Bubble Dynamics and Heat Transfer in Microgravity Pool Boiling

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Abstract: - Boiling is an extremely complicated and illusive process. Microgravity experiments offer a unique opportunity to study the complex interactions without external forces, such as buoyancy, which can affect the bubble dynamics and the related heat transfer. Furthermore, they can also provide a means to study the actual influence of gravity on the boiling. Two research projects on pool boiling in microgravity have been conducted aboard the Chinese recoverable satellites. Ground-based experiments both in normal gravity and in short-term microgravity in the Drop Tower Beijing and numerical simulations have also been performed. Steady boiling of R113 on thin platinum wires was studied with a temperature-controlled heating method, while quasi-steady boiling of FC-72 on a plane plate was investigated with an exponentially increasing heating voltage. It was found that the bubble dynamics in microgravity has a distinct difference from that in normal gravity, and that the heat transfer characteristic is depended upon the bubble dynamics. Lateral motions of bubbles on the heaters were observed before their departure in microgravity. The surface oscillation of the merged bubbles due to lateral coalescence between adjacent bubbles drove it to detach from the heaters. Slight enhancement of heat transfer on wires is observed in microgravity, while diminution is evident for high heat flux in the plate case.

Key-Words: - microgravity, pool boiling, bubble dynamics, heat transfer

1 Introduction
Boiling is an extremely complicated and illusive process. Microgravity experiments offer a unique opportunity to study the complex interactions without external forces, such as buoyancy, which can affect the bubble dynamics and the related heat transfer. Furthermore, they can also provide a means to study the actual influence of gravity on the boiling. On the progress in this field, several comprehensive reviews, for example, Straub [1] Di Marco [2], Kim [3], and Ohta [4] among many others, are available.

In the past years, two research projects on pool boiling in microgravity have been conducted aboard the Chinese recoverable satellites. Ground-based experiments both in normal gravity and in short-term microgravity in the Drop Tower Beijing and numerical simulations have also been performed. Some of the research findings will be highlighted here, focusing particularly on the bubble dynamics and its influence on the heat transfer characterictic.

2 Experimental Facilities
In the first project, a temperature-controlled pool boiling (TCPB) device has been developed [5~8]. The working liquid was degassed R113 at subcooled conditions. A platinum wire of 60 μm in diameter and 30 mm in length was simultaneously used as heaters and thermometers. The heater resistance, and thus its temperature, was kept constant by a feedback circuit. There're 16 set-points in the range of the heater temperature from 35 ^{o}C to 135 ^{o}C. The heater temperature was controlled stepping up-down-up in the experiments. According to Straub [1], each step lasted about 30 seconds in order to obtain steady pool boiling. The TCPB device was flown aboard the 22nd Chinese recoverable satellite RS-22 in September, 2005. Control ground experiments using the same facility were conducted before and after the space flight, while a series of experiments were also performed utilizing the Drop Tower Beijing of the National Microgravity Laboratory/CAS before the space flight.

In the second project, a quasi-steady pool boiling (QSPB) device has been developed [9~11]. The working fluid was degassed FC-72. A plane plate heater with an effective heating area of 15×15 mm^2 was used. A quasi-steady heating method was adopted, in which 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. In order to make the heating process as a quasi-steady state, the parameter τ_0 was set for 80 s. The system pressure and the liquid subcooling were also controlled separately during the experimental runs.

The QSPB device was flown aboard the Chinese recoverable satellite SJ-8 in September, 2006. Control ground experiments using the same facility were conducted only before the space flight, due to the facility wasn't recovered after the space experiments.

The level of residual gravity aboard the Chinese recoverable satellites was estimated in the range of 10^{-3}~$10^{-5}g_0$, while that during free fall in the Drop Tower Beijing is no more that $10^{-5}g_0$.

3 Results and Discussions

3.1 Pool boiling on wire in microgravity

In the drop tower tests, bubble behaviors were dramatically altered by the variation of the acceleration [5]. It was difficult to observe the lateral oscillation of bubbles along the wire in nucleate boiling regime in normal gravity, but this kind of motion was always able to observe in both short- and long-term microgravity. It could lead to the lateral coalescence between adjacent bubbles, and then detached the coalesced bubble from the wire. Sometimes, the coalesced bubble could enclose the wire and a bright spot appeared there. It couldn't, however, last long period and the boiling continued as nucleate boiling. In the two-mode transition boiling regime, the Taylor instability disappeared in microgravity, and then the surface tension reformed the shape of the wavy film appeared in normal gravity to a large spheroid bubble encircling the wire. Then the film part receded after releasing the drop capsule, while the part of nucleate boiling expanded along the wire. The center of the large spheroid bubble wiggled along the wire and its size increased slowly. Sometimes, the wire near the center of the large spheroid bubble brightened up, but no real burn-out was observed in the short-term microgravity experiments.

