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FLICKER NOISE AND SELF-ORGANIZED CRITICALITY IN CRISIS BOILING REGIMES

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The paper describes an experimental study of thermal fluctuations during transition from bubble to film boiling of water on a wire heater and fluctuations of the shape of a superheated liquid jet discharged from a high-pressure vessel. It is found that for a heat-transfer crisis on the wire heater and for intense volume boiling of the superheated liquid jet, the fluctuation power spectrum has a low-frequency component (flicker noise) that diverges under the law $1/f$. This effect is due to nonequilibrium phase transitions in the system: the heat-transfer crisis during transition from bubble to film boiling and a flow crisis during boiling of the superheated liquid jet.

Introduction. Different systems are characterized by stochastic processes in which a considerable portion of energy is expended in larger-scale low-frequency fluctuations. Mathematically, this is expressed by the exponential frequency dependence of the spectral density of fluctuations $S \sim 1/f^\alpha$ (S is the spectral density and f is the frequency). The fluctuation processes are called $1/f$-noise (or flicker noise) if the exponent α is close to unity. In contrast to conventional Gaussian stochastic processes, flicker noise is characterized by exponential distribution laws, which implies the possibility of large catastrophic spikes. It should be noted that $1/f$ noise is observed in different systems [1, 2]. Previously, flicker noise was detected during change of nitrogen boiling regimes on the surface of current-carrying thin-film bridges of high-temperature superconductors [3, 4], in film boiling of water [5, 6], in vibratory combustion regimes [7, 8], and in arc electric discharges [9].

Recently, interest in $1/f$ noise has considerably increased in connection with the discovery of self-organized criticality [10]. In the case of self-organized criticality, the evolution of a system can result in a critical state that does not require fine tuning of the controlling parameters and is a basic state of the system. The theory of self-organized criticality, which describes the dynamics of avalanches, is being actively developed and is still far from complete.

Self-Organized Criticality and $1/f$ Noise during Interaction of Nonequilibrium Phase Transitions. A phenomenological theory of the occurrence $1/f$ of noise and self-organized criticality is proposed in [4, 7–9]. According to this theory, $1/f$ noise and critical behavior result from the simultaneous occurrence and interaction of various nonequilibrium phase transitions. In the case of two phase transitions, the simplest system of equations that predicts flicker noise has the form

$$\frac{d\varphi}{dt} = -\varphi\psi^2 + \psi + \Gamma_1(t), \qquad \frac{d\psi}{dt} = -\varphi^2\psi + \lambda\varphi + \Gamma_2(t), \tag{1}$$

where φ and ψ are dynamic variables (order parameters), Γ_1 and Γ_2 are Gaussian δ-correlated noises (white noise), and the parameter $\lambda > 1$ is related to the presence of macroflows in the system (nonpotentiality of the system). System (1) can be extended to the case of spatially distributed systems [7–9]:

$$\frac{d\varphi}{dt} = D\,\frac{\partial^2\varphi}{\partial x^2} - 2\varphi\psi^2 + \psi + \Gamma_1(t), \qquad \frac{d\psi}{dt} = -2\varphi^2\psi + \varphi + \Gamma_2(t). \tag{2}$$

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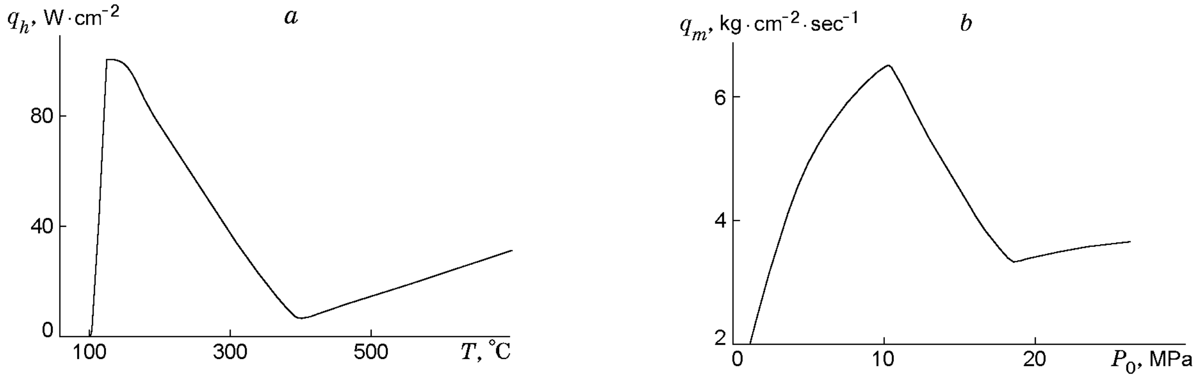

Fig. 1. Curve of water boiling (a) and discharge characteristic for boiling of a superheated water jet (b).

