Technical Physics Letters, 2023, Vol. 49, No. 11

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Complete opening of a boiling-up jet discharged through short cylindrical nozzles

© *K.A. Busov, N.A. Mazheiko*

Institute of Thermal Physics, Ural Branch of the Russian Academy of Science, Yekaterinburg, Russia
E-mail: kbusov@itpuran.ru

Received August 3, 2023
Revised September 13, 2023
Accepted September 13, 2023

An experimental investigation has been conducted of the boiling-up dynamics of a jet of superheated water discharged through short nozzles with six different diameters: $d = 0.15$, $d = 0.2$, $d = 0.3$, $d = 0.4$, $d = 0.5$, $d = 0.6$ mm. Changes in the shape of a boiling-up jet have been traced in a wide temperature range $T = 383-583$ K. The necessary conditions for a complete opening of the flow have been established. On the basis of experimental data a map has been plotted regarding the change of the shape of the discharged liquid and the dependence of the change of the opening angle of the jet on the initial liquid pressure on the saturation line.

Keywords: Superheated liquid, explosive boiling-up, complete jet opening, short cylindrical nozzle.

DOI: 10.61011/TPL.2023.11.57190.19698

The study of atomization of substances is made relevant by the fact that sprays are used widely in various types of technical equipment [1–3]. Particular emphasis is placed upon the production of atomized media with large opening angles (straight one included). Intense boiling-up of liquid is one of the efficient ways toward volumetric fine spraying [4–9]. When liquid was discharged through a short straight cylindrical channel with a metallic surface, which had cylindrical and diffuser parts, mounted beyond its exit, a disk-shaped two-phase flow was observed. This flow was detected in the process of discharge of superheated liquid through a cylindrical channel $l = 0.7$ mm in length and $d = 0.5$ mm in diameter [10]. Subsequent experimental studies of this phenomenon revealed the required conditions for complete opening of a jet: the use of a short channel, vigorous nature of the liquid–vapor phase transition (intense boiling-up), manifestation of the Coandă effect, and stability of pressure in the working chamber [11].

In the present study, the results of experiments into variation of the shape of a jet of superheated water discharged from a high-pressure chamber into the atmosphere through different short cylindrical channels are summarized. Channels with diameters ranging from $d = 0.15$ to 0.6 mm were drilled in titanium plates and had sharp inlet and outlet edges. The temperature and pressure of liquid in a vessel satisfied the binodal conditions and varied within the following ranges: $T = 383-583$ K, $p = 0.1-9.8$ MPa. A detailed description of the experimental setup and procedure was provided in [11,12].

Various characteristic types of jets were observed in experiments at different degrees of liquid heating in the working high-pressure chamber [12–15]. A jet retains its cylindrical shape before the onset of boiling-up in the bulk of liquid. An increase in the initial water temperature in the working chamber leads to intense evaporation from the jet surface and phase transformations within the discharged liquid, thus resulting in the formation of a conical jet. The more evident the liquid–vapor phase transition in the flow is, the greater is the opening angle of a two-phase jet. Complete opening of the superheated liquid (a fan-shaped jet) is observed in the shock boiling-up regime (explosive boiling-up). A complex study of the process of discharge of hot water through cylindrical channels of varying diameters allowed us to summarize the results of experiments and plot a shape map for the working liquid (Fig. 1). Different regions in Fig. 1 correspond to stable shapes that the medium assumes in the process of discharge from a high-pressure vessel through a short cylindrical channel. Having analyzed this map, one may note certain features of shaping of the flow, both general and particular in nature. Let us list the most important of the obtained experimental results.

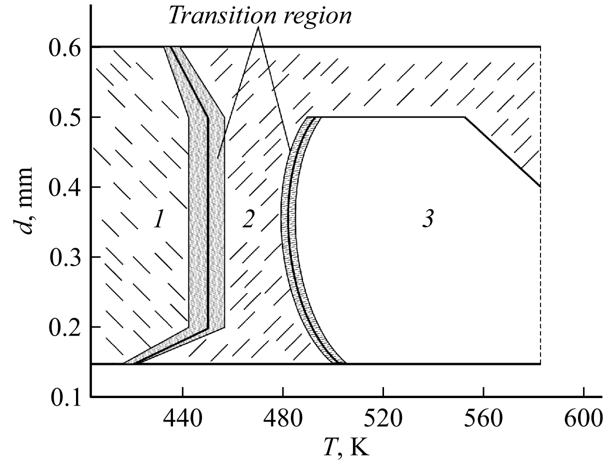

Figure 1. Map of shapes of a superheated water jet. *1* — Cylindrical shape, *2* — conical shape, and *3* — complete opening.

1. Three different types of jets (cylindrical, conical, and complete opening) were observed in characteristic temperature intervals in experiments with channels with diameters ranging from $d = 0.15$ to 0.5 mm.

2. Channel diameter $d = 0.5$ mm was the maximum one at which the effect of complete opening of boiling-up liquid could be observed. Disk-shaped jets were not detected at larger channel diameters [11].

3. In the case of discharge of hot water through a short channel $d = 0.15$ mm in diameter, the transition from a rod-shaped jet to a conical one occurred at lower (compared to other channels) temperatures, while the transition from a conical shape to a disk shape occurred at higher temperatures.

4. The conical shape of boiling-up liquid (region 2) was observed within a narrow temperature interval (450–480 K) in experiments with channels with diameters $d = 0.3$ and 0.4 mm.