In the space experiment in long-term microgravity, special bubble behaviors were observed firstly [6, 7]. There existed three critical bubble diameters in the discrete vapor bubble regime in microgravity, which divided the observed vapor bubbles into four regions (I) ~ (IV) (Fig.1): Tiny bubbles were continually forming and growing on the surface before departing slowly from the wire when their sizes exceeded the first critical value. The bigger bubbles, however, were found staying on the surface again when their diameters were larger than the second critical value. If they grew further larger than the third critical value, departure would be observed once again. Furthermore, the first critical value exhibited no obvious difference between in normal gravity and in microgravity. Among the commonly used models for bubble departure, no one can predict the whole observation. A qualitative model was proposed by Zhao et al. [6], in which the Marangoni effect was taken into account. In normal gravity, the function for the total forces acting on the growing bubble, $f(y)$, has only one zero-value point, indicting only one critical diameter for bubble departure. When the residual gravity decreases to no more than $1.36\times10^{-4}g_0$, the second and third zero-value points will be predicted by the new model. Comparing the prediction with the observation, the agreement is quite evident.

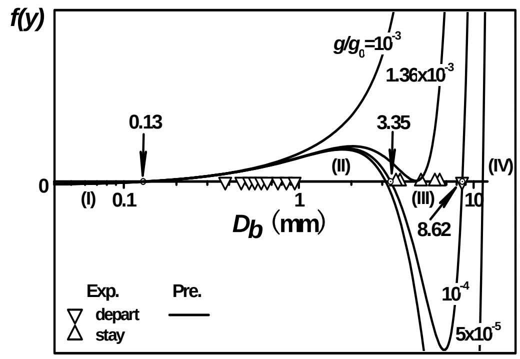

Fig. 1. Bubble departure in the discrete vapor bubble regime in microgravity.

Comparing with those in normal gravity, the heat transfer of nucleate boiling was slightly enhanced in short- and long-term microgravity (Fig.2), while about 20% and 40% decrease of heat flux was observed for two-mode transition boiling in short- and long-term microgravity, respectively [5, 8].

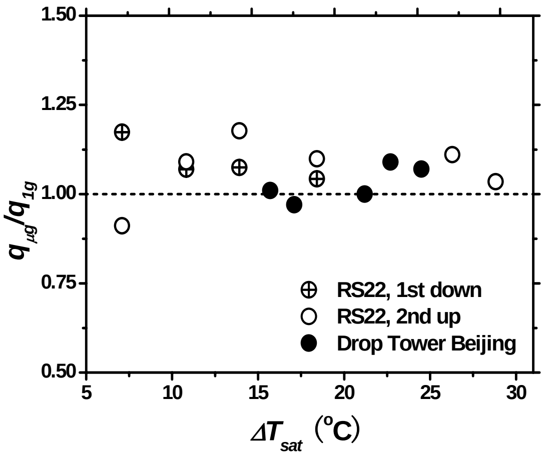

Fig. 2. Microgravity efficiency on heat transfer of nucleate boiling on wires.

The scaling of CHF with the gravity based on the data obtained both in the present study and in other researches reported in the literature was shown in Fig.3. It was found that the Lienhard-Dhir model, established on the mechanism of hydrodynamic instability [12], can provide a relative good prediction on the trend of CHF in different gravity conditions, though the value of dimensionless radius $R' = R\sqrt{(\rho_L - \rho_G)g/\sigma}$ was far beyond the initial application range of the model. This observation was consistent with Straub [1].

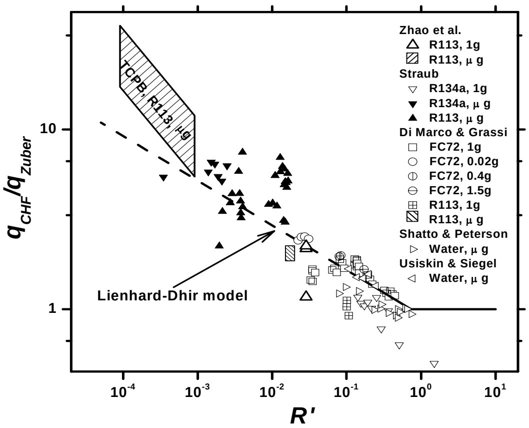

Fig. 3. Scaling of CHF on wires with gravity.

