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Water jet impingement onto a hot steel plate

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The research studies the interaction between subcooled small diameter water jet and thick steel heater at different surface temperatures, liquid velocities and jet angles. Although the heater surface temperature exceeded the Leidenfrost temperature and reached 340°C, the liquid, according to visual observations, wetted the surface. Geometrical characteristics of the heater surface wetted area and jet deflection angles were measured. It was hypothesised that jet deflection from the surface, accompanied by finely dispersed drops generation, occurs when thermal boundary layer, which develops in the liquid near the heater surface, reaches the liquid's outer surface. The preliminary measurements seem to confirm the hypothesis

Keywords: Free-surface jet, quenching, jet impingement boiling, liquid film, Leidenfrost temperature.

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Introduction

Cooling with free subcooled liquid jets directed at a surface is one of the promising methods of high-intensity cooling and quenching that are used extensively in industry. Although these techniques have been available for quite a while and a considerable amount of practical experience has been accumulated, major challenges arise in the development of a theoretical model of this phenomenon. The visually observable liquid–surface contact at temperatures exceeding considerably both the maximum allowed superheating temperature of a cooling liquid and the critical temperature of this liquid itself is one of the key questions that still remains unanswered [1–4]. Thermodynamics states that a direct contact between liquid and a heated surface is not possible at such temperatures. A considerable number of studies (mostly experimental ones) focused on this phenomenon and the process of jet–surface interaction in general have already been published.

The following process diagram is implemented in the majority of experiments: a free solid jet from a nozzle is directed down at a right angle to a heated surface (see reviews [1,2]). The initial surface temperature is such that it prevents direct contact with liquid; a vapor layer forms as a result, and the film boiling regime is established. As the surface cools, a visually observable dark zone with a smooth shiny surface without any external features of boiling forms in the region of jet deceleration. This zone is believed to be the wetted surface region.

The free surface near the boundaries of the wetted region becomes cloudy and perturbed, thus providing indications of vigorous boiling of liquid. This region is commonly referred to as a transition one. The transition boiling regime is established in it, and the heat flow transferred from the surface is maximized here [1,3,4]. It is hard to identify the tentative external boundary of the transition region (the wetting front). As the process unfolds, the area of the wetted region grows, but its growth rate drops quickly almost to zero.

Depending on the ratio of experimental parameters, two different flow configurations may be established beyond the wetting front.

The first configuration is as follows. Liquid is deflected from the surface in the form of a thin film and forms a corona that is then dispersed into droplets. This phenomenon is usually ascribed to vigorous evaporation in the region of the wetting front where the local density of the heat flow is maximized. As the wetting front moves in the radial direction, the liquid momentum decreases. As a result, the angle between the surface of the deflected liquid film and the heater surface grows, while the velocity of dispersed liquid decreases [5,6].

The second flow configuration may be observed if the heater has a substantial size. The repulsion of the liquid film may cease completely in these conditions. The film boiling regime is then established, and large liquid formations, which behave as large liquid droplets in the Leidenfrost regime, emerge on the periphery of the wetting front. Apparently, this is observed in systems where the characteristic surface size exceeds considerably the characteristic jet size [7,8].

The results presented in [4] are of special interest, since the regime and conditions of heat exchange in the wetted region were examined in detail there. This study is specific in that one high-speed camera was positioned within a reservoir and filmed the process through the liquid layer, thus providing an opportunity to image the flow structure near the solid surface. The presence of vapor bubbles, which are indicative of vigorous boiling in the wetted region, in the near-surface region was revealed using this method. When viewed from the outside of the jet, the process betrayed no indication of boiling.

