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Gravity-independent oscillate boiling

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Abstract Heat transfer in nucleate boiling relies on the detachment and rise of the boiling bubble, in which gravity plays the dominant role. Previous studies showed that in the absence of gravity, the bubble fails to rise, causing the dryout of the heater and significantly reducing the thermal efficiency of nucleate boiling. Recently, a new boiling regime termed *oscillate boiling* was discovered. By localizing thermal energy as high as 50 mW into an area as small as $15 \times 15 \mu m^2$, a boiling bubble is formed and oscillate at high frequency while remaining pinned at the heating spot. This regime was proposed to be independent of buoyancy as its operation does not involve the detachment and rise of the boiling bubble. To test this hypothesis, we compared experimental observations of oscillate boiling in low gravity, normal

gravity and hyper gravity. The results support the hypothesis and promote its potential for outer-space heat transfer application.

Keywords Microgravity · Boiling · Bubble · Oscillation · Thermal Management

1 Introduction

The development of space technology involves lightweight, compact and high-power devices, while at the same time requires strict temperature control to maintain proper operation. In ground applications, i.e. terrestrial condition, such tasks are managed by boiling heat transfer as it ensures high thermal efficiency and low temperatures of the dissipating devices [1]. Here, the heat transfer mechanism is attributed to the detachment and rise of the nucleate boiling bubbles [2], in which gravity plays an important role. However, in space with greatly reduced gravity, buoyancy-based boiling encounters serious limits. Earliest observation of pool boiling in microgravity reported by Abe et al. [3], Ohta et al. [4] using sounding rockets, and Oka et al. [5] on parabolic flights show that without buoyancy, boiling bubbles fail to rise. Instead, they grow, coalesce with their neighboring bubbles and hover close to the substrate's proximity. Later on, using a set of multiple temperature-controlled heating elements, Kim et al. [6] managed to capture the boiling curve and the substrate's temperature during the boiling process. The results reveal that as the bubbles fail to rise, they cause the dryout of the substrate and trap thermal energy within. Consequently, the heater experiences a significant rise in temperature together with a drop in the critical heat flux (CHF). The same observations have been reported in numerous studies on pool boiling with

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Fig. 1 (a) One typical oscillate boiling cycle. Here the heating power is 86 mW. (b) Oscillate boiling preserves its characteristics when the substrate is oriented parallel to gravity. Here the heating power is 62 mW. The scale bars in each figures represents 20 μ m.

different heater's geometries, test liquids [7–12], and microgravity platforms [13–16]. These works are extensively reviewed by Mudawar et al. [17] and Colin et al. [18]. Thermocapillary stress has been speculated to be capable of transporting heat from the substrate into the bulk liquid in the absence of gravity. However, its efficiency is still far inferior compared to convection in terrestrial condition [6,19–21]. Thus, utilizing pool boiling for outer-space thermal management remains a challenge.

Recently, we reported a new boiling regime termed *oscillate boiling*, which may provide a solution for micro gravity environments [22,23]. Unlike nucleate boiling, oscillate boiling is expected to be independent of gravity since its heat transfer is not dependent on the detachment and rise of vapor bubbles from the heater surface. Instead, by concentrating thermal energy between 50–100 mW into an area as small as $15 \times 15 \mu\text{m}^2$, a boiling bubble is formed that remains pinned on the surface while undergoing repetitive high frequency volume oscillation, up to several 100 kHz. Figure 1a shows captured images of one typical period of the oscillate boiling bubble. The presence of a solid boundary induces non-spherical collapses of this bubble [24]. As a result, a liquid jet is developed during each collapse and impacts onto the high temperature heater. Upon this impact, the jet is vaporized, resulting thermal energy being removed from the substrate and transported into the bulk liquid. The heat is carried by a flow driven by the thermocapillary stress (Marangoni flow [25]) and a streaming flow set up by the bubble oscillations [22], both of which are independent on buoyancy. Preliminary experiments with earth gravity g_e show that oscillate boiling retain normal performance on a substrate inclining 30 degree [22] and even 90 degree (Fig. 1b) to

Fig. 2 (a) The design of the electrical microheater (b) Sketch of the experimental setup where red lines represent power connections and black lines represent flow of electrical signals. (c) 3D-view of the devices used.

horizontal direction. However, there has not been any study on the behavior of oscillate boiling in actual non-conventional gravity environment, i.e. low- g and high- g .

In this work, we report on experimental observation of oscillate boiling in water both in low- g and high- g on-board parabolic flights. We then compare its behavior with results collected in terrestrial condition to draw conclusion on the effect of gravity on oscillate boiling. The experiments utilize a compact, simple, yet effective setup that can inspire future high-speed imaging experiments in low-gravity conditions.