Furthermore, comparing the trend of CHF in Fig. 3 with the common viewpoint on the scaling of CHF which was built upon a large amount of experimental data with variable heater diameter on the ground, it was inferred, as pointed out by Di Marco & Grassi [13], that the dimensionless radius R', or equivalently the Bond number, may not be able to scale adequately the effects and to separate groups containing gravity due to the competition of different mechanisms for small cylinder heaters. A parameter, named as *the limited nucleate size* d_{LN}, and a non-dimensional coefficient $\Gamma = d_{LN}/d_{wire}$ were introduced to interpret this phenomenon [8]. It was assumed that the limited nucleate size is not dependent with gravity but with the other parameters of the boiling system, such as the material parameters of the working fluid and the heater, the heater surface condition, an so on. If Γ is small enough, the initial vapor bubbles will be much smaller than the heater surface and then the occurrence of the CHF will be caused by the mechanism of hydrodynamic instability. On the contrary, it will be caused by the mechanism of local dryout if Γ is so large that the initial bubble larger than the wire diameter d_{wire} may easily encircle the heater. Further researches, however, are needed for the delimitation of the two mechanisms.

3.2 Pool boiling on plate in microgravity

There were 8 runs performed in the space experiment. Unfortunately, video images were obtained only in the five runs of the first stage. The corresponding experimental conditions are listed in Table 1, in which the estimated values of CHFs and the corresponding superheats are also listed.

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

Run#	pressure p (kPa)	subcooling ΔT_{sub} (K)	CHF q_{CHF} (W/cm^2)	superheat ΔT_{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

Because of the residual gravity, there could exist a week single-phase natural convection before the incipience of boiling. In the first five runs with recorded video images, the first appearance of bubbles was observed at 21.89 s, 8.68 s, 8.12 s, 4.54 s, and 4.84 s, respectively. Figs. 4~7 show some typical processes of bubble generation and growth, the heating histories, and the corresponding boiling curves in the space experiments. In order for the clarity, the heater temperature curve in the run I-5 was shifted-up 30 ^oC.

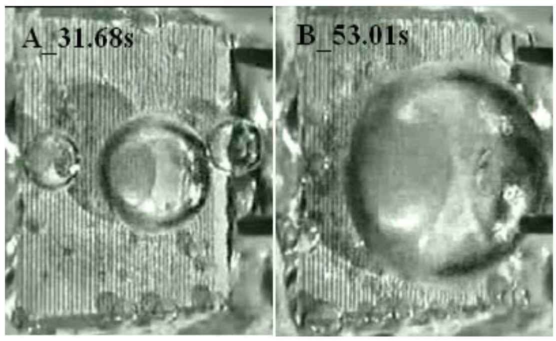

Fig. 4. The processes of bubble generation and growth in the run I-1.

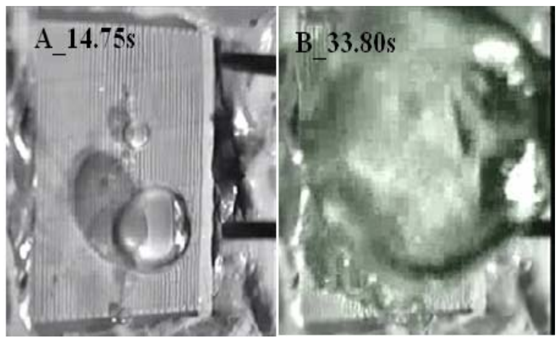

Fig. 5. The processes of bubble generation and growth in the run I-5.

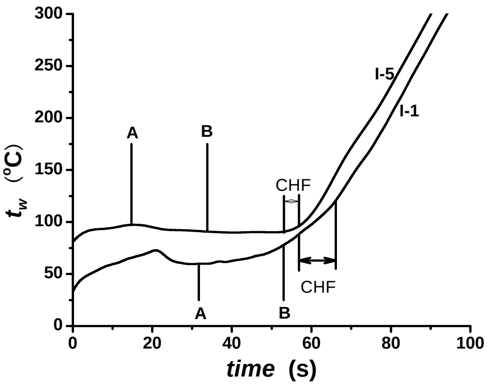

Fig. 6. Heating histories in the runs I-1 and I-5. Symbols A and B are corresponding to the images in Figs. 4 and 5.

