Evolution of steam-water flow structure under subcooled water boiling at smooth and structured heating surfaces

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Abstract. Experimentally studying of subcooled water boiling in rectangular channel electrically heated from one side was conducted. Flat surfaces, both smooth and coated by microarc oxidation technology, were used as heating surfaces. The tests were conducted at atmospheric pressure in the range of mass flow rate from 650 to 1300 kg/(m\textsuperscript{2} s) and water subcooling relative to saturation temperature from 23 to 75 °C. Using high-speed filming a change in the two-phase flow structure and its statistic characteristics (nucleation sites density, vapor bubble distribution by size, etc.) were studied. With an increase in the heat flux density (with the mass flow rate and subcooling being the same) and amount and size of the vapor bubbles increased also. At a relatively high heat flux density, non-spherical vapor agglomerates appeared at the heating surface as a result of coalescence of small bubbles. They originated in chaotic manner in arbitrary points of the heating surface and then after random evolution in form and size collapsed. The agglomerate size reached several millimeters and their duration of life was several milliseconds. After formation of large vapor agglomerates, with a further small increase in heat flux density a burnout of the heating surface occurred. In most cases the same effect took place if the large agglomerates were retained for several minutes.

1. Introduction

Boiling of liquids subcooled relative to their saturation temperature (so called “surface” boiling) is widely used in engineering practice: rocket engines cooling systems, electronic devices for power, metallurgy etc. This cooling technology makes it possible to remove extremely large (up to several tens of MW/m\textsuperscript{2}) heat fluxes \( q \). For normal operation of cooling systems it is necessary to have corresponding experimental data and certain ideas concerning the values and physical nature of critical heat fluxes \( q_{cr} \) (CHF). In [1] the comprehensive review of the main mechanistic models of CHF is presented. They are as follows: the near wall bubble crowding, the sublayer dryout, and the interfacial lift-off models. These models provide rather good results for certain fluids and within somewhat range of subcooling and mass flow rate values. Nevertheless, there is no universally recognized theory of the subcooled liquid boiling crisis under forced flow conditions. An amount of reliable experimental data on CHF under the above conditions, which are suitable for verifying the existed models or developing new, more universal ones, is limited.
Changes in the flow structure under subcooled liquid boiling in channel and a value of CHF are interrelated and interdependent. Therefore, CHF values measuring technique must be combined with high-speed video filming, as it has been done in the best experimental studies of the process [2 – 6].

Gunter [2] visualized the regimes of subcooled water boiling in rectangular channel on a flat heater by high-speed filming. He reported vapor-bubble parameters (radius, period of existence, bubble density on the heating surface) as a function of time. From the experimental data analysis he has conclude that there is a correlation between CHF incipience and the vapor film emergence due to coalescence of bubbles.

Fiori and Bergles [3] supposed the CHF occurs as a result of hot spot formation during vapor slug passing through a channel.

Celata et al. [4 – 6] observed the changes in the boiling pictures on the surface of cylindrical rod under the conditions of high subcooling, pressures, and flow rates values. With an increase in $q$ values the flow regime changed from the first small bubbles up to large ones prior to a burnout. They presented the following boiling regime classification depending on vapor the bubbles shape and size: micro bubbles, isolated bubbles, coalesced bubbles, and large bubbles. It was pointed out that the bubble dimension decreased with an increase in subcooling, pressure, and mass flow rate. At the boiling crisis beginning (at the hot spots appearance under the large-bubbles regime) a decrease in the boiling intensity was observed. Further, with a small increase in $q$ a hot-spot area under the vapor film and a heating surface burnout were seen.

In the present work we present the new visualization data concerning vapor bubble evolution on the smooth and structured heating surfaces in the course of heat flux $q$ increasing and approaching CHF conditions.

2. Experimental setup

The experimental studies were conducted at the experimental setup, the layout of which is shown at Figure 1. The water flow rate the closed circuit was provided by UPA-15-90 pump and measured using Flow-X3 flow meter with an accuracy of 0.5%. The upward water flow was chosen to provide the same direction of natural (buoyancy) and forced motion of bubbles. To maintain or change water temperature in the circuit the electric heater of 1 kW with controlled electricity voltage and a shell-and-tube heat exchanger cooled by tape water were used. The copper thermal-resistor gage was applied for measuring water temperature at the test section inlet. An accuracy of these measurements was 0,5°C. The circulation loop was assembled on the basis of 0,5” flexible reinforced silicone tubes with fiberglass cord.

