

Visualization of the Structure of Vapor-Liquid Flow During Subcooled R113 Refrigerant Boiling Under Preburnout Conditions

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Abstract

Boiling of dielectric liquids subcooled to the saturation temperature is a promising method for cooling modern electronic devices. This method makes it possible to remove sufficient heat flux densities (q), maintain the temperature of chip interfaces at the required level, and not create undesirable conditions leading to electrical breakdown in the event of a leak in the coolant circuit. The safe use of the boiling process of subcooled liquid is limited by heat flow densities, at which large agglomerates of the vapor phase appear in the core of the coolant flow, which carries the risk of hydraulic expansion of the applied cooling systems from parallel channels.

In this work, using visualization through high-speed video recording (with a frequency of 5–10 kHz), an experimental study of the evolution of the structure of a two-phase flow during boiling of subcooled dielectric liquid R113 under preburnout conditions was carried out. It has been shown that, also characteristic of water, at q close to critical, the formation of large vapor agglomerates in the R113 flow. It has been established that an increase in the degree of subcooling and mass velocity leads to an increase in q at the moment vapor agglomerates appear. The influence of the heating rate of the heat-transfer plate on the structure of the two-phase flow in preburnout conditions and on the value of q at the moment of burnout is shown.

Keywords: boiling, subcooled liquid, freon R113, vapor agglomerates, critical heat flux density, high-speed video recording.

1. Introduction

Currently, the miniaturization of elements of electronic devices and microcircuits creates the need to remove increasingly high heat flux densities [1]. Under these conditions, traditional cooling systems begin to fail to cope with the task. In order to prevent an electrical short in the event of a leak in the cooling system circuit, it is advisable to use dielectric liquids as coolants. However, the low thermophysical properties of such liquids do not allow the required q to be removed when using a single-phase coolant flow. An additional argument for the use of two-phase cooling systems based on dielectric coolants is their low saturation (boiling) temperature (t_{sat}) at atmospheric pressure (for example, for Novec 649 liquid – 49°C, for R113 refrigerant – 47.5°C). This circumstance allows you to maintain the temperature of the processors at the required level (below 75–80°C).

Subcooled liquid boiling in a channel is one of the most effective ways to remove extremely high heat flux densities [2–4]. Boiling of subcooled dielectric liquids is used in cooling systems of data processing centers, power electronics, supercomputers, avionics, lasers, etc. [5]. Research is being carried out on the possibility of using this cooling method in space applications [6]. With this cooling method, the temperature of the liquid in the flow core (t_{liq}) remains below the saturation temperature, and the vapor bubbles formed on the heat transfer surface condense (collapse) without entering the flow core. This feature makes it possible to ensure, in addition to high heat transfer coefficients (due to the combination of two high-intensity processes – boiling and condensation), the absence of a vapor phase in the core of the coolant flow. However, it should be noted that it is implemented under conditions that allow all the vapor to condense near the heat transfer surface, that is, at high subcooling ($\Delta t_{sub} = t_{sat} - t_{liq}$), liquid mass velocities (ρw) and heat flux densities far from critical (q_{cr}).

To determine the boundaries of the safe use of subcooled liquid boiling technology, you need to know the value of q_{cr} . However, in our previous works [7–9], we showed the appearance of large steam agglomerates in the flow of subcooled water when approaching a crisis ($q > 0.75\text{--}0.8 q_{cr}$). In the case of a frequently used system of parallel channels, this carries the risk of hydraulic reaming (failure of one or more channels due to “clogging” with vapor). Therefore, this circumstance also requires increased attention and additional research when considering the use of specific dielectric coolants in cooling systems, which are very different from water in thermophysical properties.

In this work, an experimental study was carried out of the evolution of the structure of a two-phase flow during boiling of subcooled dielectric liquid R113 in pre-crisis conditions depending on the regime parameters (heat flux density, degree of subcooling in the range $\Delta t_{sub} = 12\text{--}45^\circ\text{C}$, mass velocity in the range $\rho w = 0\text{--}1500 \text{ kg}/(\text{m}^2\cdot\text{s})$) through visualization using high-speed video recording (a method successfully used in research in the field of heat transfer in two-phase systems [7–11]).