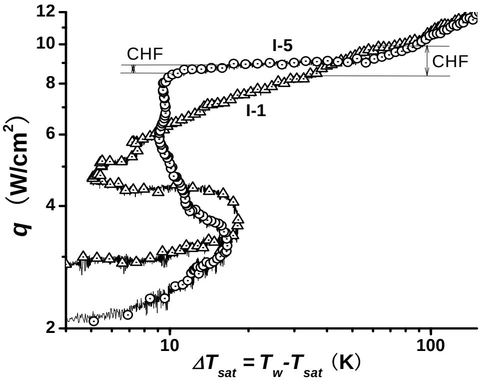

Fig. 7. Boiling curves in the runs I-1 and I-5.

A great amount of vapor appeared abruptly and explosively at the incipience in the first run I-1. Surface tension then compelled the vapor to form several segregate bubbles. An obvious over-shooting was observed in the history of the heater temperature, correspondingly. This drop of the heater temperature causes additional heat flux from the Al_2O_3 ceramic substrate to the liquid, and results in the maximum of the heat flux to the liquid in the transitional regime despite of monotonous increasing of heating rate. On the contrary, the first bubble in the following runs was observed to grow slowly after its first appearance. The process was even at an obvious standstill. Correspondingly, no over-shooting could be observed in the history of the heater temperature. Comparing with the first run, the nucleate boiling occurred significantly earlier in the following runs. Considering the experimental procedure, it may indicate that there could be residual micro-bubbles in cavities after the preceding runs. These micro-bubbles would make the cavities easier to be activated, and boiling will thus be initiated at a lower wall superheat temperature of the heating surface.

It was observed that primary bubbles generated consistently, slid on the surface, and coalesced with each other to form a larger coalesced bubble. Although the video images were taken only from the sole direction of 45^o with respect to the heater surface, it was able to be observed that some primary bubbles generated under the coalesced bubble. The coalesced bubble also engulfed small bubbles around it. It can be inferred that, as pointed out by Ohta et al. [14], a macro-layer may exist underneath the coalesced bubble, where primary bubbles are forming.

For the cases of higher subcooling, the coalesced bubble with a relative smooth surface was observed oscillating near the center of the heater surface. Higher was the subcooling, smaller and smoother at the same heating time. The coalesced bubble shrank to an elliptical sphere under the action of surface tension. Its size increased with the increase of the surface temperature, but it was very difficult to cover the whole surface. Thus, the bottom of the coalesced bubble may dry out partly at high heat flux, while the other places, particularly in the corners of the heater surface were still in the region of nucleate boiling. Unfortunately, dry spot was not able to be observed directly in the present study. The fact, however, that there existed a much smooth increase of the averaged temperature of the heater surface and no turning point corresponding to CHF in boiling curves indicated a gradual transition to film boiling along with the developing of the area of local dry area, as described by Oka et al. [15]. In this case, it was difficult to determine the accurate value of CHF. However, the trend of the increasing heater temperature with the heating time provided some information of CHF. Supposing the rapid increase of heater temperature corresponds to the beginning of the transitional boiling while a constant slope of the temperature curve to the complete transition to film boiling, the range of CHF and the corresponding superheat were estimated, which were also marked in Figs. 6 and 7. The estimated data and corresponding experimental conditions were listed in Table 1 for all the space experimental runs.

The bubble behavior and the characteristics of the boiling curves at lower subcooling were different from those at higher subcooling. In these runs, the size of the coalesced bubble increased quickly, and a strong oscillation appeared on its surface. Higher was the pressure, stronger the surface oscillation. Furthermore, before the abrupt transition to film boiling, the heat flux remained increasing though the surface temperature rose slowly or even fell down along with the heating time. The above observations can be interpreted as follows. Because of the decrease of surface tension with the increase of the saturation temperature and the corresponding pressure, local dry spots underneath the coalesced bubble with a strong surface oscillation can not develop steadily. They may be re-wetted by the surrounding liquid, and nucleate boiling will remain on the heater surface. Furthermore, even more nucleate sites could be activated under the action of the strong oscillation of the coalesced bubble. Thus, heat transfer was enhanced.

Comparisons of boiling curves in microgravity showed that heat transfer was deteriorated with the decrease of subcooling at the same pressure but enhanced with the increase of pressure at the same subcooling. The estimated values of CHF in microgravity increased with the subcooling at the same pressure, and also increased with pressure at the same subcooling. These trends are similar with those observed in normal gravity. Unfortunately, the pressure and temperature of the liquid cannot be isolated completely because of the passive control of the pressure inside the boiling chamber used here. Thus, there existed some cross-influences of pressure and subcooling on CHF.

