Scientific Visualization, 2023, volume 15, number 3, pages 1 - 6, DOI: 10.26583/sv.15.3.01

Visualization of the Evolution of a Single Vapor Bubble During Boiling of a Subcooled Liquid: Experience in Automating the Processing of High-Speed Video Recording Results

N.V. Vasil'ev[1,A,B], S.N. Vavilov[2,A], Yu.A. Zeigarnik[3,A], N.A. Azarov[4,B]

[A] Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia
[B] Bauman Moscow State Technical University, Moscow, Russia

[1] ORCID: 0000-0001-9883-1280, nikvikvas@mail.ru
[2] ORCID: 0000-0002-4318-9777, sergeynv@mail.ru
[3] ORCID: 0000-0001-7642-2590, zeigar@oivtran.ru
[4] ORCID: 0009-0007-2256-704X, k.azarov@bk.ru

Abstract

Subcooled liquid boiling makes it possible to remove extremely high heat flux densities (tens, and under certain conditions even hundreds of MW/m2). This method is used for cooling rocket nozzles, in metallurgy, in thermonuclear power and special installations (cooling of beam targets), pulsed magnetohydrodynamic (MHD) installations. However, the calculations of this process are based on purely empirical correlations. The lack of experimental data on the characteristics of bubbles (size evolution, life time, formation frequency) hinders the development of mathematical models and calculation methods.

The paper presents a program developed in the Python 3.10 environment for automated processing of high-speed video recordings of the evolution of a single bubble during boiling of a subcooled liquid. Comparison of frame processing, carried out «manually» and with the help of the developed program, showed a fairly high agreement between the results. The developed method makes it possible to significantly reduce the time spent on processing the experimental material and to include a significantly larger array of experimental data in the analysis.

Keywords: boiling, subcooled water, single bubble, laser heating, high-speed video recording, computerized frame processing.

1. Introduction

The boiling of highly subcooled liquid flow (mainly water) is actively and widely used in the cooling systems of apparatuses and installations that require removal of extremely high heat flux densities (q). The record q values recorded in [1] under conditions of high mass velocities, subcooling, and pressures are higher than 200 MW/m^2. An additional attractiveness of this cooling method is given by the fact that the boiling process itself is concentrated in a thin surface layer. As a result, at q far from critical, the hydraulic resistance of the flow differs slightly from that in the case of single-phase flow [2].

A large number of works have been devoted to studying the boiling of a flow of a strongly subcooled liquid, but their main goals were to study the integral characteristics of the process (critical heat flux density and heat transfer coefficients). Less attention has been paid to the statistical characteristics of vapor bubbles (distribution over diameters, evolution of sizes and shapes, average lifetimes, etc.) [3]. However, for the development of the theory and models of the process, it is quite important to have a volume of reliable experimental data on such characteristics. In classical works [4, 5], along with modern [6], the main method for obtaining statistical data was video filming of bubble evolution in the direction perpendicular to the boiling surface. This method did not allow tracking the evolution of the bubble shape, information about which can be obtained by visualizing the bubble in profile.

In [7–9], the characteristics of vapor bubbles were studied using video filming in profile during boiling of subcooled water. Heating of the boiling surface of a large area (compared to the size of the bubble) was carried out by electric current. The works [7, 8] were devoted to the study of separation diameters of bubbles. In [9], the evolution of the shape and size of vapor bubbles was studied. The studies described in these articles were carried out in the range of low q corresponding to the regime of "isolated" bubbles during boiling of subcooled water. In experiments [7, 8], the values of the heat flux density were up to 200 kW/m^2, and in [9] up to 500 kW/m^2. When going to higher q, it is impossible to trace the evolution of an individual vapor bubble with the help of video recording in profile due to the electrical heating of a large area surface due to the shading of each other by the bubbles. This problem can be solved by using localized heating of a surface of a small area (comparable to the size of a bubble) to obtain and study a single bubble. In the present work, surface heating was localized using a laser beam. Water with a high degree of subcooling $\Delta t_{sub} > 40°C$ was used as a heat carrier. The experiments were carried out in the range of heat flux densities corresponding to the developed bubble boiling regime (q = 1.0–1.6 MW/m^2).