As was already mentioned, jets directed perpendicularly to a cooled surface have been studied extensively. The case when a jet is directed at an angle to a surface is less studied. This case is specific in that liquid within the area of contact between an oblique jet and a heated surface moves above the surface in the form of a fairly thin film ($20-50\,\mu$m) with a relatively high velocity ($2-10$ m/s). The examination of interaction between oblique jets and a heated surface may help understand the dynamics of liquid deflection from a surface and determine the parameters that enhance the area of a liquid spot. In the present study, the influence of the initial jet inclination, the heater temperature, and the liquid velocity on the shape of the wetted region and the jet deflection parameters is investigated. A thorough understanding of the mechanisms governing liquid deflection from a surface allows one to determine the parameters affecting the size of the wetted surface region and the cooling intensity within it. It is obvious that such studies are of both academic and applied interest.

1. Experimental setup

A series of experiments on cooling of solid steel surfaces by an oblique jet of distilled water with an initial temperature of 25°C was performed as part of research activities at the Moscow Power Engineering Institute. The setup presented in Fig. 1 and samples of stainless steel (12Kh18N10T) $100 \times 100 \times 20$ mm in size were used in these experiments. The surface of these samples was smooth (polished with sand paper with a grain size of $14-20\,\mu$m).

Liquid impinging on the surface was ejected from a hollow cylinder with a piston (syringe). This cylinder was mounted on a stand that allows one to adjust the jet inclination. The cylinder was designed so that different diameters of capillaries for liquid discharge could be used. Its graduated volume was 5 ml.

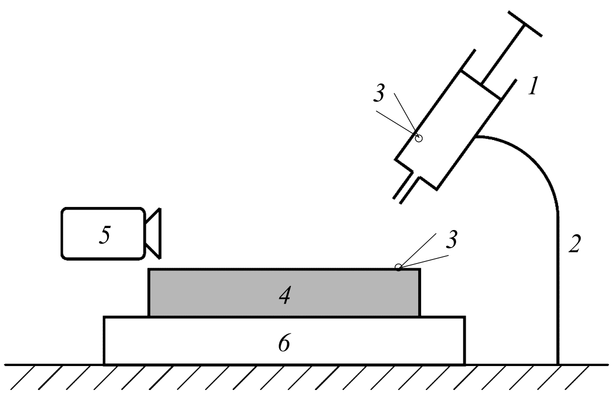

Figure 1. Diagram of the experimental setup: *1* — hollow cylinder with a displaceable piston; *2* — retention device holding the capillary at angles 0−90°; *3* — temperature measurement instruments; *4* — steel plate; *5* — camera; *6* — heating element.

The obtained data were used to determine the average rate of cylinder emptying and calculate (knowing the inner diameter of the capillary, which was 0.5 mm in most experiments) the outflowing jet velocity. The maximum relative error of velocity measurements estimated based on the mean-square deviation of the cylinder emptying time was $\sim 10\%$. The liquid velocity was monitored additionally by inspecting the recorded video frames: since the surface of an impinging jet is not entirely uniform, one may determine the velocity by tracking the motion of nonuniformities. It should be noted that the system was found to respond fairly weakly to changes in the liquid velocity. This agrees with the results of experiments performed in other studies.

The studied surface sample was positioned on an electric heater with a preset power. Liquid was supplied following stabilization of the sample surface temperature. A chromel–alumel thermocouple was used to check the sample surface temperature before the experiment. The tail end of the thermocouple was put into contact with the external face of the sample. A Flus IR-871 infrared pyrometer was used for additional monitoring of the sample temperature and the uniformity of its distribution over the surface. The nonuniformity of the surface temperature field was as high as $10-15$°C and was attributable to the annular geometry of the heating element, which produced a temperature maximum at a distance of around 30 mm from the plate center. However, the characteristic temperature nonuniformity within the region of jet–surface interaction (with a characteristic size of $5-15$ mm) did not exceed 5°C. The process was recorded on video (in the majority of experiments) with a NIKON 1 J1 camera that features shooting speeds of 400 and 1200 frames per second.

The geometrical parameters of the wetted spot on the heater surface were also determined in the course of experiments on jet–surface interaction.

