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Life of a single bubble growing within an electric field in microgravity: some preliminary results of the *Reference mUltiscale Boiling Investigation*

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Abstract. The experimental outcomes of single bubbles nucleated and growth from a heated surface immersed in an electric field in high-quality microgravity level are presented. Data were obtained between September 2019 and January 2021 from the European experiment known as *Reference mUltiscale Boiling Investigation* (also *multiscale boiling project*), in which single bubbles of FC-72 were nucleated on a heated surface, on-board the International Space Station. In the experiments reported here, an electrostatic field is imposed in the boiling region by a washer-shaped electrode, centred above the nucleation site. The bubbles are heavily distorted by the electric stresses; in particular, contact angles and contact line length increase with electric field intensity. In the appropriate conditions, bubbles are continuously and regularly sucked towards the electrode, because they are attracted to regions of weaker electric field. The significant contribution of electro-convection is highlighted by the bubbles growth rate. These preliminary results contribute to the insight of the basics of boiling and show promising opportunities for practical application of electric fields in space.

1. Introduction

Pool boiling is an effective means to remove heat in many application fields, and no moving parts are required, which made it attractive for space applications. Different physical mechanisms at different scales are involved. However, bubble removal from the surface is largely dominated by buoyancy in terrestrial conditions. Many involved physical phenomena taking place at higher rate, or at microscale, are difficult to observe on Earth, while in microgravity they become slower and their characteristic lengths increase. RUBI is an experiment conceived by a European Science Team under the umbrella of ESA, as part of a wider scientific program, with a twofold aim: unveiling mechanisms masked by gravity, and provide design criteria for future boiling equipment to be operated in space vehicles. This work deals in particular on the effects of an electrostatic force, which may act as replacement of buoyancy in microgravity.

2. Experimental facility and data reduction

RUBI experiment is designed to work in the Fluid Science Laboratory of the European module Columbus [1]. The investigation possibilities go beyond what is described here: an extended description of the apparatus characteristics and diagnostics is reported in [2]. Basically, the working fluid (FC-72) is thermalized and pressurized (defining the pressure p and the subcooling ΔT_{sub}); then the heater substrate is activated at a certain heat flux q'' for the time t_w ; after that, the bubble



nucleation on an artificial site is triggered by a laser pulse. The evolution of the bubble is observed by means of a high speed B/W camera. The schematic of the experimental setup is shown in figure 1a.

2.1. Experiments with electric field

847 different experiment settings were investigated during RUBI mission, with three repetitions each. Among them, 255 include the presence of the electric field: a washer-shaped metal electrode is placed and centered above the nucleation site. The electrode produces an axisymmetric uniform electric field. In most of the experiments, the electrode was placed at 6 mm from the surface (the remaining few at 8.5 mm). Three voltage levels were imposed between the electrode and the grounded surface: 5 kV, 10 kV and 15 kV.

2.2. Analysis of the data

The output of the experiments considered in this work consists of the black and white images of the side camera that recorded 9 seconds at 500 fps for each experiment. Other data is available from other diagnostic systems (infrared camera, micro-thermocouples) but they will be not discussed here. The following results refer to the images processed through a Matlab code that detects the bubble boundaries using algorithms based on Canny method, and calculate important geometrical properties (volume, contact angle, etc.); the methods are described in detail in [3]. Errors are quantified as ± 0.04 mm for lengths and 2% for volumes.

3. Results

When a vapor bubble nucleates and grows in the absence of buoyancy, its shape is a spherical segment defined by its volume and the contact angle (that depends on fluid properties, substrate and heat flux among others). The bubble in contact with a heated surface grows as a consequence of a balance between the evaporation rate and the condensation rate, but it does not detach in microgravity. This behaviour was observed systematically in the experiments performed without external fields. However, applying an electric field has noticeable implications, described in the following sections.