Here D is the diffusion constant. System (2) describes random walks in a system with the potential

$$\Phi = \Phi_0 + \int \left(\varphi^2\psi^2 - \varphi\psi + \frac{1}{2}(\nabla\varphi)^2\right) dx. \tag{3}$$

The physical meaning of the potential (3) is easily revealed when converting to the new variables $u = \varphi + \psi$ and $v = \psi - \varphi$. In this variables, the potential is expressed as

$$\Phi(u, v) = \int (u^4 - u^2 + v^4 + v^2 - 2u^2v^2 + (\nabla u)^2 + (\nabla v)^2 - 2\nabla u \nabla v)\, dx. \tag{4}$$

The representation of the potential as (4) is valid within the framework of the mean field theory for the interaction of a subcritical phase transition (of the first kind) with order parameter u and a supercritical phase transition with order parameter v. We note that the supercriticality of a transition means spatial localization of the corresponding order parameter.

A typical nonequilibrium phase transition (change of steady states of the system away from thermodynamic equilibrium) is transition from bubble boiling of liquids to film boiling. In addition, the boiling of a superheated liquid jet can also be treated as a nonequilibrium phase transition in a boiling system. Figure 1a shows a curve of water boiling in a large volume [11] and Fig. 1b shows a discharge characteristic for steady-state discharge of a superheated water jet through a short nozzles with the initial parameters corresponding to the saturation line [12] (q_h is the heat flux and q_m is the mass flow). From Fig. 1 it is evident that the discharge characteristic of the boiling superheated liquid jet can be regarded as an analog of the boiling curve, and boiling in the jet as a nonequilibrium phase transition.

The present paper describes experimental investigation of fluctuations in the crisis boiling regimes on a wire heater and during discharge of a superheated liquid jet.

Experiment. *Transition to Film Boiling on a Wire Heater.* The experiments were conducted with distilled water, in which a platinum wire heater of 100 μm diameter and about 2 cm length was immersed. In the experiments, we recorded the fluctuations of circuit voltage and transport current due to boiling.

When a site of film boiling occurred on the horizontally placed heater, the steam film extended for about 1.5 cm along the heater. The curves of volt–ampere characteristics were of the hysteresis form. Fluctuation power spectra were determined from the measured time characteristics of the process using a fast Fourier transform. With transition to the film boiling regime on the horizontal heater, the power spectra took the Lorentz form $S \sim 1/(f_0^2 + f^2)$ with a typical ledge in the range of low frequencies ($f < f_0$). A different picture was observed in the case of vertical position of the heater. Having arisen on a weak place of the wire, the film boiling site traveled a distance of about 1 cm. A cone-shaped steam jet arose from the bottom of the hot region along the wire. The length of the hot region fluctuated noticeably. The visual pattern resembled an upturned heap of sand [10]. An increase in heat power input enlarged the film boiling region. Over a wide range of thermal loads, the fluctuation power spectra were of the form $1/f^\alpha$ with exponent α close to 1 (curve 1 in Fig. 2). Immediately before the loss of stability of the film regime, the fluctuations of the boundaries of the hot region were accompanied by irregular motion of the film boiling region as whole. In this case, the exponent α was close to 2 (curve 2 in Fig. 2).

Thus, during transition to the film boiling regime on the vertical wire heater, intense thermal pulsations with a power spectrum of the type of $1/f^\alpha$ are observed.

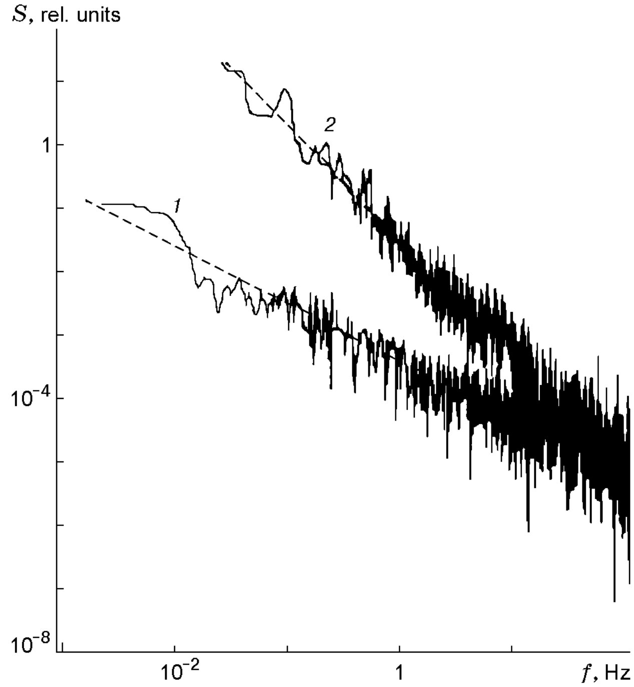

Fig. 2. Fluctuation power spectra during transition to the water film boiling regime on the vertical wire heater for $S \sim 1/f$ (1) and $S \sim 1/f^2$ (2).

