Power spectra of pressure pulsations in the processes of evaporation/boiling of a liquid at low pressures

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Abstract. This paper presents experimental data on pressure fluctuations during evaporation/boiling of a thin liquid film under conditions of reduced pressure. The experimental data were obtained as a result of studying heat transfer on a smooth horizontal surface in a wide range of changes in the height of the liquid layer. Using the fast Fourier transform, the power spectra of pressure pulsations versus frequency were obtained. It was found that the power spectra of pressure pulsations differ depending on the mode of evaporation/boiling in the system.

1. Introduction

Currently, much attention is paid to fluctuations (noise) of various quantities measured in the system to determine the characteristics or state of the system. Of particular interest are fluctuations with a power spectrum inversely proportional to the frequency $S \sim 1/f$, where $S$ and $f$ are power spectrum [em] and the frequency [Hz], respectively. Most often in the literature, $1/f$ noise is understood as fluctuation processes with a power spectrum proportional to $1/f^\alpha$, where the exponent $\alpha$ varies within certain limits. An inversely proportional power spectrum is found in various systems, for example, in physical, chemical, mechanical, and biological systems [1-8].

In physics, $1/f^\alpha$ spectra of current pulsations in semiconductor materials, metal films, and radiophysical components are known [1-3]. In chemical technologies, $1/f^\alpha$ power spectra of pulsations can be used to interpret the data obtained on gas sensors [4], also, using power spectra, one can trace the kinetics of material synthesis [5]. In geophysics, $1/f^\alpha$ power spectra are used to describe seismic activity, drought, and floods [6, 7]. In biology, $1/f^\alpha$ spectra are observed in fluctuations in the potential energy of plastocyanin, an electron transport protein containing copper [8].

In the last few decades, the object of intensive research is the processes associated with the influence of fluctuations on the phase transition processes [9]. Since heat and mass transfer in two-phase systems is characterized not only by the average values of the process parameters but also by chaotic fluctuation deviations from the average values of these parameters. In particular, a strong increase in fluctuations occurs in critical and transient regimes of heat and mass transfer. The dynamics and evolution of random pulsations can be characterized by the dependence of the fluctuation power spectrum on frequency [10, 11].

The authors of [10, 11] showed that using the power spectra of voltage pulsations on a wire heater, it is possible to determine the moment of transition from one boiling mode to another, determining the
change in the exponent $\alpha$ in the power-law dependence of the power spectrum of voltage pulsations on frequency ($S(f) = 1/f^\alpha$).

The purpose of this work is to determine the transition to the crisis mode of evaporation/boiling by the nature of pressure pulsations by analyzing the power spectra of pressure pulsations obtained by the fast Fourier transform method.

2. Experiments

The experiments were carried out on an experimental heat-exchange vacuum installation, the working chamber of which is shown in figure 1.

![Figure 1. Working chamber of the experimental setup: 1 – case; 2 – bottom; 3 – brass plate; 4 – electric heater; 5 – heater mounting bracket; 6 – viewing windows; 7 – heating coil; 8 – cooling coil; 9 – vacuum inlet; 10 – branch pipe for mounting the pumping system; 11 – pressure sensors Setra 730; 12 – valve.](image)

The case (1) of the working chamber is a cylindrical vessel made of steel 12X18H10T with an inner diameter of 120 mm, a height of 300 mm, and a wall thickness of 1 mm. A cooling coil (8) is located on the outer surface of the upper part of the working chamber. The chamber was cooled with water flowing through the coil. To reduce heat losses due to overflows along the walls of the chamber from the bottom to the cooling coil, as well as for a more uniform temperature distribution along the bottom of the chamber, a coil for heating (7) the side vertical wall of the chamber is located above the viewing window (6). The bottom (2) of the chamber is also made of steel 12X18H10T. There are five holes in the bottom with a pitch of 2 mm for installing thermocouples. Between the bottom and the electric heater (4), there is a brass plate (3) for a more even distribution of temperatures from the electric heater to the bottom. The electric heater is fixed with a bracket (5). For visual observation from above and from the side, there were observation windows on the working chamber (6). The pressure in the working chamber was measured with a Setra-730 ionization-deformation pressure sensor (11) and maintained by constant regulation using a valve (12). The measurement error of this sensor is ± 0.5% of the current reading. To enter the operating mode, the sensor needs to warm up, the
warm-up time is at least 15 minutes, and the sensor response time is less than 20 ms. The data from the
sensor were read out using the National Instruments module into the LabVIEW application software
package with a frequency of 1 kHz. A more detailed description of the setup is given in [12, 13].

