The emergence of technogenic risks in the event of a heat exchange crisis in nuclear power plants

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The emergence of technogenic risks in the event of a heat exchange crisis in nuclear power plants

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Abstract. In this article, the main problems and man-caused risks are considered in the event of a heat exchange crisis in nuclear power plants (NPP). A thermophysical booth simulating the operation of a nuclear reactor was developed. The data of acoustic diagnostics of the boiling of the coolant on the basis of the work of the laboratory stand were collected. Methods for processing and analyzing data collected from acoustic sensors have been developed. The recording and processing of signals was carried out using the application package and MATLAB programming language. The article describes the application of correlation and spectral analysis for data processing and analysis. The authors also use regression analysis to find the dependence of wall temperature on the frequency of acoustic oscillations. Forecasting the values of the wall temperature from the frequency of sound vibrations makes it possible in the future to find diagnostic features and build a mathematical model for detecting boiling and heat transfer crisis in nuclear power plants.

1. Introduction

Providing effective heat removal and avoiding overheating and burnout of heating surfaces, in particular fuel elements of nuclear reactors, are necessary conditions for safe operation and prevention of severe accidents with the release of radioactivity beyond the safety barriers at nuclear power plants.

A vivid example of an accident with a violation of the heat sink is an incident in 1979 at the Three Mile Island NPP, where the residual heat emission played a significant role. The cause of the accident was the average leakage from the first circuit, which led to a decrease in the pressure in the core and effervescence of the coolant on the residual heat release.

In emergency modes, when the pressure in the reactor decreases and the coolant flow through the active zone decreases, boiling of the coolant can begin. The boiling is the process of intense evaporation occurring in the entire volume of the liquid at the saturation temperature or somewhat superheated relative to the saturation temperature, with the formation of vapor bubbles.

At surface boiling, the temperature of the shell is higher than the boiling point of water (saturation temperature), and the temperature of the coolant is lower than the saturation temperature. In this case, a bubbling boiling mode is observed, where bubbles freely leave the surface of the shell and are carried away by the flow of water.

In this case, heat transfer only improves, as the heat transfer coefficient increases. However, if the heat flux locally increases markedly and the rate of bubble formation at this point increases, and the rate of their entrainment by the coolant decreases (for example, the flow through the zone decreases, or the deformation of the fuel grid), a steam film can form on the TVEL surface. With the formation of a local vapor film, the heat transfer coefficient falls by a factor of tens and the shell overheats, as a result of which a heat exchange crisis of the first kind occurs, as described in the book [1].

Thus, the first modification of the crisis (a crisis of the first kind) is interpreted as a consequence of the transition of the bubbling boiling of liquid into a film one. The reverse transition from film boiling to bubble is called a crisis of the second kind. Its peculiarity consists in the fact that the vapor film breaks down and boiling occurs throughout the volume of the liquid, the so-called bulk boiling. In the event of a heat exchange crisis on the surface of the TVEL envelope, both the first and the second kind, the shell begins to warm up to high temperatures, at which the chemical reaction of zirconium oxidation begins when interacting with water.

From all the above, it follows that the diagnosis of boiling and the heat transfer crisis, which is the boiling stage, refers to the classic problems of diagnostics at nuclear power plants. In his article [2], E.I. Nesis asserted that a theoretical analysis of numerous experimental data made it possible to detect the presence of a correlation between the thermal parameters and the characteristics of the sound accompaniment during boiling. This statement is the basis for requiring the development of passive acoustic diagnostics of heat transfer in boiling liquid.

Thus, the most important task for ensuring the safe operation of nuclear power plants is the creation of a comprehensive diagnostic system, with the possibility of automatically recognizing abnormal and pre-emergency thermal-hydraulic regimes in nuclear reactors.

2. Materials and methods

2.1. Thermophysical stand

The developed thermophysical stand is shown in figure 1. The stand is a closed system under pressure consisting of several parts. A tank with purified water is the working fluid of the installation. Heating elements are installed in the tank. They simulate the operation of TVELs at nuclear power plants. During the operation of the heating elements, water boils, then the water is converted into steam and moves along the connecting pipes. Steam enters the turbine connected to the alternator. The turbine rotates under the steam pressure. Steam enters the refrigerator after the turbine. Steam condenses on pipes in which water circulates from the cooler vessel. The condensed steam returns to the tank [3].