2. Experimental results

The stage of settling of the liquid flow in the interaction region follows the moment when a jet first impinges on the solid heated surface in the course of an experiment. At high surface temperatures, this settling is likely to be accompanied by the formation of a vapor film between the solid surface and liquid. A quasi-steady flow pattern forms after the initial stage of interaction that lasts for less than 0.5 s. This pattern remains unchanged in the process of emptying of the working cylinder volume within at least $3-4$ s.

The mechanisms of interaction between a jet of the same velocity and the surface heated to different temperatures differ. A wetted spot forms on the surface at temperatures that are close to the liquid boiling point but do not exceed it (Fig. 2). The film thickness increases abruptly (the so-called hydraulic jump, which is associated with abrupt flow deceleration, occurs) in the region of the wetted spot that is the most distant from the point of actual jet–surface contact.

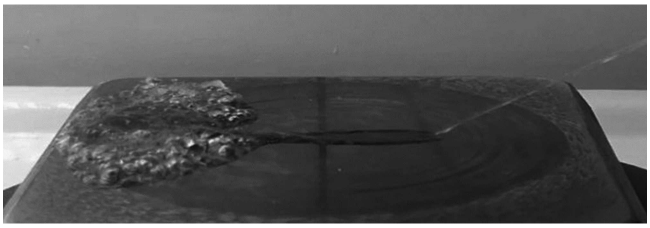

Figure 2. Photographic image of a jet impinging on the heater surface at temperature $T = 94°C$ in the central part at the quasi-steady stage of the process. Boiling is observed due to the fact that the plate temperature on the periphery is $10-15°C$ higher than in the central part.

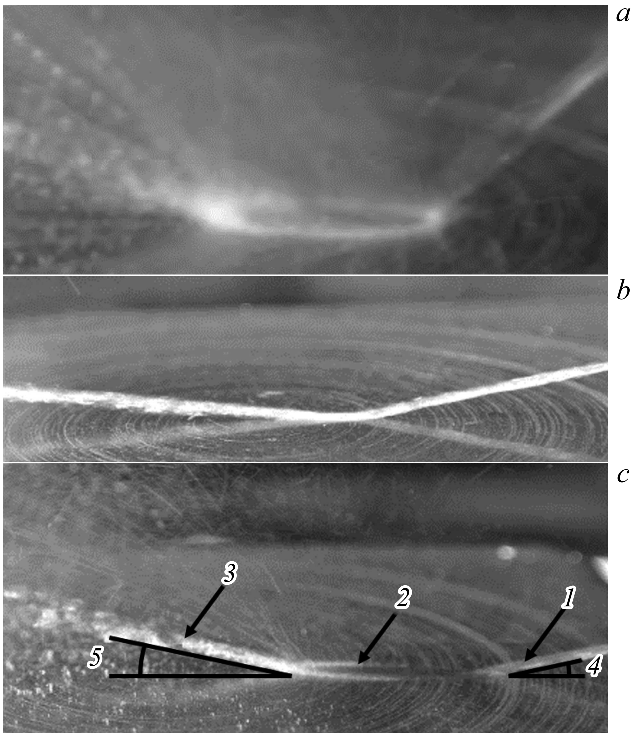

Figure 3. Photographic images of a jet impinging on the heater surface at the quasi-steady stage of the interaction process at different initial surface temperatures: a — $T = 330°C$, $\alpha = 45°$; b — $T = 330°C$, $\alpha = 15°$; c — $T = 230°C$, $\alpha = 15°$; *1* — initial jet, *2* — liquid film on the surface, *3* — reflected jet, *4* — jet incidence angle α, *5* — jet reflection angle β.

Experiments were carried out at a temperature of 94°C in the central part of the plate and at different impingement angles and yielded the same results. Following the jump, almost stationary liquid starts to boil on the heated plate surface.

