Experimental study of multi-scale heat transfer characteristics at pool boiling

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Abstract. This study presents the results of the experimental investigation of local and integral characteristics of heat transfer at liquid pool boiling. Saturated ethanol and water were used as the working fluids. Thin, resistively heated indium-tin oxide films deposited onto the sapphire substrates were used as the heaters. The synchronized measurements of the heater surface temperature field and dynamics of vapor bubbles were performed by high-speed infrared thermography with the frame rate of 1000 fps and resolution of up to 0.13 μm/px and high-speed video recording. In this paper new data on major local boiling characteristics, such as nucleation site density, dynamics of vapor bubbles, temporal characteristics and nucleation frequency at different heat fluxes and superheating and their comparison with correlations are presented.

1. Introduction
Nucleate boiling is one of the most effective heat transfer modes, so it is widely used in various technological applications: thermal and nuclear power engineering, chemical technology, thermal stabilization of intense heated equipment, etc. Despite a large number of papers published since the middle of the last century, devoted to the study of different aspects of boiling liquid, many questions remain open, and there is no generally accepted boiling theory [1]. This is associated with the fact that boiling is a very complicated process by the need to consider phenomena that occur over multiple length scales, ranging from centimeters down to a few nanometers. In particular, the importance of evaporation from a liquid microlayer with a thickness of several microns, developing underneath a bubble during its initial growth, is still debated in boiling society.

Also in the literature there are almost no experimental data on the boiling local characteristics, such as nucleation site density, temporal characteristics of ebullition cycle in a wide range of heat flux density for liquids with different properties. At the same time information of these important local characteristics is very necessary for understanding the physics of boiling process and basic mechanisms of boiling heat transfer, since there is a relation between local characteristics and integral heat transfer. For example, such relation is the basis of mechanistic approach to the description of heat transfer at boiling [2], known as the RPI model. Therefore, understanding of vapor bubbles growth and departure mechanisms and possibility of qualitative and quantitative description of temporal characteristics and nucleation site density are very important in general to create a boiling theory.

The aim of the present work was to investigate the local and integral characteristics of nucleate pool boiling of various liquids with the use of modern experimental techniques, such as high-speed video recording and infrared thermography.

2. Experimental setup and methods
Experiments were carried out at pool boiling of saturated ethanol and deionized water at the atmospheric pressure. The detailed description of experimental setup and measurement techniques are
presented in [3]. A thin (1 μm) conductive indium tin oxide (ITO) with exposed area of 30 × 20 mm², vacuum deposited onto the 400 μm thick sapphire substrate was used as the heater. The main advantage of using the ITO film as a heater is its property to be opaque in the mid-IR spectrum (3-5 μm) and transparent for visible spectrum (380-750 nm). When it was deposited onto the thin sapphire substrates, transparent to both IR and visible spectrum, it became possible to investigate the unsteady temperature field of ITO film by infrared recording and record the dynamics of vapor bubbles and contact line with the use of high-speed video camera.

Measurements of the surface temperature field were performed by high speed infrared thermographic recording (IR) with the use of FLIR Titanium HD 570M camera (spectral range 3.7-4.8 μm). Thermographic recording was made with the frame rate of 1000 fps at resolution of up to 13 μm/px. High-speed visualization (HSV) was performed using the Vision Research Phantom v. 7.0 camera with 2000 fps and resolution of 640 × 480 (1 px ≈ 0.07 mm). A quick-response incandescent lamp located under the work area was used to synchronize IR and HSV recordings in time.

3. Results and discussion

3.1. Integral heat transfer and nucleation site density

Boiling curves of saturated ethanol and deionized water were obtained in the study with the use of the data of infrared thermography. The analysis has shown that results are in good agreement with experimental data of other researchers obtained at boiling on smooth surfaces (ITO, silicon, polished copper) [4-6]. It is well known [4, 7, 8] that the appearance of vapor bubble on the heating surface during nucleate boiling results in a decrease of local temperature. On the infrared images, these regions look like the darker spots (cold spots). Counting of cold spots number allows us to analyze active nucleation site density (NSD) at boiling in the wide range of heat fluxes up to crisis phenomena development. For this, the heater temperature fields obtained in the present study were averaged over time. Fig. 1a shows the IR image of the heater surface at ethanol pool boiling. The number of sites was automatically determined using the algorithm implemented in MatLab software. The processed image is also shown in Fig.1a, and permanent nucleation sites are labeled with markers. The error in measuring the number of sites with the use of this algorithm was less than 10%.