2. Experimental setup and research methodology

The experimental setup on which the study was carried out is described in detail in [7]. In fig. 1 shows a 3D model of the main elements of the setup. The test section (position 1 in fig. 1) in the form of a channel 70 mm long had a rectangular cross-section of 21 x 5 mm. The boiling of the flow of subcooled refrigerant R113 occurred on the surface of a plate made of stainless steel Ch18N10T 30 mm long and 4 mm wide (position 2 in fig. 1), glued to the rear wall of the body of the test section. The plate was heated by passing direct current through it using two copper current leads with a diameter of 8 mm and a length of 50 mm.

The boiling process was visualized through a special glass viewing window on the front wall of the test section using high-speed video recording with a frequency of 5–10 kHz on a Phantom VEO 410s camera (position 4 in Fig. 1). Synchronized with video recording, changes in current strength and voltage drop on the heat transfer plate were recorded with a frequency of 10–1000 Hz on a data acquisition system (DAS) based on the NI Compact DAQ-9178 chassis. In most of the experiments, the experiments were carried out with a dynamic continuous increase in the heat load until the heating plate burned out. The heat flux density was calculated taking into account the surface area of the plate washed by the liquid, neglecting heat losses into the body of the test section. In fig. 2 shows a typical curve of increasing q versus time in the experiment.

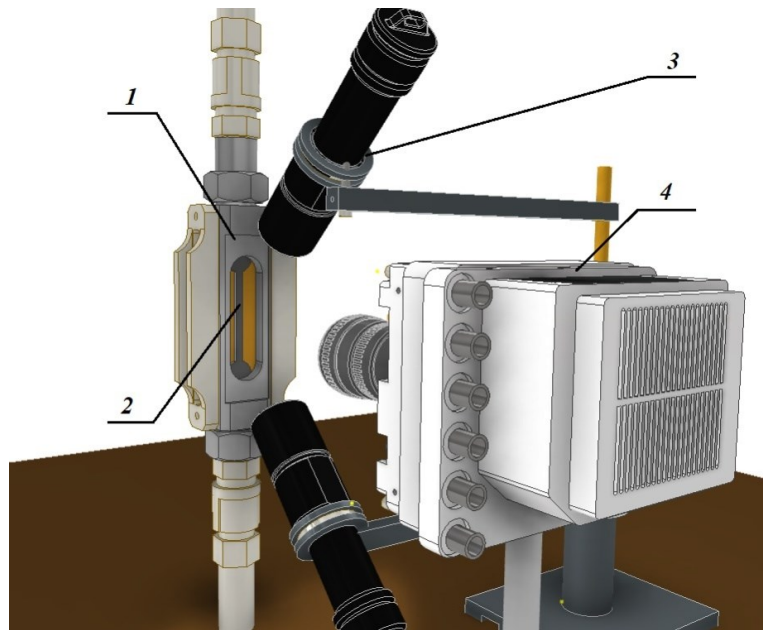


Fig. 1. 3D model of the main elements of the experimental setup: 1 – test section; 2 – heat transfer plate; 3 – backlights; 4 – high-speed video camera.