Depending on the combination of parameters, a number of different characteristic steady flow regimes were observed when a subcooled jet impinged on the surface of the studied samples at temperatures higher than approximately 140°C (this correlates well with the Leidenfrost temperature of water). With heater surface temperature $T_m = 330°C$ and the jet incident at an angle of 45° (Fig. 3, a), a dark wetted region forms on the surface in the area of contact. This region has the shape of an ellipse with major axis l aligned with the jet and minor axis b (Fig. 4).

The underlying metallic surface is seen clearly through the flowing liquid surface in the contact area. The transition region (white border) is seen at the external boundary of the wetted region, being most noticeable in the direction of liquid flow. This agrees with the results of observations made in [4]. Apparently, this transition region is composed of microbubbles. In contrast to the wetted region, the heater surface is not visible here. Liquid is deflected (becomes separated with nonzero horizontal and vertical velocities) from the solid surface at the external boundary of the transition region. When the heater surface temperature was reduced to $T_m = 230°C$, a more extensive (in the direction of liquid flow) wetted region (Figs. 3, b, c) formed with well-marked liquid deflection from the solid surface at the boundary of the transition region.

The dependence of the ratio of maximum length l to maximum width b of the wetted region on jet impingement angle α was determined for a smooth steel plate (Fig. 5, a). This ratio naturally tends to unity as the impingement angle increases. The heater temperature has a considerable effect on the extent of the wetted region. A 50°C change in the heater temperature translates into a $1.5-2$-fold change in length/width ratio l/b.

The dependence of angle β of liquid deflection from the surface at the boundary of the transition region on the jet impingement angle was also determined experimentally (Fig. 5, b). The angle of liquid deflection from the surface increases with the jet impingement angle. This trend persists up to angles $\alpha = 40-45°$ and then gives way to the apparent reduction to a certain constant value that is retained up to $\alpha = 90°$. Unfortunately, we cannot provide a convincing explanation for this phenomenon.

If we assume that a direct liquid–surface contact is established in the jet–surface interaction in the visually observable dark region where liquid moves in the form of a thin film, the liquid temperature in the contact area is normally estimated based on the following considerations. The solution of the double-layer heat conduction problem is used [9]. Two half-spaces with a common contact line are considered in this problem, while the other walls are assumed to be thermally insulated. The initial temperatures of bodies differ: T_m (for metal) and T_0 (for liquid). It is assumed that the half-spaces come into immediate contact at the initial time. Within a fairly short time, the temperature

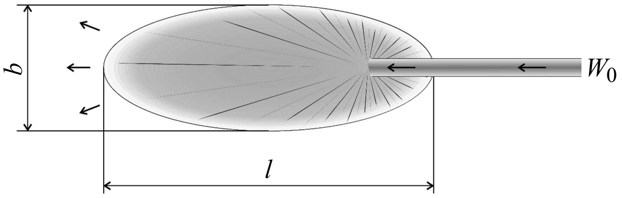

Figure 4. Diagram of the wetted surface region: top view.