The stand is also equipped with multiple sensors and instruments for measuring pressure, temperature and other characteristics. The stand is compact and mobile. This allows it to be easily transported and operated in any environment. This installation allows observing such phenomena as: different boiling regimes, evaporation processes, dependence of the boiling temperature of water on pressure, generation of electricity through a dynamo machine.

2.2. Data collection equipment

Experimental data on diagnostics were obtained with the help of acoustic sensors and thermocouples installed in a laboratory bench. The data was then processed using the MATLAB software. Four microphones were used as acoustic sensors with a frequency range from 4 Hz to 20 kHz, a sensitivity of 0.25 mV / Pa, a dynamic range of 146 dB. The temperature range is from -400 to + 1200 ° C. The general view of the acoustic sensor is shown in figure 2.

Industrial thermocouples of the brand - TXA-108-4x11-0-KX-7 / 0.2-2000 were used as temperature sensors. Thermocouples are shown in figure 3. The range of measured temperatures is from 50 to 300 ° C, and the operating temperature range of the cable is from 5 to 200 ° C.

The ADC-LVDS module was used to collect data from acoustic sensors. The ADC module is shown in figure 4. The main characteristics of the ADC-LVDS are: the number of analog channels is 4, the range of the input voltage of the channel is ± 1V, the ADC is 12 bits in length, the conversion speed is up to 65 Ms / s, and the bandwidth is 315 MHz.

Figure 1. Thermophysical stand.

Figure 2. Acoustic sensor.

Figure 3. Thermocouple TXA-108-4h11-0-KX-7 / 0.2-2000.

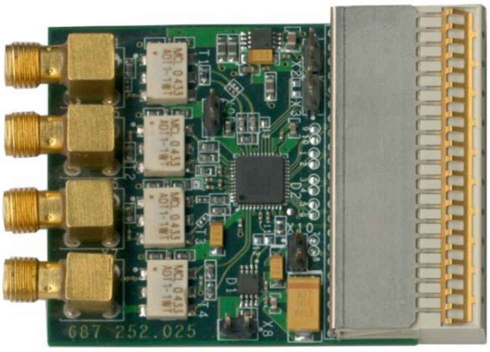


Figure 4. ADC-LVDS.

The main task in diagnosing the heat exchange crisis is to diagnose and determine the boiling point. The main signals for diagnosing boiling are acoustic noises. They are taken from pressure waves and bubble bursts during boiling in nuclear power plants, as described in [4].

Correlation analysis was used to process and synchronize signals from acoustic sensors. Correlation analysis allows us to evaluate the temporal properties of a signal without using spectral analysis. For example, to estimate the rate of change or duration of a signal and temporarily correlate one signal with another. The mutual correlation function (VKF) determines the time coupling of two signals in time. The autocorrelation function (ACF) shows the statistical relationship of one random variable over time.

Spectral analysis consists of decomposing a signal into its frequency or spectral components and evaluating or measuring their spectral characteristics. The mathematical basis of the spectral analysis of signals is the Fourier transform. The allocation of the frequency of the regular components of a signal noisy with interference is the main purpose of the Fourier transform. A direct Fourier transform takes a description of the signal from the time domain to the frequency domain. The fastest Fourier transform (FFT) is most often used for spectral analysis. The signal can be decomposed into its component oscillations of different frequency and amplitude using a fast Fourier transform. The windowed Fourier transform is a function of time, frequency, and amplitude. Window Fourier transform allows to receive the characteristic of frequency distribution of a signal with amplitude in time.

3. Results and discussion

3.1. Correlation analysis

The MATLAB application package was used for the experiment. The "recorder" function built into MATLAB was used to record a signal from an acoustic sensor. Each signal is given its own time interval, depending on its length. Temporal signal implementations are shown in figure 5. Correlation analysis was used to process and synchronize signals from acoustic sensors using the methods and algorithms described in the book [5].

