Subcooled liquid boiling: details of the mechanism and phenomenological description

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Abstract. Using high-speed filming (with a frame frequency up to 100 kHz) the important details of the subcooled liquid boiling mechanism are specified, which allow to conclude that Snyder-Bergles phenomenological model describes the process with the maximal likelihood. This model accounts for the main subprocesses of the subcooled liquid boiling (evaporation of the liquid microlayer located under the bubble near the dry spot boundary, vapor condensation at the bubble dome, liquid inflow to the microlayer). It corresponds to the modern ideas regarding to boiling mechanism and qualitatively well meets the experimental data. On the basis of the conducted experiments the description of several subprocesses of the model is defined more exactly: nucleation sites deactivation, het removal from the bubble dome by means of unsteady heat conduction, bubble size evolution as a result from the balance of masses of the evaporating and condensing vapors. It was shown that large vapor agglomerates appear in the flow due to small vapor bubbles coalescence with a heat flux density increase. Formation of dry patches under the agglomerates was studied. These dry patches are precursors of the boiling crisis. Superheating of the surface under dry patches immediately leads to the heating surface burnout.

1. Introduction

Boiling of a liquid subcooled relative to the saturation temperature is one of the most efficient heat removal technologies at extreme thermal conditions. Heat transfer coefficients at subcooled liquid flow boiling are extremely high. For water they are of many tens and may exceed a hundred kW/(m\textsuperscript{2} K). Two-phase medium is absent in the coolant flow under subcooled liquid boiling. Due to this reason the above technology can be efficiently applied in the channels of a complex form, of small diameter, in branched cooling systems. This radically simplifies cooling systems design. It is very important that a hydraulic resistance of channels, in which subcooled boiling is implied, is at a level of that in the channels cooled by single-phase (non boiling) liquid, at the coolant mass flow rates being the same.

There is no full mathematical description of the subcooled liquid boiling, as it is the case for the boiling process at the saturation temperature also. To a certain extent the absence of the strict description is compensated by developing phenomenological models. For subcooled liquid boiling some of them are presented in [1–5]. In our opinion, Snyder-Bergles model [4, 5] is the maximal likelihood one. According to this model (see figure 1), at the vapor bubble basis, in the zone of three
phases line (vapor, liquid, an solid wall) contact near the boundary of a dry spot extremely intense liquid evaporation and correspondingly the main (gigantic) sink of heat took place. Gradient of the microlayer curvature provides liquid inflow to the evaporation zone [6].

Figure 1. Heat transfer model for boiling subcooled liquid.

There are rather many works on experimentally studying subcooled boiling characteristics [7–10]. Bubble dimensions, bubble shape and their evolution in time were studied, as well as bubble numerical density per unit of the heating surface area and bubble lifetime.

In the work presented, using high-speed filming of the process new data on nucleation-site stability, a growth and collapsing vapor bubbles, appearing dry patches under large vapor agglomerates, when approaching heat flux density to the critical one, were obtained.

2. Experimental rig

The experiments were conducted at the experimental rig, the scheme of which is shown in figure 2. The experimental rig and the instruments used are described in [11, 12] in detail. Therefore, below we shall describe only the test section and the high-speed filming technique of the boiling process.

The test section (1 in figure 2) was made of glass textolite. It had a rectangular 21 mm wide and 5 mm high cross section. The length of the channel was 70 mm. The 0.1 mm thick Kh18N10T stainless steel plate or 0.2 mm thick Kh20N80 nichrome plate was glued by high-temperature hermetics to the removable back wall of the test section casing. This plate formed a heated surface, at which boiling process occurred. Heating the plate was accomplished by passing direct electric current. The plate width was 3–4 mm, while the distance between the current leads was 30 mm. The experiments with a solitary bubble were also conducted. In this case heating was accomplished by a focused laser beam, which was concentrated on the surface of 13 mm disk of 0.1 mm thickness made of stainless steel. 100 W capacity JOLD-100-CPXF-LP laser diode of Jenoptik with a wavelength 808 nm was used a heating source. The irradiated circle was 1–2 mm in diameter. Grafit 33 aerosol was deposited on the outer surface of the plate to increase absorbing of laser radiation. The measured emissivity at 808 nm was 0.92.

The test section was installed vertically, and the boiling liquid flowed upward in vertical direction. This provided coincidence of the forced flow and buoyancy forces directions. The front and side walls of the test section had quartz windows to provide boiling process filming in normal and side directions.

