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Flow boiling in microgravity

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Abstract. This study reports some results obtained on nucleate flow boiling on an isolated nucleation site in microgravity. The experiments have been carried out aboard the International Space Station thanks to the Reference Multiscale Boiling Investigation (RUBI) device. Results reveal the pronounced influence of heat flux, subcooling temperature, flow rates on the bubble behavior, and more specifically on its growth rate. Deviations from the classical square-root time law of diffusive growth are observed at high subcoolings and high flow rates.

1. Introduction

Boiling plays a crucial role in various technical processes on Earth and in space such as cryogenic fuel storage, propulsion systems, survival mechanisms and advanced cooling systems. This complex process involves multiple physical parameters governing heat and mass transfers. Despite existing correlations, predicting boiling heat transfer remains challenging and understanding local phenomena like bubble growth and detachment is crucial to enhance modeling. Under terrestrial gravity conditions, both buoyancy and natural convection result in fast growth and detachment of small bubbles that complicate experimental observations and modeling. Microgravity experiments are thus relevant to observe larger bubble with a significantly slower growth. This study, conducted aboard the International Space Station (ISS), explores the effects of several control parameters (pressure, liquid subcooling, heat flux, flow rate, waiting time, etc) on the boiling process.

The growth of a vapor bubble inside a thermal boundary layer that develops over an overheated wall is a complex multi-scale phenomenon. Part of this complexity arises from the non-uniformity of the liquid temperature field surrounding the bubble. Nevertheless, the growth of the bubble is generally compared to growth of a vapor bubble immersed in an infinitely and uniformly heated liquid medium that leads to two growth regimes: the inertia controlled growth where the bubble radius evolves as $R(t) = A \times t$ [1], and thermal diffusion-controlled growth where $R(t) = B \times \sqrt{t}$ [1, 2, 3]. It appears that the bubble growth is generally described by the thermal diffusion-controlled regime [1, 4, 5, 6] and numerous correlations describe the growth with a $R(t) = k \times \sqrt{t}$ law. Nevertheless, there are strong variations among these correlations, particularly in the choice of the prefactor k .

In this paper, the impact of various parameters such as the flow rate, the wall heat flux, the liquid subcooling and the pressure on the dynamics of the bubble growth is explored.



2. Experimental setup

The RUBI (Reference mUltiscale Boiling Investigation) experiment, that has been designed in the framework of the ESA (European Space Agency) MAP (Microgravity Application Program) project Boiling, consists of a boiling cell connected to a forced convection loop. The boiling cell (figure 1), that is thermally controlled using peltier modules, is filled with degassed FC-72 (C_6F_{14}). A heating element made of barium fluoride crystal covered with chrome (with a roughness of 0.02 to 0.11 μm) with an L-shaped artificial nucleation site is placed at the bottom of the boiling cell. This artificial nucleation site is activated through a focused laser pulse. The liquid is circulated by a pump, through a preheater, a honeycomb and enters the test section. The channel downstream the honeycomb is 40 mm wide and 5 mm high. The velocity field in the preheater, the honeycomb and the test section has been computed using OpenFoam software. To prevent pump cavitation, the flow undergoes cooling in a subcooler before entering and is subsequently reheated by a preheater. Temperature and pressure sensors are strategically placed, and an infrared camera visualizes the heating surface temperature field. More details on the description of the RUBI experiments and operating conditions can be found in [7].

The control parameters of a typical experiment are defined by the following parameters: liquid pressure P_l , saturation temperature T_{sat} , liquid subcooling $T_{sub} = T_{sat} - T_L$, T_L being the liquid temperature, heat flux from the substrate heating device q , flow rate Q , and the time elapsed between the activation of the substrate heating element and the laser pulse t_w . Once the nucleation site is activated with the laser pulse, the bubble grows on the site, then detaches and begins to slide on the wall entrained by the liquid flow. Overall, the boiling experiments here last 10 s. Black and white images of the bubble growth are taken with a high-speed camera at 500 fps. Infrared images are also taken at 240 fps.