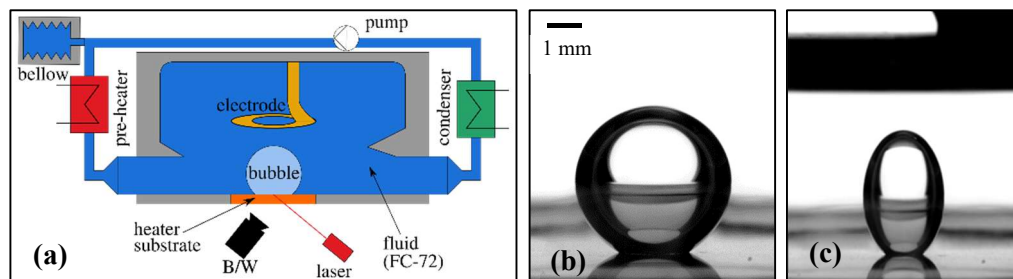


Figure 1. Experiment schematic (a); bubble shape in the absence (b) and presence (c) of an electric field (electrode placed at 6 mm from the surface and 15 kV applied).

3.1. Bubble shape

A dielectric immersed in an electrostatic field is subjected to electric stresses, that are particularly high at the liquid-vapor interface. As a consequence, the bubble assumes an ellipsoidal-like shape (figure 1c), that is more pronounced the higher is the electrode voltage.

The bubble is squeezed radially and elongated vertically, as already observed in some precursory studies on gas bubbles [3]. A deeper analysis of the images reveals that both contact line length and contact angles increase as the electric field intensity increases, as shown in figure 2.

3.2. Bubble growth rate

Bubble volume as a function of time is calculated starting from the bubble contours with the hypothesis of rotational symmetry. It represents the evaporated vapor after deduction of the condensed vapor, i.e. evolution over time of the mass balance of the bubble.

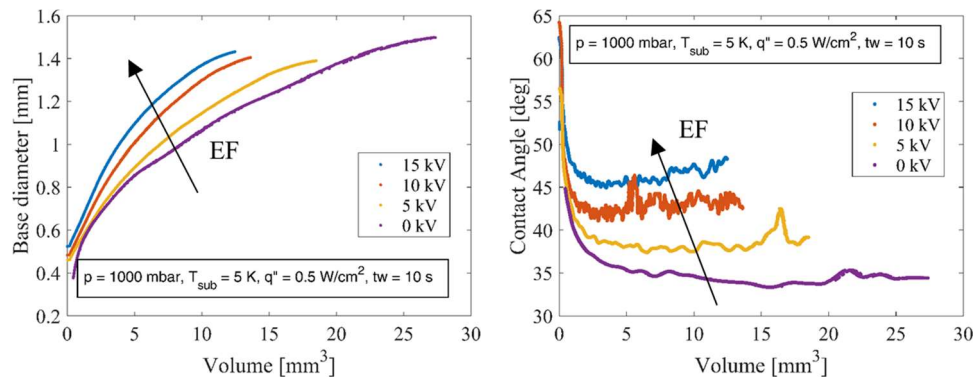


Figure 2. Base diameter and contact angle as a function of bubble volume, for three levels of voltage. Experiment parameters: $p = 1000$ mbar, $T_{\text{sub}} = 5$ K, $q'' = 0.5$ W/cm², $t_w = 10$ s.

First of all, it has been verified that even in the presence of an electric field the bubble equivalent diameter (i.e. the diameter of a sphere that has the same volume of the bubble) is proportional to the square root of the time $D_{eq} = k\sqrt{t}$ (thermally controlled growth). Secondly, the constants k have been calculated for the different experiment conditions. Remarkably, while the growth rate increases with the heat flux (as expected) it decreases with the electric field intensity. Figure 3 shows the trend for a series of experiments; error bars of figures 3 and 4 represent the dispersion of the value calculated on all the bubbles of the single experiment (from 2 to 30, depending on the conditions).

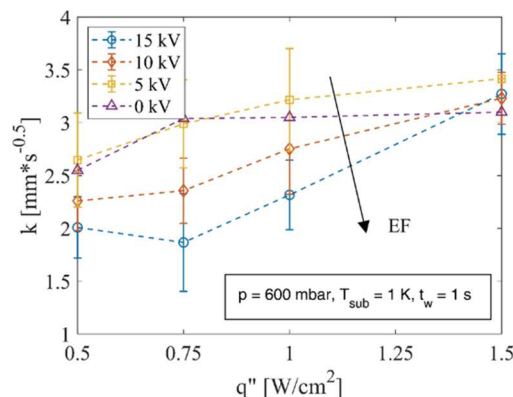


Figure 3. Growth rate as a function of heat flux, for three levels of voltage. Experiment parameters: $p = 600$ mbar, $T_{\text{sub}} = 1$ K, $t_w = 1$ s.

