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Transition to Film Boiling in Microgravity: Influence of Subcooling *

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The transition process to film pool boiling in microgravity is studied experimentally aboard the Chinese recoverable satellite SJ-8. A quasi-steady heating method is adopted, in which the heating voltage is controlled to increase exponentially with time. Small, primary bubbles are formed and slid on the surface, which coalesce with each other to form a large coalesced bubble. Two ways are observed for the transition from nucleate to film boiling at different subcoolings. At high subcooling, the coalesced bubble with a smooth surface grows slowly. It is then difficult for the coalesced bubble to cover the whole heater surface, resulting in a special region of transition boiling in which nucleate boiling and local dry areas can coexist. In contrast, strong oscillation of the coalesced bubble surface at low subcooling may cause rewetting of local dry areas and activation of more nucleate sites, resulting in an abrupt transition to film boiling.

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Pool boiling in microgravity has become an increasingly significant subject for investigation, since many potential applications exist in space and in planetary neighbors due to the high efficiency in heat transfer. However, the investigation in microgravity suffers from unique and stringent constraints in terms of the size, power and weight of the experimental apparatus, and of the number and duration of the experiments. Thus, only a partial and, in some aspects, contradictory knowledge of boiling in microgravity has been attained so far. On the progress in this field, several reviews are available. For example, Straub[1] presented a comprehensive review of his own activity on this field from the early 1980s to date, while Di Marco,[2] Kim,[3] Ohta,[4] and Zhao[5] recently issued reviews of research into boiling and other related topics in microgravity in Europe, in the 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. This may, however, cause some difficulties in determining the trend of boiling curves due to the large scattering of measured data points. Furthermore, the mechanism of the transition from nucleate to film boiling is still not in substantial agreement with each other due to lack of observation of the real process of the transition using the steady heating method.

We developed a device using a transient heating method to conduct experiments in pool boiling in microgravity aboard the Chinese recoverable satellite SJ-8.[6] The boiling chamber (Fig. 1) was filled with degassed FC-72 and fixed inside an air-proof container in which the pressure was initially about 100 kPa. Bellows connected with the chamber will allow the pressure in the chamber to be approximately constant during the boiling processes. An auxiliary heater was used for adjusting the temperature of the bulk liquid from the ambient temperature to about the middle between the ambient and saturation temperature at the corresponding pressure. The plane plate heater (Fig. 2) consisted of an Al_2O_3 ceramic substrate of $28 \times 28 \times 1\,\mathrm{mm}^3$ which was embedded in a polytetrafluoroethylene (PTFE) block 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 $15 \times 15\,\mathrm{mm}^2$ was covered by a serpentine strip of a multi-layer alloy film which was 300 µm in width and about 10 µm in thickness. The multi-layer alloy film comprised several layers of metals (Cr, Cu, Ni, Au), and had a nominal resistance of 6 Ω.

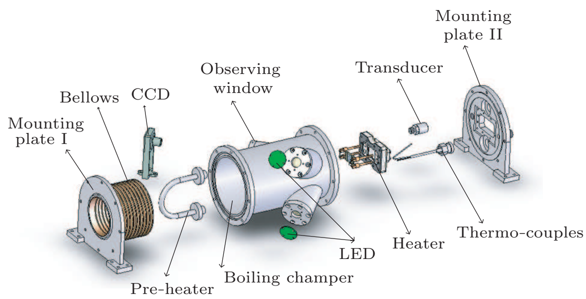

Fig. 1. The boiling chamber and its accessories.

The heating voltage was controlled as an exponential function with time, namely $U = U_0 \exp(\tau/\tau_0)$, where τ denotes the heating time, and the period τ_0 determines the heating rate. The period was set as $\tau_0 = 80\,\mathrm{s}$ in the space experiments in order to make

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the process a quasi-steady state of boiling, which was verified in the preliminary experiments on the ground. Furthermore, the period used in the present study is about 3–4 orders of magnitude larger than those in Johnson,[7] which guarantees the fulfillment of the quasi-steady condition, although different structures of the heater and working fluid were employed here.