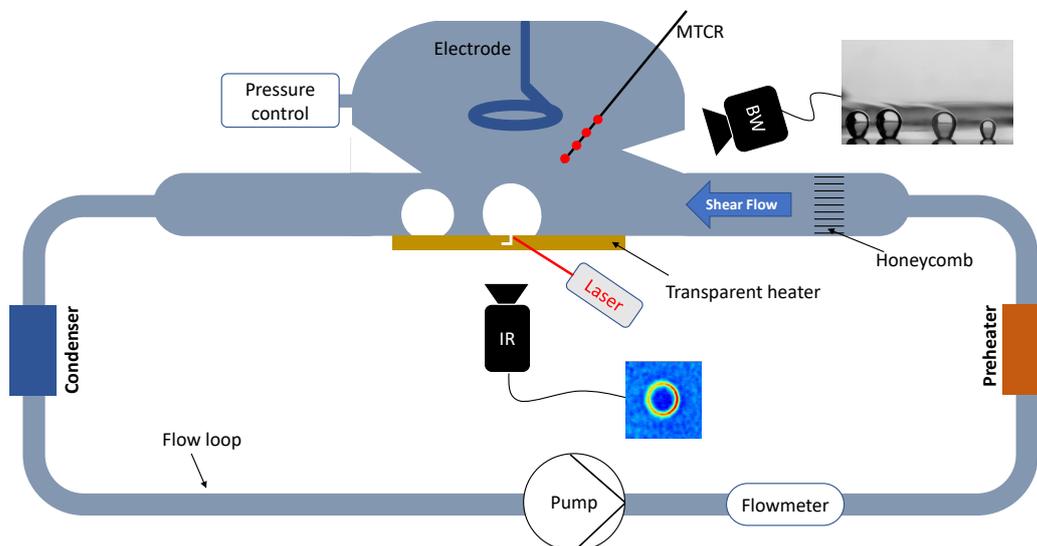


Figure 1: Schematic diagram of the RUBI experimental loop for a flow boiling configuration

This experimental configuration aims to impose external forces on a bubble through a shear flow. For each experiment, the images obtained with the BW camera are processed with Matlab (contrast adjustment, image inversion, binarization, filtering, filling of holes, segmentation, boundary detection, and tracing) to access various geometric elements of the bubble, such as its diameter, base diameter, contact angles at the bubble foot, and center of gravity, see [8] for more details.

3. Results

3.1. Effects of heat flux

The snapshots in figure 2 illustrate the influence of heat flux on the evolution of bubbles when all other parameters are kept constant. Here, three ranges of heat flux were tested: 0.5, 0.75, and 1 W/cm^2 for a liquid flow rate $Q = 0.5 L.min^{-1}$, at a pressure of 1 bar and a liquid subcooling of 3 K. For each experiment, a similar process is generally observed. After the laser pulse (local overheating of the site), a first bubble grows on the nucleation site, then detaches and just after a new one is nucleated and grows on the site. The growth dynamics of the bubbles depend on various parameters such as T_{sub} , Q , q . Indeed, in figure 2, one can observe that at detachment, the size of the bubbles increases with the heat flux. Furthermore, if we focus on the instant $t = 1.20 s$ for the three heat fluxes, it can clearly be seen that the number of generated bubbles increases with the heat flux. This effect is related to the bubble lifetime on the nucleation site that decreases with the heat flux. In other words, the higher the heat flux, the higher the growth rate, and the shorter the growth time. The same phenomenon can be observed with different parameters of the problem. To better characterize the bubble growth, we will now focus on its growth rate.