2 Experimental apparatus

2.1 Experimental setup

Figure 2 describes the complete experimental setup. The test section base was a glass wafer that contained a microfabricated $15 \times 15 \mu\text{m}^2$ electrical heater made of platinum with gold electrodes wiring (see Fig. 2a). The heater's design and fabrication steps were the same as described in Ref [23]. Microscope cover glasses formed the side walls of the $1 \times 1 \times 1 \text{ cm}^3$ liquid container. The container was filled with de-ionized water with bulk temperature of $\approx 17^\circ\text{C}$. The top of the container was covered with a layer of foam to prevent any leakage of the liquid while equilibrating with the cabin pressure ($\approx 0.8 \text{ bar}$). The electrical microheater was powered with a laser diode controller (Thorlabs LDC220) operating at constant current mode. The heater's instantaneous temperature was obtained from its resistance, which was recorded at a sampling rate of 10 MHz with 12 bits accuracy with a data acquisition (DAQ) board (model USB 2020 from MCDAC). The periodic drop of the temperature during each cycle (see below) allowed determining the bubble's oscillation frequency from the resistance signal.

The bubble oscillations were imaged with a sensitive CMOS camera (global shutter, model 1920-155um from Basler) equipped with a 5x-magnification lens (Makro lens MO-E65mm from Canon). This configuration provided a maximum temporal resolution of 1 ms and a spatial resolution of $1 \mu\text{m}$. A typical period of the bubble oscillation is $4 \mu\text{s}$, thus it demanded a short exposure time to capture the bubble dynamics free of motion blur. Because the minimum shutter duration of the camera was $100 \mu\text{s}$, a strobed light source was synchronized with the camera. In particular, the camera exposure-out signal triggered a current amplifier [26] that generated a $1 \mu\text{s}$ -long pulse for the illuminating LED (Cree CXB1304). The 1 kHz triggering signal for the camera, the current controller, and the DAQ device were controlled with a microcontroller (Teensy 3.6). It was configured with a laptop through a USB port that also stored the images from the camera and waveforms from the DAQ board. An accelerometer (Adafruit LIS3DH) connected to the laptop measured the effective gravity and provided the signal to start the experiment.

Figure 2b shows the electrical diagram and Fig. 2c shows the full mechanical design of the setup. The use of a data acquisition board and a USB-connected camera instead of an oscilloscope and a high speed camera saved weight, size and cost of the setup. The experiments enclosing dimension reduced to only $50 \times 30 \times$

Fig. 3 (a) A typical profile of the aircraft altitude and effective gravity inside the cabin during one parabolic maneuver.

25 cm^3 with a total weight of 5 kg. The setup may be used individually or, as we operated it, attached to a separate enclosed experiment. Its components can be easily assembled/disassembled during transportation

2.2 Experimental procedure

The experiments were conducted in November 2017 during the European Space Agency (ESA) 67th parabolic flight campaign totalling 3 flights on board the Airbus A310 Zero-G. Each flight contained 31 parabolic maneuvers, each starting with an initial high- g ($1.8 g_e$) pull-up, followed by a low- g ($0.01 g_e$) period of 22 seconds, and ending with a high- g ($1.8 g_e$) pullout. Data were obtained during normal- g , high- g , and low- g phases (Fig. 3). In particular, once the gravity stabilized at a certain preset level for over 3 seconds, the microcontroller initialized simultaneously the camera, LED, current controller, and data acquisition board. The electrical and imaging data were stored locally inside the acquisition board and the camera. After a run time of 0.5 s the experiment ended and the data were transmitted to the computer. All equipment were then returned to the stand-by state waiting for the next run. Besides gravity, the electrical heating power was varied between 0 mW and 120 mW to probe the parameter space.

3 Results and discussion

3.1 Captured dynamics of oscillate boiling bubbles

Figures 4a and 4d presents the dynamics of an oscillate boiling bubble at low- g and high- g driven at similar electrical powers of 63.8 mW and 64.1 mW, respectively. The resulting maximum radius at low- g is $13.2 \mu\text{m}$ and at high- g is $13.6 \mu\text{m}$. The bubble's dynamics are the same as in terrestrial condition (see Fig. 1a). During their oscillations, both bubbles release smaller

Fig. 4 Captured bubble dynamics of oscillate boiling bubbles, the temperature of the heating substrate and its frequency spectrogram in: (a-c) low- g condition and (d-f) high- g condition. Images from subfigure a and d are taken from Video 1 and Video 2. The scale bar in subfigure a,d represents $20\ \mu\text{m}$, the time difference between two consecutive frames is $1\ \text{ms}$ and the arrow indicate the orientation of the effective gravity inside the cabin. The high frequency noises that appears every $1\ \text{ms}$ in subfigure c and f is induced by the current driving the LED at $1\ \text{kHz}$.

microbubbles at their apex, which are transported in a direction perpendicular to the substrate independent on the strength of gravity. Their oscillation is controlled only by the power supply and both stop once the electrical current is switched off after $0.5\ \text{s}$. The recorded microheater's temperature is presented in Fig. 4b and 4e. When the bubble collapses, a liquid jet impacts onto the substrate and rapidly cools the heater: within less than $0.5\ \mu\text{s}$, the heater's temperature drops from $\approx 225^\circ\text{C}$ to $\approx 185^\circ\text{C}$, which is a cooling rate of $\approx 10^8\ \text{K/s}$. Having received thermal energy from the vaporization of the liquid, the bubble re-expands and creates a dry spot below on the heater. The heater thus recovers to its peak temperature and the cycle repeats. A Fourier analysis of the temperature signal reveals the oscillation frequencies of the bubbles in the two gravity conditions, namely $305\ \text{kHz}$ and $310\ \text{kHz}$ (Fig. 4c and 4f).

