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Experimental study of the nucleate boiling characteristics of water with a rapid increase in surface temperature

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The results of an experimental study on the characteristics of boiling water on the surface of a tube due to a sudden release of electrical energy are presented. For the rate of surface temperature increase up to 19 K/s, the key characteristics of bubble boiling were determined, such as the nucleation density and maximum size of vapor bubbles.

Keywords: subcooling liquid, nonstationary heating, nucleate boiling, microbubble.

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It is crucial for various practical applications to obtain a description of heat transfer under non-stationary heat flows and/or temperature fields. One typical problem here is the use of phase transformations that make it possible to establish efficient heat transfer with high levels of specific heat flows. The emergence and development of the vapor phase on heat-transfer surfaces are inexorably associated with the formation and dynamics of vapor bubbles. However, numerous ongoing studies in the field of nucleate boiling demonstrate [1] that no satisfactory generalizations for the key characteristics (the density of nucleation sites, the maximum and departure diameter of bubbles, and the rate of their nucleation) have been proposed yet. Specifically, several approaches based both on determining the thermal balance of a vapor bubble near a heat-transfer surface washed by subcooled liquid and on a mechanistic approach, wherein the problem of departure of a vapor bubble under the action of various forces is considered, are used to determine the size of bubbles [2]. The disadvantages of the first approach include the presence of feedback in the formulation of the problem: a vapor bubble is an important actor in the heat transfer process, which raises the issue of validity of such a formulation. The second approach is criticized rightly for its unreasonable idealization and, at the same time, for the presence of a large number of empirical coefficients that obfuscate the physics of the problem under consideration. The issue of finding satisfactory generalizations for the above-mentioned characteristics becomes most acute in problems with boundary conditions with a continuous and rapid increase in temperature of the heat-transfer surface [3]. In this case, the validity of characterization of the indicated key characteristics by generalizing data obtained in experiments with less intense heat flows and stationary temperature fields is questionable. In the present study, boiling on a metal surface under non-stationary conditions was examined experimentally and numerically. Reconstruction of the surface temperature on the time scale of the studied nucleate boiling process (Fig. 1) is still not a fully solved problem. Specifically, the boiling model requires closing relations based on the density of nucleation sites, the size of vapor bubbles, etc. The dynamics of the vapor phase, as is known, has a significant impact on heat transfer. Thus, experimental observations of non-stationary nucleate boiling require the application of numerical modeling.

Experiments were carried out at the Melentiev Energy Systems Institute (Siberian Branch, Russian Academy of Sciences) on the premises of the „High-Temperature Circuit“ common use center. The diagram of the experimental setup was detailed in [3]. The heater is a hollow steel cylinder with a wall thickness of 1 mm, a maximum roughness of 4 μm, an outer diameter of 12 mm, and a length of 120 mm that is positioned vertically inside a channel with a cross section of 18×18 mm. The pressure in the channel was 0.29 MPa, the average ascending velocity of deaerated water was 0.52 m/s, subcooling $\Delta T_{sub} = 23-103$ K, and the rate of heater temperature growth under pulsed heating reached 19 K/ms. Vapor structures were recorded by a Phantom V2012 high-speed video camera with a framing rate of 180 000 fps and a frame size of 256×256 px. The spatial resolution of imaging was 5.5 μm/px, which allowed us to record bubbles with sizes upward of 11 μm and lifetimes in excess of 11 μs. The error of determination of the bubble size and the density of nucleation sites was 8% and 6%, respectively. Video data on boiling regimes, interpolation of readings of thermocouples attached to the inner heater surface, and numerical calculations of non-stationary heat transfer in Comsol Multyphysics [4] were used to determine the temperature of the outer heater surface. The numerical model is based on the RPI [5] approach that supplements the solution of the energy equation with relations for separate components of heat balance in the near-wall layer of liquid in the presence of vapor bubbles. However, these closing relations themselves depend on the surface temperature.