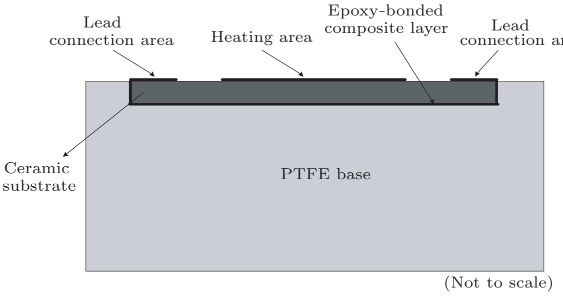

Fig. 2. The heater structure.

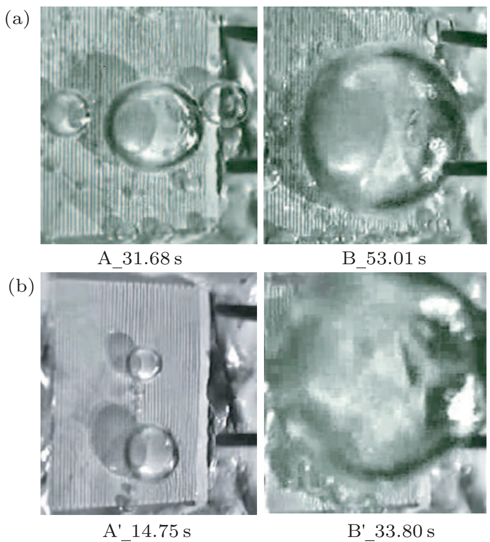

Fig. 3. Typical processes of bubble growth: (a) I-1, (b) I-5.

The space experiments, designed as two stages initially, were flown aboard the Chinese recoverable satellite SJ-8 in September 2006. Each stage included several runs. Except for the first run without pre-heating phase, each run consisted of pre-heating, stabilizing and boiling phases, and lasted about one hour. After the first stage, which was conducted under an ambient pressure condition, 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 as that inside the module, which was in the range 40–60 kPa. One more stage was added in actual flight, which was also performed under the reduced pressure condition. There were 8 runs performed in the space experiment. Unfortunately, video images were obtained only in the first five runs of the first stage. The corresponding experimental conditions are listed in Table 1, in which the estimated values of the critical heat flux (CHF) and the corresponding superheats are also listed. Figures 3 and 4 show some typical processes of bubble growth, heating history, and the corresponding boiling curves in the space experiments. The curve of the heater temperature vs time in the run I-5 was shifted up to 30°C to differentiate it from the other one in the same figure.

Table 1. Space experimental conditions and the estimated CHF values.

Run#	Pressure p (kPa)	Subcooling $\Delta T_{\rm sub}$ (K)	CHF $q_{\rm CHF}$ (W/cm^2)	Superheat $\Delta T_{\rm sat}$ (K)
I-1	90.8	36.9	8.3–10.0	28–66
I-2	97.3	25.8	6.6–9.1	34–76
I-3	102.3	21.8	7.0–7.6	40–56
I-4	105.7	19.5	7.7–8.2	20–29
I-5	111.7	18.4	8.6–8.9	11–17
Ⅱ-1	57.2	24.5	5.7–6.9	24–42
Ⅱ-2	91.1	18.8	7.4–9.5	26–55
Ⅲ-1	65.5	27.5	6.3–6.6	30–35

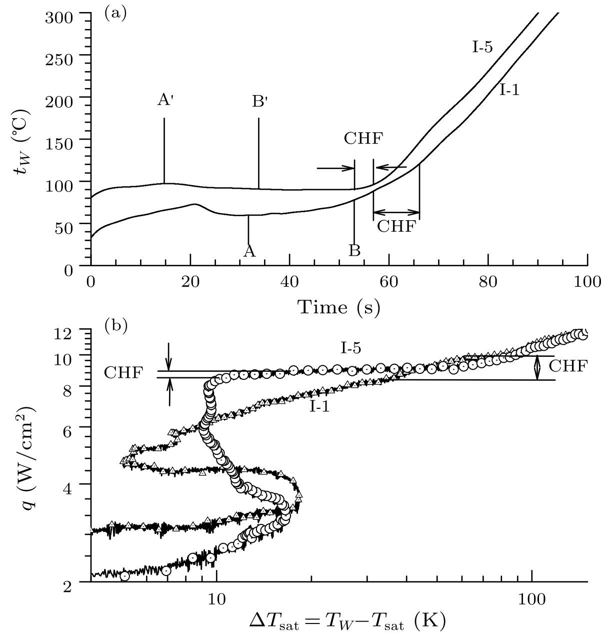

Fig. 4. Heating histories (a) and boiling curves (b) in the runs I-1 and I-5. Symbols A, B, A′ and B′ in (a) correspond to the images in Fig. 3.

In the first run I-1, a great amount of vapor appeared abruptly and explosively at the incipience of boiling. Surface tension then compelled the vapor to form several segregate bubbles. An obvious drop of the heater temperature was observed in the curve of the heating history, correspondingly. This drop caused an additional heat flux from the ceramic substrate to the liquid, and may result in a local maximum of the heat flux to the liquid in the transition region from the incipience to quasi-steady nucleate boiling despite the monotonous increasing of the heating rate. In contrast, gradual growth of the first bubble was observed in the following runs. The process of bubble growth even appeared to show an obvious standstill after its first appearance. Correspondingly, no overshooting or drop of the heater temperature can be observed in the curves of the heating history in the following runs. The first appearance of bubbles in the first five runs was observed at 21.89 s, 8.68 s, 8.12 s, 4.54 s, and 4.84 s, respectively. Compared with the first run, nucleate boiling occurred significantly earlier in the following runs. Considering the experimental procedure, we may indicate that there are residual micro-bubbles in cavities after the preceding runs. These micro-bubbles would make the cavities easier to activate, and the boiling would thus be initiated at a lower wall superheat. Furthermore, bubbles attached on the surface seemed to be able to suppress the activation of the cavities in the neighborhoods according to detailed analyses of the video images.

In microgravity, it is very difficult for the bubbles to depart from the surface. Although the images were taken only from the sole direction of 45° with respect to the heater surface, it can be observed that primary bubbles generated continually, slid on the surface, and coalesced with each other to form a larger coalesced bubble. Some primary bubbles can also generate under the coalesced bubble at the same time. The coalesced bubble also engulfed small bubbles around it. It can be inferred that a macro-layer may exist underneath the coalesced bubble, where primary bubbles were formed.

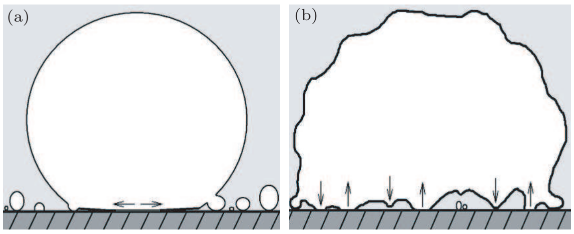

Fig. 5. Schematic diagram of the transition from nucleate to film boiling in high (a) and low (b) subcoolings.

For the case of high subcooling, e.g. I-1, it can be observed that the coalesced bubble has a relatively smooth surface, and oscillated slowly near the center of the heater surface. The behavior of the coalesced bubble is influenced by interaction between the repulsion of the primary bubbles and the pulls of liquid flow surrounding it. Its size increases with the increase of the surface temperature, but it is very difficult to cover the whole surface. The higher the subcooling is, the smoother the surface of the coalesced bubble and the slower its growth. This fact is caused by the strong condensation near the top of the coalesced bubble, where the vapor contacts directly with the subcooled liquid. Under the action of surface tension and strong condensation, the coalesced bubble shrank to an elliptical sphere. Thus, the bottom of the coalesced bubble may dry out partly at high heat flux, while on the other place, particularly in the corners of the heater surface, nucleate boiling can be kept (Fig. 5(a)).

With the expansion of the coalesced bubble and the local dry area, the boiling pattern will gradually change to film boiling, as described by Oka *et al.*[8] This kind of transition boiling led to a much slow increase of the heater temperature and no maximum on the boiling curve corresponding to the CHF point (Fig. 4).