Boiling of a Superheated Liquid Jet. The experiments were conducted on a laboratory facility which ensured steady-state discharge of a superheated liquid into the atmosphere for several tens of seconds. Because water has high critical parameters, as the model working medium we used Freon-11 with a low boiling point (23°C) to simplify experiments. The working chamber was a steel cylinder (volume 600 cm^3) with an electrical heater wound on it. In the experiments, we used a short cylindrical channel of 0.5 mm diameter and 0.7 mm length. The initial temperature and the chamber pressure were varied in the ranges of $50°\mathrm{C} \leqslant T_0 \leqslant 165°\mathrm{C}$ and $0.24\ \mathrm{MPa} \leqslant P_0 \leqslant 2.78\ \mathrm{MPa}$, respectively. Considerable superheats in the flow were ensured by using short channels with high rates of pressure decrease (about 10^6 MPa/sec).

At low initial temperature and pressure, boiling was not observed, and the jet shape was nearly cylindrical. With increase in initial temperature and pressure, separate acts of boiling were observed in the jet. Beginning with $T_0 \geqslant 90°\mathrm{C}$ (accordingly, $P_0 \geqslant 0.66$ MPa), the major factor influencing the jet shape is intense volume boiling. Boiling occurred behind the channel exit. In this case, the jet took the shape of a hollow cone. At $T_0 \geqslant 150°\mathrm{C}$, the boiling mechanism changed: the boiling was distinguished by high intensity and suddenness (explosive boiling). Explosive boiling with predominance of a homogeneous nucleation mechanism leads to displacement of the intense vaporization cross section into the depth of the channel. In this case, the jet shape is nearly parabolic.

The shape of boiling jets fluctuated severely. The fluctuations were studied by the method of photometry of transmitted laser radiation. A laser beam of about 1 mm diameter (radiation wavelength 0.65 μm) was passed through the issuing liquid jet. The laser beam intensity was measured by a photodiode with a sensitivity of 0.5 A/W. The signal was digitized by a 12-discharge analog-to-digital converter and stored in the computer memory. Photocurrent fluctuations were measured when the beam passed through various jet segments at distances of 0 to 10 mm from the place of boiling.

Fluctuation power spectra (Fig. 3) were obtained from the experimental data using a fast Fourier transform. For the discharge of a "cold" jet ($T_0 \leqslant 90°\mathrm{C}$), the fluctuation power spectrum had the shape of a white noise spectrum with a uniform frequency distribution of the fluctuation intensity (curve 1 in Fig. 3). When the initial temperature was increased and volume boiling began in the jet, we observed an increase in the low-frequency component of the spectrum (curve 2 in Fig. 3). In the range of low frequencies, the dependence of the spectral density of fluctuation power on frequency is close to $1/f$. With increase in chamber temperature T_0, the intense boiling region (cone apex) came nearer to the channel exit. In this case, the boundary of transition from white noise to $1/f$ to noise shifted toward higher frequencies, i.e., the frequency range of flicker noise extended. Under

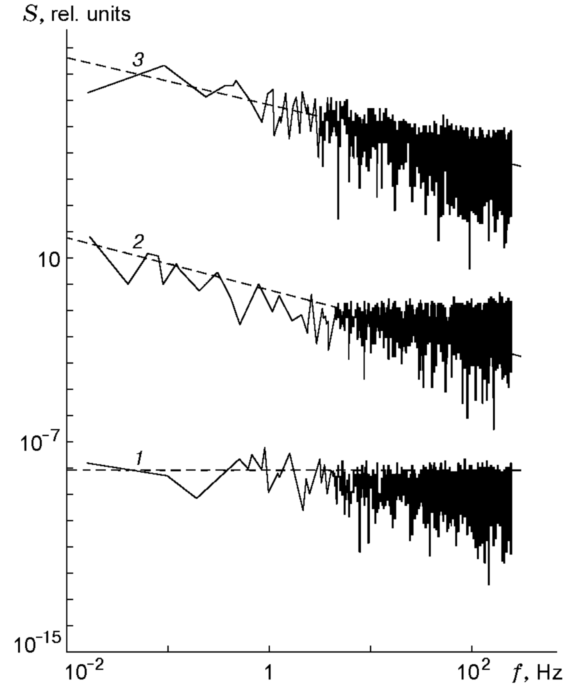

Fig. 3. Fluctuation power spectra for boiling of a jet of superheated Freon-11: 1) explosive boiling in the channel; 2) boiling behind the channel exit; 3) "cold" jet.