In the experiments, n-dodecane was used as a working fluid. Before the start of the experiments,
the calculated amount of the working fluid was poured onto the bottom of the working chamber,
which was necessary to create a layer of the required height. After that, the liquid was degassed with a
decrease in pressure in the volume of the working chamber. During degassing, a characteristic
bubbling was observed caused by the removal of dissolved air bubbles. In the course of the
experiments, several stationary heat transfer modes were realized, at which the temperatures were
recorded along with the thickness of the heated bottom, the pressure above the liquid layer in the
volume of the working chamber, and at the same time, the process was filmed with a high-speed video
camera. In the experiments, boiling curves were obtained at a constant pressure. The experiments were
carried layer heights, \( h = (1.7 - 4.0) \text{ mm} \) out at a pressure above the layer \( P(P/P_{cr}) : 133 (7.4 \cdot 10^{-5}) \),
where \( P \) and \( P_{cr} \) are pressure over liquid layer and the critical pressure [Pa], respectively.

3. Results and discussion
It was shown in [14] that nucleate boiling was absent in liquid layers on a smooth heating surface at a
pressure of \( P \leq 10^3 \text{ Pa} \). Heat transfer was carried out due to intense evaporation from the upper layer
of the liquid during the formation in it, under the influence of the under the action of the vapor recoil
force, structures in the form of “funnels” and “craters”.

![Figure 2](image_url)

**Figure 2.** The change in pressure versus time, obtained during the evaporation/boiling of n-
dodecane at an operating pressure in the chamber of 133 Pa and a layer height of 2.5 mm:
a) convection mode, heat flux \( 2.5 \cdot 10^3 \text{ W/m}^2 \); b) mode of formation of structures in the form of
“funnels”, \( 5.8 \cdot 10^3 \text{ W/m}^2 \); c) mode of formation of structures in the form of “craters”, \( 2.31 \cdot 10^4 \text{ W/m}^2 \);
d) pre-crisis mode, \( 7.45 \cdot 10^4 \text{ W/m}^2 \).
Figure 2 shows the experimental data of pressure fluctuations obtained at various heat fluxes for the evaporation of a 2.5 mm thick n-dodecane film at a pressure of $P = 133$ Pa. At low heat fluxes, the convective regime of heat transfer prevailed in the system, at this time convective rolls were observed in the liquid. The pressure pulsations are evenly distributed in time and have the appearance of white noise (figure 2(a)). With an increase in heat flux, uniformly distributed pressure pulsations begin to be interrupted by regular intensive pressure surges (figure 2(b)), these pulsations correspond to the regime of formation of structures in the form of “funnels” and “craters”, where maximum pressure pulsations correspond to the formation of single craters. With a further increase in the heat flux, the pulsations become more chaotic (figure 2(c)), and these pulsations correspond to the regime of the formation of structures in the form of “only craters”. In pre-crisis modes of evaporation/boiling, crater formation takes on a higher frequency character, this phenomenon can be seen in the pressure pulsation graph (figure 2(d)). In addition, in the pre-crisis state, the formation of structures in the form of “craters” can be accompanied by a short-term drying of the heating surface.