Synchronization of signals was carried out as follows. If there are delays between the signals, the cross-correlation function will have a maximum in the non-zero value. The most lagging signal is searched for and synchronized with the rest and the delay values are removed. The values of the delays were found and removed using a mutual correlation function. These values are shown in figure 6.

Timed realizations of signals after their synchronization are shown in figure 7. Further analysis of time series is possible only after carrying out this procedure.

3.2. Spectral analysis

Spectral analysis of signals was carried out after their synchronization using the methods and algorithms described in the book [6]. The signal spectrogram is used to estimate the signal change over time. To calculate the spectrogram, the signal vector is divided into segments. The spectrum is calculated for each segment using the "fft" function (Fast Fourier Transform (FFT)). The FFT decomposes the signal into its component oscillations of different frequency and amplitude. A set of spectra of all segments forms a spectrogram. The built-in function in MATLAB "spectrogram" is used to calculate the signal spectrogram.

The spectrogram function is used to plot the spectrograms of each synchronized signal. The size of the "window" (the number of samples per second) should be equal to the sampling frequency, i.e. 44100. The number of samples for a discrete Fourier transform was chosen taking into account the window size and the acceleration of the FFT process. This value must be 2n and not exceed the window sizes. It follows that the value 215 = 32768 is the most appropriate window size for the FFT.

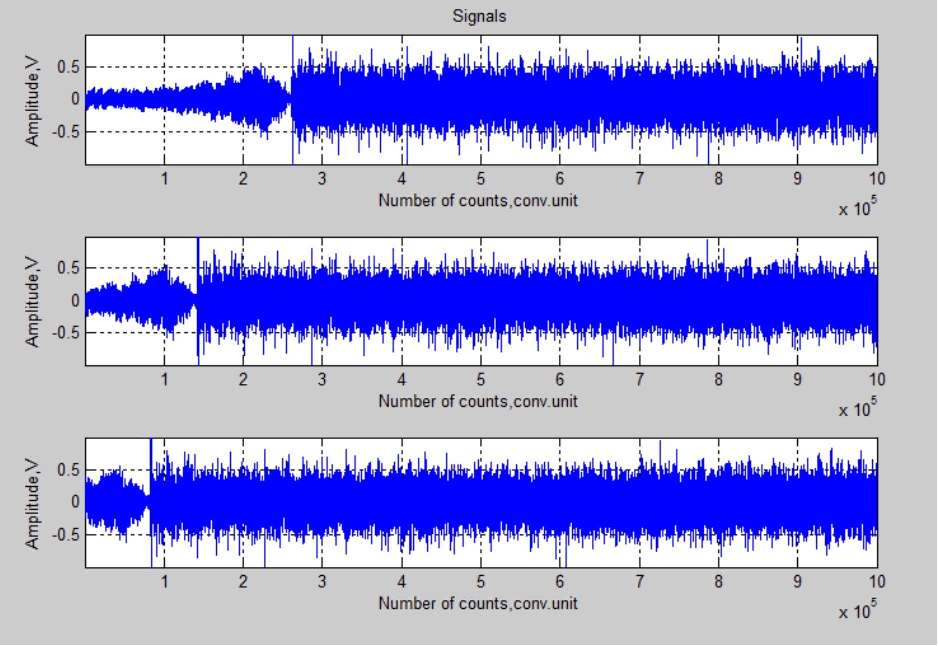


Figure 5. Time Signal Realizations.