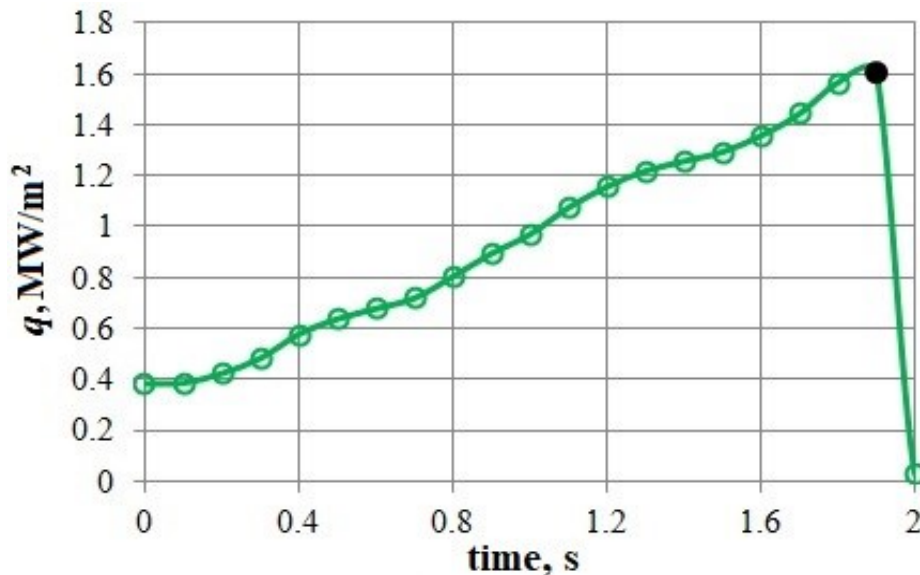


Fig. 2. Typical view of the curve of increasing heat flux density versus time in an experiment. The black dot marks the value of q at the moment of burnout of the plate.

3. Research results

In fig. 3 shows typical frames of boiling flow of subcooled refrigerant R113 at various values of q in one experiment. In fig. 3a shows a frame of the bubble boiling regime at thermal loads far from q_{cr} . With an increase in q , at some point, as in experiments on water [7–9], large vapor agglomerates begin to appear in the flow of freon R113 (fig. 3b). Then, after a further increase in q , a film boiling mode is established on the heating plate with deteriorated heat transfer characteristics (fig. 3c). The heat flux density at the moment of the appearance of agglomerates was approximately 0.7 of q at the onset of film boiling, which is also close to the values obtained for water.

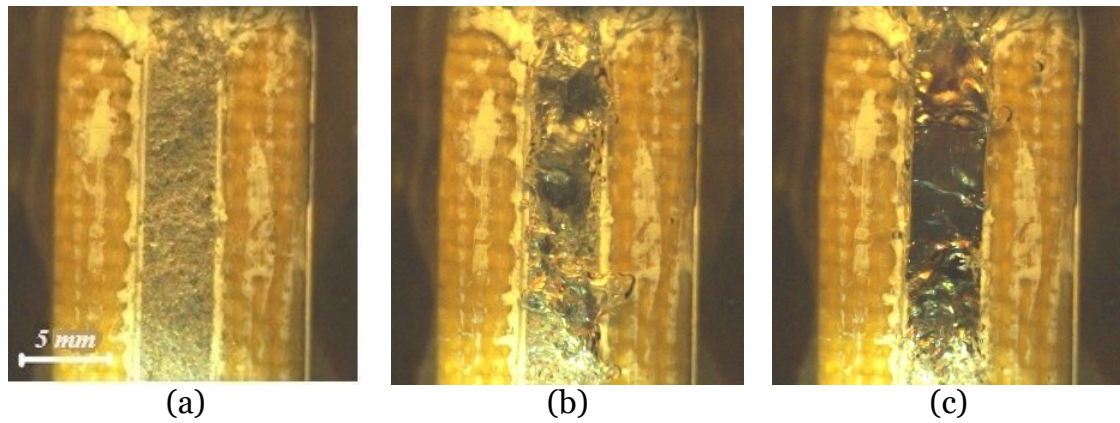


Fig. 3. Frames of boiling flow of subcooled liquid R113, $\Delta t_{\text{sub}} = 28^\circ\text{C}$, $\rho w = 1400 \text{ kg}/(\text{m}^2\cdot\text{s})$: (a) – $q = 0.64 \text{ MW}/\text{m}^2$; (b) – $q = 0.95 \text{ MW}/\text{m}^2$; (c) – $q = 1.32 \text{ MW}/\text{m}^2$. Ascending movement of fluid. Heating plate 4 mm wide in the center of the frame. Exposure time – $2 \mu\text{s}$.

