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1/*f* noise and self-organized criticality in crisis regimes of heat and mass transfer

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Abstract

Thermal fluctuations under the transition from nucleate to film boiling of water on a wire heater and fluctuations of jet form during an outflow of superheated liquid from a pressure vessel were experimentally investigated. It has been found that power spectrum of the fluctuations has got a low frequency component corresponding to a $1/f$ law (flicker noise).

The effect given is connected with the occurrence of nonequilibrium phase transitions in the systems: a crisis of heat transfer under the transition from nucleate to film boiling and a crisis of a flow in boiling-up of superheated liquid jet.

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1. Introduction

Stochastic processes whose most of power is in low frequency fluctuations are observed in systems of different nature. From the mathematical standpoint it looks like a power low frequency dependence of spectral density of fluctuations: $S \sim 1/f^{\alpha}$. In the case of α close to unity fluctuation processes bear the name of $1/f$ noise (or flicker noise). In these processes a transfer of power from small-scale motions to large-scale ones takes place. In contrast with conventional Gaussian random processes flicker noise is characterized by a presence of power law distributions. It means a possibility of catastrophic outliers.

$1/f$ noise originally discovered in radiophysics devices is observed in systems of different nature: in statistics of natural and technological catastrophes, the light from quasars, the intensity of sunspots, traffic flows, music, e.g. [1,2]. The number of examples may be gone on. Flicker noise was revealed by the authors of the present paper under the conditions of a changeover of nitrogen boiling regimes on the surface of current-carrying thin films of high temperature superconductors [3,4], of water film boiling [5,6], of oscillatory combustion regimes [7], electric arc discharges [8]. In spite of a rather wide prevalence of flicker noise and of more than 70 years history of its investigations up to now there is no conventional theory of the phenomenon. To account for flicker noise the various models are used in different processes.

Interest in $1/f$ noise has revived in recent years in connection with the discovery of self-organized criticality [9]. In self-organized criticality a system comes to a critical behavior during its evolution. The critical state does not require fine tuning of the governing parameters and is one of the main states of a system. At present the theory of self-organized criticality describing avalanche dynamics is deeply developed and has a long way from the completeness.

2. Self-organized criticality and $1/f$ noise under intersections of nonequilibrium phase transitions

In Refs. [4,6–8] a phenomenological theory of the initiation of $1/f$ noise and of self-organized criticality

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Nomenclature

f	frequency
S	power spectral density
q_h	heat flux
q_m	flow rate
Φ	potential of a system
ϕ, ψ, u, v	stochastic variables (order parameters)

was suggested. According to the theory $1/f$ noise and a critical behavior results from an intersection and interaction of different nonequilibrium phase transitions. In the case of two phase transitions the simplest set of equations predicting flicker noise takes the form:

$$\begin{aligned}\frac{\mathrm{d}\phi}{\mathrm{d}t} &= -\phi\psi^2 + \psi + \Gamma_1(t),\\ \frac{\mathrm{d}\psi}{\mathrm{d}t} &= -\phi^2\psi + \lambda\phi + \Gamma_2(t).\end{aligned} \tag{1}$$

The ϕ and ψ are the dynamical variables (order parameters), Γ_1, and Γ_2 are Gaussian δ-correlated noises (white noise). The parameter $\lambda > 1$ is connected with the availability of macrofluxes in the system (nonpotentiality of the system). The lumped system (1) permits the generalization to spatially distributed systems [6,8]:

$$\begin{aligned}\frac{\mathrm{d}\phi}{\mathrm{d}t} &= D\frac{\partial^2\phi}{\partial x^2} - 2\phi\psi^2 + \psi + \Gamma_1(t),\\ \frac{\mathrm{d}\psi}{\mathrm{d}t} &= -2\phi^2\psi + \phi + \Gamma_2(t),\end{aligned} \tag{2}$$

where D is the diffusion coefficient. The set of Eq. (2) describes random walks in the potential:

$$\Phi = \phi^2\psi^2 - \phi\psi + \tfrac{1}{2}D(\nabla\phi)^2. \tag{3}$$

It is easy to understand the physical meaning of the potential (3) if we perform a linear transformation of the variables: $u = \phi + \psi$; $v = \psi - \phi$. In the new variables the expression for potential will take the form:

$$\begin{aligned}\Phi(u,v) = {}& u^4 - u^2 + v^4 + v^2 - 2u^2v^2 + \tfrac{1}{2}D(\nabla u)^2\\ &+ \tfrac{1}{2}D(\nabla v)^2 - D\nabla u\nabla v.\end{aligned} \tag{4}$$

The potential (4) is a conventional expression of the intersection and interaction of a subcritical (a first-order phase transition with the order parameter u) and supercritical (a second-order phase transition with the order parameter v) phase transition in the Landau mean–field theory. The potential has two hyperbolic valleys and a saddle point at zero. Notice that the supercritical phase transition means a localization of the order parameter. The random walk in the potential (3) or (4) can lead to the self-organization of a critical state. The power law behavior of the spectra points to it.