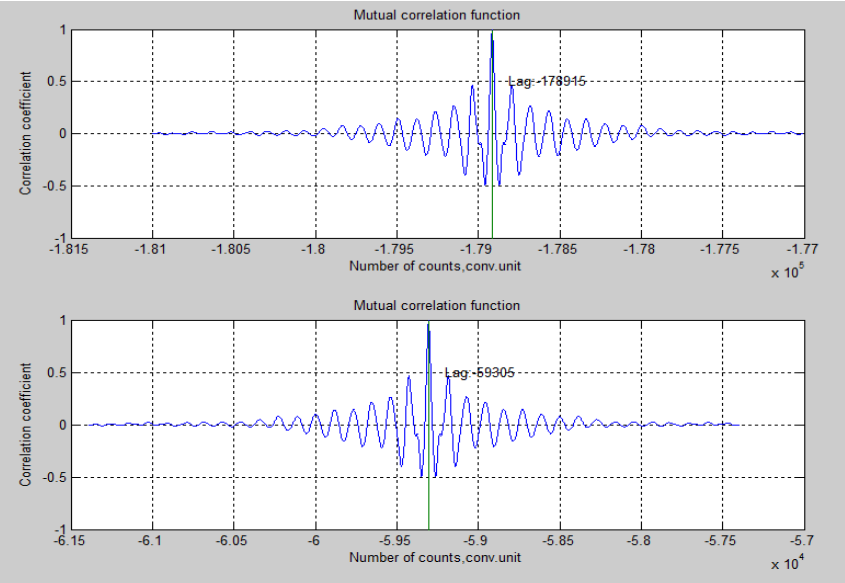


Figure 6. Cross correlation function of non-synchronized signals.

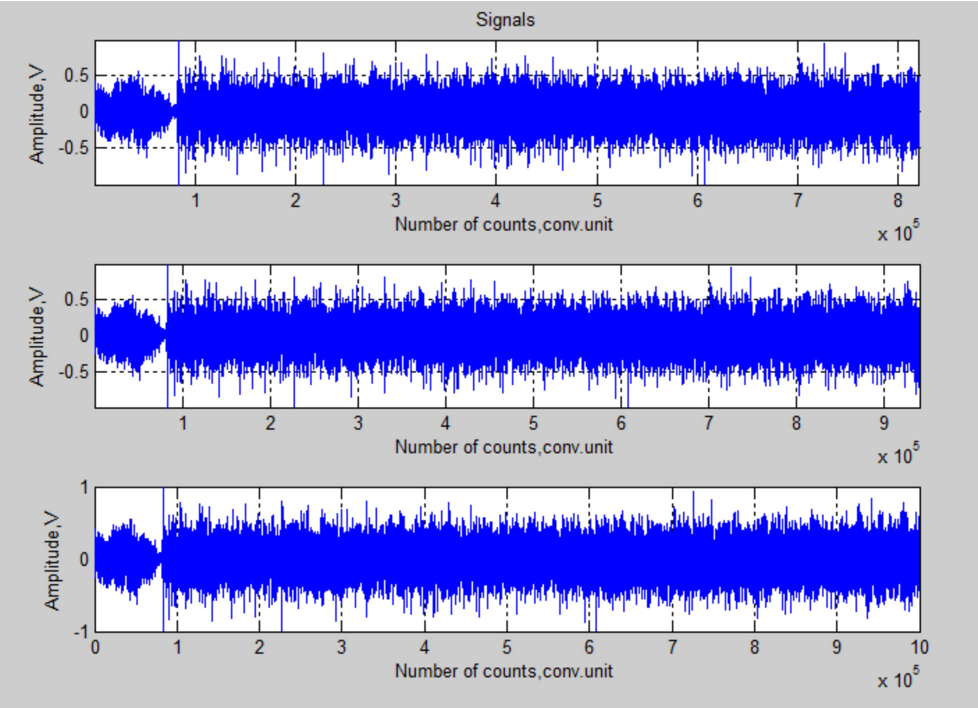
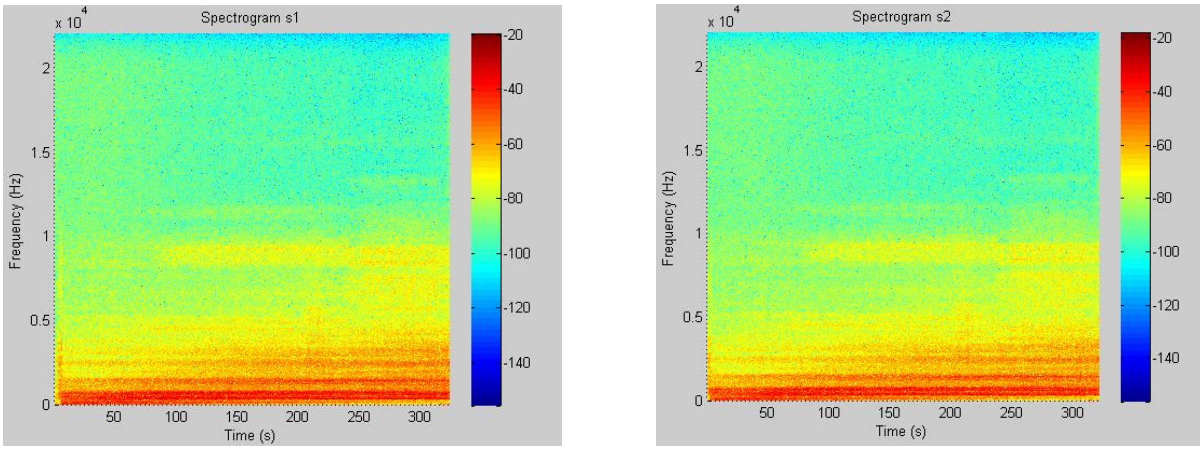