The test section (channel) of 50 mm length had a rectangular cross section of 21 mm width and 5 mm height. The metallic plate of 30 length between current supply leads was used as a heating surface. It was 0,2 mm thick and was made of Kh20N80 nichrome (4 mm wide) or of VT1-0 titanium (3 mm wide) coated by TiO$_2$ layer. This layer was fabricated by micro-arc oxidation technology (MAO). The plates were heated by direct electric current. The power released was measured with an accuracy of 1%. At the front wall of the test section the window was located to provide facet video monitoring of the boiling process over the plate length. The side walls of the test section casing also had rectangular windows for filming the boiling process in profile direction. To detect the vapor phase presence at the test section exit the 300 mm long transparent glass insert of 14 mm inner diameter was installed there.

The data acquisition system comprised 4 channels and recorded voltage drop and electric current at the test plate, and water flow rate in the test loop and its temperature at the test section inlet, respectively. The interrogation frequency was 1 kHz.

The instrumental system included thermo visor also, which made it possible, if necessary, to determine temperature distribution along the heating surface.
3. Experiments on boiling in the isolated bubbles regime on the MAO-coated titanium plate

The coatings of up to 30 μm thickness was made using MAO technology on the 0.2 mm thick VT1-0 titanium foil. According to the method described in [7] the original sample was immersed into a bath with silicate-alkaline electrolyte, where due to action micro arc electric discharges in the anodic-cathode regime with a frequency of 50 Hz for approximately 30 min TiO₂ layer was formed. This occurred due to interaction between the basic metal and electrolyte components. A porosity of the coating was 18±3%.

The experiments were conducted at two values of the water subcooling relative to the saturation temperature $\Delta t_{\text{sub}} = 75$ and $35^\circ \text{C}$ at a pressure $p$ value close to the atmospheric one. The mass flow rate was varied from $\rho_w = 650$ to 1300 kg/(m²s).

For visualizing boiling process at $q$ values, which corresponds to isolated-bubbles regime, frontal video filming with 50 kHz frequency using Photron Fastcam SA4 video camera was applied. Specially developed calculating program made it possible to determine mean diameters of vapor bubbles $d_m$. From Figure 2 we can see that $d_m$ increase with an increase in $q$ and the values of $d_m$ are considerably larger at $\Delta t_{\text{sub}} = 35^\circ \text{C}$ than those at $\Delta t_{\text{sub}} = 75^\circ \text{C}$. Moreover, the density of the nucleation sites (an amount of bubbles at the heating surface) increased also with an increase in $q$.

**Figure 1.** Layout of the experimental installation: 1 – test section; 2 – water closed loop; 3 – flow meter; 4 – thermo visor; 5 – video camera; 6 – illumination; 7 – circulation pump; 8 – water temperature gage; 9 – valve; 10 – transparent insert; 11 – electrical heater; 12 – cooler; P – pressure probe.

**Figure 2.** Mean vapor bubble diameter $d_m$ as a function of heat flux density $q$ at a surface of titanium plate with MAO coating: $\rho_w = 650$ kg/(m²s), $p = 0.1$ MPa; 1 – $\Delta t_{\text{sub}} = 35^\circ \text{C}$, 2 – $\Delta t_{\text{sub}} = 75^\circ \text{C}$.
With the heat flux density being the same, $d_{\text{m}}$ value and an amount of bubbles on the heating surface decrease with an increase in subcooling relative to the saturation temperature and the water flow rate. This can be seen in Figures 3 and 4, respectively. Apparently, this fact is connected with a considerable effect of the heat release from the bubble surface by forced convection under the isolated bubbles regime.

![Figure 3](image1)

**Figure 3.** Comparison of the data of video filming of boiling process on titanium surface with MAO coating at $q = 2.9$ MW/m$^2$; $\rho_w = 1300$ kg/(m$^2$ s); (a) - $\Delta t_{\text{sub}} = 35^\circ$C; (b) - $\Delta t_{\text{sub}} = 75^\circ$C.
The frame dimension 4 x 2.5 mm.

![Figure 4](image2)

**Figure 4.** Comparison of the data of video filming of boiling process on titanium surface with MAO coating at $q = 2.9$ MW/m$^2$; $\Delta t_{\text{sub}} = 75^\circ$C; (a) - $\rho_w = 650$ kg/(m$^2$ s); (b) - $\rho_w = 1300$ kg/(m$^2$ s).
The frame dimension 4 x 2.5 mm.

At subcooled boiling in the regime of isolated bubbles on the plate with MAO coating we recognized chaotic spatial distribution of the nucleation sites, as it was observed earlier during boiling at the smooth surface [8], at the surface with artificial roughness [9], and at the surface formed by deposition of Al$_2$O$_3$ particles during nano fluid boiling [10].

**4. Formation and behavior of large bubbles**
Experiments on boiling in the regimes that are close to burnout conditions were conducted on nichrome Kh20N80 plate at atmospheric pressure at three regimes, which differ by water subcooling values: $\Delta t_{\text{sub}} = 70, 43$, and $23^\circ$C. The mass flow rate value was $\rho_w = 650$ kg/(m$^2$ s).

