Diagnostics of coolant boiling onset based on the analysis of fluctuations of thermohydraulic parameters

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Abstract. When operating heat-exchange facilities, it is of interest to develop methods of diagnostic and prediction for coolant boiling onset. It is known that the surface temperature of a heating element always has stochastic oscillations around an average value, the analysis of such fluctuations will make it possible to predict the change in the heat transfer regimes. This paper presents the results of an experimental study of temperature fluctuations for an inertial heater and using of method of diagnostic are based on statistical and frequency analysis of temperature fluctuations. It is shown that there is a correlation between the frequency characteristics of heater temperature fluctuations and oscillations in the thermohydraulic parameters of the coolant (temperature, flow, pressure). The obtained results will find application in the development of an automated system for diagnostics the coolant boiling onset in power facilities.

1. Introduction

Nucleate boiling heat transfer is an effective heat transfer mode and it is widely used in various industrial and commercial systems: nuclear and renewable energy, water desalination systems, heat exchangers, chemical industry, cooling systems of microelectronics, etc. The importance of nucleate boiling arises from its ability to remove more quantities of heat per unit time and area from a hot surface than during the other heat transfer modes. However, the boiling heat transfer has an upper limit, i.e. the critical heat flux (CHF). As soon as the critical heat flow is reached, the nucleate boiling is changed to the film boiling mode, overheating the boiling surface. This may lead to premature failure of the equipment. Therefore, diagnostics the heat transfer regimes are interesting in the design and operating heat exchange equipment.

Boiling modes were mostly investigated through visualization methods using high-speed video cameras. The optical images of vapor bubble dynamics were obtained for entire boiling regimes including natural convection, nucleate boiling, transition boiling, and film boiling during the one of the earliest study in this field by Gaertner [1]. More recent studies have used laser interferometry and infrared (IR) thermometry as other visualization techniques. For example, Gao [2] has used the laser interferometric method and high-speed camera techniques to study dynamic characteristics of the microlayer beneath an ethanol vapor bubble during nucleation process. Surtaev at al. [3] have demonstrated the efficiency of using the high-speed IR thermography technique to obtain the
nonstationary temperature field and integral characteristics of heat transfer at boiling on a thin-film heater. The results of developing a machine learning methodology for investigating boiling processes in real time are presented in [4]. The paper proposes to use neural networks to measure bubble growth time, bubble period, and nucleation site density directly from the radiation recorded by the high-speed infrared camera. However, identification of boiling modes based on visualization data is associated with high costs for organizing optical access to the boiling system and is not applicable in complex industrial installations.

Boiling processes are always accompanied by an intense noise sound that can be heard and easily detected by invasive and non-invasive methods. The advantage of these methods lies in the absence of the necessity to provide optical access to the system during measurements. For example, Tang et al. [5] analyzed the acoustic signals of sound emission in subcooled pool boiling with a small plate heater using sound pressure level (SPL), fast Fourier transform and discrete wavelet transform (DWT). It is shown that during the transition from the nucleate boiling to the microbubble emission boiling or transition boiling, the SPL exhibited a step increase, which, combined with a DWT analysis, could be used to identify boiling modes. In the study [6], the acoustic emission measurements were analyzed for each boiling regime and characterized by their statistical and spectral parameters. It is shown that acoustic emission signals have low-frequency components in nucleate boiling and high-frequency components in film boiling mode. The paper also notes a unique peak in the spectrum of acoustic emission signal at boiling crisis. The paper [7] presents the identical result. A sudden shift in peak frequency of acoustic emissions when the system transitions from stable nucleate boiling regime to CHF at boiling crisis is observed.

It is known that operating parameters such as the surface temperature of the heating element, heat flux, pressure and flow rate, regardless of the heat exchange mode, always have stochastic fluctuations near the average value in a stationary mode. The analysis of these parameters is of interest in identifying heat transfer regimes. Wojtasik, et al. [8] performed a statistical analysis of the time evolution of heat flux based on probability density functions (PDFs) to investigate the influence of various operating parameters on the boiling behavior. This analysis is shown to represent an effective tool to characterize the type of boiling by defining the shape of the curve. In work by Lu et al. [9] was noted that during the transition from the convective heat transfer regime to nucleate boiling, the dispersion of temperature fluctuations reaches a local maximum. The authors of the work [10-12] showed that in various liquids before the onset of the transition process, the low-frequency spectrum of temperature fluctuations becomes close to the flicker noise spectrum. These results suggest that statistical and frequency analyses of fluctuations of the coolant thermohydraulic parameters will allow us to diagnose the onset of boiling.

Diagnostics methods for changing heat transfer regimes based on the analysis of temperature fluctuations of the heat transfer surface of heaters with small thermal inertia (thin platinum wires) are described in previous works of the authors [13, 14]. The methods were tested experimentally for various fluids (liquid nitrogen, saturated water, subcooling water) both under pool boiling conditions and during forced movement. This work is devoted to testing the applicability of diagnostic methods for an inertial heater.