To obtain detailed information about the change in the size and shape of bubbles at different stages of its evolution (growth, constant size, collapse), a high speed of video recording is required. For example, the duration of the growth stage to the maximum size is usually 100–150 μs. In order for at least 5 frames to fit into this period of time, a shooting speed with a frequency of at least 50 kHz (20 μs between frames) is required. The average bubble lifetime in the studied range of parameters was 500–900 μs. Consequently, each bubble at a shooting frequency of 50 kHz was recorded for at least 25 frames. To obtain statistics, information about the evolution of several bubbles is needed, which requires the processing of a large number of frames. In order to automate the processing of video frames of single bubbles, a program was written in the PyCharm integrated development environment with the Python 3.10 interpreter, the processing results of which showed high efficiency. The developed program will allow processing large arrays of experimental data at acceptable time and labor costs.

2. Experimental setup

The experimental setup (fig. 1) consisted of a closed circuit with water, the temperature of which was varied using two heat exchangers (heater and cooler). The flow rate and liquid temperature were measured by a turbine flow meter and resistance thermometers, respectively.

The length of the test section of the setup was 70 mm, its cross section was made rectangular 21 x 5 mm. Glass windows were installed on two sides and front walls of the test section to enable video recording of the boiling process in different directions. The heating plate, the thickness of which was 0.1 mm, was made of Kh18N9T steel. The plate was mounted on a single wall of the test section that did not have a glass viewing window. Its diameter was 13 mm. Laser radiation was used to heat the outer surface of the plate.

To obtain a focused laser beam on an area 1–2 mm in diameter (a Jenoptik laser diode with a power of up to 100 W was used as its source), a system of two lenses was used. The first lens converted the beams emerging from the laser fiber into a parallel beam, and the second lens (position *4* in fig. 1) focused it on the outer surface of the heating plate. To increase the degree of absorption of laser radiation, a thin layer of a special aerosol based on graphite was deposited on the surface of the plate. At the corresponding wavelength of the laser diode used (808 ± 3 nm), the emissivity of such a coating was measured, which was ~0.9.

Using a high-speed video camera (position *2* in fig. 1), the evolution of single vapor bubbles on the heating plate was visualized through the side windows. The video recording frequency was 50 kHz with an exposure time of up to 3 μs. To measure the temperature of the outer surface of the plate, a thermal imaging camera (position *3* in fig. 1) was used, from which the temperature of the boiling surface was then recalculated.

Fig. 1. General view of the experimental setup, measuring and auxiliary equipment. The numbers indicate: *1* – test section; *2* – camera for high-speed video recording; *3* – thermal imaging camera; *4* – lens for focusing laser radiation; *5* – backlights.

3. Results of automated processing of video recording

To automate the processing of frames obtained as a result of high-speed video recording, a program was written in the PyCharm integrated development environment with a Python 3.10 interpreter using a specialized library of computer vision and image processing algorithms OpenCV.

The source data was a video in .avi format obtained as a result of the experiment, which was cut into frames using the first module of the program. Frames were saved in a special directory. Then, using the second module of the program, written on the basis of the J. Canny algorithm [10], a black-and-white version of each frame was created, where the boundaries of objects were highlighted with white contours. Fig. 2 shows frames from a video recording of a single bubble, and fig. 3 their version after processing.

The black-and-white version of the frames obtained this way made it possible to accurately determine the size of the bubbles. The bubble diameter is indicated as *d* in fig. 2a and fig. 3a. To determine the size of the bubbles using the obtained black-and-white versions of the frames, the algorithm of the third module of the program was used, in which a loop was run over the matrix of pixels and their maximum and minimum values were found along the ordinate axis. By subtracting the minimum value from the maximum value, the bubble diameter was determined in pixels, which was then recalculated in μm using the known frame scale.