The main parameters influencing the value of the critical heat flux density during subcooled liquid boiling are the degree of its subcooling and the mass velocity [3]. Naturally, these two parameters should also influence the value of q at the moment of the appearance of large vapor agglomerates of the liquid under study in the flow. In figures 4 and 5 show frames from the video illustrating this effect of the degree of subcooling and mass velocity, respectively, with the other parameters being the same. In fig. 4b shows the moment of appearance of vapor agglomerates several millimeters in size (10–15 mm in length and 4–8 mm in width, also depending on the width of the heating plate) in the liquid flow. At the same time, in fig. 4a, which shows a video frame from an experiment with a higher degree of subcooling at the same ρw and q , a typical nucleate boiling regime is still observed. Accordingly, with an increase in Δt_{sub} , in addition to an increase in q_{cr} , there is also an increase in the value of q , at which vapor agglomerates appear in the boiling flow.

In fig. 5b for comparison, shows a video frame from an experiment with the absence of forced coolant flow in the circuit (i.e. at a minimum value of mass velocity – $\rho w = 0$) at the same Δt_{sub} and q as in the experiment in the frames of fig. 4a and fig. 5a. From which we can conclude that an increase in mass velocity, as well as an increase in the degree of subcooling, “delays” the moment of the appearance of vapor agglomerates in the liquid flow towards higher q . Which seems quite logical, since an increase in these parameters (ρw and Δt_{sub}) intensifies the process of heat removal from the surface of bubbles and thereby the process of their condensation.

Quite interesting are the data on sudden boiling and the formation of dry areas, obtained under conditions of a sharp increase in the heating power of the heat-transfer plate (fig. 6) – a situation often encountered in real equipment. The rate of increase in q in this experiment was $\sim 14.5 \text{ MW}/\text{m}^2$ per second, which is approximately 20 times higher than in most of the experiments performed (fig. 2). In fig. 6a shows the moment of the beginning of a sharp increase in q and boiling at three centers (marked with white arrows). After 1 ms (fig. 6b), dry areas with dimensions of about 2–3 mm were formed on these centers with the appearance of several more boiling centers (marked with black arrows). After another ms (fig. 6c), dry regions, as a result of mutual merging and growth, occupied most of the plate, and after a few more ms they reorganized into film boiling in the center of the plate along its length with pockets of nucleate boiling at the edges (fig. 6e). After $\sim 65\text{--}70 \text{ ms}$ (fig. 6f), a film boiling regime was established over almost the entire surface of the plate. A regime with the presence of vapor agglomerates in the flow was not observed in this case. This, apparently, can be explained by the rapid formation of a film boiling regime and the absence of a high density of bubbles, from which large agglomerates are usually formed [7].

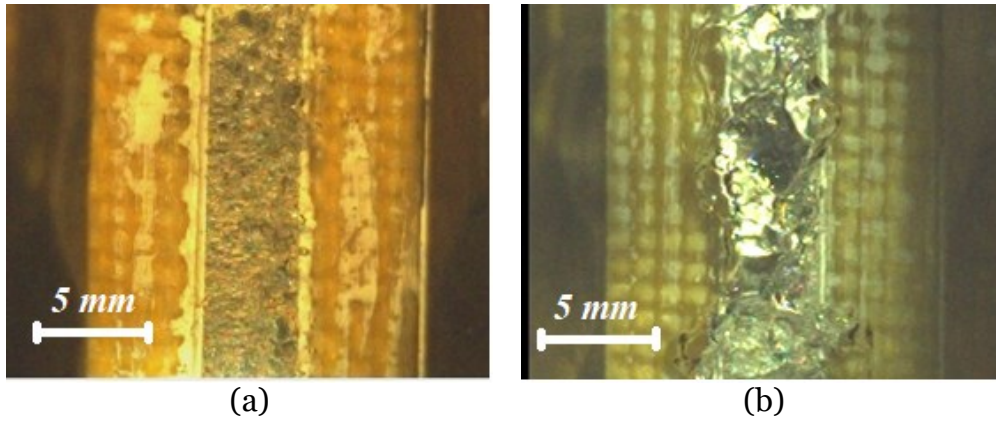


Fig. 4. Frames of boiling flow of subcooled liquid R113, $q = 0.65 \text{ MW/m}^2$: (a) – $\Delta t_{\text{sub}} = 28^\circ\text{C}$, $\rho w = 1400 \text{ kg/(m}^2\cdot\text{s)}$; (b) – $\Delta t_{\text{sub}} = 13^\circ\text{C}$, $\rho w = 1500 \text{ kg/(m}^2\cdot\text{s)}$. Ascending movement of fluid. Heating plate 4 mm wide in the center of the frame. Exposure time: (a) – $2 \mu\text{s}$; (b) – $1 \mu\text{s}$.