The experiments were conducted with distilled water at mass flow rates $\rho w$ of up to 1200 kg/(m$^2$s), subcooling values of $\Delta t_{\text{sub}} = 35–75^\circ\text{C}$, and atmospheric pressure ($p = 0.1$ MPa). For maximally removing the dissolved air the water was experienced to 4-5 h boiling in a special vessel (13 in figure
2). The efficient deaeration was needed to exclude air bubbles emission at the heating surface, the presence of which strongly distorts the boiling picture recorded by video cameras.

![Diagram of experimental rig](image)

**Figure 2.** Scheme of the experimental rig: 1 – test section; 2 – closed circuit with a water; 3 – circulation pump; 4 – flowmeter; 5 – water temperature sensors; 6 – high-speed video cameras; 7 – lightning; 8 – thermovisor; 9 – valves; 10 – transparent insert; 11 – electrical heater; 12 – cooler; 13 – deaerator; 14 – heat exchanger for deaerated water cooling; P – pressure gauge.

Photron Fastcam SA4 camera was used for filming subcooled liquid boiling process. In the case of electric heating it was installed at a normal direction to the heating surface, while it looked from the side (6 in figure 2) when filming a solitary bubble. Maximal filming speed was 100 kHz with the minimal exposure time – 3 µs.

To observe the boiling process with the presence of large coalesced bubbles (agglomerates) two cameras (VideoSprint/C/G4 (normal viewing) and VideoSprint/G2 for side viewing) with a filming frequency of up to 5 kHz were used. They were also applied in so-called “dynamic heating” regimes when the heat flux density $q^* = q/q_{cr}$ was continuously increased from 0.5 to the heating plate burnout ($q_{cr}$).

### 3. Results

#### 3.1. Characteristics of the process

The analysis of the frames obtained at 50–100 kHz frequency allows to make the following conclusions regarding the subcooled liquid boiling characteristics.
3.1.1. Nucleation sites, their stability. As at the saturated liquid boiling, vapor bubbles originate in separate points of the heating surface (nucleation sites). While vapor bubble collapsing in the subcooled liquid, the nucleation site that was active earlier becomes fully deactivated and a new nucleation site appears at new point of the heating surface, most frequently, in the vicinity of the old one. This fact is in contrast with the case of saturated liquid boiling, where permanently acting nucleation sites exist. Significant liquid subcooling promotes such a phenomenon. A series of successive frames shown in figure 3 illustrates such a behavior of the nucleation sites.

![Figure 3. Distribution of nucleation sites in the snapshots recorded successively each 1 ms: Δt_{sub} = 75°C; ρω = 650 kg/(m²*s); q = 3.5 MW/m²; the frame size is 3.0 x 3.0 mm.](image)

Permanently active nucleation sites are absent. The nucleation site distributions, both in space and in time, have a clearly seen stochastic character. This is not surprising because the deactivated nucleation site, which was earlier active, had “collected” all the heat from the adjacent surface, which dimension is approximately 1 mm². A temperature of the neighboring sections was somewhat higher, and a probability of the appearance of new nucleation site is greater there.

3.1.2. Vapor bubble evolution. Figure 4 shows the experimental data on the behavior of solitary bubbles under focused laser beam heating. It should be pointed out that the curves of vapor bubble diameter evolution at the heating surface of a large area under forced liquid flow are similar to those presented in figure 4 [12]. Two facts attract one’s attention. The first one is the time of the bubble growth, which lasts less than 100–150 µs. During this time, the bubble reaches its maximal diameter of 500–700 µm. That is, the initial stage of the bubble life has an explosion-like nature. This provides forming the edge-like liquid microlayer at the contact line of three phases at the vapor basis, due to which intense liquid evaporation takes place. The second fact is as follows. During the entire second phase of the vapor bubble lifetime (at the heat flux density, which is rather less than the critical one) it decreases in dimensions. That is, in the typical case (a great number of infinitely repeated elementary processes “originating – collapsing” of the bubbles) an amount of vapor removed from the bubble is greater than that inputted.

At the interface between the vapor bubble and the surrounding cold liquid the temperature experiences a sharp change (a jump), the value of which is equal to the liquid subcooling to the saturation temperature Δt_{sub}. A heat sink into this infinite (as compared to the vapor bubble dimension) cold space takes place by means of unsteady heat conduction [13]. Under these conditions turbulent heat transfer from this micro spherical bubble merely has no time to be formed (typical Kolmogorov’s time scale of turbulence for such a flow is about 1.5 ms, while the total bubble lifetime is 0.5–0.7 ms, on the average). The density of this heat flux is proportional to the thermal activity coefficient of a liquid (ρCλ)½, where ρ is a density, C is a specific heat, and λ is a heat conductivity coefficient, liquid subcooling value Δt_{sub}, and inversely proportional to the square root of time τ. At the initial period a density of this heat flux reaches several tens of MW/m² and it rapidly decreases with time. Because of a great area of the condensation surface an amount of heat removed due to condensation is greater than
that inputted due microlayer evaporation, and in several hundreds of microseconds the vapor bubble collapses.