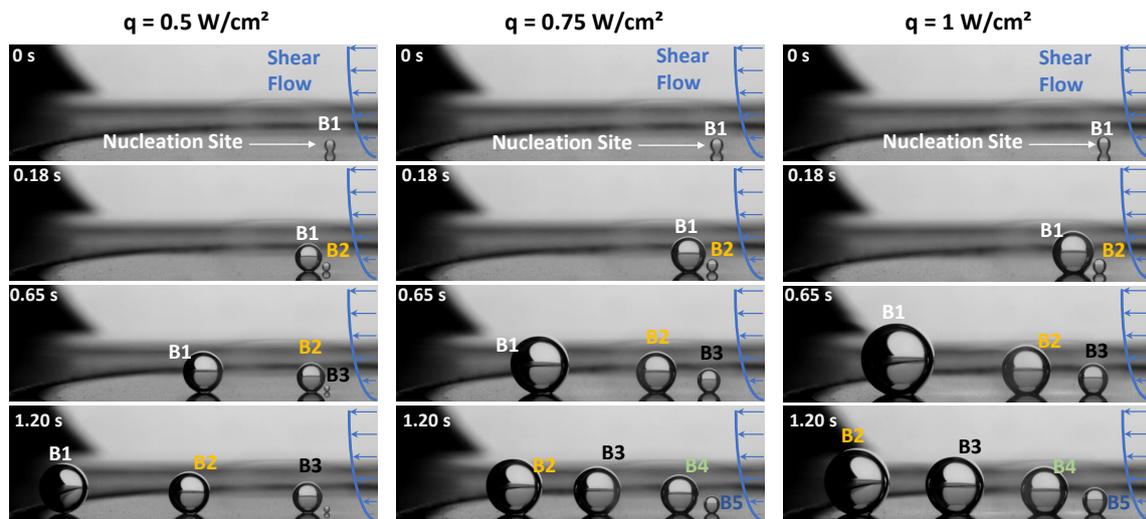


Figure 2: Effect of heat flux on bubble growth for various experiment durations and for $P = 1 bar$, $T_{sub} = 3 K$, $Q = 0.5 L.min^{-1}$ and $t_w = 5 s$. Three heat flux values were tested; left for $q = 0.5 W/cm^2$; middle for $q = 0.75 W/cm^2$ and right for $q = 1 W/cm^2$.

3.2. Bubble growth rate

In our study on flow boiling, in figures 3 (top) and (bottom), we plotted the evolution of bubble diameter with time for two flow rates (low flow rate, $Q = 0.1 L.min^{-1}$ and high flow rate, $Q = 0.7 L.min^{-1}$) under specific flow conditions ($P = 1 bar$, $T_{sub} = 5 K$, $q = 1 W/cm^2$, and $t_w = 5 s$). In figure 3 (top), corresponding to a low flow rate, it is observed that over a 10-second period, 5 bubbles were generated. The growth time of each bubble t_{det} ranges between 1.1 and 1.5 seconds, with a final diameter (diameter at detachment) D_{det} ranging from 2 to 3 mm. This provides a high spatial and temporal resolution for a detailed analysis of bubble growth dynamics.

In figure 3 (top) subplot b), the graph of $D^* = D/D_{det}$ versus $t^* = t/t_{det}$ shows that all normalized temporal growth curves overlap on a line with a slope of 0.5 in a log-log scale. This indicates that, in this run, all bubbles grow similarly, although not necessarily at the same rate. This is further evident in the graph with a dual vertical axis for n and k versus

t_{exp} , where n represents the time growth exponent, and k represents the bubble growth rate prefactor. The wall temperature increases with time, the thermal boundary layer develops, and the temperature field around the bubble increases, leading to a higher growth rate with time. For moderate subcooling temperatures and low flow rates, the bubbles appear to follow a \sqrt{t} growth. At low velocity, convection does not dominate the thermal diffusion. At low subcooling, the recondensation at the bubble top is negligible.