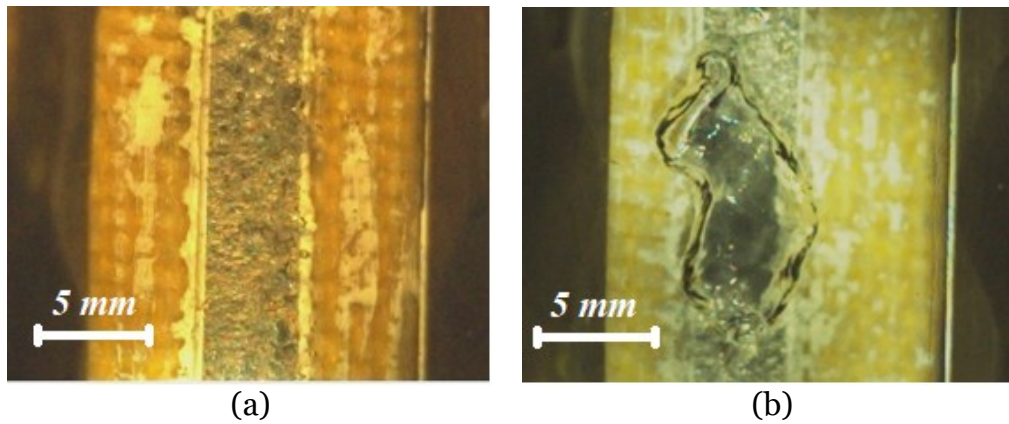


Fig. 5. Frames of boiling flow of subcooled liquid R113, $q = 0.65 \text{ MW/m}^2$: (a) – $\Delta t_{\text{sub}} = 28^\circ\text{C}$, $\rho w = 1400 \text{ kg/(m}^2\cdot\text{s)}$; (b) – $\Delta t_{\text{sub}} = 35^\circ\text{C}$, $\rho w = 0 \text{ kg/(m}^2\cdot\text{s)}$. Ascending movement of fluid. Heating plate 4 mm wide in the center of the frame. Exposure time – $2 \mu\text{s}$.

During the time between frames (fig. 6a–f), the heat flux density was increased from 0.3 MW/m^2 to 1.6 MW/m^2 . In other experiments, with the same values of Δt_{sub} and ρw under conditions of a slow increase in thermal load, burnout of the heating plate occurred at approximately the same values of q . Which is not a contradiction, since the crisis of heat transfer during boiling is associated precisely with the onset of a film boiling regime at a certain q_{cr} , that is, with the formation of a vapor layer separating the liquid from the heating surface. However, with a sharp increase in q , the plate does not yet have time to warm up enough to burn out than under conditions of a slow increase in thermal load. That is, the value of q when the heating plate is burned out does not always correspond to q_{cr} , and depends on the rate of its heating in the experiment.

An increase in Δt_{sub} from 13°C to 28°C made it possible to increase q at the moment of burnout of the heating plate from 1.2 MW/m^2 to 1.6 MW/m^2 , that is, by approximately 30%. The presence of subcooled and mass velocity of the liquid ($\rho w = 1400\text{--}1500 \text{ kg/(m}^2\cdot\text{s)}$) made it possible to obtain significantly higher q compared to pool boiling, for example, dielectric liquids FC-72 and Novec 649, which are similar in properties to R113 ($q_{\text{cr}} \approx 0.25 \text{ MW/m}^2$, [12]). Also, we should not forget, based on the above analysis, about the overestimation of the data on q obtained by continuously increasing the thermal load at the moment of burnout of the plate compared to q_{cr} . This is undoubtedly a disadvantage of this technique. However, it should be noted that the main goal was to implement the possibility of high-speed visualization in one experiment of the evolution of a two-phase boiling flow of subcooled liquid depending on changes in q .