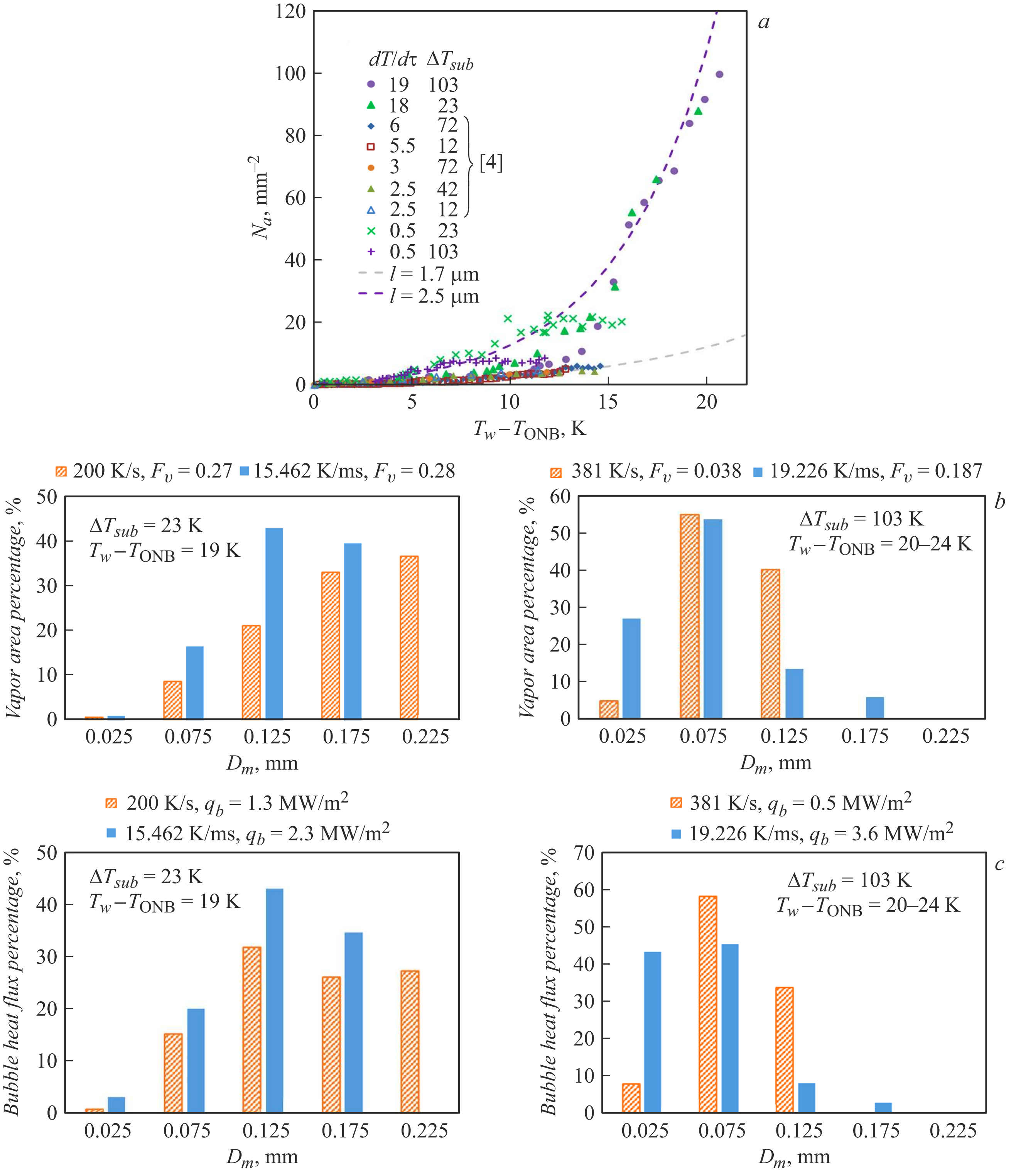

Figure 1. Boiling characteristics. *a* — Density of nucleation sites; *b* — distribution of the experimentally determined percentage of the heater surface occupied by vapor by the diameters of vapor bubbles; *c* — results of numerical modeling of the heat flow distribution by the diameters of vapor bubbles.

To rectify this contradiction, the results of experimental observations of the vapor phase dynamics were used in the numerical model. In particular, the percentage fraction of surface covered by the vapor phase was used instead of a combination of the density of nucleation sites and the diameters of vapor bubbles (Fig. 1, *b*).

