

Dynamics of bubble growth during boiling at microgravity

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Abstract. The purpose of this investigation is to study the mechanisms of boiling heat transfer in microgravity conditions. The RUBI (Reference mUltiscale Boiling Investigation) is an experiment where the basic phenomena of boiling heat transfer processes on a heated surface are investigated on the ISS (International Space Station). The special focus is paid to the coupling of macroscopic bubble dynamics from nucleation, growth and detachment combined with the microscopic phenomena in the thin films and micro layers on the heater, underneath the boiling bubbles. The image treatment program has been developed in order to extract the bubble volume as well as the contact angle from the experimental images. The first data of the bubble growth dynamics have been obtained and analysed.

1. Introduction

Boiling is a complex process used in many applications such as energy conversion, chemical industry, space industry and others. It is also encountered in the natural environment such as geothermal water, geysers, volcanoes. As a result, there is a great diversity of situations in which boiling processes are present and must be well understood and better controlled.

Pioneering work in the field of boiling goes back to Nukiyama's work in 1934 [1]. This author was the first who proposed the boiling curve. This curve characterizes the heat transmitted from the wall to boiling liquid and allows the link between the heat transfer and the boiling regimes. Since that a huge number of publications were proposed in the open literature [2]. The majority of the studies are experimental having an empirical character because of the complexity of the mechanisms (heat transfer coupling, nucleation, bubble dynamics, natural convection, evaporation, condensation, contact line dynamics, wettability, thermocapillary and nonequilibrium effects). In most cases, the authors provide characteristics curves of the heat transfer and correlations for applications such as the design of evaporators, steam generators, thermosiphons, heat pumps [3]. Among these studies several authors have proposed correlations for evaluating the heat flux density based on the thermo-physical properties of the fluid and the wall [4-11]. Studies of the single vapor bubbles growth dynamics depending on the experimental conditions are presented in the works of [12-19].

The purpose of this work is to study the boiling heat transfer mechanisms. This problem is multi-dimensional, with several interacting parameters. Among them, gravity is one of the most important parameters, since the densities of the liquid and vapor phases differ by almost three orders of magnitude. To better control the influence of this parameter, the microgravity boiling research program was implemented and supported by the European Space Agency [20]. For several years, an international



scientific group works on this problem in order to obtain new data on boiling in a very simple case. The RUBI experiment (Reference mUltiscale Boiling Investigation) was created and tested on Earth at the end of 2018 and delivered to the International Space Station in July 2019.

RUBI experiment was created for investigation of the boiling process in its most elementary form, namely, in the form of a single vapor bubble in a pure liquid with well controlled conditions. The objectives of the RUBI experiment are to study: - the heat transfer in the region of the contact line of a single vapor bubble; -the dynamics of bubble growth; -the boiling with shear flow [21]; -the boiling in the presence of an electric field [22]. The experiment focuses on the relationship between the macroscopic dynamics of bubbles (nucleation, growth, detachment) in combination with microscopic phenomena in thin films and liquid microlayers under the bubbles.

2. Experimental setup

The detailed description of the experimental setup and methods is presented in [23]. In this section we present the main components of this device and the associated measurement techniques used. The core of the RUBI experiment is the boiling cell with integrated forced convection loop (FCL). A thin foil heater is located inside the boiling cell. The boiling process takes place at the foil heater, initiated by locally superheating of an artificial nucleation site using a focused laser spot. The temperature distribution of the heating foil is measured from the back side by IR thermography while the bubble shapes are observed via high-speed camera. Two stimuli systems may be used to apply forces on the vapor bubbles: a shear flow that is created by the FCL and an electric field of a washer shaped electrode above the heating foil. The temperature inside the bubble and in the vicinity of the shape liquid-vapor interface is measured by a rack of four micro-thermocouples.

The boiling cell (Figure 1) is equipped with a thermal control system allowing homogeneously tempering the working fluid N-perfluorohexane (primary component of FC-72) in the range from 30°C to 70°C. Two stimuli systems may be used to apply forces on the vapor bubbles: an electric field of a washer shaped electrode positioned (distance from the heater from 6 to 10 mm) above the substrate heater surface, adjustable in strength (0 to 15 kV), and a shear flow (0 to 0.5 L/min) that is created by the FCL.