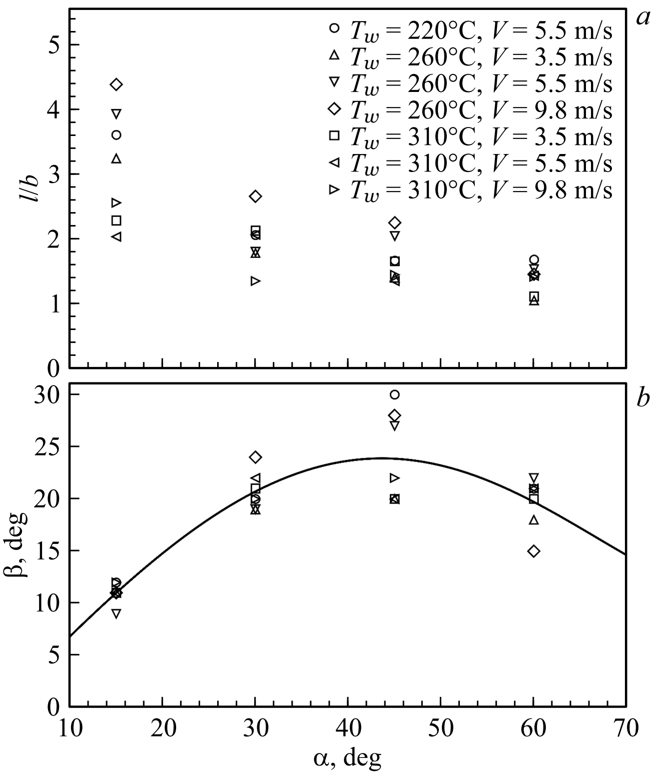

Figure 5. Parameters of the wetted region emerging in the jet–surface interaction: *a* — ratio of the length of the wetted region to its width as a function of the angle of jet incidence on the surface; *b* — dependence of the jet deflection angle on the jet incidence angle.

of liquid in contact with the hot surface reaches a value of T_w, which may be estimated as

$$T_w = T_0 + \frac{k}{k+1}(T_m - T_0), \quad (1)$$

where the ratio of thermal activities of two media is defined as

$$k = \sqrt{\frac{\lambda_m \rho_m c_{pm}}{\lambda_l \rho_l c_{pl}}},$$

where λ, ρ, c_p are the thermal conductivity, the density, and the thermal capacity, respectively; indices m, l denote the metal and liquid properties.

The values of temperature T_w of the near-surface layer of liquid (water with initial temperature $T_0 = 25°C$) in contact with the hot stainless steel surface with $T_m = 340°C$ (steel 12Kh18N10T) calculated in accordance with (1) yield temperature $T_w = 290°C$ in the metal–liquid contact region.

Apparently, it should be taken into account that a protective oxide film forms on the surface of stainless steel in the process of high-temperature heating. According to the data from [4], this film has a thickness of $1-3\,\mu$m and is composed primarily of chromium oxides (Cr_2O_3). The temperature in the region of contact between the oxide film and liquid estimated in accordance with (1) is $T_w = 230°C$.

The obtained value is significantly higher than the normal boiling point of water, but short-term superheating of water under atmospheric pressure to a temperature of 270°C has been demonstrated in certain studies [10]. According to the results of calculations performed in [11], the maximum dynamic superheating of water is estimated at 325°C. Therefore, the obtained value of temperature in the contact region appears to be consistent with thermodynamic considerations. Thus, the introduction of any theoretical constructs differing from more or less standard ones into the description of the liquid–wall heat and mass exchange is not needed. This is what distinguishes the present work from studies [1–4] where the contact region was observed reliably at temperatures well above the critical one.

Naturally, the presented estimates do not resolve the issue of whether an ultrathin ($5-10\,\mu$m) and very smooth vapor layer forms in the contact region near the surface. It is technically impossible to detect such a layer from the outside of the film by optical means. However, the presence of this layer (or lack of it) has no effect on subsequent considerations and estimates.

The following hypothesis was formulated in the course of processing the experimental data: when a heat wave propagating from hot metal to liquid reaches the free liquid surface, the film moving along the metal surface starts disintegrating (boiling) and is deflected from the surface, producing a large number of small droplets.

It is quite possible that this is attributable to the development of a Landau instability on the free surface of superheated liquid [12]. In fact, this is one of those few cases where such a scenario is directly applicable. However, It will be out of place to discuss this controversial issue in detail in the present concise paper. At least several alternative explanations are possible. One of them involves the use of the notion of a lifetime of metastable superheated liquid (similar to the one applied in the experiments of V.P. Skripov [13]). However, there are other alternatives. We do not see it fit to advance any additional arguments in favor of the validity of the proposed hypothesis beside the results of experiments presented in Fig. 6. Experimental data appear to be the most compelling arguments.

In estimating the thickness of the liquid film forming at the jet–surface contact spot, we rely on the following considerations.

The average liquid velocity in the film needs to be estimated first. This estimation may involve both experimental and theoretical insights.