![Figure 4. Evolution of vapor bubble sizes in time: $q = 1.4 \text{ MW/m}^2$; $\rho w = 0 \text{ kg/(m}^2 \text{s)}$; $\Delta t_{\text{sub}} = 42^\circ \text{C} – \text{blue curves}; \Delta t_{\text{sub}} = 59^\circ \text{C} – \text{red curves.} “]

### 3.2. Development of dry patches under large vapor agglomerates

As it was said above, under the conditions of the experiments conducted, the typical bubble lifetime value was 0.5–0.7 ms. If at rather high densities of the heat flux inputted to the heating surface several bubbles could not collapse during this time, the disbalance of the condensing and evaporating vapor flows changes in favor of evaporation process and the conditions appear for the bubble coalescence and the development of large vapor agglomerates.

These agglomerates appeared in the test section channel at heat flux densities $q > (0.75–0.80)q_{\text{cr}}$ [14, 15]. Under the conditions of the experiments their dimension was equal to several mm. The agglomerates were some kind precursors of the boiling crisis and heating surface burnout. An immediate reason of the boiling crisis was the development of dry patches, the appearance of which was promoted by agglomerates. At $q/q_{\text{cr}} > 0.85–0.90$, several local irreversible (unwetted by liquid flow) dry patches of approximately 1–1.5 mm in diameter were formed along the heated plate after passing this zone by the vapor agglomerate (figure 5). The dimensions of these dry patches increased with an increase in the heat flux density and the patches united into the continuous vapor film. After the vapor film formation, the heating plate burnout occurred. The dry patches coalesced first in longitudinal direction and then they expanded over the entire width of the heating surface. Apparently, the reason of this effect was the simpler water access to the heating plate periphery.

In [15, 16] the presence of the individual vapor bubbles in the liquid film (microlayer) under the vapor agglomerates was observed. This fact attests the existence of boiling in the microfilm. In this case, the mechanism of developing irreversible dry patches is like that described in Yagov’s model [17, 18], where it is considered as the result from the progressive growth and consequent coalescence of bubbles and dry spots at their basis.
Figure 5. Formation of the irreversible dry patch after vapor agglomerate passing. $\Delta t_{sub} = 43 ^{\circ}C$; $\rho w = 660 \text{ kg/(m}^2\text{s)}$; $q = 5.6 \text{ MW/m}^2$. Time interval between the frames – 6.5 ms.

Flow direction from the right. The frame size 3.5 x 17.9 mm.

In [19], at pool saturated liquid boiling the expansion of the residual dry patches, which retain at the heating surface after large bubble departure, is pointed out as the main reason of the boiling crisis occurrence. It is supposed that the dry area expands because of weakening a “fresh” liquid supply to the line of three phases contact due to intense nucleate boiling near it. At the same time, an intensity of the nucleate boiling near dry patches increases due additional wall superheating in dry patch vicinity. This fact is confirmed by the work [20], in which using optical-fiber micro probes high-frequency nucleate boiling was recognized near dried points. We also observed intense nucleate boiling in dry patch vicinity. Under the subcooled flow boiling conditions, due to higher surface superheating, as compared to the pool saturated liquid boiling case, the intensity of the dry patch origination and growth must be greater.

It is expedient to point out that at small superheating ($\Delta t_{sub} < 30–35 ^{\circ}C$ for water) the crisis appearance is most likely connected with drying (full evaporation) of the liquid sublayer in the course of passing of the large vapor agglomerate over the heating surface (the dimensions of several agglomerates reached the entire test section length [14]) and this case is rather well described by Lee-Mudawar model [21].

4. Conclusions

As a result from the experimental studies of subcooled liquid boiling the effectiveness of Snyder-Bergles phenomenological model was confirmed regarding to the description of the typical characteristics of this process and some additional items of this model were specified, such as nucleation sites deactivation, heat removal from the vapor bubble dome by unsteady heat conduction, bubble dimension evolution in time as the result from the disbalance of masses of evaporating and condensing vapors.

At high subcooling values ($\Delta t_{sub} > 35–40 ^{\circ}C$) the presence of the vapor agglomerates above the heating surface aggravates liquid inflow to the liquid sublayer and promotes originating of irreversible
dry patches on the heating surface, the expansion of which leads to the boiling crisis and the heating surface burnout.

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