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Forecasting of Heat Carrier's Boiling Regime Due to Fluctuation Analysis of Heater Surface Tempereature

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Abstract. In the operation of water cooled nuclear reactor and other heat exchange installations have importance predict a heat transfer crisis and boiling onset. The paper presents a method for predicting changes in heat transfer regimes in power energy equipment. The technique is based on the amplitude-frequency analysis of temperature fluctuations of the heater surface. It was found experimentally that in the region of heat transfer regime change (from convective to nucleate boiling or from nucleate boiling to film boiling) the fluctuation spectrum is close to flicker noise.

Keywords: Boiling, fluctuations, amplitude-frequency analysis, flicker noise, diagnostic of boiling regimes.

1. Introduction

Nucleate boiling is widely used as an efficient method of heat transfer in power equipment cooling systems, therefore, diagnostic of boiling regimes is important practical task. Working with heat exchanging equipment, it is of interest to predict the boiling onset of the coolant and a heat transfer crisis. This problem has a great importance in the operation of VVER-type nuclear reactors. Bibliographic analysis shows that, despite on the progress made in diagnosing transient regimes using acoustic methods, their practical application is difficult to implement and requires the use of special equipment. There are other methods, that use the analysis of temperature fluctuations of heater surface for diagnostics [2-5]. This paper presents a generalized method for predicting the heat transfer regime changes (from convection to nucleate boiling and from nucleate to film mode) base on an analysis of the amplitude-frequency characteristics of temperature fluctuations of the heater at the forced movement of the coolant.

In the previous works [1, 2], where the boiling of a liquid was studied, it was found that there are various heat exchange modes: single-phase convective mode, nucleate, transition, and film boiling. The authors of [3] proposed to additionally highlight the areas of transient modes: from purely convective (single-phase) mode to bubble mode and from bubble mode to film boiling. Usually, the classification of heat transfer modes is carried out according to average values ofsuperheating of the heater and heat flux from its surface based on an analysis of the boiling curve. However, it is necessary to fully investigate the boiling curve, which is not known a priori. The acoustic method is free from this disadvantage. In [4], on the basis of a large amount of experimental data on the spectra of sound vibrations and noise pressure, methods are proposed for predicting the heat transfer crisis during boiling. Information on methods for determining the onset of boiling and diagnosis of transient modes of heat transfer are poorly presented in the literature.

2. Experimental installation

The methodology of performed studies of temperature fluctuations of a heater at pool boiling of liquid is presented in [4]. To carry out experiments in the case of forced movement of water that is underheated to the saturation temperature, the authors created a new experimental system (Fig. 1).

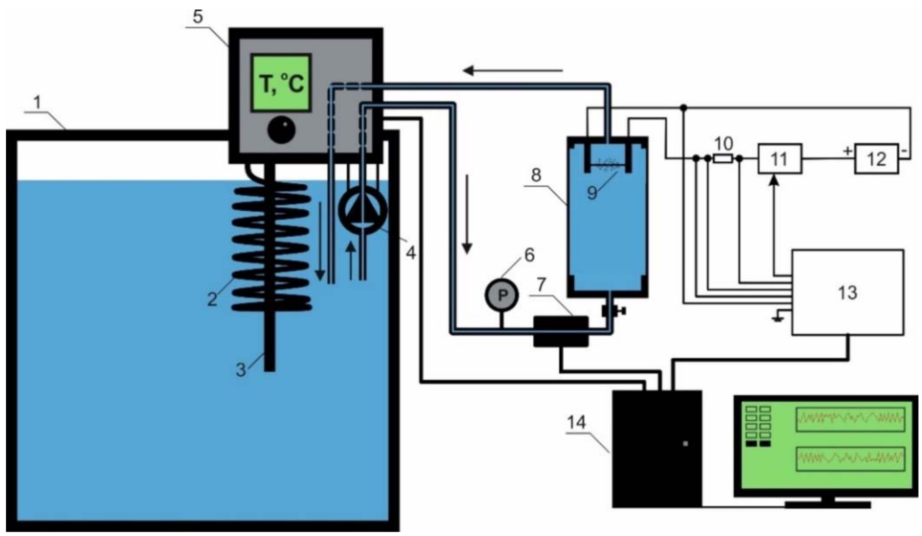

Fig. 1. - Scheme of the experimental system. 1 - thermostat, 2 - heater, 3 - temperature sensor, 4 - pump, 5 - thermostat control unit, 6 - pressure gauge, 7 - flowmeter, 8 - working volume, 9 - working section, 10 - exemplary resistance, 11 - voltage stabilizer, 12 - power supply, 13 - device to control experiments with the ADC, 14 – computer.