![Figure 3](image_url)

**Figure 3.** Power spectra of pressure pulsation versus frequency obtained during the evaporation/boiling of n-dodecane at an operating pressure of 133 Pa in the chamber and a layer height of 2.5 mm:

- **a)** convection mode, heat flux $2.5 \cdot 10^3$ W/m$^2$;
- **b)** mode of formation of structures in the form of “funnels”, $5.8 \cdot 10^3$ W/m$^2$;
- **c)** mode of formation of structures in the form of “craters”, $2.31 \cdot 10^4$ W/m$^2$;
- **d)** pre-crisis mode, $7.45 \cdot 10^4$ W/m$^2$.

Using the fast Fourier transform, the power spectra of pressure fluctuations versus frequency were obtained (figure 3) during the evaporation/boiling of n-dodecane at an operating pressure in the chamber of 133 Pa and a layer height of 2.5 mm. In the modes of evaporation/boiling in the entire range of variation of heat fluxes, the obtained power spectra of pressure pulsations had the form $1/f^\alpha$.

For low heat fluxes, spectra with $1/f^\alpha$ were observed in the low-frequency district and had one
inflection point (figure 3(a)) onward, the inflection point in the low-frequency zone corresponds to “inflection point №1”. At these heat fluxes, convective rolls were observed, and low-frequency fluctuations could appear in the system, which cannot be determined visually. In the modes of evaporation with the formation of structures in the form of “funnels” and “craters” in the liquid layer, the obtained spectra had the form $1/f^\alpha$ in the higher-frequency district and had two inflection points (figure 3(c), (d)) onward, the inflection point in the high-frequency zone corresponds to “inflection point №2”. In the transition to the pre-crisis regime of evaporation/boiling, the power spectra of pressure fluctuations versus frequency are similar to the spectra obtained in the regime of formation of structures in the form of “only craters”. However, the obtained spectra had a distinctive feature, in the form of a characteristic peak (arrow in figure 3(d)) in comparison with the regime of formation of structures in the form of “only craters”.

During the transition to the crisis mode of evaporation/boiling, the power spectra of pressure fluctuations versus frequency at liquid heights of 1.7 mm and 4.0 mm also had a characteristic peak (arrow in figure 4(a), (b)).

![Figure 4](image-url)  
**Figure 4.** Power spectra of pressure pulsations versus frequency for the pre-crisis regimes of evaporation/boiling of n-dodecane at an operating pressure in the chamber of 133 Pa: a) liquid layer height 1.7 mm, heat flux $5.16\times10^4$ W/m$^2$; b) 4.0 mm, $7.17\times10^4$ W/m$^2$.

The frequency value at which peaks and breaks observed in the power spectra of pressure pulsations are presented in table 1.

| $h$, mm | Regimes                                      | Inflection point №1, Hz | Inflection point №2, Hz | Characteristic peak, Hz |
|---------|---------------------------------------------|-------------------------|-------------------------|-------------------------|
| 2.5     | convection (fig. 3(a))                      | 1.27                    | -                       | -                       |
|         | “funnels” and “craters” (fig. 3(b))         | 1.43                    | 77                      | -                       |
|         | “only craters” (fig. 3(c))                  | 1.48                    | 127                     | -                       |
|         | pre-crisis (fig. 3(d))                      | 3.85                    | 226                     | 3.85                    |
| 1.7     | pre-crisis (fig. 4(a))                      | 3.85                    | 220                     | 3.85                    |
| 4.0     | pre-crisis (fig. 4(b))                      | 3.22                    | 296                     | 3.22                    |

4. Conclusion
Analysis of experimental data shows that the processes of evaporation/boiling are accompanied by pressure pulsations, the nature of which changes depending on the magnitude of the heat flux. One of the possible tools for extracting useful information from pressure pulsations during...
evaporation/boiling of thin layers of n-dodecane under conditions of reduced pressure in a wide range of changes in layer heights is the analysis of the power spectra of pressure pulsations obtained using Fourier analysis.

It is shown that the processing of the pressure fluctuation spectrum makes it possible to identify the relationship between the behavior of the spectral power function of pressure pulsations in different heat transfer regimes and the degree of approximation to the critical heat flux during the development of crisis phenomena.

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