After obtaining the size of the bubble on each frame, the program allowed plotting the change in diameter over time. Fig. 4 shows a comparison of graphs of changes in the size of the bubble (which video frames are shown in fig. 2) versus time, obtained when processing each frame «manually» and using the developed program. Points are highlighted in red on the graphs corresponding to the sizes of bubbles on the corresponding frames before (fig. 2) and after processing in the program (fig. 3). According to fig. 4, it can be seen that the processing of frames, carried out «manually» and with the help of the program, showed a fairly high coincidence of the results.

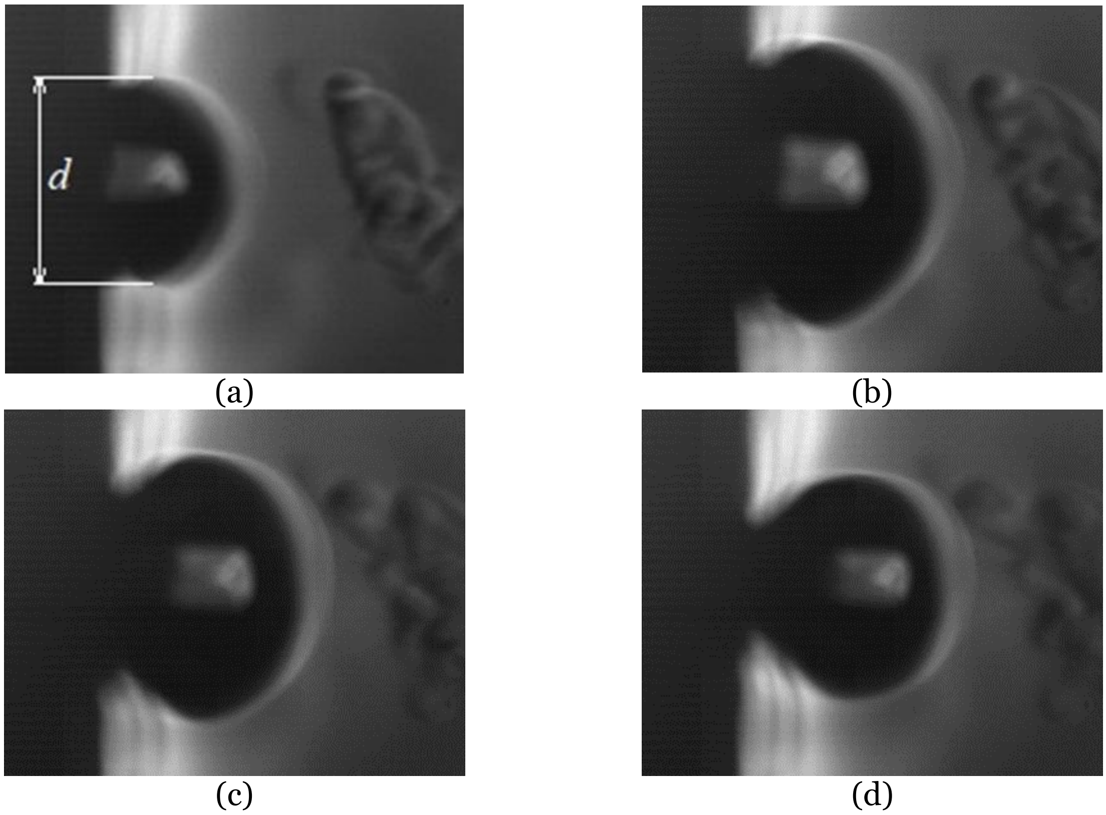


Fig. 2. Frames of video recording of the evolution of a single vapor bubble: Δt_{sub} = 42 °C; ρw = 0 kg/(m²·s); q = 1.4 MW/m². Time from bubble initiation: (a) – 60 µs; (b) – 200 µs; (c) – 340 µs; (d) – 460 µs. Frame size 0.8 x 1.0 mm. The exposure time is 3 µs.

