Dynamics of the wall thermal boundary layer at the initial stage of the nucleate boiling

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Abstract. This paper presents the results of the experimental study of the water nucleate boiling on the surface of the cylinder heater. We investigated the initial stage of formation of the thermal boundary layer with rise and departure of bubbles with the departure diameter of 50 μm. To build the field temperature at the moment prior to the start of boiling, we used a numerical model implemented in the COMSOL multiphysics software. The experimental data on bubbles dynamics was compared to the numerical calculation of the temperature, and the relationship between the temperature growth rate, the bubble departure diameter and the Jacob number was established. The outcome results demonstrated that the non-transient heat influences the departure diameter and we need to employ the modified Jacob number to build predictive models.

1. Introduction
At present, it is impossible to quantitatively estimate the nucleation centers density [1,2], which is the decisive value for the heat transfer coefficient and intensive vaporization start time calculation. Therefore, the extension of the experimental data about the onset of critical heat flux conditions is as relevant as ever. So far, only a few number of the research papers dealing with the problem of experimental investigation of transient boiling on thin wire-wound heaters and in micro-channels [3-5] have been published. However, the data for the large-size heater is lacking.

Although the individual bubble size and lifetime are stochastic values, their scales can be described and predicted in terms of dimensionless criteria. Kim and Kim [6] published their experimental results together with a review of the partial nucleate pool boiling data, which they have been accumulating for more than 40 years. According to their study, many researchers included the bubble radius at departure, \( R_d \), in the Bond number that sets the balance between the buoyancy and the interfacial tension forces

\[
Bo = g(\rho_l - \rho_v)(2R_d)^2 / \sigma,
\]  

and expressed the Bond number in terms of the Jacob number that sets the ratio of the superheat and the latent heat:

\[
Ja = \rho_l C_p \Delta T / (\rho_v h_{fg}) = \rho_l C_p (T_{wall} - T_i) / (\rho_v h_{fg})
\]
$Bo = \gamma Ja^\alpha$  \hspace{1cm} (3)

Here $T_w$ stands for the wall temperature, $T_s$ denotes the saturation temperature, $\rho_l$ is the liquid density, $\rho_v$ is the vapor density, and $h_{fg}$ denotes the latent heat.

Kim et al [7] have shown that the effect of various pool temperature conditions can be taken into account if the characteristic superheat includes the pool temperature $T_0$

$$Ja = \rho_l C_p \Delta T^* / (\rho_v h_{fg})$$  \hspace{1cm} (4)

$$\Delta T^* = (T_w - T_s) \beta + (T_0 - T_s)(1 - \beta)$$  \hspace{1cm} (5)

As shown in [7], the data for the constant temperature and the constant heat flux conditions can be fitted with $\beta = 0.7$. In case of the fast temperature growth, the wall thermal boundary layer can be much thinner than that one for the stationary flow, affecting the departure diameters and the departure time of bubbles. In the present study, the experimental data on bubbles dynamics is compared with numerical calculation of the temperature field in order to clarify the relationship between the temperature growth rate, the bubbles diameter, the coefficient $\beta$, the Jacob number and physical meaning of the characteristic temperature.

2. Experimental study of bubbles dynamics

Experiments with rapidly increasing heating power were conducted on flowing water in a channel with a cylindrical type 321 stainless steel heater in the center. The heater has the following characteristics: 12 mm outer diameter, 10 mm inner diameter, 4 μm roughness. The channel has optically transparent windows and is equipped with the temperature, voltage and pressure measuring probes.

The channel is mounted into a closed contour designed for studies of transitional processes during boiling. The contour comprises the following parts: channel with a high power pulse heater, pump, cooler, additional heater with automatic control of inflow temperature, bypass line for adjustment of pressure and flux.

Heating power was generated by conducting three-phase rectified electric current through the heater with the pulse duration of 60–300 ms and the temperature growth rate of 1000–7000 K/s. The water flowed along the channel upwards with the average velocity of 0.2 m/s, the inflow pressure of 0.11 MPa, and the inflow temperature of 30 °C, 60 °C and 90 °C, corresponding to the 13–73K subcooling.

The heater wall temperature, the nucleation, the bubble growth and the collapse were studied considering such parameters as the inflow temperature and the heating rate.

The wall temperature was measured by a thermocouple, the dynamics of nucleation was recorded using a speed videography.