It was found experimentally that the velocity of the jet deflected from the surface is approximately e times lower than the velocity of the incident jet (for example, the processed video footage demonstrates that the deflection velocity of a jet impinging on the surface with velocity $W_0 = 5$ m/s in the angle range of $15-45°$ is close to $w = W_0/e = 2$ m/s). The velocity in the film halfway to the deflection point (i.e., where the contact spot width is maximized and is equal to b) may then be estimated at $W_0 e^{-0.5} \approx 0.6\,W_0$.

The theoretical estimate of the velocity in the film may be obtained based on the following considerations. The velocity of liquid on the free external jet boundary (W_0) should be preserved at the immediate moment of impingement of the jet on the surface. Further on, liquid is decelerated in the moving film, and the velocity profile is transformed under the influence of viscous forces over the metal–liquid boundary.

Assuming that the motion of liquid in the film is turbulent, the following equation of motion may be written, following [14], for the average liquid velocity in the film in a Langrangian coordinate system:

$$\rho\delta\frac{dW}{dt} = -\tau_w, \quad (2)$$

where δ is the film thickness, ρ is the liquid density, τ_w are shear wall (metal–liquid boundary) stresses, and ν is the kinematic viscosity. The following relation may be used for shear wall stresses:

$$\tau_w = 0.023\rho W^2\left(\frac{\nu}{\delta W}\right)^{0.25}.$$

Equation (2) is integrated easily in the approximation of a constant film thickness and takes the form

$$W(t) = W_0\left(1 + 0.018\left(\frac{\nu}{\delta W_0}\right)^{\frac{1}{4}}\frac{W_0 t}{\delta}\right)^{-\frac{4}{3}}.$$

This yields an approximate formula for length L over which the velocity in the film decreases by a factor of two:

$$L \approx 40\delta\left(\frac{\delta W_0}{\nu}\right)^{0.25}.$$

Since the kinematic viscosity of water corresponding to 100°C is $\nu = 3\cdot 10^{-7}\,\mathrm{m^2/s}$, the characteristic velocity of the impinging jet is $W_0 = 5\,\mathrm{m/s}$, and the characteristic film thickness is $\delta = 50\,\mu\mathrm{m}$, we obtain a value of $\sim 1\,\mathrm{cm}$ for L. This corresponds with the characteristic size of the contact region and the experimental data on the velocity of the jet reflected from the surface. Thus, the liquid velocity in the film at the center of the contact region may be estimated as $W_{0.5} = (0.7{-}0.8)W_0$.

Average thickness δ of the liquid film was estimated based on the balance of liquid flow rates in the jet and in the contact region in experiments. On the one hand, the volumetric liquid flow rate in the film is set by the liquid flow rate in the jet:

$$Q = \frac{W_0\pi d^2}{4},$$

where W_0 is the velocity of liquid in the jet and d is the jet diameter.

On the other hand, assuming that the velocity of liquid in the film is $W_{0.5} \sim W_0\cos(\alpha)$, the volumetric liquid flow rate in the film may be determined based on the experimental value of width b of the wetted region

$$Q = W_0\cos(\alpha)b\delta.$$

Thus, we obtain the following for the film thickness:

$$\delta = \pi d^2/\big(4b\cos(\alpha)\big).$$

The solution for the problem of heating of a semi-infinite array may be used to obtain an approximate estimate of thickness δ_τ of the liquid layer heated in time t:

$$\delta_\tau = (6at)^{1/2},$$

where a is the temperature conductivity of water (its value at 25°C is used for numerical estimates).

Thus, if the hypothesis is valid, thickness δ of the liquid film at the end of the contact region needs to be equal to thickness δ_τ of the heated layer that develops in time interval t_W within which liquid resides on the heated surface.

Time t_W spent by liquid in the contact region may be estimated as

$$t_W = \frac{l}{W_0\cos(\alpha)},$$

where l is the contact region length (measured experimentally).