2. Statistical and frequency analysis methods

During statistical analysis, it was found that there is always an asymmetry in the histograms of the temperature distribution. As a characteristic criterion of asymmetry $A_s$ has chosen an absolute value of the ratio of the third central moment $\mu_3$ to the third power of the standard deviation:

$$A_s = \left| \frac{\mu_3}{\sigma^3} \right|$$

In the transition regime, which is accompanied by a significant increase in the heat transfer coefficient, there is a local maximum in this criterion.

For the frequency analysis, the amplitude spectra of fluctuations $\psi(\nu)$ were calculated by the fast Fourier transform of the temperature fluctuations of the heat transfer surface. All amplitude spectra were approximated by a power function with an exponent $\alpha$:
\[ \psi(\nu) = \frac{C}{\nu^\alpha} \]  

and a Lorentz function with a parameter \( \beta \):

\[ \psi(\nu) = C \frac{|\beta|}{\beta^2 + \nu^2} \]  

Detailed information about the methods can be found in the previous works of these authors [13, 14].

3. Experimental setup
The experimental setup was designed to conduct an analysis of fluctuations in the surface temperature of an inertial heater under pool boiling conditions. The setup scheme is shown in figure 1. The setup consists of a LOIP LT-424B thermostat, an automated control system and working area. The liquid temperature in the working volume of the thermostat (24 liters) was set by the control unit 4 and maintained with an accuracy of 0.1 K. The working area was a cylindrical heater with a length of 160 mm and a diameter of 6.5 mm. The shell of the working area is made of stainless steel. The working area was positioned horizontally relative to the gravity field and heated by Joule heating during the passage of alternating electric current through it. All experiments were conducted in saturated and subcooled water at atmospheric pressure. Micro thermocouples K-type was attached to the heater surface. During the experiments, the value of the transport current, the voltage drop across the heater, and the surface temperature of the heater were measured.

![Figure 1. Experimental setup: 1 – thermostat, 2 – heater, 3 – temperature sensor, 4 – thermostat control unit, 5 – working area, 6,7 – thermocouples, 8 – measuring unit, 9 – computer.](image)

The obtained data were used to calculate the heat flux density \( q \) and superheat of the heater surface relative to the liquid temperature in the working volume \( \Delta T \). The heat flux density determination error did not exceed 10%, and the absolute error of \( \Delta T \) was less than 0.5 K.

4. Results
Initially, the boiling curves based on the values of the working area superheat and heat flux averaged for each series of experiments were constructed. Figure 2 shows boiling curves during the pool boiling conditions obtained from the time-average values of superheat and heat flux for two cases: working area was performed as a thin wire and an inertial heater. Here and further, all results for boiling on a thin wire are taken from the previous studies of the authors [14].
Figure 2. The boiling curves:

(a) – thin wire (points 1–6 correspond steady-state convective heat transfer regime; points 8–11 correspond steady-state nucleate boiling regime; point 7 presents the transition from the convective to the nucleate boiling regime) [14];

(b) – inertial heater (points 1–6 correspond steady-state convective heat transfer regime; points 8–12 correspond steady-state nucleate boiling regime; point 7 presents the transition from the convective to the nucleate boiling regime).

The lines in figures depict: 1 – convective heat transfer given by equations (4); 2 – boiling heat transfer given by equations (5).

Figure 2 presents the result of calculating the convection heat transfer coefficient according to Kutateladze [15]:

$$Nu_d = 0.54Ra^{0.25},$$

where $d$ is the diameter of the platinum wire or inertial heater and it’s used as the characteristic scale of the process.

For the case of saturated water boiling, the heat transfer coefficient was determined as follows:

$$h_d = A \cdot \frac{q_{av}^m}{\Delta T_{av}},$$

where the coefficients are $A = 0.6$ (a) and $A = 1.15$ (b), $m = 0.8$ [16]. Detailed calculations are given in [14].

As it can be seen from the figure 2, the results of the calculations are in good agreement with the experimental data.

The change in the slope of the approximating lines is associated with an increase in the heat transfer coefficient and the development of boiling. The points are numbered for easy interpretation of the analysis results.

The results of determining the asymmetry coefficient of the distribution of heat-transfer surface fluctuations are shown in figure 3.
Figure 3. The dependencies of asymmetry coefficient $A_s$ on the heat flux: (a) – thin wire [14]; (b) – inertial heater.

Both dependencies in figure 3 have a local maximum ((a): point 7; (b): point 8) in the region of the onset of the transition process from convection to nucleate boiling.

The results of statistical analysis are presented below. Figure 4 shows the dependencies of the exponent $\alpha$ in the approximation function (2) of the temperature fluctuation spectra on the heat flux.