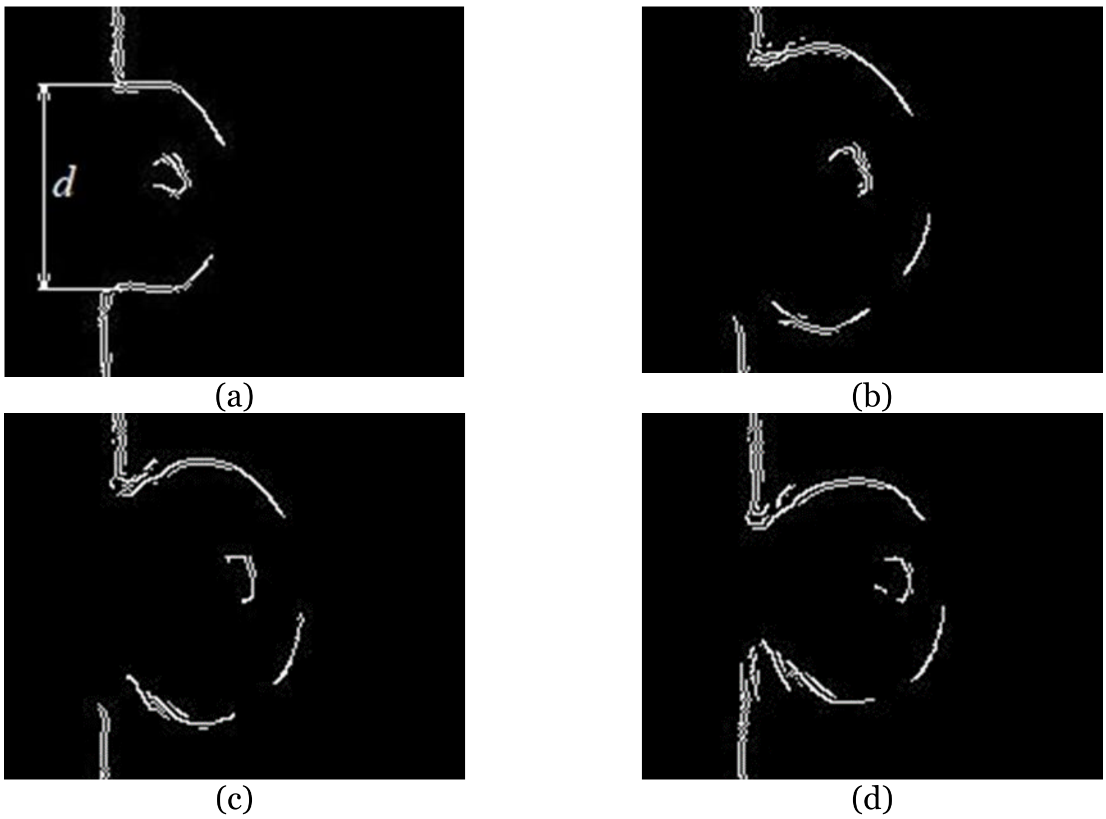
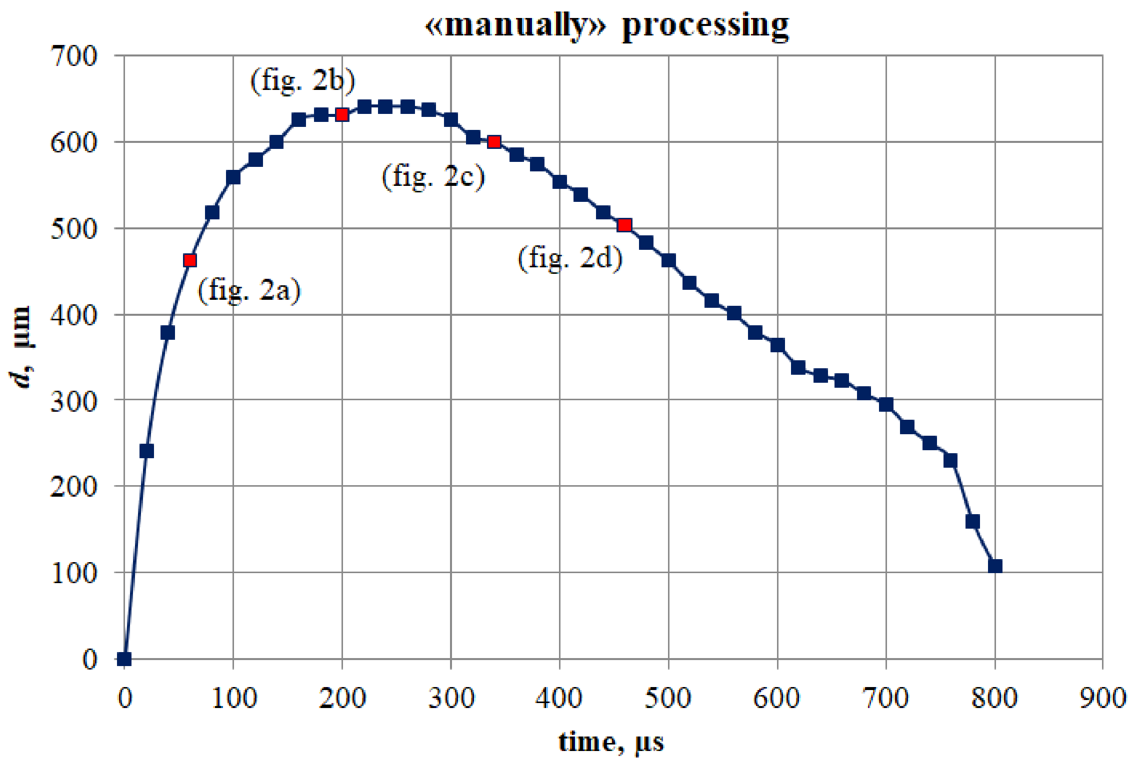