The validity of the hypothesis was verified at different angles of jet incidence. The obtained results are presented in Fig. 6 in the form of a dependence of the ratio of the liquid film thickness (determined experimentally) to the thickness of the heated liquid layer on the heater temperature. The liquid film thickness determined in experiments is close to the values of thickness of the heated liquid layer produced within the time spent by liquid on the heater surface. The highest film thickness ($\delta = 95\,\mu$m) corresponds to wall temperature $T_w = 310$°C, jet velocity $W_0 = 3.5\,\mathrm{m/s}$, and jet inclination $\alpha = 45°$. The lowest film thickness ($\delta = 23\,\mu$m) was determined at $T_w = 220$°C, $W_0 = 5.5\,\mathrm{m/s}$, and $\alpha = 30°$. The highest ($\delta_\tau = 60\,\mu$m) and lowest ($\delta_\tau = 24\,\mu$m) values of thickness of the heated layer

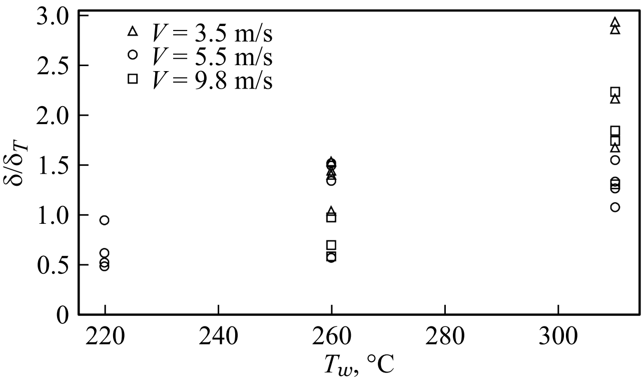

Figure 6. Dependence of the ratio of the experimentally determined thickness of the liquid film to the calculated thickness of the heated liquid layer on the heater temperature.

were obtained at $T_w = 220^\circ$C, $W_0 = 5.5$ m/s, $\alpha = 60^\circ$ and $T_w = 310^\circ$C, $W_0 = 9.8$ m/s, $\alpha = 45^\circ$, respectively.

The obtained results apparently suggest that the proposed hypothesis is valid; however, they obviously require a more thorough verification.

The spread of experimental points in Fig. 6 warrants further comment. The probable explanation for this effect is as follows.

It is estimated that the motion of liquid in the liquid film is laminar. The Reynolds number, which is defined as $\mathrm{Re} = W_0 \cdot 4 \cdot \delta/\nu$, falls within the range of $200-1000$. While small, it is not sufficiently low for the influence of relatively large vortices, which may be produced both in the flow of liquid in the needle prior to ejection to the surface and in the jet–surface collision, on the heat transfer to be negligible. In view of this, it is entirely possible that the thickness of the thermal boundary layer increases at a rate higher than the one set solely by the molecular thermal conductivity mechanism. If this is true, greater-than-unity ratios of the film thickness to the thickness of the thermal boundary layer observed in Fig. 6 at relatively high Reynolds numbers are not surprising, since the thickness of the thermal boundary layer is understated.

Conclusion

The geometrical characteristics of the wetted surface region in the interaction between subcooled water jets and a solid surface were determined experimentally at different initial surface temperatures, jet incidence angles, and liquid velocities. The angles of liquid deflection from the heated surface and their dependence on the jet incidence angle were also determined. The indicated dependence has a maximum at incidence angle $\alpha = 40-45^\circ$.

The temperature in the region of contact between the heater surface and liquid was estimated. The obtained value $(T_w = 290^\circ\mathrm{C})$ does not contradict the available data on short-term dynamic superheating of water up to temperatures of 325°C.

A hypothesis associating the phenomenon of deflection of the liquid film from the heater surface with the emergence of superheated liquid at the external boundary of the liquid film was proposed. Estimates obtained based on the experimental results apparently suggest that the proposed hypothesis is valid.

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Conflict of interest

The authors declare that they have no conflict of interest.

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