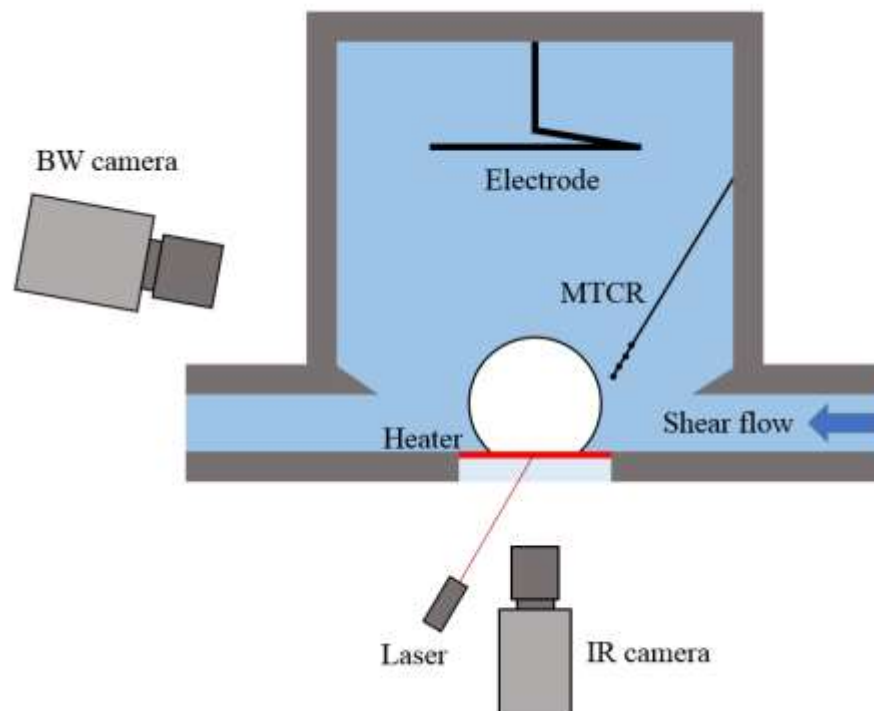


Figure 1. Scheme of the RUBI boiling cell

3. Experimental results

In this paper we report the first experimental results without external forces. This corresponds to the pool boiling case on a single nucleation site. A technique for automatic analysis of experimental images has been developed. The algorithm analyses the shape of the bubble, calculates its diameter, contact line diameter and contact angle. The analysis includes the following stages: binarization (analysis of brightness and contrast), finding the baseline, determining the bubble contour, determining the parameters of the bubble using various approximations. In the absence of external forces (shear flow and electric field), the bubble has a spherical shape. Figure 2 shows the typical images during bubble analysis.



Figure 2. Bubble contour detection steps

The first step is the preparation of the image. The background (the image where the bubble is absent) is subtracted from the original image. Next, the image containing only the bubble is processed. Then the image is binarized by analyzing the brightness (grayscale level), as well as the gradient. The second step is to identify the baseline. A bubble reflection is used to determine the baseline. The algorithm searches for the coordinates of the line between the bubble and its reflection by searching for the minimum distance between the side points. The measurement error is determined by the image resolution, which is $20 \mu\text{m}/\text{pixel}$. For a small bubble size, due to uncertainty of measurement, the baseline can “jump” by one pixel, which can significantly affect the measurement results, especially the value of the contact angle. To improve the accuracy of determining the position of the contact line, the average value for several frames determined during the calculation is used. At the third step, the bottom part of the binary image is cropped. After that, the contour of the bubble is determined using Matlab functions. At the fourth step, bubble parameters, such as the diameter of the bubble and the coordinates of the contact points are determined. Contact points are located on the baseline. Diameter is defined as the maximum distance between the side points. The measurement error is determined by the resolution of the image, as well as by determining the baseline. To determine the diameter of the contact line, the algorithm determines the contact points on the baseline. In this case, the error is already determined by the resolution of the image, as well as the accuracy of determining the position of the contact line. At the fifth step, we approximate the shape of the bubble and to determine the contact angle. Under microgravity conditions and in the absence of external forces (shear flow and electric field), the bubble shape is spherical. Therefore, the circle approximation is used. The circle is determined by the least square method, which describes the contour of the bubble by the best method. This algorithm uses two contact points, as well as the side points of the bubble with maximum diameter. Schematically, the points are shown in Figure 3. Since the camera resolution is limited, a single value of X_1 and X_2 corresponds to several values of Y_1 and Y_2 , respectively. To determine Y_1 and Y_2 , an average value was calculated among these values. Further, a circle is constructed through these points.