Nowadays there are several approaches to describe the value of nucleation site density at boiling. One of the first physically-based approaches was proposed by Labuntsov [9], who suggested that the value of nucleation site density is proportional to the number of cavities per surface, which have a size similar to the minimum critical diameter of the vapor bubbles in metastable liquid. Based on dimension analysis and taking a simple law for the size distribution, the following relationship for calculating the NSD value has been proposed:

\[
NSD = C_0 \cdot \left( \frac{\rho \cdot h_{fg} \cdot \Delta T}{2 \sigma \cdot T_{sat}} \right)^2.
\]

On the other hand, experimental data presented in the literature show that the NSD value depends not only on surface morphology, but also on its thermophysical and wetting properties. In [10], the attempt to take into account the influence of thermophysical properties and roughness of heating surface on the NSD value at boiling was made. For analyses the authors have used experimental data obtained at pool boiling of saturated water, carbon tetrachloride, hexane and acetone on stainless steel and aluminum surfaces with different roughness. As the result of data generalization, the following dependence was proposed, where \( \gamma \) and \( \Theta \) are the surface–liquid interaction parameter and dimensionless surface roughness parameter, respectively:

\[
NSD = C_1 \cdot \text{Pr}^{1.63} \left( \frac{1}{\gamma} \right)^{0.4} \Theta^{-0.4} \Delta T^3.
\]

As it can be seen from Fig. 1b, dependence (1) does not describe the behavior of experimental data on the NSD value, especially at high superheating. On the other hand, calculation using (2) with an
empirical constant $C_1 = 92$ and heating surface roughness $R_a = 3$ nm obtained from the morphological analysis shows good agreement with experimental data in almost whole range of superheating.

![Figure 1](image1.png)

**Figure 1.** a) Time-averaged IR frame of the surface temperature field and processed image; b) nucleation site density at ethanol pool boiling.

It should be noted that expression (2) is semi-empirical and contains adjustable parameter $C_1$. Also, this model does not take into account the influence of the wetting properties of surface on nucleation site density at boiling. To create a general model for describing the nucleation site density at liquid boiling, it is necessary to provide further complex investigations.

### 3.2. Vapor bubble dynamics

Vapor bubble dynamics at boiling of ethanol was studied with the use of high-speed video recording (Fig. 2). It is known that at vapor bubble growth in its center there is a contact area of vapor and heating surface, the so-called "dry spot", whose boundary is the triple contact line (solid wall, liquid and vapor). It can be seen from Fig. 2 that obtained data make it possible to study both vapor bubble diameter ($D_o$) and dynamics of contact line in its base ($D_i$). The analysis of experimental data showed that the evolution cycle of a bubble can be divided into two stages. The first stage corresponds to the bubble growth. At this stage, the growth of the outer diameter of bubble is observed according to model [11]. The second stage corresponds to bubble departure from the heater. Here, a sharp decrease of the contact line area occurs with dry spot rewetting. At the departure stage, the outer bubble diameter remains constant.

![Figure 2](image2.png)

**Figure 2.** Dynamics of vapor bubble outer diameter $D_o$ and contact line $D_i$ at ethanol pool boiling ($q = 50$ kW/m$^2$).
3.3. Temporal characteristics and nucleation frequency at boiling

High spatial and temporal resolutions of infrared thermography have allowed us to investigate evolution of the averaged heating surface temperature in the area under single vapor bubbles (ebullition cycle) at pool boiling of water (Fig. 3) and ethanol. It can be seen that bubble nucleation is followed by a rapid surface temperature drop. During bubble growth the temperature continues decreasing until approaching the maximum size of a bubble, corresponding to the bubble departure diameter. At the stage of bubble departure with a sharp decrease in the contact line area (as can be seen from Fig. 2), the surface temperature starts increasing monotonically. After reaching the threshold temperature of site activation, the vapor bubble appears again on the heater surface and the process repeats. The figure shows that it is reasonable to divide the ebullition cycle into two stages, characterized by fundamentally different heat transfer mechanisms: the stage of vapor bubble growth until approaching the departure diameter and the stage of its departure and transient liquid heating until new bubble appearance.

Figure 3. Ebullition cycle of single vapor bubble at boiling of water and corresponding IR frames (\(q = 50 \text{ kW/m}^2\)).

Dependences of bubble growth time, waiting time of new bubble appearance and nucleation frequency on heat flux density at boiling of water and ethanol were analyzed based on the obtained experimental data. It has been shown that to determine nucleation frequency, it is necessary to take into account the waiting time, which depends on the heat flux density. At water boiling in the whole range of heat fluxes (\(q = 0 - 450 \text{ kW/m}^2\)) waiting time \(t_w\) exceeds the growth time of bubbles \(t_g\). In the region of developed nucleate boiling, simple empirical relationship \(t_w = 3t_g\) can be used to estimate the waiting time value [12]. For ethanol, an increase in the heat flux leads to significant reduction in the waiting time and it becomes comparable with growth time of the developed nucleate boiling region.

