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Boiling-up of a jet of superheated water discharged through a nozzle of small diameter

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An experimental investigation of the boiling-up dynamics of a jet of superheated water being discharged through a short nozzle of a small diameter ($d = 0.2$ mm) has been conducted. A change in the shape of a boiling-up jet has been traced at various degrees of superheat. A complete flow opening has been established in the temperature range of $T = 493-583$ K. The instability of a complete breakup has been revealed. On the basis of experimental data, the dependence of variations in the jet opening angle on the saturation pressure has been plotted in dimensionless coordinates. Low-frequency pulsations with a power spectrum inversely proportional to the frequency ($1/f$-spectrum) have been found under changes of shapes of the boiling-up flow.

Keywords: complete jet opening, superheated liquid, explosive boiling-up, short nozzle, $1/f$-spectrum.

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Different-intensity phase transformations essentially affect the shape [1,2], spray angle [3–5], and dispersion composition [6–8] of a metastable (superheated) liquid jet [9,10]. For instance, a slightly superheated free jet discharged through a short cylindrical nozzle retains the rod-type shape (the shape of a cold liquid jet). Under the condition of intense boiling-up (heterogeneous nucleation), a cone-shaped flow is observed. When there occurs intense homogeneous fluctuation evaporation, the jet takes the shape of an elliptic paraboloid. However, under certain conditions (in the presence of external equipment components downstream of the nozzle exit) the complete opening of the superheated liquid jet is observed [11].

Achieving of the straight opening angle is of both the fundamental and applied interest. Some issues concerning the necessary and sufficient conditions for realizing the jet breakup, temperature range of its occurrence, and stability of its disklike (fanlike) shape still remain open.

In this work we studied variations in the shape and opening angle of the superheated distilled-water jet during its discharge from a high-pressure vessel through a short nozzle into motionless air at room temperature and atmospheric pressure. The operating nozzle $d = 0.2$ mm in diameter was made in a titanium plate $l = 1$ mm long with sharp inlet and outlet edges. Initial parameters (temperature and pressure) of the working–chamber fluid were consistent with the conditions on the line of the liquid–vapor phase equilibrium and varied in the following ranges: $T = 383-583$ K, $p = 0.1-9.8$ MPa.

Figs. 1 and 2 present images of a superheated water jet, which are specific of different superheat levels, and data on variations in the boiling-up jet opening angle, respectively. The figures show that the flow shape and opening angle are directly associated with the phase transformation dynamics and transient boiling-up modes.

In the case of low oversaturation of the system, the jet retains the rod-type shape characteristic of cold liquid (Fig. 1, a). When the temperature of the working–chamber liquid increases gradually, intensity of evaporation from the jet surface increases [12], which results in damaging the liquid core (Fig. 1, b) and forming a two-phase spray cone with increasing opening angle (Fig. 1, c). The jet shape change from cylindrical to conical was observed at the temperature of about $T = 463$ K (indicated by the small arrow in Fig. 2) at which the changeover of the boiling-up modes takes place [1], namely, transition from single boiling-up acts to heterogeneous nucleation [9,10].

As long as temperature remained increasing from $T = 463$ to 493 K, the flow had the conical shape with the opening angle at the apex varying from $\alpha = 15$ to 60° (Fig. 2). Further increase in the initial thermodynamic parameters of the liquid resulted in more intense phase

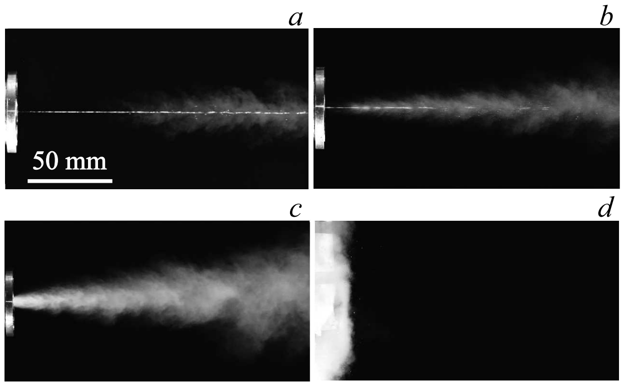

Figure 1. Photos of the boiling-up water jet at $T = 433$ (a), 463 (b), 483 (c), and 573 K (d).

transformations (explosive boiling-up [9]) in the superheated water jet. At the liquid temperature $T = 493$ K, the flow changed its shape, namely, a transition from the conical shape to the disklike one took place being accompanied by essential pulsations of the opening angle. In the temperature range $T = 503-583$ K, a stable complete opening of the jet was observed (Fig. 1, *d*). Notice a number of peculiar features revealed in this study for the case of a complete breakup. The first feature consisted in a shift of the lower (by 10 degrees) and upper (by 35 degrees) temperature limits towards higher values. The second feature was associated with a sharp increase in the jet opening angle from $\alpha = 60°$ to the straight angle. In the case of a cylindrical nozzle with the aperture $d = 0.5$ mm in diameter, transition to the complete breakup occurred beginning from $\alpha = 120°$. As the third distinctive feature, it is possible to regard the appearance of significant pulsations of the boiling-up water opening angle (indicated by the large arrow in Fig. 2), which were observed during the transition from the conical jet shape to disklike one.