The bubble behavior and the characteristic of the boiling curve at low subcooling, such as in the run I-5, were different from those at high subcooling. Due to relatively lower subcooling, it is difficult for bubbles to condense. The size of the coalesced bubble increases quickly, and a strong oscillation caused by continuous coalescences appears on their surface. Furthermore, the higher the pressure is, the stronger the surface oscillation. This may be caused by the fact that the surface tension on the coalesced bubble decreases with increasing pressure and corresponding saturation temperature. Thus, local dry spots underneath the coalesced bubble can not develop steadily. They may be rewetted by the surrounding liquid, and nucleate boiling may be kept on the whole heater surface (Fig. 5(b)), even more nucleate sites may be activated. Thus, unless there is an abrupt transition to film boiling, the heat flux would keep increasing although the surface temperature rises slowly or even falls. An abrupt increase of the heater temperature both in the curve of heating history and in the boiling curve can be clearly observed.

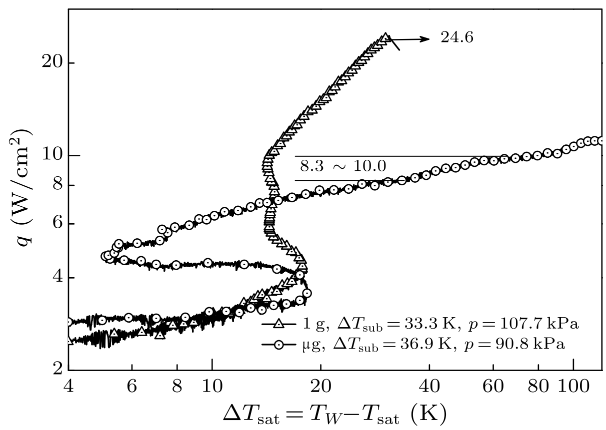

Fig. 6. Comparison of boiling curves in different gravities.

The gradual transition from nucleate to film boiling brings on some difficulties in determining the occurrence of CHF. However, the trend of increasing heater temperature with heating time can provide some information on CHF. A rapid increase of the heater temperature in the curve of the heating history may indicate the beginning of the transition from nucleate to film boiling, and a constant slope of the curve may suggest its accomplishment. The corresponding ranges are marked in Fig. 4, while the estimated values of CHF and the corresponding superheats for all runs of the space experiments are listed in Table 1. As shown in Fig. 4, the estimated CHF values at low subcooling by the method mentioned above are in good agreement with those determined directly according to the trend of the boiling curve, and the corresponding transition range is evidently much narrower than that in the high one.

The estimated values of CHF in microgravity increase with the increase of subcooling at the same pressure, or decrease with the decrease of system pressure at the same subcooling. These trends are similar to those observed in normal gravity. Unfortunately, the pressure and temperature of the liquid cannot be isolated completely because of the capability of the passive control method of the pressure inside the boiling chamber used in the present study. Thus, some cross-influences of pressure and subcooling on CHF exist.

Figure 6 shows a comparison of boiling curves under different gravity conditions at similar pressure and subcooling. There are three major features in the comparison. First, the superheats at the incipience of boiling are actually the same in different gravities, which means that the gravity has little effect on the incipience of boiling. Second, the value of CHF in microgravity is only about one third of that under terrestrial conditions. Third, the boiling curve in microgravity has a slope which is obviously smaller than that in normal gravity. Generally, boiling heat transfer in microgravity is deteriorated as compared to that in normal gravity, particularly at high superheats or heat fluxes. Very obvious enhancement, however, can be observed just beyond the incipience, which is consistent with those in steady state pool boiling experiments.[9]

In summary, bubble behaviors in pool boiling on a plane plate heater in microgravity have a direct effect on the characteristic of the transition from nucleate to film boiling at different subcooling. At high subcooling, it is difficult for the coalesced bubble with a smooth surface and small size to cover the whole heater surface, resulting in a special region of gradual transition boiling in which nucleate boiling and local dry areas can coexist. Correspondingly, there is no maximum in boiling curves corresponding to CHF. In contrast, the strong surface oscillation of the coalesced bubble at low subcooling may cause rewetting of the dry spots and even more activated nucleate sites, and then the surface temperature may remain constant or even fall with the increasing heat flux unless an abrupt transition to film boiling occurs with a quick increase of the heater temperature.

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