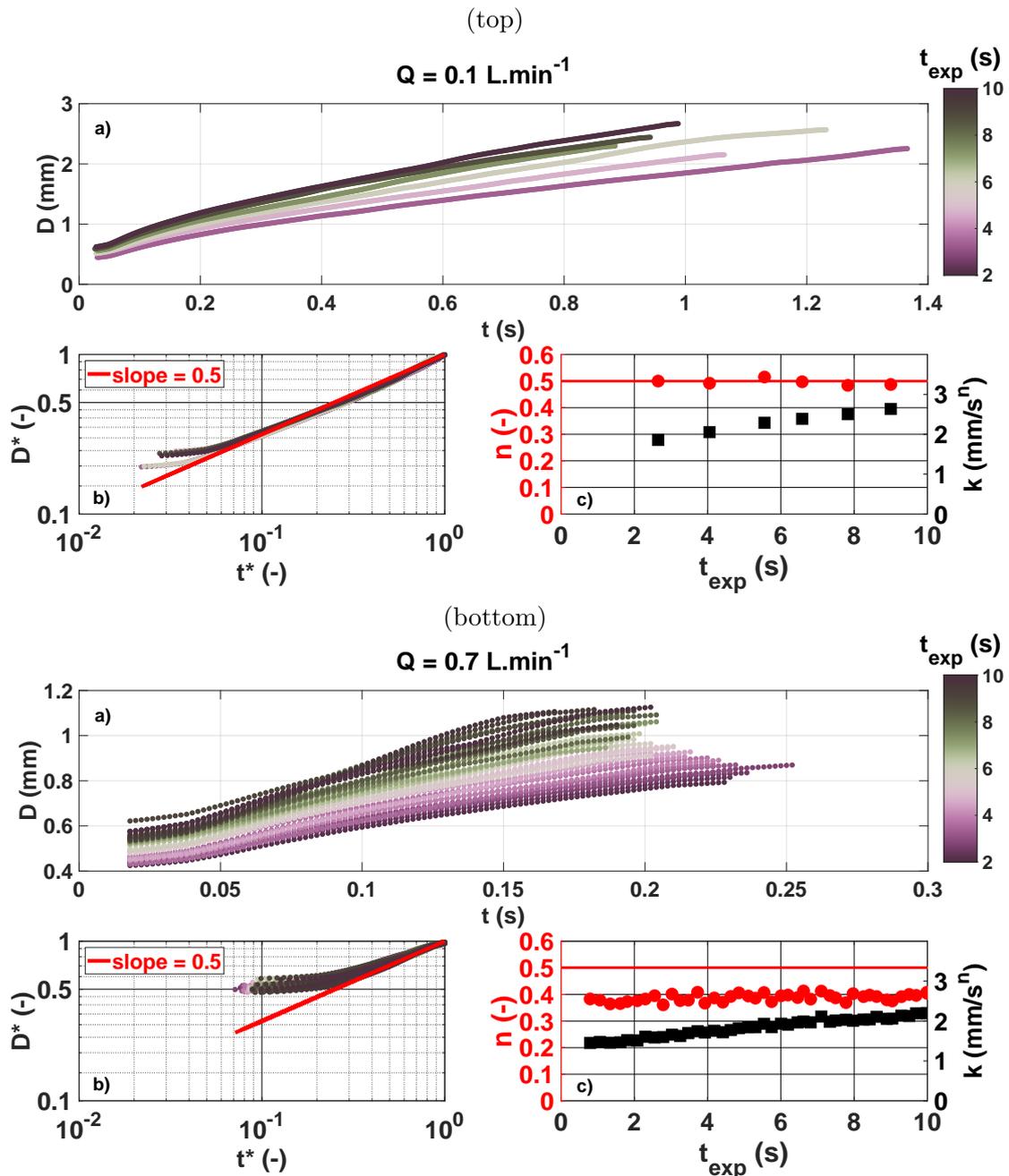


Figure 3: Temporal growth of the bubble diameter, along with the evolution of the growth rate (k) and the growth exponent (n), for: (top): $Q = 0.1 \text{ L.min}^{-1}$; (bottom): $Q = 0.7 \text{ L.min}^{-1}$. Common conditions for both cases: $P = 1 \text{ bar}$, $T_{sub} = 5 \text{ K}$, $q = 1 \text{ W/cm}^2$, and $t_{wait} = 5 \text{ s}$.