The experimental system consists of a thermostat with a control unit that allows one to maintain with high accuracy the desired temperature and water flow. The working volume is a vertical sealed transparent cylinder with a height of $500\,mm$ and a diameter of $50\,mm$. A platinum wire with a diameter of $100\ \mu m$ and a length of $15-20mm$ was used as a working sample for the study of heat transfer.The wire was fixed in the working volume horizontally and located perpendicular to the fluid up-flow (Fig. 1). The working area simultaneously served as a heater and a resistance thermometer. To determine fluctuations of fluid flow rate through the working volume, an additional flow meter based on the Venturi tube was used with the ability to record instantaneous flow rates. The installation was used to study temperature fluctuations of the heat-transfer surface and the flow rate of the liquid at various heat exchange conditions.The experiments were conducted in intervals of underheated water at the entrance to the working volume from $5 \text{ to } 40\,K$ and the flow rate from $4 \text{ to } 12\,l/\min$. All experiments were conducted at pressures close to atmospheric.

3. Experimental results

During the experiments, the following were measured: instantaneous values of the voltage drop at the working section and exemplary resistance with a sampling frequency up to 1kHz; values of fluid flow rate and water temperature at the entrance to the working volume with a sampling frequency of up to $1 Hz$. Further measured data was used to calculate instantaneous values of heater surface superheat and heat flux into the liquid at various flow rates and underheating of water to the saturation temperature.

A typical pool boiling curve (dependence of time-averaged heat fluxes q on superheating of heat transfer ΔT) of saturated water is shown in fig. 2. As it can be seen from the figure, three areas can be distinguished on the pool boiling curve: convective heat exchange mode (points 1-3), the transition region (4-5) and the nucleate boiling region (6-8).

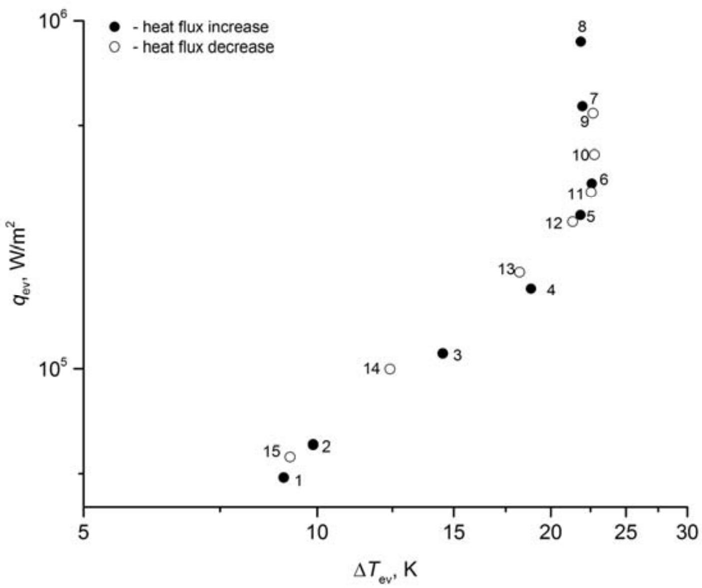

Fig. 2. The boiling curve of saturated water at atmospheric pressure

For each series of experimental data, an amplitude-frequency characteristic of superheating fluctuations was obtained using the fast Fourier transform.

$$\Psi_j = \mathrm{Re}\left[\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}\left(\Delta T_k \cdot e^{2\pi i \frac{j}{N} k}\right)\right]$$

As an example the amplitude of superheat fluctuations Ψ as a function of frequency $\nu$is presented in fig. 3. This data corresponds to the end of the convective heat transfer regime (point 3 in Fig. 2). The amplitude-frequency characteristics obtained in different heat transfer modes in the low frequency range were approximated by a power function of the form $\Psi(\upsilon) = C \cdot \nu^{-\alpha}$. At frequencies above $10\,Hz$ amplitude-frequency characteristics always corresponded to the spectrum of white noise and were not analyzed in this work.

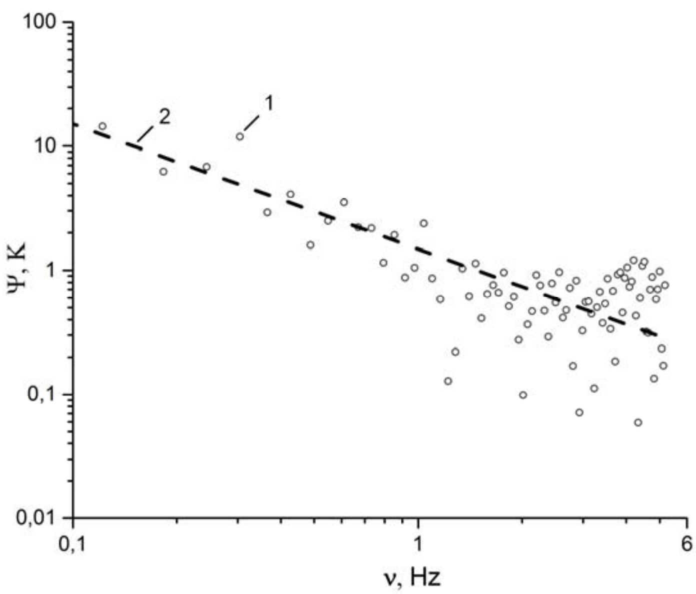

Fig. 3. The dependence of the amplitude of fluctuations on the frequency for liquid nitrogen in the region of convective heat transfer: 1 - experimental data, 2 - approximation by function.

