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Deflection of a jet of boiling-up water during its discharge from an inclined cylindrical nozzle

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The paper presents the results of an experimental investigation of the effect of the slope angle of a short cylindrical nozzle with a diameter $d = 0.4$ mm on the path of a jet of superheated water. Changes in the path of a boiling-up jet have been traced in a wide temperature range $T_s = 110-310\,^{\circ}$C. Dependences of the opening angle and the angle of deflection of the flow axis (with respect to the nozzle axis) on changes in the temperature of the working liquid in a high-pressure vessel have been constructed. A considerable deflection of the spray cone axis with respect to the axis of the cylindrical nozzle has been revealed.

Keywords: superheated liquid, explosive boiling-up, short cylindrical nozzle, deflection angle.

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On the one hand, interest in the study of boiling-up liquids [1,2] is connected with obtaining new and extending available information about a substance in a metastable state. A free (noninteracting with any other flows and setup elements) jet of superheated liquid is a unique thermal system, whose characteristic external view (shape, opening angle, and flow stability) makes it possible to judge the interior processes in it (the appearance, growth and interaction of vapor bubbles), which presents the boiling-up flows of a substance as a considerable addition to the available thermophysical complexes and methods of investigation of superheated liquids: the method of heating droplets [3], the bubble chamber [4], the method of pulse heating [5,6], liquid boiling-up in a glass capillary [7,8], the method of lifetime measurement [9], etc.

On the other hand, the attention to superheated media is caused by their use in various aspects as in intense phase transitions there arise conditions of creating a voluminous, homogeneous and finely dispersed medium [10–12]. With a complex approach (the attainment of the necessary degree of superheating, the choice of the geometry of the nozzle and the establishment behind it of some definite form of structural elements owing to the interaction with which a spray cone forms) there appear some interesting possibilities (unreproducible or demanding some additional equipment and power supply during the discharge of an underheated substance) for an efficient and rational employment of a metastable liquid. By way of illustration, one may use the effect of a complete opening of a boiling-up flow [13,14] and the phenomenon of deflection of the jet axis (to 18°) with respect to the axis of the outlet orifice, which was observed during the discharge of metastable water through nozzles with an oblique cut [15].

The present experimental work has revealed a considerable deflection of a boiling-up jet of superheated water during its discharge through a straight cylindrical nozzle with sharp inlet and outlet edges drilled in a one-millimeter-trick plate of stainless steel at an angle $\beta = 10^{\circ}$ (Fig. 1). The investigations were conducted with the use of a multifunctional experimental setup providing hermeticity and the heating of the liquid under investigation up to high values of temperature ($T_s = 310\,^{\circ}$C) and pressure ($p_s = 9.9$ MPa).

The results of experiments conducted with a straight short cylindrical nozzle [10,14] normally drilled to the plate plane have shown that the jet path changes at different degrees of superheating, but in doing so retains a symmetrical form with respect to the nozzle axis. In this case no deflections of the flow axis from the axis of the nozzle have been noticed.

In setting a plate with a cylindrical nozzle drilled at an angle $\beta = 10^{\circ}$ depending on the heating one could observe some definite forms of a jet of superheated water (Figs. 2 and 3). The experimental dates were also used to plot diagrams reflecting changes in the opening angel and the deflection angel of the axis of a jet of a boiled-up liquid in the whole temperature range under study (Fig. 4).

Up to the instance of manifestation of phase transitions in the bulk of the liquid being discharged the jet axis coincided with that of the nozzle. At relatively small degrees of superheating, where the liquid temperature didn't exceed $T_s = 120\,^{\circ}$C, one could observe a continuous cylindrical part of the jet near the nozzle outlet section, and downstream it broke into stretched fragments and very large drops. In the temperature range $120 < T_s < 160\,^{\circ}$C the flow of the medium under study had no continuous part — the jet broke totally into separate parts and large drops (Fig. 2, *a*). On the achievement of the temperature $T_s = 160\,^{\circ}$C three important peculiarities were observed on the discharge of a metastable liquid: an increase in the angle of the spray cone (the angle between the visible boundaries) of the jet, the