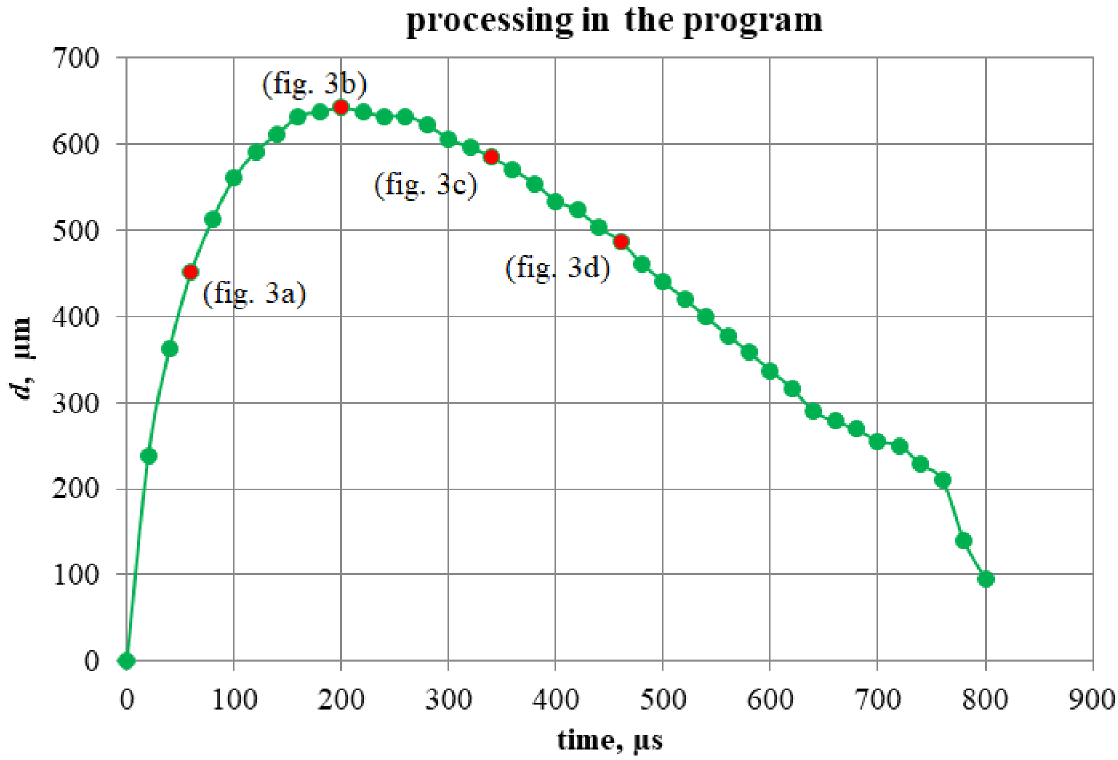


