this situation. In such a case it is also problematic to transfer the results of experiments on a real object, because laboratory experiments are usually carried out under ideal conditions.

Then it is necessary to solve the problem of acoustic emission signal evaluation in order to recognize various stages of boiling on an object with a complicated structure. One of the possible ways of solution is the application of pattern recognition methods /2/.

Pattern recognition is a discipline of cybernetics dealing with problems of machine recognizing of phenomena. The task of such a machine is to classify the unknown object, state, situation etc. The structure and parameters of a machine are variable and they are adapted for the solution of a particular problem i. e. for the recognition of the states of a particular object. The basic characteristic of pattern recognition methods is that they use the object to be recognized in the process of adapting the machine.

In the practice, on the basis of a simple physical model and laboratory experiments, suitable features of the states of the object are selected. The features are characteristics of signals from sensors placed on the object bearing an information about selected states of object. The response of the set of sensors to a definite state of the object is called a pattern. It is necessary to initiate all required states of the object and to carry out such an amount of measurements of values of the features in order to obtain a representative set of patterns. This set, so called "training set", represents the experience which must be transferred into the machine. This is done by special procedure of evaluating the training set. As a result we obtain a special algorithm for the classification and so the parameters and structure of the machine - the classifier.

With complicated objects (e.g. LWR), difficulties with the initiation of requested states can appear. Power reactor works practically at constant parameters (pressure, temperature, coolant flow). There is no problem to measure the features for an arbitrary long time for the state without boiling. However, the initiation of boiling is here difficult and it would be in any case only the boiling in small localities of the core. This problem can be solved e. g. by the initiation of boiling in a special channel in reactor core by lowering the coolant flow through this channel.

The reliability of boiling detection system could be increased on the basis of the fact that the reactor operates practically at constant parameters. Every deviation of acoustic emission signal from stationarity means a potential danger. Therefore the detection system could be supplemented with a detector monitoring the deviation of the signal from stationarity.

Conclusion

The importance of boiling process diagnostics increases when great pressure water reactors are developed, because economy and safety are of the utmost importance. Boiling detection in PWR core is a difficult problem. This report implies that this problem could be solved. But experiments direct on some power reactor are for it necessary.

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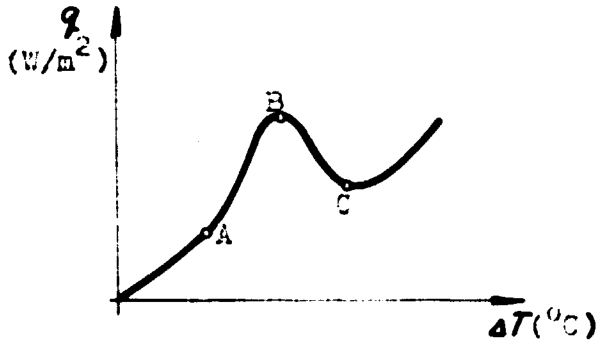

Fig. 1. Heat flow as a function of temperature gradient

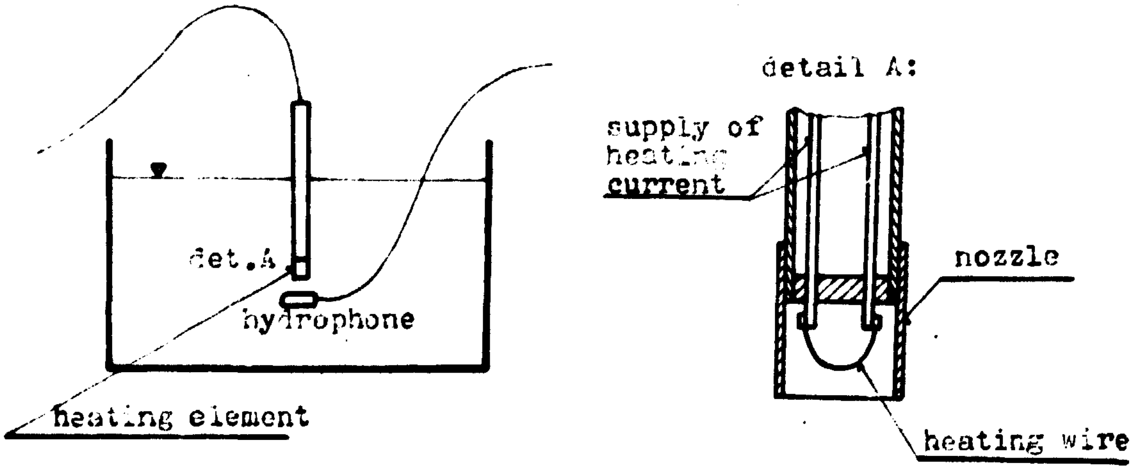

Fig. 2. Experimental equipment in water tank

Fig. 3. Block scheme of measuring equipment

H - hydrophone Brüel-Kjaer (0 - 200 kHz)