Figure 4. The dependence of the exponent $\alpha$ in approximation function (2) on the heat flux: (a) – thin wire [14]; (b) – inertial heater.

In this case, the dependencies again have a local maximum ((a): points 5–6; (b): points 6–7) in the region of the onset of the transition process from convection to nucleate boiling.

Figure 5 shows the dependencies of the parameter $\beta$ in the approximation function (3) of the temperature fluctuation spectra on the heat flux.
Figure 5. The dependencies of the parameter $\beta$ in approximation function (3) on the heat flux:
(a) – thin wire [14]; (b) – inertial heater.

As can be seen from figure 5 (a), under the convection and nucleate boiling (points 1–4 and 9–11), the values of the parameter $\beta$ are several orders of magnitude higher than the values in the transition region (points 5–8). It is connected with high sensitivity to small perturbations for a non-inertial heater, which is expressed in a sharp dip at points 5–8, which belong to the unstable transition mode. This effect is not observed on an inertial heater. In addition, the expression (3) is derived in the approximation of a small number of Bio, but it is not correct for an inertial heater.

Thus, it is relevant to apply techniques based on frequency analysis to diagnose boiling onset on the surface of non-inertial heaters. The parameters $\alpha$ and $A_s$ are appropriate for diagnosing the onset of boiling on the surface of inertial heaters.

In addition, the paper [17] shows the possibility of performing the Fourier transform using software and hardware package “UMIKON” in real time. Thus, the obtained results can be used in the development of an automated system for diagnostics of the onset of coolant boiling in heat exchange systems.

5. An experimental study using flow loop
It is worth to investigate not only temperature fluctuations for diagnostics of transients but also other related parameters. For example, in [18] it is shown that there is a correlation between temperature fluctuations and sound noise that attend the process of subcooled boiling.

To search for a correlation between the characteristics of fluctuations in the heater temperature and the coolant thermohydraulic parameters (pressure and flow), an experimental flow loop was created. The flow loop has two circulation lines for conducting experiments with forced (Reynolds numbers up to $5 \cdot 10^4$) and natural circulation. The total volume of distilled water in the loop is 800 liters. The pressure in the loop is atmospheric.

In the transparent working volume are removable test sections with heaters. In this study heaters with a diameter of 6.5 mm and a length of 160 mm were used. The heat flux from the surface of the heaters varied in the range from 0 to $5 \cdot 10^5$ W/m², which made it possible to achieve the nucleate boiling of the coolant.

The flow loop is equipped with various types of temperature, pressure and flow sensors. The arrangement of the sensors is shown in figure 6. To control the temperatures of the heaters and coolant in the working volume, thermocouples were used. More detailed information about the experimental flow loop is presented in work [19].
Figure 6. The arrangement of sensors:
G - flow meters, T - thermal sensors, P - pressure gauges.

In the experiments, fluctuations of superheat of the heater surface relative to the coolant temperature in the working volume were measured. An example of the amplitude spectrum of such fluctuations is shown in figure 7(a). As can be seen from the figure, in the transition regime the Lorentz spectrum is achieved. Data were obtained in experiments with forced water circulation.

Figure 7. The amplitude spectrum:
(a) - temperature fluctuations; (b) - pressure fluctuations.

Also, in this study, a statistical and frequency analyzes of fluctuations of pressure, flow, and temperature of the coolant were carried out. An example of the amplitude spectra of the pressure of the coolant is shown in figure 7(b).

The obtained amplitude spectra are qualitatively similar to the spectrum of temperature fluctuations of a heater surface.

At present, there are a number of works devoted to the study of the correlation between thermohydraulic regime parameters and neutron fluxes. For example, [20] presents the results of a thermohydraulics surveillance of pressurized water reactors by experimental and theoretical investigations of the low frequency noise field. The paper shows that the space dependent neutron noise effects caused by the coolant boiling were observed in experiments and declares the possibility to detect subcooled boiling in a PWR via neutron noise signals. Further investigations of the effect of coolant fluctuations on neutron fluxes are presented in [21,22]. The papers identify the characteristic features of
neutron flux noise caused by fluctuations in the parameters of the coolant in the VVER core and select the simplest method for monitoring the state of the coolant based on the analysis of neutron flux fluctuations. The combination of various diagnostic methods will improve the efficiency of boiling detection and the safety of equipment operation.

6. Conclusion
The applicability of the frequency and statistical methods of analyses for the diagnostics of coolant boiling onset on the surface of inertial heaters is tested. A correlation was found between the frequency characteristics of fluctuations in the temperature of the heater and fluctuations in the coolant thermohydraulic parameters.

The obtained results will find application in the development of an automated system for diagnosing the coolant boiling onset in heat-exchange facilities.

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