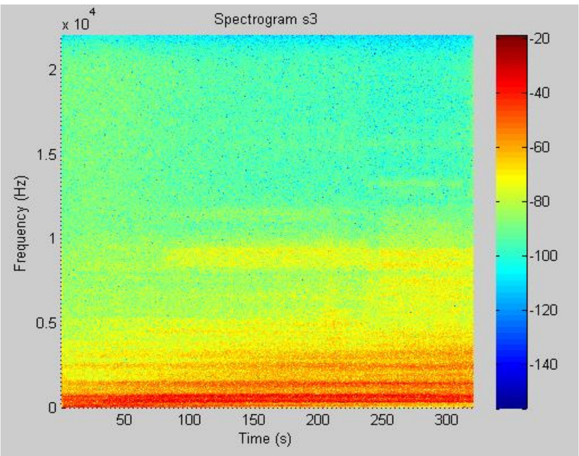
Figure 7. Timed implementations of synchronized signals.

Spectrograms of signals from acoustic sensors are shown in figure 8. By spectrographs, one can observe the boiling process, its duration, and also the frequency and amplitude of the acoustic oscillations of the bubble collapse.

For the construction of power spectra, MATLAB uses the Fast Fourier Transform algorithm. The power spectra for signals from acoustic sensors are shown in figure 9. The spectra show the distribution of signal power as a function of frequency.