5. Complete jet opening was revealed only in the case when the mechanism of explosive boiling-up was activated in a jet under the conditions of steady-state discharge.

Another significant corollary is that the temperature interval of the transition from a rod-shaped jet to a conical jet was wider than the one corresponding to the transition from a conical flow to a disk-shaped flow. In both cases, a sudden shape change was observed in the course of transitions from one type of boiling-up liquid to another (Fig. 2).

The presence of a considerable number of distinguishing features of jet shaping is indicative of the importance of choosing a specific channel and Its application potential.

The opening angle varied with the degree of superheating of liquid. The variation of the jet angle with increasing values of the initial parameters in the working chamber is presented (in reduced coordinates) in Fig. 3. A straight angle ($\alpha/\alpha_{\max}$, $\alpha_{\max} = 180^\circ$) and the pressure of the thermodynamic critical point of water (p/p_c, $p_c = 22.1$ MPa) were chosen as a scale for the jet opening angle and the pressure, respectively.

It is evident that all the examined channels have a certain pressure range (with specific boundaries corresponding to each channel) within which a jet has a zero opening angle prior to the onset of phase transformations in the bulk of it. The more pronounced the events of formation and interaction of vapor bubbles in the discharged medium are, the higher is the rate of growth of its opening angle. The opening angle of a jet of boiling-up liquid reached its maximum ($\alpha = 180^\circ$) in the case of intense boiling-up (shock boiling regime). The atomization of liquid discharged through a channel with diameter $d = 0.6$ mm had certain specific features. The opening angle started increasing earlier in this case, reached its maximum ($\alpha = 90^\circ$) under explosive boiling-up, and decreased afterwards.

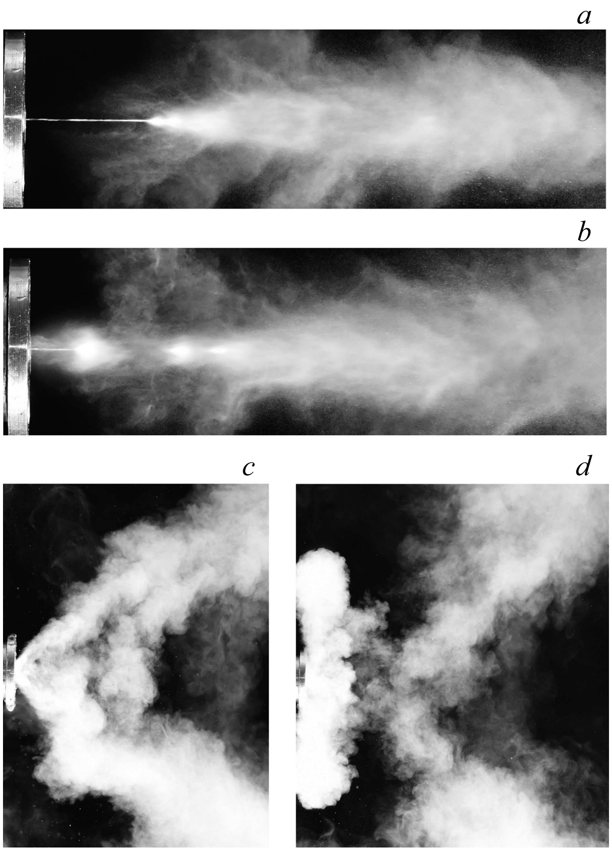

Figure 2. Shape instability of a boiling-up water jet in transition from a rod shape (*a*) to a conical one (*b*) and in transition from a conical shape (*c*) to complete opening (*d*).

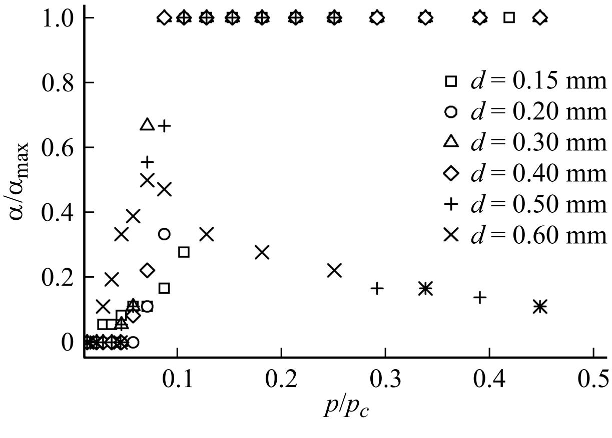

Figure 3. Dependence of the variation of the jet opening angle on the initial liquid pressure (in reduced coordinates).

Thus, the results of complex experimental studies into the discharge of a jet of metastable water from a high-pressure chamber through short cylindrical channels into a stationary air medium were summarized. The variation of shape and opening angle of a jet of superheated water was examined experimentally within a wide temperature range ($T = 383-583$ K) for all the studied channels. A map of flow shapes and a dependence of the variation of the jet opening angle on the initial conditions were plotted. Temperature intervals corresponding to specific shapes of a boiling-up jet were determined. The loss of stability of a discharged liquid jet occurring in the process of variation of its shape was revealed. This instability was found to be accompanied by significant fluctuations.

It was also established that straight cylindrical channels of various diameters may be a worthy alternative to complex atomizer nozzles that require the use of expensive atomization equipment.

Funding

This study was supported by grant No. 22-29-00426 from the Russian Science Foundation (https://rscf.ru/project/22-29-00426/).

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin