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Bubble Behaviors in Quasi-steady Pool Boiling in Microgravity

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Abstract

Bubble behaviors, particularly the number density, size and velocity of bubbles and other relevant factors, in quasi-steady pool boiling on a plain plate in microgravity aboard the Chinese recoverable satellite SJ-8 were reported and analyzed in the present paper. Degassed FC-72 was used as the working liquid in the space experiments. The heating voltage was controlled to increase exponentially with time to achieve quasi-steady state of pool boiling process. It's found that primary bubbles generated continually, slid on the surface, and coalesced with each other to form a larger coalesced bubble. The coalesced bubble engulfed small bubbles around it, and oscillated on the heating surface throughout the boiling process in microgravity. Generation of primary bubbles was also observed underneath the coalesced bubble. The growth rate of bubbles decreased with the increase of subcooling, which is caused by the strong condensation near the top of the coalesced bubble.

1. Introduction

Boiling is an efficient method for transferring high heat flux and then can be used in many potential applications in space as well as on the ground. However, the physics of boiling process is not properly understood yet because of the complex interactions of numerous factors. Among them, gravity is the most important one due to large difference between the densities of two phases. The investigation of boiling in microgravity can weaken the influence of buoyancy, enlarge the temporal and spatial scales of the dynamics of growing bubbles, simplify boiling process and thus be helpful to reveal the mechanism of boiling. Progress has been made in the past decades, though researches suffer much severe limits of the size, weight, power supply, possibility of space experiment, and so on. There have been several comprehensive reviews on this subject. Among many others, Straub [1)] presented comprehensive results obtained by him and his co-workers from the early 1980s, while Di Marco [2)], Kim [3)], Ohta [4)], and Zhao [5)] issued reviews of researches of boiling and other related topics in microgravity in Europe, in US, in Japan, and in China, respectively. The steady heating method was usually adopted, in which the heat flux or surface temperature was adjusted step-by-step. For each step, the heating time lasted for a period long enough to obtain a steady state of boiling. It may, however, cause some difficulties in determining the trend of boiling curves due to the large scattering of measured data points.

Quasi-steady pool boiling of FC-72 on a 15×15mm^2 plain plate was studied experimentally in microgravity aboard the Chinese recoverable satellite SJ-8 [6,7)]. In the present paper, bubble behaviors observed in the space experiment were reported and analyzed, focusing on the influence of subcooling.

2. Experimental Facility

The boiling chamber, as shown in **Fig.1**, was filled with degassed FC-72 as work fluid and fixed inside an air-proof container in which the pressure was initially 100 kPa. A bellows connected with the chamber allowed the pressure in the chamber to be approximately constant during the boiling processes. An auxiliary heater was used for heating the bulk liquid to adjust the temperature from the ambient temperature to about the middle between the ambient and saturation temperature at the corresponding pressure. The plate heater (**Fig. 2**) consisted of an Al_2O_3 ceramic substrate of 28×28×1 mm^3 which was embedded in a PTFE (Polytetrafluoroethylene) block of 25 mm in thickness. An epoxy-bonded composite layer of mica sheets and asbestos was set between the ceramic substrate and PTFE base to reduce the heat leakage. The effective heating area with an area of 15×15 mm2 was covered by a serpentine strip of multi-layer alloy film which was of 300 μm in width and about10 μm in thickness. It was also used as thermometer to measure the averaged temperature of the heater surface in the experiments.

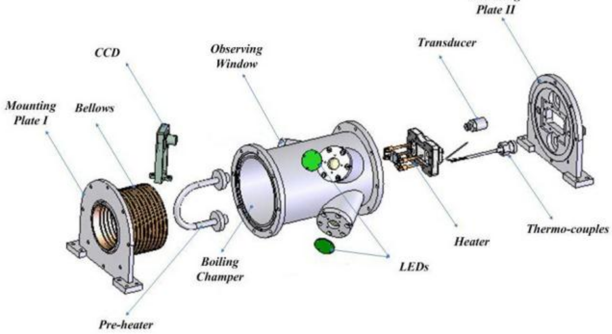

Fig. 1 The boiling chamber and its accessories

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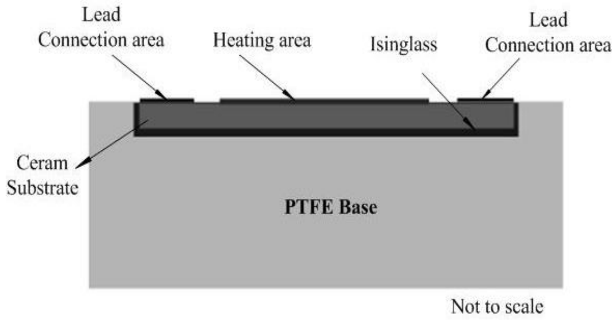

Fig. 2 The heater structure

A quasi-steady heating method was adopted, in which the heating voltage was controlled as an exponential function of heating time, namely $U = U_0 \exp(\tau/\tau_0)$, where, τ is the heating time, while the parameter τ_0 determines the heating rate. In order to make the heating process as a quasi-steady state, the parameter τ_0 was set as 80 s in the space experiment, which is large enough to satisfy the quasi-steady heating condition [8].

3. Results and Discussions

There were 8 runs obtained in 3 stages during the space experiment. Each stage included several runs. Except the first run of each stage without pre-heating phase, every run consisted of pre-heating, stabilizing and boiling phases, and lasted about one hour. The first stage was conducted in an ambient pressure condition with the initial pressure of about 100 kPa. After the first stage had been finished, a solenoid valve was opened to vent air from the container to the module of the satellite, and then the pressure inside the container was reduced to the same of that inside the module, which was in the range of 40 to 60 kPa. Two stages were performed in the reduced pressure condition. Unfortunately, video image was not available for the last two stages. Thus, only the results of the 5 runs in the first stage will be reported and analyzed in the present paper. The corresponding experimental conditions, time for the appearance of the first bubble, and the estimated parameters for CHF (critical heat flux) are listed in **Table 1**.

In the first run, as shown in **Fig.3**, the appearance of vapor phase was abrupt and explosive. Then under the action of surface tension, the vapor formed several small bubbles quickly. An obvious drop of the heater temperature was observed [6], correspondingly. It's difficult for primary bubbles to depart from the surface due to absence of buoyancy, and then they slid on the surface, coalesced with each other and formed a larger coalesced bubble. The coalesced bubble engulfed small bubbles around it, and oscillated on the heating surface throughout the boiling process in microgravity. Generation of primary bubbles was also observed underneath the coalesced bubble. The coalesced bubble was smooth, and it was very difficult to cover the whole surface. Although the bottom of the coalesced bubble might dry out partly, other places, particularly the corners of the heater surface, were still in the region of nucleate boiling. With the developing of the size of the coalesced bubble and the area of local dry area, the boiling pattern gradually changed to film boiling. Contrary to normal observations, there was no maximum on the boiling curve corresponding to CHF [7].

A gradual growth of the first bubble was observed after its first appearance in the following runs. The process of bubble growth even appeared an obvious standstill after its first appearance. Correspondingly, no over-shooting or drop of the heater temperature was observed in the curves of the heating history in the following runs. As the decrease of subcooling, the diameters of the coalesced bubbles increased more quickly, and the surface oscillation became more violent (**Fig. 4**). Particularly in the last 2 runs with the lowest subcooling, the fastest growth and the strongest oscillation of the coalesced bubbles may prevent local dry spots underneath the coalesced bubble to develop steadily. Then the local dry spots may be re-wetted by the fresh liquid around the coalesced bubble. Thus, unless the whole surface is covered by coalesced bubble, the boiling won't turn to film boiling. Correspondingly, there existed a maximum on the boiling curve corresponding to CHF as usual [7].

Table 1 Conditions of the first stage in space experiment.

Run#	p (kPa)	ΔT_{sub} (K)	$t_{first\ bubble}$ (s)	t_{CHF} (s)	q_{CHF} (kW/cm^2)	ΔT_{sat} (K)
I-1	90.8	36.9	21.89	58～66	8.3 ~ 10.0	28 ~ 66
I-2	97.3	25.8	8.68	56～64	6.6 ~ 9.1	34 ~ 76
I-3	102.3	21.8	8.12	48～60	7.0 ~ 7.6	40 ~ 56
I-4	105.7	19.5	4.54	50～56	7.7 ~ 8.2	20 ~ 29
I-5	111.7	18.4	4.84	54～58	8.6 ~ 8.9	11 ~ 17

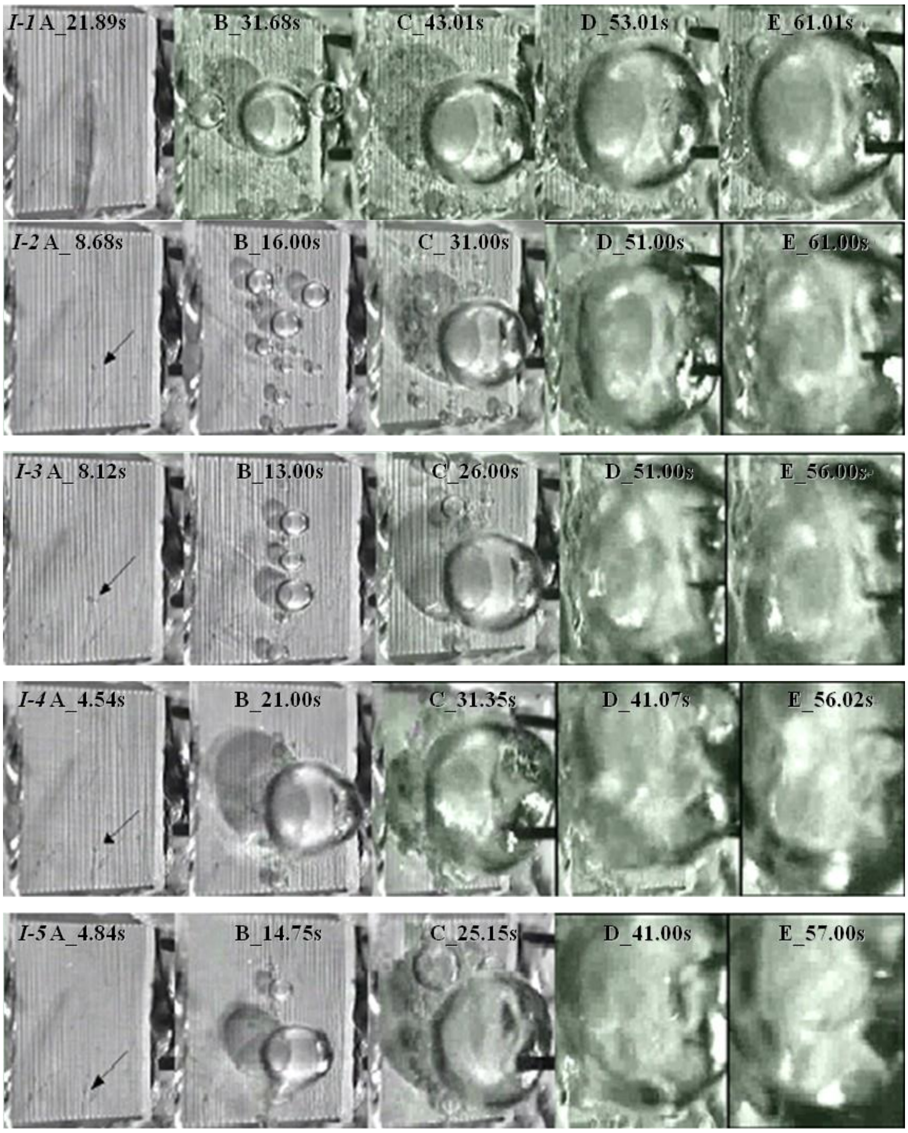

Fig. 3 Bubble behaviors in the space experiment

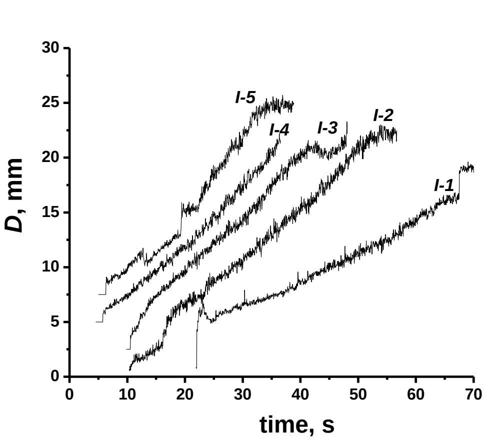

Fig. 4 Comparison of coalesced bubble diameter

The diameter of coalesced bubble was increasing with heating time as shown in **Fig.4**. In order for the clarity, the curves for the last three runs (I-3, I-4, and I-5) were shifted up 2.5, 5.0, and 7.5 mm, respectively. Higher is the subcooling, slower the growth rate of coalesced bubble is. This fact may be caused by the strong condensation near the top of the coalesced bubble, where the vapor connects directly with the subcooled liquid.

The lateral velocities of bubbles moving on the surface in each run are shown in **Figs. 5** and **6** for the coalesced bubbles and some typical primary small bubbles, respectively. It can be clearly observed that small primeval bubbles are easier to be affected than the coalesced bubbles. The velocity of the coalesced bubble is slower than those of small primeval bubbles. Furthermore, the curves for the coalesced bubbles fluctuate more gently than those for small primary bubbles.

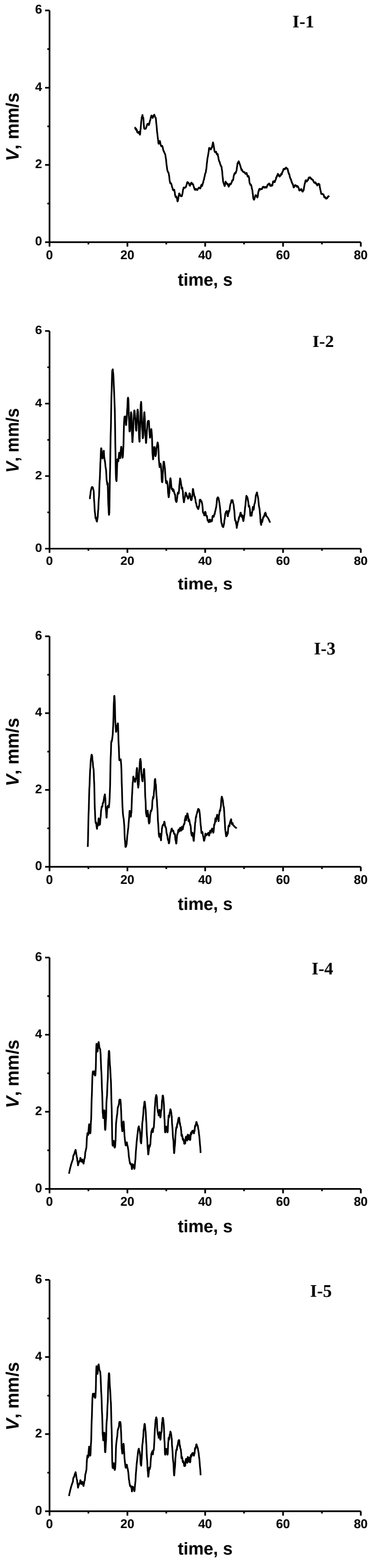

Fig. 5 Lateral motion of coalesced bubbles

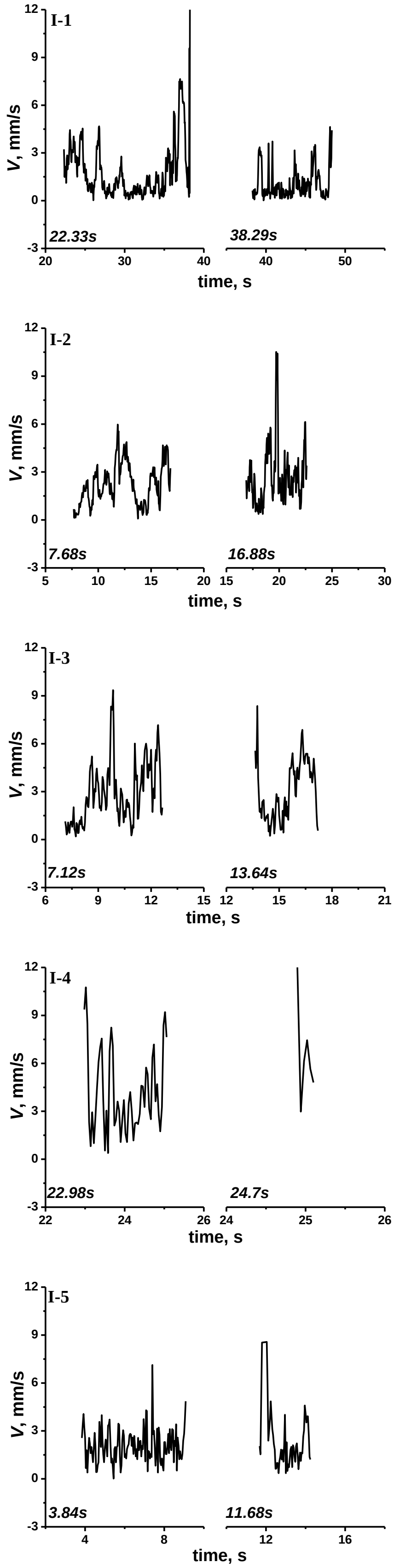

Fig. 6 Lateral motion of some primary bubbles

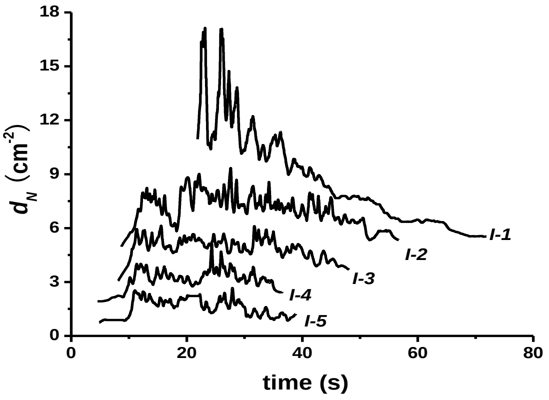

Fig. 7 Comparison of the bubble number density

Figure 7 shows the comparison of the bubble number density in different runs. In order for the clarity, the curves for the first four runs (from I-1 to I-4) are shifted up 5.0, 4.5, 3.0 and 1.5 cm^{-2}, respectively. The bubble number density in I-1 is remarkably higher than the other runs, and the first appearance of bubbles in these runs was observed at 21.89, 8.68, 8.12, 4.54, and 4.84 s, respectively. It can be inferred that it's difficult to hold the residual gas for the cavities on the heater surface after a long-term soak in FC-72 due to its high wettability and heavy shake during the launch of the satellite. Thus, it'll be much difficult to be activated in the first run unless a much high overheating is achieved. This was verified by the observed drop of the heater temperature at the incipience of boiling in the first run. On the contrary, the residual micro-bubbles may stay in cavities after the first runs because of the short calm period between the adjacent two runs. Therefore, nucleate sites are easier to be activated, and then no obvious overheating is needed to initiate boiling. Furthermore, activated nucleate sites may prohibit the activities of other cavities around them, which may be the major reason for the decrease of the bubble number densities in the following runs.