To analyze the pulsations, the method of laser photometry was used [4,13]. The two-phase liquid flow was transilluminated with a laser beam. Variations in the transmitted radiation intensity were fixed with a LED. The signal was digitized by a 16-bit analog-to-digital converter and recorded in the computer memory. Based on the obtained time series, pulsation-power spectra were determined by using the fast Fourier transform. Such a spectral diagnostic of pulsations is quite important because it enables revealing transient and crisis phenomena in systems of different natures [13–15].

In previous works we have established that power spectra varying inversely proportional to frequency ($1/f$ spectra) are observed in transient and critical cases [1,4,15]. This behavior of spectral density evidences for the energy accumulation at low frequencies and for possible emergence of large-scale pulsations whose amplitudes are comparable with and even higher than average magnitudes of the pulsating parameters [15]. Fig. 3 presents the power spectrum of pulsations in jet of metastable water heated to $T = 463$ and 493 K (the spectrum had the same shape at both temperatures). As noticed above, the liquid jet at such levels of heating underwent the shape changeover accompanied by high fluctuations. At $T = 463$ K there is observed a transition from the cylindrical shape to conical one (intense evaporation changes over to boiling-up), while at $T = 493$ K the jet changes its shape from conical to disklike (the boiling-up intensity increases sharply, which means the transition to heterogeneous nucleation).

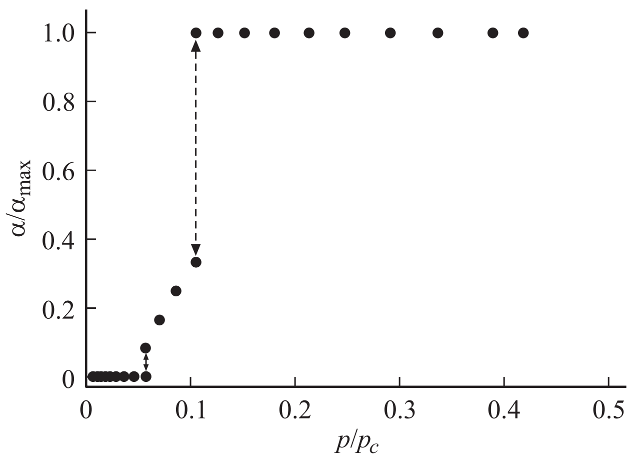

Figure 2. Opening angle of the superheated liquid jet versus binodal pressure (in reduced coordinates: $\alpha_{\max} = 180°$, p_c is the critical pressure of the liquid). The arrows indicate transitions from one shape to another.

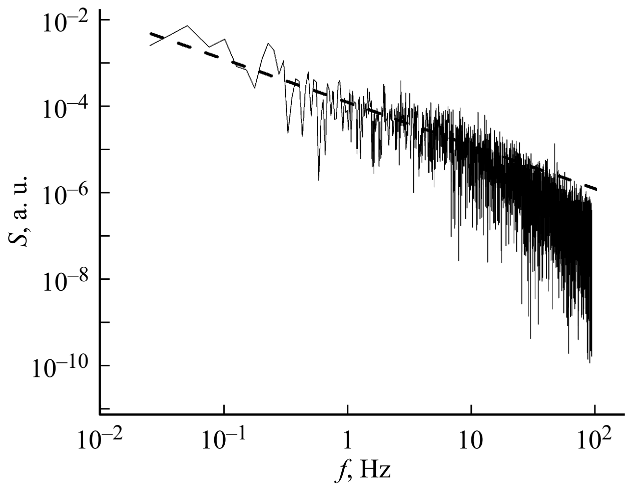

Figure 3. Power spectrum of the opening angle pulsations of the boiling-up water jet at $T = 463$ K. The dashed line is $S = 1/f$.

Thus, in this work the changes in the superheated water jet shape and opening angle were studied experimentally in a wide temperature range ($T = 383-583$ K) during the jet discharge through a short nozzle $d = 0.2$ mm in diameter. The predominant effect of such a factor as intense phase transformations on the process of metastable liquid discharge was confirmed.

An important aspect of our study was revealing the effect of complete jet opening for the used nozzle; the effect was observed in a wide temperature range ($T = 493-583$ K). A fundamental novelty of the accomplished investigation consisted in revealing the instability of the complete opening of the jet. In addition, variation in the angle of the jet spray opening from small values ($\alpha = 60°$) to the straight angle was fixed for the first time.

The research results may be useful for evolving the available concepts of the mechanisms for breakup of metastable (superheated) jets, and also for creating and improving devices providing bulk fine-dispersion spraying.

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Conflict of interests

The authors declare that they have no conflict of interests.

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