The dependence of approximating function exponent on the average heat flux q_{ev} is shown in Fig. 4. Three characteristic maxima on the exponent curve α as a function of the heat flux q were found.

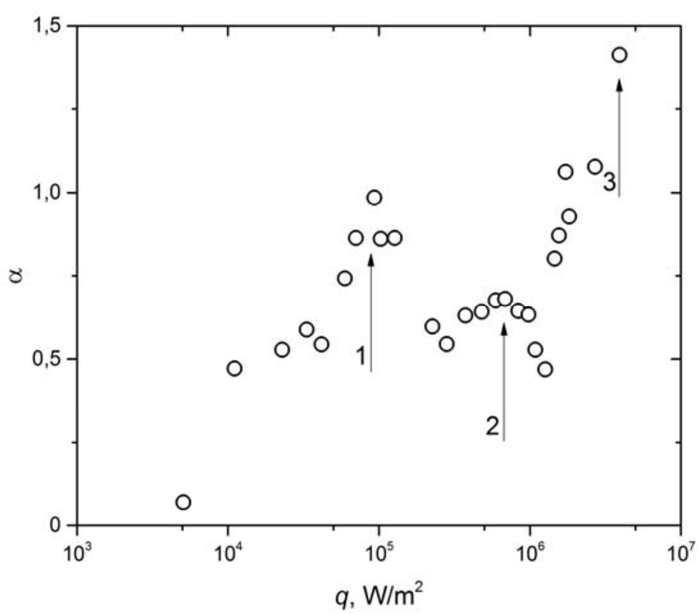

Fig. 4. The dependence of the exponent on the value of the warm flow at underheating of 14.9 K and flow rate of 4.7 l / min

The first maximum is presumably associated with the transition from laminar to turbulent flow regime in the working volume. This is confirmed by visual observation of the intensive mixing of the flow in the working volume. At the same time, the wire temperature was less than the saturation temperature. The second maximum corresponds to the onset of nucleate boiling (transition region from convection to nucleate boiling), which is confirmed visually. Similar maximum in a transition area between convection and nucleate boiling is also observed in work aimed to study amplitude-frequency analysis of superheat fluctuations at pool boiling [3-4]. The third maximum corresponds to the transition from nucleate to film boiling (heat transfer crisis). When a heat transfer crisis occurs, the value of exponent $\alpha(q_{ev})$ rapidly increased reaching the value closed to 1. The theoretical explanation of this maximum is widely presented in the literature [5-6].

4. Conclusion

Universal technique for analysis of the boiling occurrence and transition to film boiling at forced movement of saturated and underheated water has been developed. The technique is based on the analysis of amplitude-frequency characteristics of temperature fluctuations.It worth to note that in a transient regime the maximum of approximation function exponent is always observed. Based on performed work, it is possible to conclude that a diagnostic system for predicting the boiling of the coolant and the transition to film boiling (heat transfer crisis) can be developed.

References

[1] B.M. Dorofeev, V.I. Volkova, Acoustic Method of Investigation of the Process of Boiling // High Temperature. Vol. 43, No. 4, 2005, pp. 620–627.

[2] F. Lu, X.F. Peng, B. Bourouga, Nucleate Boiling Modes of Subcooled Water on Fine Wires Submerged in a Pool // Experimental Heat Transfer, Vol. 19, 2006, pp. 95-111.

[3] V.I. Deev, K.V. Kutsenko, A.A. Lavrukhin et al., Frequency analysis of fluctuations of the temperature of a heater and of audible noise in boiling used for the diagnostics of the changes in the heat exchange regimes // Thermal Engineering, Vol. 61, No. 8, 2014, pp. 590–593.

[4] B.V. Balakin, M.I. Delov, K.V. Kutsenko et al., Analyzing temperature fluctuations to predict boiling regime // Thermal Science and Engineering Progress, Vol. 4, 2017, pp. 219-222.

[5] V.N. Skokov, V.P. Koverda, A.V. Vinogradov et al, Low frequency fluctuations with 1/f α power spectrum in transient modes of water boiling on a wire heater // High Temperature, Vol. 48, 2010, pp. 706–712.

[6] V.N. Skokov, V.P. Koverda, A.V. Reshetnikovet et al., 1/f noise and self-organized criticality in crisis regimens of heat and mass transfer // International Journal of Heat and Mass Transfer, Vol. 6, 2003, pp. 1879-1883.