Fig. 3. Frames of the evolution of a single vapor bubble after processing in the developed program: Δt_{sub} = 42 °C; ρw = 0 kg/(m²·s); q = 1.4 MW/m². Time from bubble initiation: (a) – 60 µs; (b) – 200 µs; (c) – 340 µs; (d) – 460 µs. Frame size 0.8 x 1.0 mm.



(a)



(b)

Fig. 4. Graph of the change in the diameter of a single vapor bubble over time (Δt_{sub} = 42 °C; ρw = 0 kg/(m²·s); q = 1.4 MW/m²): (a) – obtained by «manually» processing; (b) – obtained by processing in the developed program.

4. Conclusions

Using the program developed in the PyCharm integrated development environment with the Python 3.10 interpreter, a method for automated processing of the results of high-speed video recording of the evolution of a single vapor bubble during boiling of a subcooled liquid is implemented. The developed method significantly reduces the time and labor costs for processing the experimental material and makes it possible to include a significantly larger array of experimental data in the analysis.

Funding

This work was supported by the Ministry of Science and Higher Education of the Russian Federation (State Assignment № 075-01129-23-00).

References

1. Mudawar I., Bowers M. B. Ultra-high critical heat flux (CHF) for subcooled water flow boiling — I: CHF data and parametric effects for small diameter tubes // Intern. J. Heat and Mass Transfer. 1999. V. 42. № 8. P. 1405–1428.

2. Zeigarnik Yu.A., Kirillova I.V., Klimov A.I., Smirnova E.G. Some measurements of hydraulic resistance in boiling heated to bellow the saturation temperature // High Temperature. 1983. V. 21. № 2. P. 234–239.

3. Vasil'ev N.V., Zeigarnik Yu.A., Khodakov K.A. Boiling in Forced Convection of Subcooled Liquid as a Method for Removing High Heat Fluxes (Review): Part 1. Characteristics, Mechanism, and Model of the Process, Heat Transfer, and Hydraulic Resistance // Thermal Engineering. 2022. V. 69. № 4. P. 235–251.

4. Gunther F.C. Photographic study of surface boiling heat transfer to water with forced convection // Transactions of the ASME, J. Heat Transfer. 1951. V. 73. P. 115–123.

5. Treshchev G.G. Experimental study of the mechanism of heat transfer in the surface boiling of water // Thermal Engineering. 1957. № 5. P. 44–48.

6. Vasil'ev N.V., Zeigarnik Yu.A., Khodakov K.A., Maslakova I.V. Boiling of liquid subcooled to saturation temperature in channels as a method for removal of ultimate heat fluxes // Thermal Engineering. 2019. V. 66. P. 350–360.

7. Sugrue R., Buongiorno J., McKrell T. An experimental study of bubble departure diameter in subcooled flow boiling including the effects of orientation angle, subcooling, mass flux, heat flux, and pressure // Nuclear Engineering and Design. 2014. V. 279. P. 182–188.

8. Xu J.J., Chen B.D., Xie T.Z. Experimental and theoretical analysis of bubble departure behavior in narrow rectangular channel // Progress in Nuclear Energy. 2014. V. 77. P. 1–10.

9. Cao Y., Kawara Z., Yokomine T., Kunugi T. Visualization study on bubble dynamical behavior in subcooled flow boiling under various subcooling degree and flowrates // Intern. J. Heat and Mass Transfer. 2016. V. 93. P. 839–852.

10. Canny J. F. A computational approach to edge detection // IEEE Trans. Pattern Analysis and Machine Intelligence. 1986. V. 8. P. 678–698.