Figure 1. Video frames of periodic growth and collapse of a bubble in the near-wall water layer at the 20000 frame per second rate.
The lighting scheme proposed in [8] was applied to obtain a high speed and high quality video. The green light-emitting CVT-120 diode with nominal power of 77 Watt was subjected to the short pulse current with a 4–5 times excess of the nominal amplitude. Such a short overload does not destroy the light-emitting diode and provides the high brightness light pulse. The short exposition of 5–10 μs improves sharpness of moving objects in the video frame. The videography rate was equal to 20000 frames per second. The diode emitting surface was small enough (12 mm²) to form a parallel light beam by means of a convex lens.

As one can see at the video frames (Fig.1), processes of nucleation, bubbles growth and collapse repeat each 200–400 μs at the same location. It was established that during the first stage of boiling, from the first micro-bubbles to the beginning of intensive boiling, the wall thermal boundary layer increased by 25% only. At the same time, the water is heated at the bigger distance from the wall by means of the vapor condensation at the bubbles top. Hence, the conditions for transient explosive boiling are formed in the same way as it happens during large over-cooling.

3. Numerical estimation of the temperature field
Using the COMSOL Multiphysics software, we performed the numerical analysis and obtained the water temperature near the heater surface. We only modeled heating of the homogeneous liquid phase, and therefore the temperature field remained adequate until the first bubbles appeared.

The axisymmetric 2D model of the steel heater and the water tank was build and verified against a full 3D model and thermocouple data. The laminar flow, the convective and the conductive heat transfer in water, the conductive heat transfer and the joule heat in solid are analyzed using temperature-dependent material properties. The metal temperature at the bottom and at the top was the same as the inflow temperature, taking three values of 30 °C, 60 °C and 90 °C, corresponding to the 73 K, 43 K and 13 K subcooling.

Both in the physical experiment and in the numerical model, the heater temperature was increased due to electric current. The actual voltage history was measured during the physical experiment and subjected as an input data during the numerical simulation.

4. Results and discussions
In each experiment, we considered from one to five of the first collapsed bubbles and calculated the wall temperature $T_w$ and the water temperature $T(x)$ as a function of distance from the heater. We selected only the bubbles with the biggest diameter ± 2.5 μm, which collapsed in 0.5 ms or less after the collapse of the first bubble.

The examples of heating history for two experiments are shown at Fig. 2.

![Figure 2. Temperature growth and first bubbles collapse times and diameters for experiments with $T_0=60$°C. (a) - low heating rate, (b) – high heating rate.](image-url)
The overheat at different levels with respect to the bubble diameter was plotted and fitted against the characteristic overheat (5) and the diameter of each selected bubble. According to Fig. 3, the temperatures at $x=0.1 \div 0.2D$ give the most relevant representation of the characteristic overheat, because at smaller distances the short time temperature fluctuations distort the relationship, and at bigger distances the temperature might go below the saturation level, resulting in the negative overheat. Then the overheat $[T(x)-T_s]$ correlates to the formula (5) with $\beta=0.79\pm 0.01$. At this level, the overheat is 20–40 K.

Figure 3. Calculated overheat at the distances, proportional to the bubble diameter.

Figure 4. Comparison of the measured and estimated bubble diameter.

Then, according to (3), (4) and (5), the biggest bubble diameter was estimated by the formula

$$d(T_w, T_0, dT/dt) = (\gamma_1 + \gamma_2 dT/ dt)[(T_w - T_0) \beta + (T_0 - T_s)(1-\beta)]^\alpha$$

(6)

It fitted the data for the pool temperature $T_0$ from 30°C to 90°C and the average heating rate $dT/dt$ from 2.5 to 5.5 K/ms, giving $\alpha=0.69\pm 0.01$, $\gamma_1=0.013\pm 0.002$, $\gamma_2=-0.0013\pm 0.0003$.

Therefore, we conclude that the influence of subcooling is described well by the equation (5) proposed by Kim et al. [7], and the relation (6) can include the value of the transient heater temperature as a coefficient. It has been revealed that for the faster heating rates the bubbles become smaller, although the characteristic temperatures correspond to the temperatures in the liquid at the distance from the wall measured as 0.15 of the bubble diameter. Thus, for the bigger heat flows the bubbles have smaller departure diameters due to the thinner thermal boundary layer.

5. References

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