For analyzing boiling process in the large-bubble regime video filming was conducted in two directions using two video cameras: VideoSprint/C/G4 camera (in frontal direction) and VideoSprint/G2 camera (in side direction). The tests were conducted in so called dynamic regime, when heat flux density $q$ was constantly gradually increased from $q^* = q / q_c = 0.5 - 0.6$ to $q^* = 1$
(heating plate burnout) during the time interval of 2.5 s. This time interval was limited by the volume of the clipboards (buffer memory) of the video cameras used at the filming frequency of 2 kHz. Taking into account a small heat inertia of the thin test plate used such a method of heat supply is quite acceptable. Video filming by two cameras with an exposing time of 20 μs was synchronized. Boiling process video filming was also synchronized with the data acquisition. A size of the picture at the video camera was chosen from the condition of using the entire frame width for the plate width reproducing. Both video cameras were directed to the 15 mm long exit part of the heating plate, which is equal to one half of the entire plate length.

At a rather great heat flux density ($q^* \sim 0.75 - 0.8$) large nonspherical vapor bubbles (agglomerates) appeared in the flow. This was a result of coalescence of smaller bubbles. The general behavior of such agglomerates remained the same as that for smaller bubbles. They originated in chaotic manner in arbitrary points of the heating surface and after somewhat chaotic evolution in size and shape departed from the wall and collapsed. At $\Delta t_{\text{sub}} = 23^\circ\text{C}$ subcooling value large bubbles were similar to somewhat vapor “plug,” which occupied the entire channel cross section above the heated surface. At $\Delta t_{\text{sub}} = 70^\circ\text{C}$ mean values of the vapor agglomerates were $l = 4.5$ mm in length, $h = 2.25$ mm in height, and $b = 2$ mm in width (Figure 5).

![Figure 5. Typical view of large bubbles. (a) - frontal view, frame dimension: 3 x 10.6 mm; (b) - side view, frame dimension: 3.9 x 10.6 mm. $\Delta t_{\text{sub}} = 70^\circ\text{C}$; $\rho w = 650$ kg/(m² s); $p = 0.1$ MPa; $q^* = 0.95$.]

Some time later the vapor agglomerates appearance at the heating surface local hot spots formed near the heating plate mid ($q^* \sim 0.9$). Their dimension increased in time and large bubbles merged into a solid vapor film (Figure 6), beneath of which the plate burned out. We should note that with the appearance of hot spots the amount of vapor agglomerates sharply decreased and then they completely disappeared, as it was shown in [5] also. Apparently, this occurred because the sites of large bubbles formation were occupied by hot spots and could not absorb small vapor bubbles as earlier.
With the further increase in heat flux density ($q^* > 0.9$) the hot spots form solid vapor layer, whose thickness changed in time (the value of $h$ varied from 0.7 to 2 mm, see Figure 7, for instance). We can see that, when this happens, the hot spots merge into the solid film, first in longitudinal direction thus forming a some kind of the vapor cord, and after that this the cord expands over the entire width of the plate. Most likely, that the reason of such a two-stage process is better water make-up from the plate periphery. We should note that at $\Delta t_{\text{sub}} = 23^\circ \text{C}$ the regime of large bubbles in the form of vapor plug is immediately substituted by solid vapor film over the entire plate length without hot spot origination.

Figure 6. Hot spots merging. Subsequent frames with 150 $\mu$s time interval. Frame dimension: 3.5 x 17.9 mm. $\Delta t_{\text{sub}} = 43^\circ \text{C}; \rho w = 650 \text{ kg/(m}^2\text{s); } p = 0.1 \text{ MPa}$.

Figure 7. Vapor film at the heating surface. $\Delta t_{\text{sub}} = 23^\circ \text{C}; \rho w = 650 \text{ kg/(m}^2\text{s); } p = 0.1 \text{ MPa}$. (a) frontal view, frame dimension: 3.7 x 18.7 mm.; (b) side view, frame dimension: 5.0 x 18.7 mm.
5. Conclusions
Using high-speed filming technique the visualization of subcooled water boiling process in the regime of isolated bubbles on the heating surface with MAO coating was carried out. It was revealed that there are no considerable differences between boiling process picture on the coated surfaces and that on the smooth surfaces.

Synchronized high-speed video filming with high resolution in two mutually perpendicular directions of the subcooled water boiling was conducted at high heat flux values up to critical ones. The efficiency of this technique when studying intense boiling process is demonstrated.

Evolution of the vapor-liquid flow structure near the burnout point is described. The difference in the vapor agglomerates dimensions in the course of the vapor film development at different water subcooling values relative to saturation temperature is demonstrated.

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