As flow rate increases from $Q = 0.1 \text{ L.min}^{-1}$ to $Q = 0.7 \text{ L.min}^{-1}$, as illustrated in figure 3 (bottom), the bubble diameter at detachment and the growth time are significantly reduced. The bubbles seem to grow with a $t^{0.4}$ dependence, contrary to the literature suggesting $t^{0.5}$ growth. The thermal boundary layer is thinner at higher velocity. Convection is probably significant and some recondensation at the bubble top may appear.

To further elaborate and clarify the relationship between the time exponent (n) and the imposed heat flux (q), figure 4 focuses on n plotted against q , for various subcooling temperatures ($T_{sub} = 3, 5, 10 \text{ K}$), represented by the colorbar, and for various flow rates ($Q = 0.1, 0.3, 0.5, 0.7 \text{ L.min}^{-1}$), represented by different symbols. The results reveal that, for a given heat flux, n is close to 0.5, particularly at lower flow rates. Furthermore, n tends to approach 0.5 as the subcooling decreases. In general, for moderate flow rates ($<0.5 \text{ L.min}^{-1}$) and moderate subcooling temperatures ($<5 \text{ K}$), bubbles appear to exhibit a $t^{0.5}$ growth. However, beyond these ranges, thermal-diffusion-controlled growth is mixed with convection and recondensation, reducing the value of the n exponent.

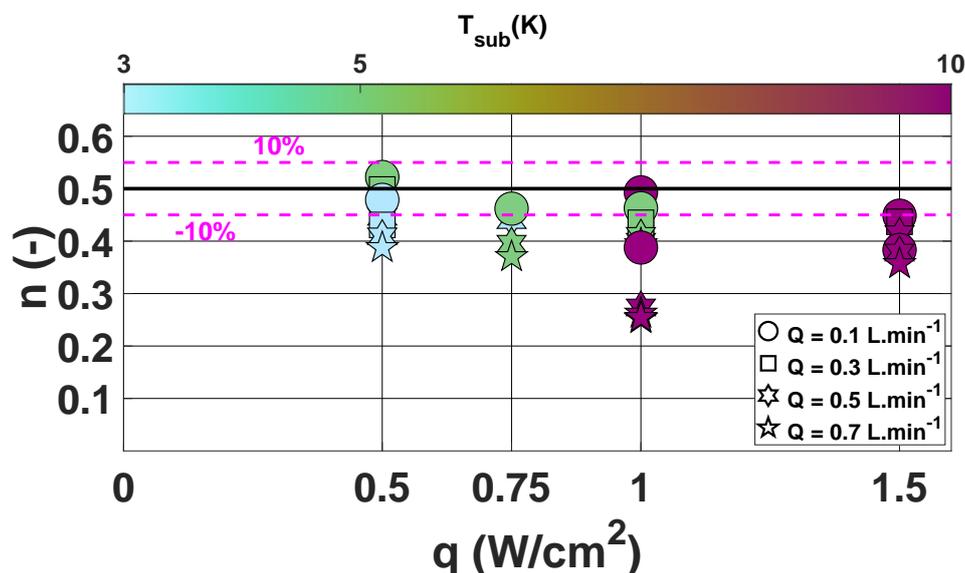


Figure 4: n versus q for different T_{sub} values (colorbar) and different Q values.

4. Conclusion

In summary, our exploration of the bubble growth rate in microgravity has unveiled intriguing insights. The experiments, conducted under various flow rates and specific conditions, revealed a consistent $t^{0.5}$ growth rate for moderate subcooling and low flow rates. However, a deviation from the expected growth from $t^{0.5}$ to $t^{0.4}$ was observed with increasing flow rates.

Different growth rates evolution with time have also been found in pool boiling configurations by [9]. First numerical simulation of the bubble growth in the RUBI experiments in pool boiling have also been performed [10] and allow to characterise the thermal field around the bubble. Such simulations will be helpful to model the bubble growth rate.

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