Nowadays, in the literature there is a relationship between nucleation frequency and bubble departure diameter in the form of \(fD_{dep}^n = \text{const}\), where \(n=1\div3\). However, in this work it has been shown that the value of waiting time, which is necessary to take into account for nucleation frequency determination, does not depend on the value of \(D_{dep}\). Thus, in this case the use of mentioned relationship is invalid, especially at low heat fluxes.

Also in this work the statistical analysis of the data on nucleation frequency in different areas of the heating surface at boiling of ethanol was made. It has been shown that for the given heat flux density (\(q = 25 \text{ kW/m}^2\)) nucleation frequency value can vary from 20 to 100 Hz due to the different superheating thresholds of nucleation site activation in various areas of the surface. This imposes additional difficulties for comparing theoretical correlations of the nucleation frequency at boiling liquid with the experimental results.
4. Conclusion
The new experimental data on integral and local characteristics of heat transfer at pool boiling were obtained using the modern high-speed experimental techniques including infrared thermography and special design of thin-film heaters. Analysis of experimental results shows that data on nucleation site densities at pool boiling of saturated ethanol are in cubic dependence on superheating \( NSD \sim \Delta T^3 \) and agree with Benjamin’s correlation [10]. It was shown using high-speed video recording that quite a long stage of bubble detachment occurs at ethanol boiling between the stage of vapor bubble growth and transient heating of liquid after bubble separation. At this stage, the contact line area decreases sharply, and dry spots are rewetted in short time. The temperature fields under a single vapor bubble at water and ethanol boiling were determined using IR macro recording with high spatial (~ 13 \( \mu \)m/pix) and temporal (1000 fps) resolution. In particular, it allowed us to estimate the periods of bubble growth and departure, time of transient heating before new bubble appearance on the surface and nucleation frequencies in dependence on the heat flux. It is shown that at theoretical description of nucleation frequency it is not correct to neglect bubble waiting time (especially in the range of low heat fluxes). Also, the data obtained on evolution of the temperature fields under a single vapor bubble can be used in future to determine the contribution of different boiling heat transfer mechanisms (microlayer evaporation, transient heat transfer, microconvection) in the overall heat balance by numerical simulation.

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6. References
[1] Yagov V V 2014 Heat transfer in one-phase media and at phase transformations (in Russian) (Moscow Power Engineering Institute) p 542
[2] Podowski M 2012 Toward mechanistic modeling of boiling heat transfer Nuclear Engineering and Technology 8 889–896
[3] Surtsev A S, Serdyukov V S, Moiseev M I 2016 Application of high-speed IR thermography to study boiling of liquids Instruments and Experimental Techniques 59(4) 615-620
[4] Gerardi C, Buongiorno J et al 2010 Study of bubble growth in water pool boiling through synchronized, infrared thermometry and high-speed video International Journal of Heat and Mass Transfer 53(19) 4185-4192
[5] Jun S, Sinha-Ray S, Yarin A L 2013 Pool boiling on nano-textured surfaces International Journal of Heat and Mass Transfer 62 99-111
[6] Moita A S, Teodori E, Moreira A L N 2015 Influence of surface topography in the boiling mechanisms International Journal of Heat and Fluid Flow 52 50-63
[7] Theofanous T G. et al 2002 The boiling crisis phenomenon: Part I: nucleation and nucleate boiling heat transfer Experimental Thermal and Fluid Science 26(6) 775-792
[8] Golobic I et al 2009 Experimental determination of transient wall temperature distributions close to growing vapor bubbles Heat and mass transfer 45(7) 857-866
[9] Labuntsov D A 1963 Proc. of the USSR Academy of Sciences: Energy and Transport
[10] Benjamin R J and Balakrishnan A R 1997 Nucleation site density in pool boiling of saturated pure liquids: effect of surface microroughness and surface and liquid physical properties Experimental Thermal and Fluid Science 15(1) 32-42
[11] Yagov V V 2001 Bubble growth rate at pool boiling in wide range of reduced pressures International Journal of Heat and Technology 19(2) 17-24
[12] Van Stralen S J D et al 1975 Bubble growth rates in nucleate boiling of water at subatmospheric pressures International Journal of Heat and Mass Transfer 18(5) 655-669