A - third octave spectral analyser, Brüel-Kjaer type 2607, 1614 (2 Hz - 200 kHz)

Z - recording equipment

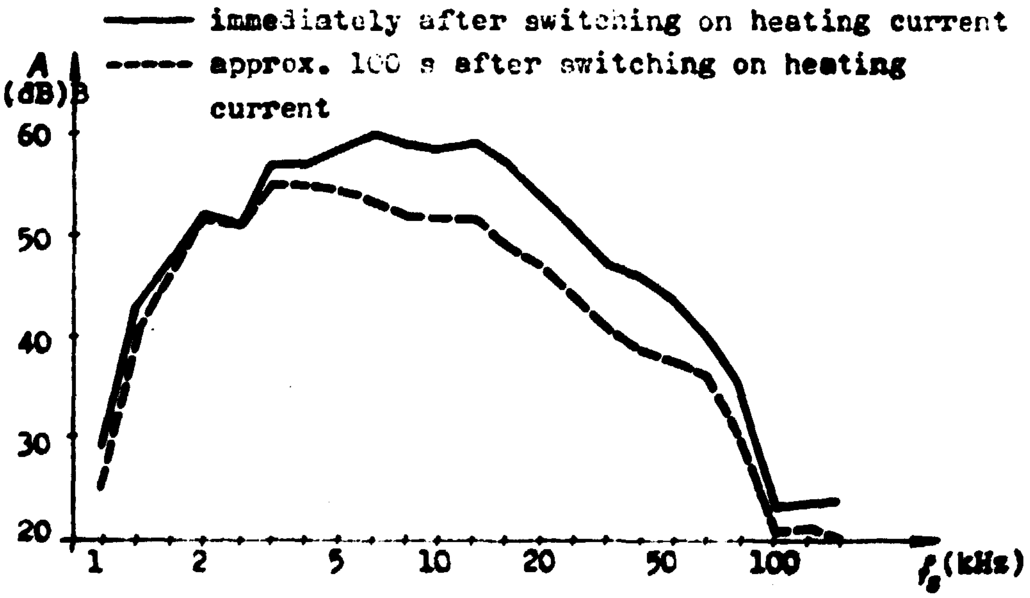

Fig. 4. Spectrum of acoustic emission signal

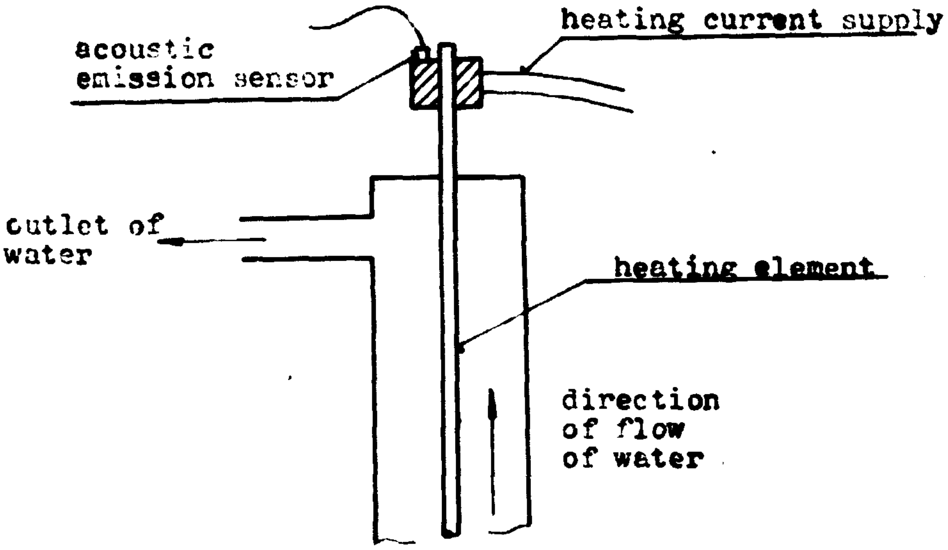