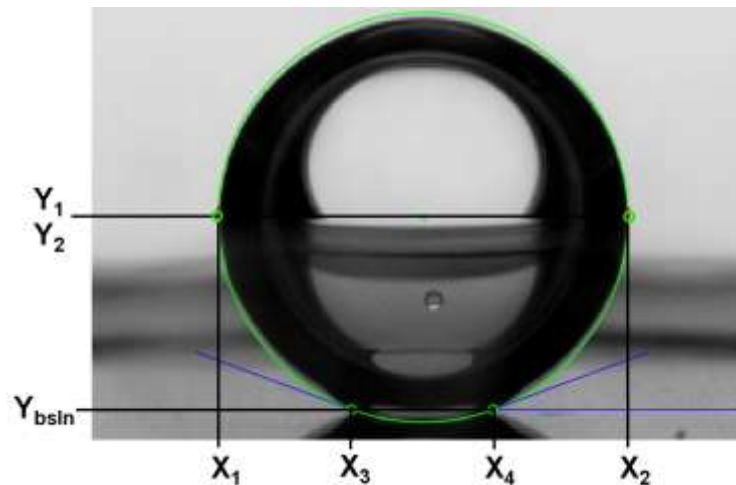


Figure 3. Method of the bubble shape circular approximation

Figure 4 shows the results of processing the bubble diameter, contact line diameter and contact angle versus time. Data are shown for the following experimental conditions: $P = 500$ mbar ; $T_{\text{sub}} = 1^\circ\text{C}$; $q = 0.5$ W/cm² ; $t_{\text{wait}} = 2$ s. Subcooling temperature T_{sub} corresponds to the difference between saturation temperature and liquid temperature. Waiting time t_{wait} is the time interval between activation of the heater and the initiation of bubble grow by the laser. On the figure 4a, the bubble volume as a function of time is calculated from the moment of its detection on the nucleation site to the detachment. On the same graph, the bubble diameter variation is deduced. On the figure 4b, the measured contact line diameter (D_{CL}) and the contact angle (CA) are shown. As we can see, these two bubble parameters exhibit different variation laws. The D_{CL} increases with time while the CA remains constant during all the bubble period growth.

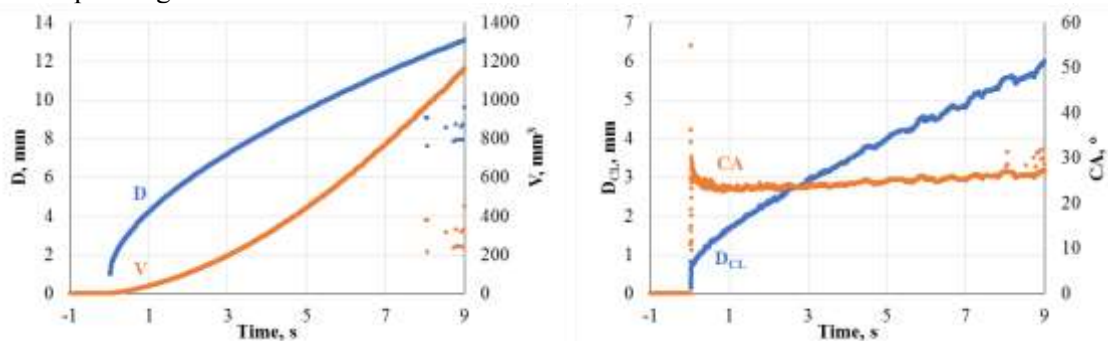


Figure 4. Influence of pressure on the dynamics of bubble growth.
Experimental conditions: $P = 500$ mbar; $T_{\text{sub}} = 1^\circ\text{C}$; $q = 0.5$ W/cm²; $t_{\text{wait}} = 5$ s.

Similar experiments have been carried out for different operating conditions (pressure, subcooling temperature, waiting time, and laser pulse time). All these results will be analyzed and will contribute to the development of reliable theoretical models. These combined approaches will help to better understand the mechanisms of bubble behavior in the boiling process.

4. Conclusion and perspectives

This paper shows the first results on the dynamics of bubble growth carried out on the ISS (International Space Station). One of methods of image analysis is presented to demonstrate the possibility to determine the main fundamental parameters of bubbles in boiling process. The next step is the development of the several experimental data analysis techniques. For this purpose, a benchmark of the

several image analyses will be carried out in a dedicated paper. This work will be followed by a detailed fundamental analysis of data on boiling in microgravity for several operating conditions.

Acknowledgments

The present work has been carried out in the framework of the European Space Agency Research projects AO-2004-111: BOILING, AO-1999-110: EVAPORATION, AO-2004-096: CONDENSATION. For space reasons, the complete acknowledgement is reported in <http://www.den.unipi.it/paolo.dimarco/eps/RUBI-ack.pdf>

Co-authors from Kutateladze Institute of Thermo-physics would like to acknowledge funding by the Russian Science Foundation (Project No. 19-19-00695).

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