Hence, the suggested model predicts that an external white noise can induce a critical behavior characterized by large-scale outliers in a complex system with nonequilibrium phase transitions.

The transition from nucleate to film boiling is a typical first-order nonequilibrium phase transition (a changeover of steady states in a system far from thermodynamical equilibrium). In which case the N-shaped boiling curve may be considered by analogy with a thermodynamics equations of state under the conditions of ordinary "equilibrium" phase transitions. A similar synergetic approach to stability analysis of different boiling regimes was successfully used in [10,11]. This approach was based on the method of Lyapunov functional. In [12–14] the autowave processes of a vapor film propagation along a wire heater were investigated. Thermal fluctuations with the spectrum of $1/f$ type were experimentally revealed under the transition from nucleate to film boiling of water [4,7].

Besides the transition from nucleate to film boiling the process of boiling-up of superheated liquid jets may by classified as a nonequilibrium phase transition in boiling systems. Outflow of boiling-up liquid from a pressure vessel through short channels is accompanied by a strong deviation of flowing medium state from

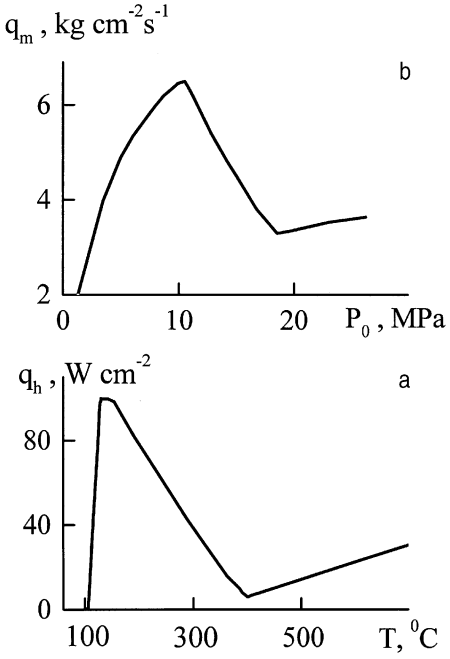

Fig. 1. Boiling curve of water (a) and flow rate characteristic in boiling of superheated water jet (b).

thermodynamic equilibrium. It causes a complex hydrodynamic flow picture and the difficulties of an analytical description of the process.

In Fig. 1a a boiling curve of water in a pool is shown [15]. Fig. 1b presents a flow rate of superheated water under the condition of steady outflow through a short channel into the atmosphere. The initial states of water correspond to the saturation line [16]. One can see that the flow rate characteristic of boiling-up liquid can be considered as an analogy with the boiling curve. As for the boiling-up itself in the jet it is a nonequilibrium phase transition.

The aim of the paper is to study fluctuations in crisis regimes of boiling on a wire heater and in jets of boiling-up liquids by experiment.

3. Experiment

3.1. A transition to film boiling on a wire heater

The experiments were performed with distilled water in which a platinum wire heater 100 μm in diameter and about 2 cm long was immersed. In the experiments, the oscillations of voltage drop and transport current due to boiling were recorded. In the case of film boiling on the horizontally arranged heater, the vapor film spread to a length of about 1.5 cm. The current–voltage characteristics of the heater had a typical form with hysteresis [12,13]. The power spectra were determined from the measured time series by the method of fast Fourier transform. In the experiments with horizontally oriented heater the power spectra had a Lorentz form: $S \sim 1/(f_0^2 + f^2)$ with a typical horizontal shelf in the low frequency region ($f < f_0$).

A different pattern was observed with a vertical arrangement of the heater. A center of film boiling appeared on a weak spot of the heater wire and spread through a distance of the order of 1 cm. A cone-shaped vapor jet rose from the bottom of the hot zone along the wire. The length of the hot zone fluctuated markedly. The external appearance of the cone-shaped vapor jet resembled a sand pile turned upside-down [9]. As the power input was increased the longer became the size of the hot zone. Fig. 2 gives the current–voltage characteristic of a vertically arranged heater. The transition from nucleate to film boiling (straight line AB in Fig. 2) occurred along the load line of the electric circuit defined by the equation $U = E - IR_0$, where E is the source voltage, I is the transport current, and R_0 is the ballast resistance. The reverse transition from film to nucleate boiling occurred along the line CD in Fig. 2.

