Multiscale characteristics of pool boiling in vacuum

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Abstract. In this paper the results of comprehensive study on the multiscale characteristics and heat transfer rate during water boiling in the pressure range from 8.8 to 103 kPa are presented. The experimental data are obtained using the modern experimental techniques, including high-speed video recording and infrared thermography. The usage of the special design of a transparent heating surface allows gaining a full set of major multiscale pool boiling characteristics. In particular, new data have been revealed on the vapor bubble growth rate and departure diameter, bubble emission frequency and nucleation site density during pool boiling in vacuum. The simple expression to predict the effect of pressure reduction on nucleation site density value is also presented.

1. Introduction
Pressure is one of the most important system parameters which have a significant effect on the intensity and multiscale characteristics of heat transfer during nucleate boiling. Moreover, as was noted by many researchers, if the pressure increase up to the pre-critical values is only quantitative in nature, while all the basic regularities and the pattern of boiling remain unchanged, then in the region of subatmospheric pressures the process undergoes significant qualitative changes.

In addition to the interest of the fundamental science in studying the features of liquid boiling in vacuum, this process is of great importance to various industries [1, 2]: absorption refrigeration machines, desalination plants, cooling of microelectronic devices, etc. First of all this is due to the fact that the pressure reduction allows significantly decreasing the boiling point of the working fluid and as a result reducing energy consumption in a particular industrial cycle. In addition, this leads to a decrease in the corrosion rate of heat exchange equipment in various types of evaporators [3].

To date, there are a lot of experimental studies [4-12] devoted to the investigation of the features of boiling in vacuum. However, many questions still remain open. In particular, the effect of pressure reduction on the dynamics of the triple contact line at the base of vapor bubbles and the nucleation site density remains poorly studied. In addition, there are practically no comprehensive studies in which all multiscale characteristics of boiling in vacuum (nucleation site density, growth dynamics of vapor bubbles and its departure diameter, bubble emission frequency) are studied within the framework of one experiment. Among other things this is due to the disadvantages of the traditionally used video recording from the side of a heating surface for visualization and analysis of the nucleation dynamics during boiling in vacuum. In particular, the appearance of large number of vapor bubbles on a heating surface even at relatively low heat fluxes complicates identification of individual vapor formations, calculation of their amount and detailed statistical analysis using such recording format [13]. Present work is devoted to a comprehensive study of the multiscale characteristics and heat transfer rate
during boiling in vacuum using modern high-speed experimental techniques and special design of the heating surface.

2. Experimental setup and techniques

The pool boiling experiments were performed using the setup, detailed description and diagram of which are presented in [14]. MiliQ deionized water on the saturation line for a given reduced pressure $p_s$ was used as the working fluid. The experiments were performed with varying pressures in the range of 8.8 kPa - 103 kPa taking into account the influence of hydrostatic pressure of a liquid column over a heater. Transparent 3 mm thick sapphire substrate with a vacuum deposited transparent thin-film indium-tin oxide heater was used as a heating surface. The advantage of such heater design is the possibility not only to visually record the evolution of vapor bubbles on the surface of the sapphire substrate using high-speed video recording from its bottom side, but also to study the unsteady temperature field of the ITO film surface using infrared thermography [15].

To visualize the nucleation dynamics both from the side and bottom of the transparent heating element video recording was performed with a frequency of up to 20 kHz (Phantom VEO410 camera). High-speed infrared thermography with a frequency of 1 kHz (FLIR Titanium 520M camera) was used to study the unsteady temperature field of the heating surface.

3. Results and discussion

3.1. Heat transfer rate during pool boiling in vacuum

First of all, using high-speed thermography data on the evolution of the unsteady temperature field of the heating element during water boiling at various reduced pressure $p_s$ values were obtained and the corresponding boiling curves were constructed for conditions of heat load decrease. Figure 1 shows the values of the dimensionless heat transfer coefficient $HTC/HTC_0$ (where $HTC_0$ is the heat transfer coefficient for atmospheric pressure boiling) calculated for different pressures $p_s$ at a given heat flux density ($q = 152$ kW/m$^2$). It can be seen that the pressure reduction from 103 kPa to 8.8 kPa leads to a deterioration in heat transfer by almost 40%. Also Figure 1 shows the experimental data of other authors [6,7,9,10] obtained during water boiling on various technical surfaces at various pressures.