3.2 Parameters study

By changing the electrical power, three regimes of oscillate boiling can be achieved. Below a threshold power the heater is not able to nucleate a bubble. Above $40\ \text{mW}$ a bubble starts forming at the heating spot and undergoes unstable oscillation. In this unstable mode, the bubbles show neither microbubble pinch-off nor periodic cooling of the heater. After $\approx 10\ \text{ms}$, the oscillations halt and the bubble grows similar to a conventional nucleate boiling bubble [23]. Once the input

Fig. 5 Three oscillate boiling regimes at different input power and gravity conditions. The height of the column represents the mean power and the error bar represents the standard deviation of the sample. Each columns contained at least 8 data points.

power surpasses $60\ \text{mW}$, stable oscillation featuring microbubble pinch off and microbubble streaming together with the periodic cooling of the heater is observed, see Fig. 4. Figure 5 categorizes the observed oscillate boiling regimes and plots their electrical current as a function of gravity. Overall we find very similar behavior with no clear dependency on gravity.

In the stable oscillate boiling mode the oscillation frequency decreases monotonically with increasing maximum bubble radius, which is also predicted with a simple model. The model is the same as proposed in Ref. [22], in which two main equations are used. The

Fig. 6 The frequency-radius characteristics of oscillate boiling bubble in different gravity conditions. The simulation data follows the calculation reported in reference [22] with a change of ambient pressure to 0.8 bar, matching the cabin's pressure. All data points share the same experimental error and is indicated by the error bar plotted in the bottom-left corner.

first equation describes the evolution of the bubble's radius R , which follows Keller-Miksis model:

$$\left(1 - \frac{\dot{R}}{c}\right) R \ddot{R} + \frac{3}{2} \dot{R}^2 \left(1 - \frac{\dot{R}}{3c}\right) = \left(1 + \frac{\dot{R}}{c}\right) \frac{p_l}{\rho} + \frac{R}{\rho c} \frac{dp_l}{dt} \quad (1)$$

where c is the sound velocity, p_l is the liquid pressure and ρ is the density of the bubble's inner gas-vapour mixture. The second equation describes energy conservation of the bubble's interior:

$$pdV + dU = dQ \quad (2)$$

where p is the work done to the gas as the bubble expands/collapses, V is the bubble volume, U is the potential energy accounting for evaporation and condensation, Q is the supplied energy from the electrical heater minus the heat transfer into liquid by diffusion and latent heat. At every time-step, these two equations are coupled to solved for two unknowns: namely the bubble's radius R and inner temperature T . As presented in Ref. [22], each input power results in a stable's maximum radius and resonant frequency. Figure 6 presents the radius-frequency relationship when the input power varies, both experimentally for different gravity conditions and numerically from the model prediction. While there is some scatter, we find overall quantitative agreement with the model (black line in Fig. 6) and its independence of gravity.

3.3 Discussion

The analysis of the bubble's dynamics and its oscillation frequency shown in Figs. 5 and 6 demonstrates that its quantitative and qualitative characteristics are independent of the effective gravity conditions: high- g ,

low- g , and normal g . These bubble's behaviors might indicate the independence of the oscillate boiling regime on gravity within the ranges tested. We attribute this characteristics to the governing physics: the oscillation is driven by the bubble's inertia and the liquid jet impact, the rise of the microbubble stream is driven by the Marangoni flow along the bubble's interface and likely by a streaming flow caused by the bubble oscillation. These driving factors are independent of buoyancy. The experimental verification not only demonstrates the independence on gravity but also that the previously proposed explanations and model are sound [22].

Within our system, the working capacity of oscillate boiling is limited by the heater. Above a certain input power, the heater breaks, likely because of thermal stress and mechanical stress induced by the bubble's collapse. The maximum power achieved in this experiment is 120 mW with a $15 \times 15 \mu\text{m}^2$ heater size, corresponding to a heat flux of 10^8 W/m^2 . This number is significantly higher as compared to previously reported critical heat fluxes of 10^5 W/m^2 for water [4], 10^6 W/m^2 for FC-72 [6], and nPFH [27,15]. This may be partly explained that oscillate boiling operates above the critical Leidenfrost temperature [23].

One limiting factor of oscillate boiling is that the size of the heat source must be smaller than $20 \mu\text{m}$ [22,23]. Currently only miniature devices such as high power transistors or microfluidic platforms may benefit from this boiling mode. The next challenge is to scale-up the regime, thus to widen the range of application.

4 Conclusion

Experiments in various gravity conditions on-board parabolic flights confirm the independence of the oscillate boiling bubble on gravity. In low- g and high- g conditions, oscillate boiling bubble retains its characteristic behavior and operation limits. The gravity-free feature together with its high thermal efficiency encourage the development of oscillate-boiling-based heat transfer devices for applications in terrestrial and outer space environments. To achieve this, the driving, packing, and the interaction of many heaters and oscillate boiling bubbles should be studied.

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