(a) s1 (b) s2

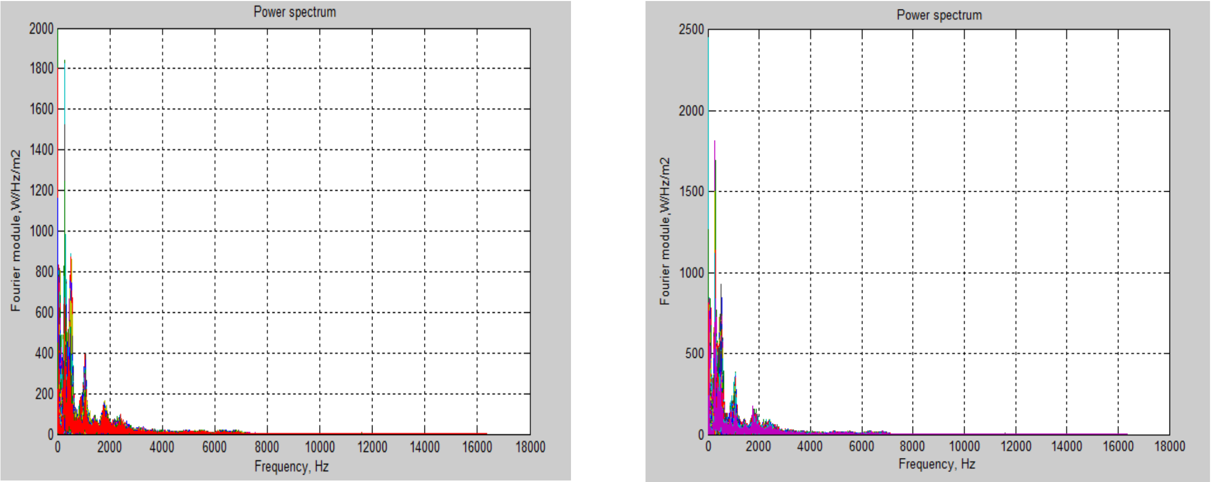


(c) s3

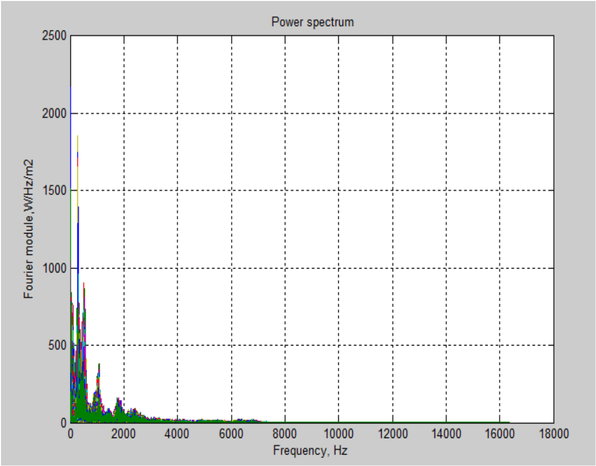
Figure 8. Spectrograms of signals from acoustic sensors; (a) s1, (b) s2, (c) s3.

The main task was to find the dependence of the wall temperature on the frequency of acoustic oscillations. The calculation of the correlation coefficient says k = 0.45, that such a relationship exists. Such a dependence was found by isolating the frequencies at which the signal power was maximal and the thermocouple measurements installed on the laboratory bench. Dependence on the frequency of sound vibrations and the wall temperature is linear with the help of OLS. The graph of the dependence of the wall temperature on the frequency of acoustic oscillations is shown in figure 10.

As can be seen from the graphs, the values of the maximum frequency powers will shift to low frequencies with increasing wall temperature, and the line will decrease with increasing temperature, as shown in figure 10. In the future, to predict the wall temperature from the frequency of sound vibrations at normal and other pressure it is necessary to use more complex regression models.



(a) s1 (b) s2



(c) s3

Figure 9. Power spectra for signals from acoustic sensors; (a) s1, (b) s2, (c) s3.

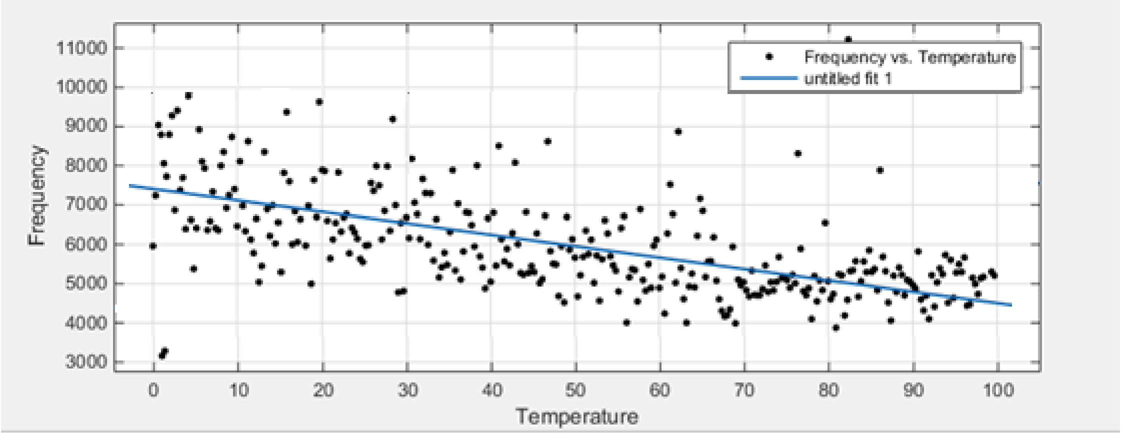


Figure 10. Dependence of the wall temperature on the frequency of acoustic oscillations.

4. Concluding remarks

The prospect of this development is the possibility of using it in the educational process to demonstrate the processes that arise during a heat exchange crisis, as well as when debugging algorithms and machine learning methods for predicting boiling regimes. The experiment showed that acoustic control systems for the heat transfer crisis for thermophysical systems can be realized, and it is also possible to create algorithms for indirect measurement of the temperature of the shell of heating elements.

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