It can be seen from the comparison that the values of the heat transfer coefficient obtained in the present work in the pressure range of 42–72 kPa are quite lower than those obtained by other authors. Similar to the case of water boiling at atmospheric pressure [15], this is due to the small roughness value of the used sapphire heating surface ($R_a < 8$ nm). At the same time, the comparative analysis shows that the behavior of the $HTC/HTC_0(p_s)$ curve obtained in the framework of the study is generally similar to the trend of experimental studies [6,7,9,10]. In particular, it can be seen that the pressure reduction down to 42 kPa has a small effect on the heat transfer intensity during boiling. A further decrease in pressure leads to an almost linear decrease in the heat transfer coefficient value.
3.2. Bubble departure diameter and bubble emission frequency

Figure 2 presents the frames of high-speed visualization (HSV) of the boiling dynamics at various pressures, taken from the bottom and side of the heating surface. As can be seen from the figure, video recording from the heater’s bottom allows studying in detail the growth dynamics of the vapor bubbles and their temporal characteristics and also analyzing the number of nucleation sites. In addition, using such recording format it becomes possible to study the evolution of the triple contact line at the base of the bubble and to study the growth rate of dry spots. These results are presented and described in detail in [14]. In turn, video recording from the side of a heater allows analyzing changes in the shape of vapor bubbles with pressure reduction and studying the departure diameters of non-spherical bubbles during boiling in vacuum.

Figure 1. The influence of pressure reduction on the heat transfer coefficient during water boiling.

Figure 2. The frames of bottom and side view high speed visualization of water pool boiling on the surface of transparent heater at various pressures.
It was found that with the decrease in pressure the bubble growth rate during boiling and the time of its contact with the surface increase significantly. Meanwhile the process of bubble growth in the low-pressure boiling region ($p_s < 22 \text{ kPa}$) can be divided into three stages: the inertia-controlled stage ($D(t) \sim t$), during which the growth process is described by the Rayleigh equation; the stage at which the growth rate is determined by both inertial and thermal effects ($D(t) \sim t^{0.75}$); and the final heat diffusion-controlled stage ($D(t) \sim t^{0.5}$), during which the bubble growth is determined by the rate of heat supply to the interface from the liquid. In turn, the growth rate of bubbles at near-atmospheric pressures is described by terms of heat diffusion-controlled regime for almost the entire lifecycle.

In addition, with pressure reduction the average departure diameter of vapor bubbles $D_{dep}$ noticeably increases (Figure 3). This result is consistent with the general trend of a number of experimental works, the results of some of which are also demonstrated in Figure 3a. In Figure 3b the comparison of the obtained experimental data with popular models for describing the $D_{dep}$ value at pool boiling [16–18] is shown. The data are presented as the dependences Bo($p_s$), where $Bo = g(\rho_l - \rho_v)D_{dep}^2/\sigma$ is the Bond number. It can be seen from the plot that with decreasing pressure the Bond number increases significantly. This indicates that the value of the bubble departure diameter during boiling in vacuum is not determined only by the balance of surface tension and buoyancy forces. Indeed, authors of [12] examined the balance of forces acting on a vapor bubble under various conditions and proved that for sub-atmospheric boiling the inertia force is decisive along with the buoyancy force. Moreover, the obtained experimental data at pressures above 42 kPa are well described in the framework of the presented models and lie between the calculation curves for the low-pressures range.

![Figure 3](image-url)

**Figure 3.** The dependence of vapor bubble departure diameter on pressure during water pool boiling: a) comparison with experimental data of others authors; b) comparison with models.