3.3. Bubble detachment

The most noticeable effect of the presence of the electrode, is that bubbles can detach. When the bubble is high enough, it is abruptly attracted upwards and the vapor accumulates in the middle and hollow part of the electrode, which is a region in space with a local minimum of electric field intensity. Immediately after the bubble leaves the surface, another one starts to grow to detach in turn, and the process becomes stationary after a while. The detachment volume depends strongly on voltage value and slightly on heat flux (figure 4).

4. Discussion

The bubble is affected by the electric stresses, that elongate it vertically and compress it radially. This shape is the result of the stress balance at interface, modified by the electric stress; previous experiments with adiabatic gas bubbles in FC-72 [3] found egg-shaped bubbles; in the experiments presented in the current work, the shape is more similar to an ellipse. This difference is due to the

different boundary conditions between the two sets of experiments, and in particular to the absence of heating in the former ones.

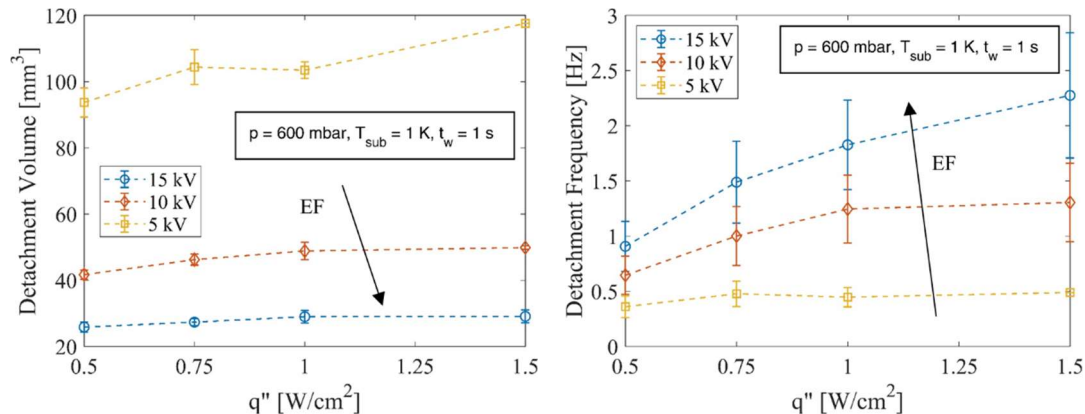


Figure 4. Detachment volume and frequency as a function of heat flux, for three levels of voltage. Experiment parameters: $p = 600 \text{ mbar}$, $T_{\text{sub}} = 1 \text{ K}$, $t_w = 1 \text{ s}$.

The growth rate of a bubble within the electric field is lower than the corresponding bubble growing in the same conditions but without field. Bubble volume at each instant of time results from the balance between the evaporation rate and condensation rate. Being all the others parameters equal, the electric field increases the single-phase convective heat transfer (electro-convection), that may increase in turn the condensation rate of the vapour at bubble top, or reduce the heat transferred through the bubble base. This results in reduction of bubble growth rate.

Lastly, when bubbles are able to grow enough with respect to the electrode, a continuous and regular detachment is observed. Detached bubbles are smaller for higher electric field intensities and detachment volume remains almost the same for a certain voltage level, indicating that it can be accurately controlled by tuning the electrode voltage. The detachment frequency consequently is higher when the detachment volume is smaller. Due to the electrode shape, the vapor is driven towards the electrode central cavity, where the electric field is lower than the surrounding regions. The stagnating mass of vapor of the detached bubbles is clearly visible in that area.

5. Conclusions

A preliminary investigation was conducted on some of the data collected in the past months in the framework of RUBI. A single bubble growing in an electric field is distorted by electric stresses; in the process, the contact angle and contact line length increase with the increasing electric field intensity. The bubble growth rate is reduced in the presence of an electric field, because of electro-convection. The application of electric field promotes regular bubble detachment. These findings contribute to provide insights on EHD-boiling and suggests possible applications for two-phase space devices.

Acknowledgments

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