The power spectra were determined from the experimental time series. Fig. 3 gives power spectral density of the fluctuations under the transition to film water boiling on a vertical wire heater. In a wide range of power input the power spectra had the form of $1/f^{\alpha}$ with the exponent α close to unity (Fig. 3, plot 1). Near a loss of film boiling stability at the point C (see Fig. 2) the fluctuations of the hot zone boundaries were observed. At the same time an irregular movement of the film boiling zone as a whole was happened. In this case the exponent α was close to two (Fig. 3, plot 2).

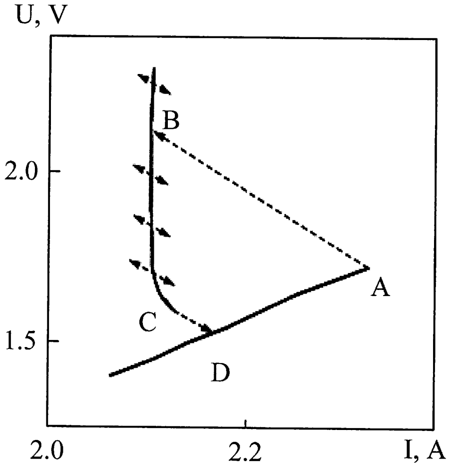

Fig. 2. The current–voltage characteristic of a vertically oriented wire heater in boiling crisis of water.

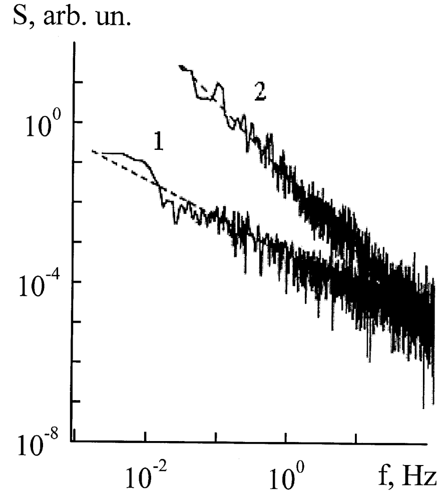

Fig. 3. Power spectral density of the fluctuations under the transition to film water boiling on a vertical wire heater.

Thus, the intensive thermal oscillations with the power spectrum of $1/f^{\alpha}$ type were observed under the transition to film boiling regime on a vertical wire heater.

3.2. Boiling-up of superheated liquid in a jet

The experiments were carried out on a laboratory setup, which ensured a steady regime of outflow of superheated liquid into the atmosphere for some decades of seconds. Since water has rather high parameters of the thermodynamic critical point, freon having the low boiling temperature (23 °C) was used as a working model fluid. It made it possible to simplify our experiments. The working chamber was a cylinder steel barrel with wound electric heater. Its volume was about 600 cm^3. In experiments a short cylindrical channel was used. Its diameter was equal to 0.5 mm, the length was 0.7 mm. The initial pressure P_0 was varied from 0.24 to 2.78 MPa along the saturation line. It corresponded the temperature range $T_0 = 50$–165 °C. Significant superheating in the jet was ensured by the use of short channels with high rates of pressure decrease (about 10^6 MPa/s). For non-high initial parameters (P_0, T_0) the boiling-up was not observed and the shape of the jet was close to a cylindrical one. As the initial temperature (pressure) was increased the individual acts of boiling-up were observed in the jet. Beginning from the temperature $T_0 \approx 90$ °C (or the pressure $P_0 \approx 0.66$ MPa), the main factor affecting the jet shape was intensive volume boiling-up. The jet acquires the shape of a hollow cone. For $T_0 \geqslant 150$ °C, the mechanism of boiling-up became different. In this case the boiling-up was characterized by high intensity and concentration (explosive boiling-up). The explosive boiling-up with a predominance of homogeneous nucleation mechanism can lead to a shift of the intensive vapor generation section inward the channel. In this case the jet shape was close to a parabolic one. The shape of boiling-up jets fluctuated appreciably. In this investigation the fluctuations were studied by photometering of a passed laser beam. The laser beam of diameter about 1 mm (wavelength 0.65 μm) was passed through the jet of escaping fluid. The measurements of laser beam intensity were performed by means of a photodiode with responsivity 0.5 A/W.