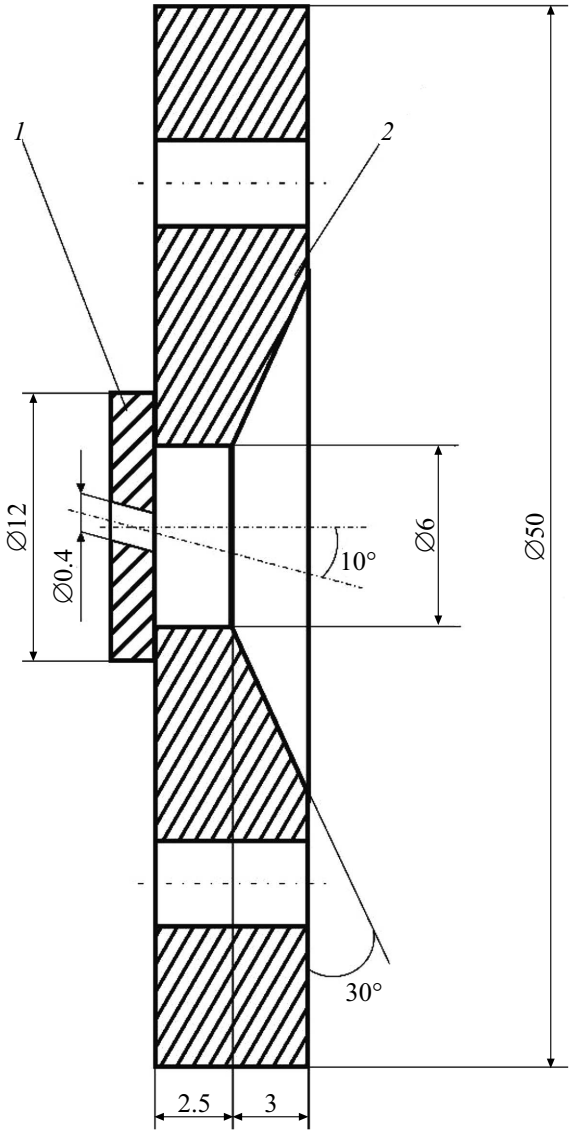


Figure 1. Cut of a short cylindrical nozzle (*1*) and a clamping flange (*2*) with cylindrical and diffusion parts.

deflection of the jet axis from the axis of the nozzle and a decrease in the sizes of the droplets composing the flow (Fig. 2, *b*).

Figure 3 presents photographs of boiled-up water, which adequately depict the significant mutual influence of thermal and constructional conditions on the formation of spraying of a metastable substance.

Thus, in heating a liquid to a temperature $T_s = 180\,^{\circ}\mathrm{C}$ one can observe a more voluminous (as compared with the previous cases) form of the flow in the shape of a cone (Fig. 3, *a*). An increase in the angle of deflection of the jet axis, which was about $\theta = 10^{\circ}$, also becomes noticeable.

A further increase in the degree of the liquid superheating leads to its explosive boiling-up. In the jet bulk one can see an exponential growth and intense interaction of vapor critical bubbles stretching the liquid into thin films, at the rupture of which there appear the smallest droplets. In the temperature range $T_s = 210-250\,^{\circ}\mathrm{C}$ a boiling-up liquid jet had the highest values of the opening angle and the angle of deflection (Figs. 3, *b* and 4, *a*, *b*). In photographs of boiling-up jets (Fig. 3), an upward flow deflection, i. e., against gravity, is clearly visible (the cylindrical nozzle was installed as shown in Figure 1), which is associated with the phenomenon of droplet reflection from the surface of a clamping flange. Due to the increasing intensity of phase transformations within a superheated liquid jet, a droplet flow formed, the composition of which varied depending on the degree of superheating of the liquid. As the temperature increased, the size of the droplets significantly decreased and their number increased sharply, which led to an increased effect of particle reflection from the flange and, of course, to a greater deflection of the jet.

It is vital to note the fact of absence of a complete jet opening, which was observed for the temperature range mentioned above in the case of employment of a straight cylindrical nozzle drilled normally in the steel plate [10,13,14].

In the temperature range $T_s = 260-310\,^{\circ}\mathrm{C}$, when the mechanism of homogeneous nucleation set in [1] boiling-up took place in the immediate vicinity of the nozzle outlet edge. In an intense liquid-vapor phase transition there arose a spray cone with a sufficiently large opening angel (about $\alpha = 100^{\circ}$), which cause a direct interaction of the moving voluminous flow with the inner geometry of the clamping flange. As a result of this interaction, one could observe a decrease in the opening angle of the cone of a boiling-up liquid (Fig. 3, *c*) and a decrease in the angle of deflection of its axis with respect to that of the cylindrical nozzle (Fig. 4, *a*, *b*).



Figure 2. Path of a water jet at small degrees of superheating corresponding to the following temperatures in the working chamber: $T_s = 140$ (*a*) and $160\,^{\circ}\mathrm{C}$ (*b*).