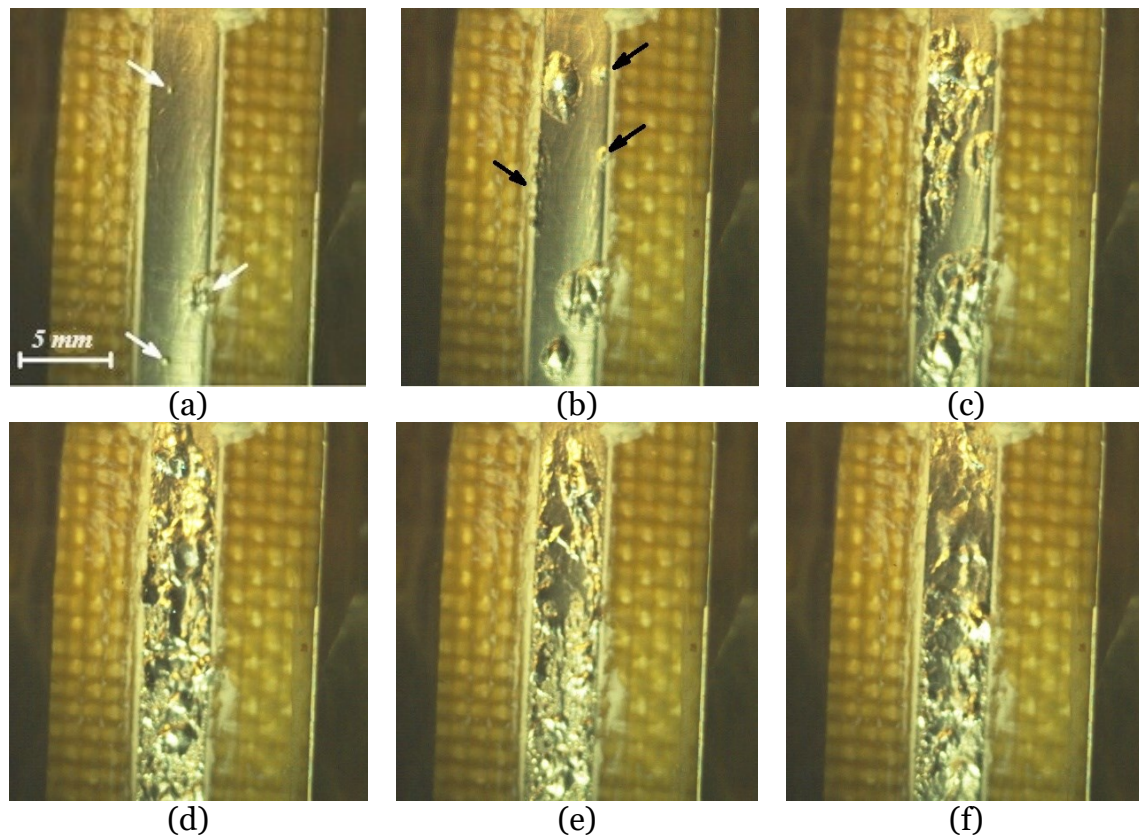


Fig. 6. Flow boiling of subcooled liquid R113 under conditions of a rapid increase in the heating power of the heat-transfer plate, $\Delta t_{\text{sub}} = 38^\circ\text{C}$, $\rho w = 1300 \text{ kg}/(\text{m}^2\cdot\text{s})$: Time from the beginning of a sharp increase in q (frame (a)): (b) – 1 ms; (c) – 2 ms; (d) – 4 ms; (e) – 8 ms; (f) – 68 ms. Ascending movement of fluid. Heating plate 4 mm wide in the center of the frame. Exposure time – 2 μs .

4. Conclusions

Using visualization through high-speed video, an experimental study of the evolution of the structure of a two-phase flow during boiling of subcooled dielectric liquid R113 under pre-crisis conditions was carried out.

It has been shown that, also characteristic of water, at q close to critical, the formation of large vapor agglomerates in the R113 flow before the onset of film boiling mode. It has been established that an increase in the degree of subcooling and mass velocity leads to an increase in q at the moment of the appearance of steam agglomerates.

The influence of the heating rate of the heat-transfer plate on the structure of the two-phase flow in pre-crisis conditions and on the value of q at the moment of burnout is shown.

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