The photocurrent fluctuations were measured during passing beam through different sections of the jet in the range from 0 to 10 mm from the boiling-up section. The results given below did not depend on the section.

Under condition of "cool" jet outflow ($T_0 \leqslant 90$ °C) the power spectrum of fluctuations had the form of white noise spectrum with uniform distribution of fluctuation intensity in the band. This spectrum is given in Fig. 4a. With a rise of initial temperature and an onset of volume boiling-up in the jet the low frequency component of the spectrum was increased (see Fig. 4b). In the low frequency band the frequency dependence of power spectral density of the fluctuations was close to $1/f$. As the temperature T_0 in the chamber was increased the section of intensive boiling-up (vertex of the jet cone) approached the channel exit. In doing so the transition boundary between white and $1/f$ noise was shifted in the region of high frequencies. That is the frequency range of flicker noise became wider. For $T_0 \geqslant 150$ °C, under the condition of explosive boiling-up of superheated liquid in the channel flicker noise was observed over more than four decades of magnitude (Fig. 4c). Typical time series of photocurrent fluctuations are given in Fig. 5. They corresponded to the spectrum in Fig. 4c. The lower limit of flicker noise was bounded by the steady-state outflow time of the liquid (the volume of the chamber).

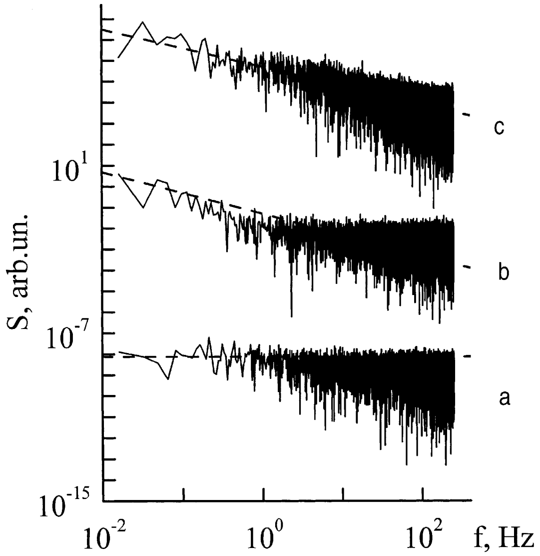

Fig. 4. Power spectral density of the fluctuations in boiling-up of superheated freon jet: (a) "cool" jet, (b) boiling-up behind the exit of the channel, (c) explosive boiling-up in the channel.

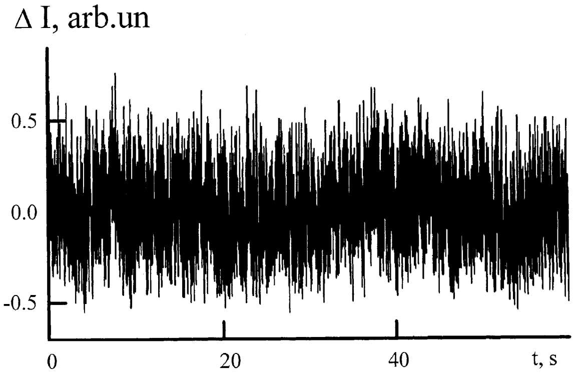

Fig. 5. Intensity fluctuations of laser beam passed through the jet of boiling-up freon-11.

4. Conclusion

Thus, the fluctuations under the transition from nucleate to film boiling on a wire heater and under the conditions of boiling-up of superheated liquid in a jet were experimentally investigated. Both the transitions (the crisis of heat transfer and the crisis of flow) can be considered as nonequilibrium phase transitions in an open system.

The fluctuations with a $1/f$ spectrum (flicker noise) were revealed in crisis regimes of boiling. $1/f$ fluctuations testified to a self-organization of a critical state of a system. The self-organization of a critical state and $1/f$ noise were due to an interaction of nonequilibrium phase transitions with white noise presence. The part of white noise played the random individual processes of vapor bubble formation. One can say that we deal with self-organized criticality induced by white noise.

A random process with $1/f$ spectrum of fluctuations is characterized by an energy transfer from high frequency fluctuations to low frequency ones. It explains the emergence of high-power low frequency oscillations in a system. The oscillations should be taken into account in the designing of jet devices with two phase flows in energetics and to analyze the possible consequences of an accident with local depressurization of apparatuses and pipelines with a hot liquid.

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