Fig. 5. Location of acoustic emission sensor on experimental water loop

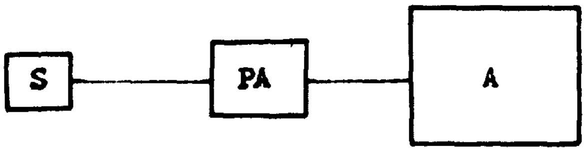

Fig. 6. Block scheme of measuring equipment

S - sensor

PA - preamplifier

A - third octave spectral analyser

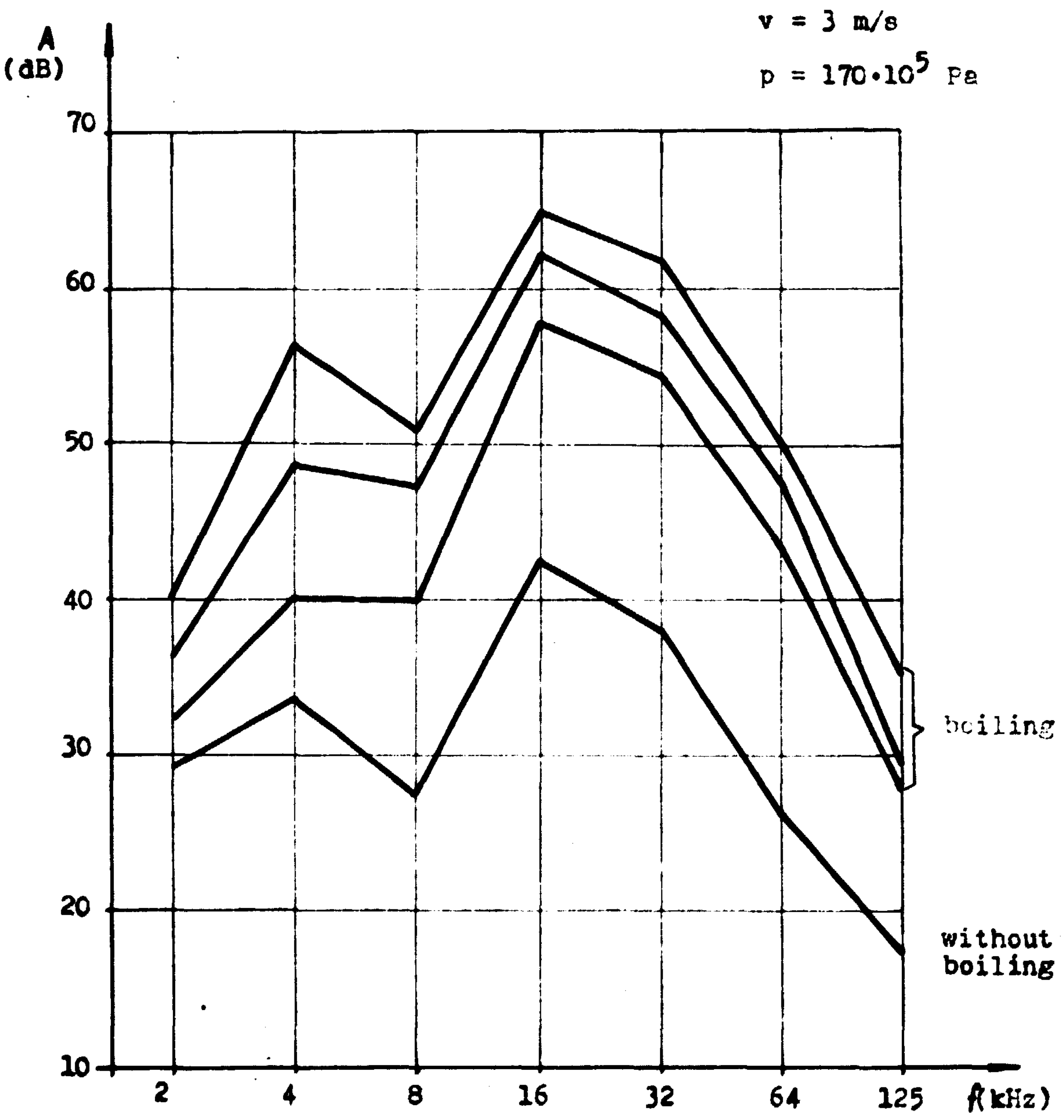

Fig. 7. Spectrum of acoustic signal