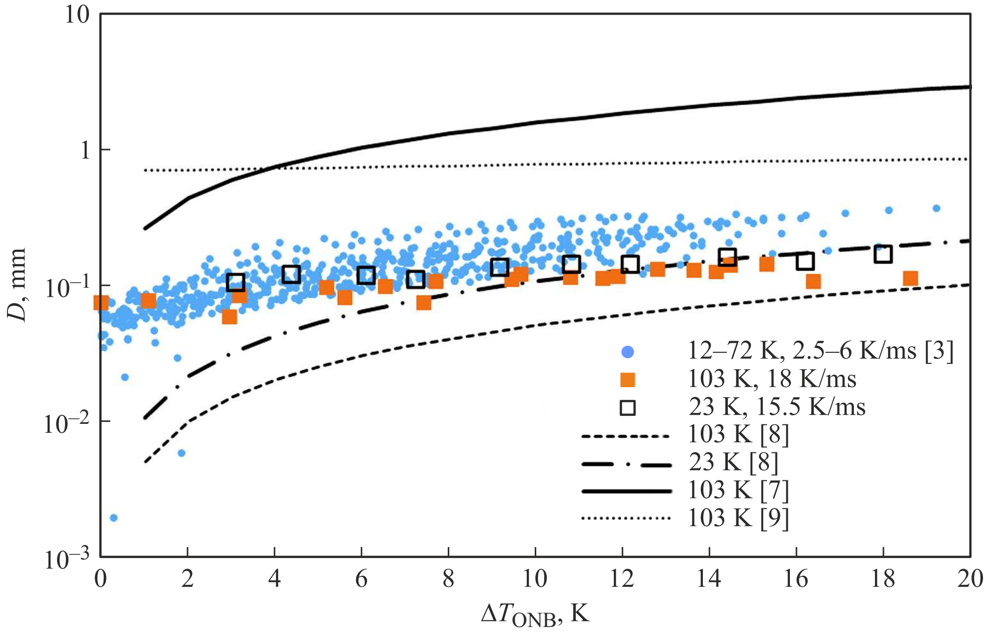

Figure 2. Volume-weighted diameters of vapor bubbles.

The data of earlier experimental observations [4] carried out within a narrower range of the rate of increase of the heater surface temperature at a pressure of 0.11 MPa are shown in Fig. 1, *a* together with the results of our study. A dependence for the density of nucleation sites was used for generalization [6]:

$$N_a = C\left[\exp\left(B\Delta T_{\mathrm{ONB}}\right) - 1\right], \qquad (1)$$

where

$$B = (l\rho_g h_{fg})/(2\sigma T_s), \quad C = N\left[1 - \exp\left(-\frac{\theta^2}{8\mu^2}\right)\right],$$

l is the characteristic size specified by the smallest depression on the surface, ρ_g is the vapor density, h_{fg} is the latent heat of evaporation, σ is the surface tension coefficient, T_s is the saturation temperature, N is the maximum possible number of nucleation sites, θ is the wetting angle, μ is the characteristic angle, and ΔT_{ONB} is the surface temperature T_{ONB} excess upon the emergence of the first vapor bubble above the saturation temperature. It is evident that quantities l, θ, and μ specify the individual characteristics of the surface and its interaction with liquid. The characteristic size was set to $1.7\,\mu$m in [4]. New data with finer spatial and temporal detail suggest a more accurate value: $l = 2.5\,\mu$m. It should be noted that no significant effect of heating rate on the density of nucleation sites was found.

New data on the sizes of vapor bubbles at high (up to 19 K/ms) rates of growth of the heat-transfer surface temperature were obtained by processing the video records. The experimental results were compared with known predictive relations (Fig. 2). Specifically, we used the analytical approach [7]:

$$D_m = 2.72\left(0.3Ja + \sqrt{0.09Ja^2 + 12Ja}\right)^{4/3}(\alpha^2/g)^{1/3}, \qquad (2)$$

and the data from oft-cited paper [8]:

$$D_m = 1.21ab^{-0.5}, \qquad (3)$$

where $a = (1 - m)k_l(T_w - T_s)\left(\rho_v h_{fg}\sqrt{\pi a_l}\right)^{-1}$ and $b = m\varphi C(T_s - T_0)(1 - \rho_v/p_l)^{-1}$ represent the contribution to the material balance of a bubble from evaporation and condensation of liquid. Figure 2 also presents the results of diameter calculation based on a widely used approximation of the bubble size that is a modification [9] of the relation obtained in [10]:

$$D = 0.19\left(1.8 + 10^5K\right)^{2/3}\left[\frac{\sigma}{g(\rho_l - \rho_v)}\right]^{0.5}. \qquad (4)$$

Here, $K = \left(\frac{Ja}{\mathrm{Pr}}\right)/\left\{\left[\frac{g\rho_l(\rho_l-\rho_v)}{\mu_l^2}\right]\left[\frac{\sigma}{g(\rho_l-\rho_v)}\right]^{3/2}\right\}$ is a function that depends significantly on two key quantities: surface temperature and pressure. It should be noted that the latter results were obtained for saturated liquid and serve as a rather rough estimate for calculating the bubble size during boiling under non-stationary conditions. It is evident (Fig. 2) that analytical solutions do not provide a satisfactory prediction of the size of a vapor bubble under a rapid increase in surface temperature. An increase in heating rate leads to a reduction in thickness of the superheated layer, which translates into a reduction in the maximum sizes of vapor bubbles at comparable surface temperatures. The estimate of the bubble growth limit in a subcooled liquid used in approach [8] may be refined by using a numerical model of a non-stationary temperature field, since factor m in (3) is determined by the ratio of the bubble diameter and the thickness of the near-wall liquid layer superheated above the saturation temperature.

New data on the density of nucleation sites and the size of vapor bubbles at surface temperature growth rates up to 19 K/ms were obtained as a result of numerical and experimental studies. This research illustrates the importance of combining empirical data and numerical modeling in characterization of nucleate boiling under non-stationary conditions. The use of analytical approaches to bubble size determination containing strong assumptions regarding the temperature field invariably limits the applicability of the obtained results (especially for non-stationary states of vapor–liquid systems).

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Conflict of interest

The authors declare that they have no conflict of interest.

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