4. Conclusion

In summary, bubble behaviors in quasi-steady pool boiling on plane plate heater in microgravity were reported and analyzed in the present paper. The absent of buoyancy prevents the bubble to depart from heater surface. Primary bubbles generated continually, slid on the surface, coalesced with each other and formed a larger coalesced bubble. The coalesced bubble engulfed small bubbles around it, and oscillated on the heating surface throughout the boiling process in microgravity. Generation of primary bubbles was also observed underneath the coalesced bubble. Small primeval bubbles are easier to be affected than the coalesced bubbles. The velocity of the coalesced bubble is slower than those of small primeval bubbles. Furthermore, the curves for the coalesced bubbles fluctuate more gently than those for small primary bubbles.

Bubble behaviors were influenced by subcooling. At higher subcooling, the coalesced bubble with a smooth surface grew slowly by the strong condensation near the top of the coalesced bubble. It's difficult to cover the whole heater surface, resulting in a special mode in which nucleate boiling and local dry spots can co-exist. Correspondingly, a gradual transition to film was observed without any abrupt mutation on boiling curves corresponding to CHF phenomenon. At lower subcooling, the coalesced bubble grew faster. The strong surface oscillation made it difficult for local dry spots to develop steadily at fixed positions. The boiling mode will turn to film boiling until he coalesced bubble is big enough to cover the whole surface. Thus, abrupt transition to film boiling can be observed as usual.

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