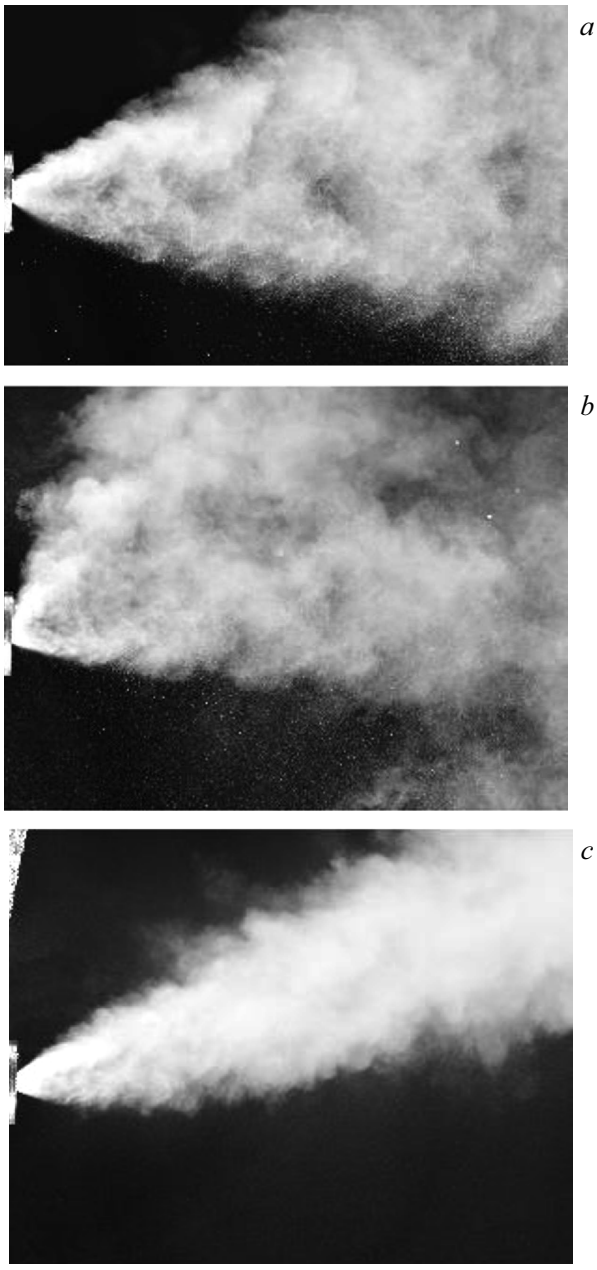


Figure 3. Jets of superheated water at different high temperatures: $T_s = 180$ (a), 210 (b) and 310 °C (c).

Thus, the present experimental investigation of a boiling-up jet of distilled water discharged through a straight cylindrical nozzle made it possible to obtain new important results about changes in the shape, the opening angle and the angle of deflection of a flow of boiling-up water in a very wide temperature range. The fundamental novelty of this investigation is the detection of the phenomenon of a more considerable deflection (with respect to the axis of the cylindrical nozzle) of the axis of a jet of a highly superheated liquid during its discharge through an inclined nozzle with a clamping flange (Fig. 1) as compared with the case of the liquid discharge through nozzles with an oblique cut [15].

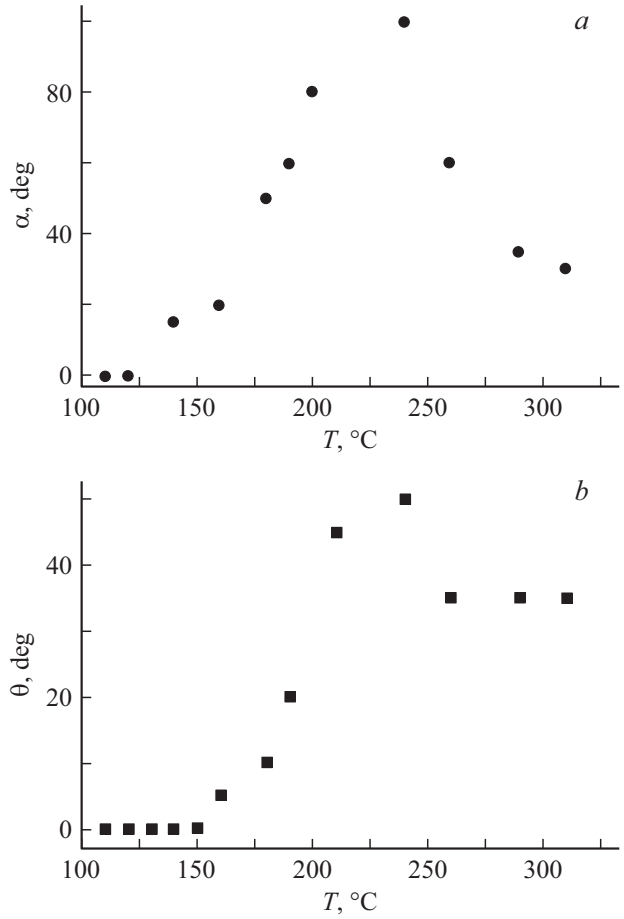


Figure 4. Temperature dependence of the opening angle (a) and the deflection angle (b) of a boiling-up liquid jet.

It is shown that the attainment of the necessary thermodynamic conditions in experiment and the use of components of a definite form have a considerable effect on the shaping of the flow, which opens up widespread possibilities for application aspects in the problems of controlled spraying.

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Conflict of interests

The authors declare that they have no conflict of interest.

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