The usage of the transparent design of the heating surface also serves to evaluate the temporal characteristics of boiling and to study the effect of pressure reduction on the bubble emission frequency. Figure 4 presents the dimensionless data in the form of $f/f_0$, where $f_0$ is the value of the bubble emission frequency during boiling under atmospheric pressure. In accordance with the analysis of the obtained data, the decrease in pressure leads to a significant decrease in the bubble emission frequency during boiling. As a result, at the lowest studied pressure ($p_s = 8.8 \text{ kPa}$) the value of frequency is not more than 0.1 Hz. A comparative analysis demonstrates that the results of present work are consistent with the general trend of data obtained in the experiments of other researchers [4,6].
3.3. Nucleation site density

With the use of video data obtained by bottom side HSV the effect of pressure reduction on the nucleation site density (NSD) during water boiling was studied. Figure 5 shows the NSD($p_s$) dependences plotted for different heat fluxes ($q = 80 \text{ and } 125 \text{ kW/m}^2$). With the decrease in pressure, the significant decrease in nucleation site density occurs (up to 45 times at $q = 125 \text{ kW/m}^2$). Moreover, during the undeveloped nucleate boiling mode ($q = 80 \text{ kW/m}^2$) the NSD($p_s$) dependence has linear form in the entire pressure range. In the case of higher heat flux ($q = 125 \text{ kW/m}^2$) the NSD($p_s$) curve also has a linear form in the pressure range of 8.8 - 73 kPa, however, the data obtained at atmospheric pressure are significantly higher than the trend line.

**Figure 5.** The dependence of nucleation site density on the system pressure during water boiling.

As the analysis of the literature shows, nowadays there are no models or approaches to describe the NSD value during liquid boiling at subatmospheric pressures. In addition, authors of the papers devoted to the experimental study of the features of boiling under such conditions usually present the
results of only qualitative observations of $NSD(p_s)$ dependence. For this reason, comparison of the experimental data of present study with other works was not possible.

It can be assumed that the nucleation site density value during liquid boiling is proportional to the number of irregularities on the heating surface, the size of which is comparable with the critical nucleation radius $R_c$:

$$R_c = \frac{\sigma T_{sat}}{h_f \rho \Delta T}.$$  \hspace{1cm} (1)

If similar to [19] assume that the distribution function of surface irregularities size has the simplest form ($\sim R^2$), the following expression can be obtained:

$$NSD = C(q) \left( \frac{r \rho \Delta T}{\sigma T_{sat}} \right)^2.$$  \hspace{1cm} (2)

To estimate the $NSD$ value for various pressures according to (2) the experimental data on the surface superheating $\Delta T$ obtained by IR thermography were used. A comparison of the results of calculations with the obtained experimental data is presented in Figure 5. As can be seen from the figure, for the heat flux density $q = 80$ kW/m$^2$ the calculation according to (2) predicts the behavior of the experimental data with an accuracy of 5% over the entire range of studied pressures. In the case of a higher heat flux ($q = 125$ kW/m$^2$), the $NSD(p_s)$ dependence is also described by expression (2) in the pressure range of 8.8 - 73 kPa.

Certainly, expression (2) does not pretend to provide a precise quantitative description of the effect of pressure on the nucleation site density during liquid boiling. In addition, the coefficient $C(q)$ in (2) is essentially a fitting parameter and its dependence on the heat flux density remains ambiguous. However, this expression takes into account the change in a number of basic thermophysical properties of the working fluid with pressure reduction and can be recommended for estimation of the $NSD(p_s)$ dependence during pool boiling.

**Conclusion**

With the use of high-speed video recording and infrared thermography new experimental data have been obtained on the effect of pressure on the major multiscale characteristics and heat transfer rate during boiling. The specially designed transparent construction of heating surface allows analyzing in one experiment the full set of data on vapor bubble growth rate and it’s departure diameter, bubble emission frequency and nucleation site density during water boiling in vacuum. With pressure reduction the nucleation site density and the bubble emission frequency are shown to decrease significantly, while the value of bubble departure diameter significantly increases. The significant heat transfer rate deterioration is also observed with the pressure decrease, especially in the range of low sub-atmospheric pressures. Obtained results have been compared with the data of other authors and existing models. The simple expression to predict the effect of pressure reduction on nucleation site density value is also presented.

Experimental data presented in the paper allow performing the detailed analysis of the influence of various heat and mass transfer mechanisms on the $HTC(p_s)$ dependence. In particular, the obtained data array on multiscale boiling characteristics serves to analyze the heat transfer rate during boiling using the popular RPI model [20]. This will help to determine which of boiling characteristics has the most significant contribution to the deterioration of heat transfer rate with decreasing pressure.

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