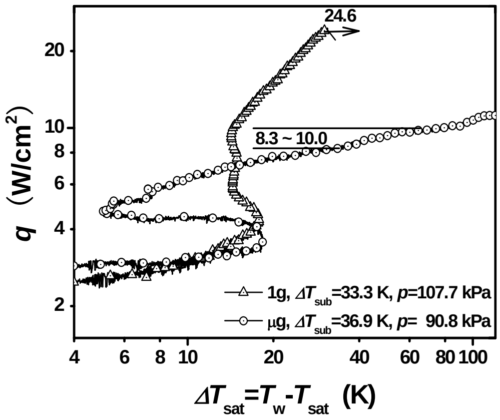

Fig. 8. Boiling curves in different gravity.

In Fig. 8, boiling curves in different gravity were compared with each other at the similar pressure and subcooling conditions. Generally, boiling heat transfer in microgravity was deteriorated comparing with that in normal gravity, particularly at high superheats or heat fluxes. The value of CHF in microgravity, however, was only about one third of that at the similar pressure and subcooling in terrestrial condition. Much obvious enhancement, however, could be observed just beyond the incipience, which was consistent with those in steady state pool boiling experiments, such as reported by Lee et al. [16]. It was also observed that the incipience of boiling occurred in microgravity at the same superheat as that in normal gravity, which was in agreement with Straub [1].

3.3 Preliminary numerical simulation of single bubble pool boiling

A model of single bubble pool boiling was studied numerically to simulate the basic feature of nucleate pool boiling. As a preliminary study, the growth of the vapor bubble, the local distributions of flow and heat transfer around the bubble in normal gravity was simulated with the Level Set method. Figs. 9 and 10 show the growth process of the bubble, while Fig. 11 shows the local distributions of flow and heat transfer around the bubble at the departure. Here, the liquid is saturated water at ambient pressure, while the superheat is 6.2 K.

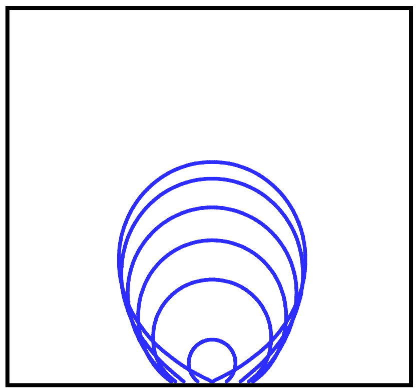

Fig. 9. The shapes of a growing vapor bubble in pool boiling of saturated water. The interval of the dimensionless time is 1/4, except the last one at t=1.17 when the bubble detach from the heater.

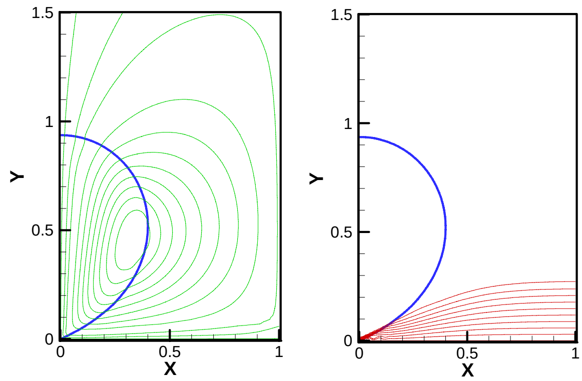

Fig. 10. The local distributions of streamline (Left) and isotherm around the bubble at the departure.

4 Conclusion

Researches on pool boiling heat transfer in microgravity, which included ground-based tests, flight experiments, and numerical simulation, were conducted in the National Microgravity

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Laboratory/CAS, which were summarized in the present paper. Two space experiments on pool boiling phenomena in microgravity were performed aboard the Chinese recoverable satellites. Steady pool boiling of R113 on a thin wire with a temperature-controlled heating method was studied aboard RS-22, while quasi-steady pool boiling of FC-72 on a plate was studied aboard SJ-8. Ground-based experiments were also performed both in normal gravity and in short-term microgravity in the drop tower Beijing. A preliminary numerical simulation of single bubble pool boiling has also conducted.

It was found that the bubble dynamics in microgravity has a distinct difference from that in normal gravity, and that the heat transfer characteristic is depended upon the bubble dynamics. Lateral motions of vapor bubbles were observed before their departure in microgravity. Only slight enhancement of heat transfer was observed in the wire case, while enhancement in low heat flux and deterioration in high heat flux were observed in the plate case. The relationship between bubble behavior and heat transfer on plate was analyzed. The results obtained here are intended to become a powerful aid for further investigation in the present discipline and development of two-phase systems for space applications.

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