conditions of explosive boiling of the superheated liquid in the channel at temperatures $T_0 \geqslant 150°$C, flicker noise was observed in the range of more than a factor of four change in frequency (curve 3 in Fig. 3). The lower time bound of flicker noise is the time of steady-state discharge of the liquid.

Conclusions. Thus, fluctuations during transition from bubble to film boiling on a wire heater and during boiling of a superheated liquid jet were studied experimentally. Both transitions (heat-transfer crisis and flow crisis) can be regarded as nonequilibrium phase transitions in an open system.

For crisis boiling regimes, fluctuations with a $1/f$-spectrum (flicker noise) were detected, which indicate self-organization of the critical state in the system. Self-organization of the critical state and flicker noise are due to nonequilibrium phase transitions in the system in the presence of white noise. The role of white noise is played by random acts of occurrence of vapor bubbles. It can be concluded that here we deal with self-organized criticality induced by white noise.

Stochastic processes with $1/f$-type fluctuation spectra are characterized by energy transfer from high-frequency to low-frequency fluctuations. This explains the occurrence of high-energy low-frequency pulsations in the system, which should be taken into account in designing jet devices using two-phase flows in power installations and in analysis of the possible consequences of accidental depressurization of apparatus and hot-liquid pipelines.

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REFERENCES

1. Sh. M. Kogan, "Low-frequency current noise with a $1/f$-type spectrum in solid bodies," *Usp. Fiz. Nauk*, **145**, No. 2, 285–328 (1985).
2. Yu. L. Klimontovich, *Statistical Theory of Open Systems* [in Russian] "Yanus" Co., Moscow (1995).
3. V. P. Koverda, V. N. Skokov, amd V. P. Skripov, "$1/f$-noise in critical nonequilibrium phase transitions," *Pis'ma Zh. Éksp. Teor. Fiz.*, **63**, No. 9, 739 (1996).
4. V. P. Koverda, V. N. Skokov, amd V. P. Skripov, "$1/f$-noise in nonequilibrium phase transitions. Experiment and mathematical model," *Zh. Éksp. Teor. Fiz.*, **113**, No. 5, 1748–1757 (1998).

5. V. N. Skokov, V. P. Koverda and A. V. Reshetnikov, "Fluctuations with a $1/f^{\alpha}$ spectrum in film boiling," *Pis'ma Zh. Éksp. Teor. Fiz.*, **69**, No. 8, 590–593 (1999).
6. V. N. Skokov, A. V. Reshetnikov, and V. P. Koverda, "Self-organization of critical fluctuations and $1/f$-spectra in crisis boiling regimes," *Teplofiz. Vysok. Temp.*, **38**, No. 5, 786–791 (2000).
7. V. N. Skokov, A. V. Reshetnikov, V. P. Koverda, and A. V. Vinogradov, "$1/f$-noise during interaction of phase transitions," *Teplofiz. Vysok. Temp.*, **39**, No. 2, 316–321 (2001).
8. V. N. Skokov, A. V. Reshetnikov, V. P. Koverda, and A. V. Vinogradov, "Self-organized criticality and $1/f$-noise at interacting nonequilibrium phase transitions," *Physica A*, **293**, 1–12 (2001).
9. V. N. Skokov, V. P. Koverda and A. V. Reshetnikov, "Self-organized criticality and $1/f$-fluctuations in nonequilibrium phase transitions," *Zh. Éksp. Teor. Fiz.*, **119**, No. 3, 613–620 (2001).
10. P. Bak, C. Tang, and K. Tang, "Self-organized criticality," *Phys. Rev. A*, **38**, No. 1, 364–374 (1988).
11. S. S. Kutateladze and V. E. Nakoryakov, *Heat Transfer and Waves in Gas–Liquid Systems* [in Russian], Nauka, Novosibirsk (1984).
12. A. V. Reshetnikov, O. A. Isaev, and V. P. Skripov, "Flow rate of a boiling liquid discharging into the atmosphere. Transition from a model material to water," *Teplofiz. Vysok. Temp.*, **26**, No. 3, 544–548 (1988).