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Nucleate Pool Boiling in Microgravity

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1. Introduction

Nucleate pool boiling is a daily phenomenon transferring effectively high heat flux. It is, however, a very complex and illusive process because of the interrelation of numerous factors and effects as the nucleate process, the growth of the bubbles, the interaction between the heater's surface with liquid and vapor, the evaporation process at the liquid-vapor interface, and the transport process of vapour and hot liquid away from the heater's surface. Among many sub-processes in boiling phenomenon, gravity can be involved and play much important roles, even enshroud the real mechanism underlying the phenomenon. Our present knowledge on nucleate pool boiling phenomenon has been built with the aid of numerous meticulous experiments in normal gravity environment on the ground where gravity is a dominant factor. Gravity strongly affects boiling phenomenon by creating forces in the systems that drive motions, shape boundaries, and compress fluids. Furthermore, the presence of gravity can mask effects that ever present but comparatively small. Advances in the understanding of boiling phenomenon have been greatly hindered by masking effect of gravity. 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 other hand, since many potential applications exist in space and in planetary neighbours due to its high efficiency in heat transfer, pool boiling in microgravity has become an increasing significant subject for investigation. Therefore, the microgravity researches will be conductive to revealing of the mechanism underlying the phenomenon, and then developing of more mechanistic models for the related applications both on Earth and in space.

Research on boiling heat transfer in microgravity has a history of more than 50 years with a short pause in the 1970s and has been advanced with the development of various microgravity facilities and with increased experimental opportunities, especially in the last two decades. On the progress in this field, many comprehensive reviews and monographs are available now. Among many others, Straub (2001), Di Marco (2003), Kim (2003), and Ohta (2003a, b) summarized the experimental and theoretical works all over the world, which provided the status of this field at the beginning of our research.

In the past decade, two research projects on nucleate pool boiling in microgravity have been conducted aboard the Chinese recoverable satellites by our group in the National

Microgravity Laboratory/CAS. Ground-based experiments both in normal gravity and in short-term microgravity in the drop tower Beijing have also been performed. The major findings are summarized in the present chapter, while a brief review on the results of the space experiments has also been provided by Zhao (2010) recently.

2. Pool boiling on wire in microgravity

A TCPB (Temperature-Controlled Pool Boiling) device was developed to study heat transfer of pool boiling on thin wires both on the ground and aboard the 22nd Chinese recoverable satellite (RS-22) (Wan et al., 2003). A platinum wire of 60 μm in diameter and 30 mm in length was simultaneously used as a resistance heater and a resistance thermometer to measure the temperature of the heater surface. The heater resistance, and thus the heater temperature, was kept constant by a feedback circuit, which was similar to that used in constant-temperature hot-wire anemometry. Each step of the heater temperature lasted about 30 seconds in order to obtain steady pool boiling according to Straub (2001). The boiling chamber was filled with degassed R113 and was pressurized in an airproof container. A bellows connected with the chamber and the surrounding housing allowed the pressure in the chamber to be practically constant.

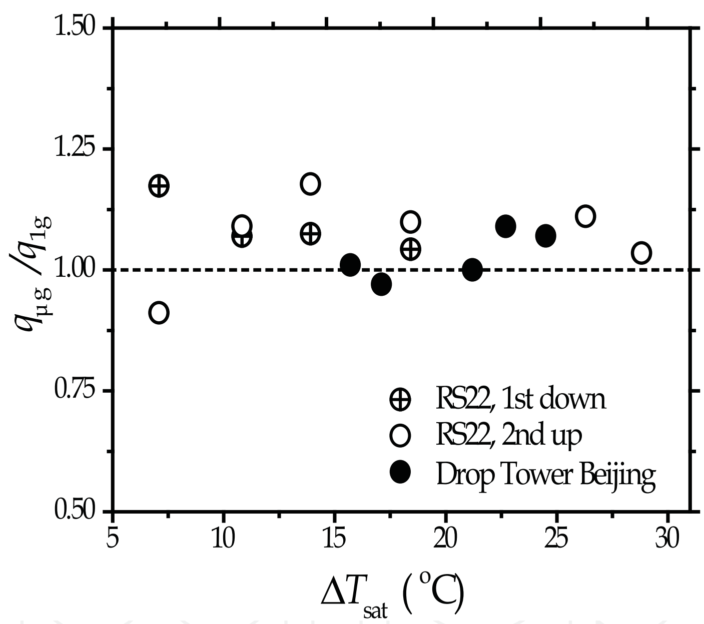


Fig. 1. Microgravity efficiency on heat transfer of nucleate boiling in microgravity (Zhao et al., 2009d).

Several preliminary experimental runs at subcooling condition were conducted in short-term microgravity utilizing the drop tower Beijing, which provides a course of about 3.6 s for microgravity experiments (Zhao et al., 2004). The space experiment was carried out aboard the 22nd Chinese recoverable satellite (RS-22) in September 2005 (Liu, 2006). The level of residual gravity was estimated in the range of 10^{-3}~10^{-5} g_0. Before and after the space flight, ground control experiments using the same facility were also conducted. Comparing with those in normal gravity, the heat transfer of nucleate boiling was slightly enhanced in short- and long-term microgravity (Fig. 1), while about 20% and 40% decrease of heat flux was observed for two-mode transition boiling in short- and long-term microgravity, respectively.

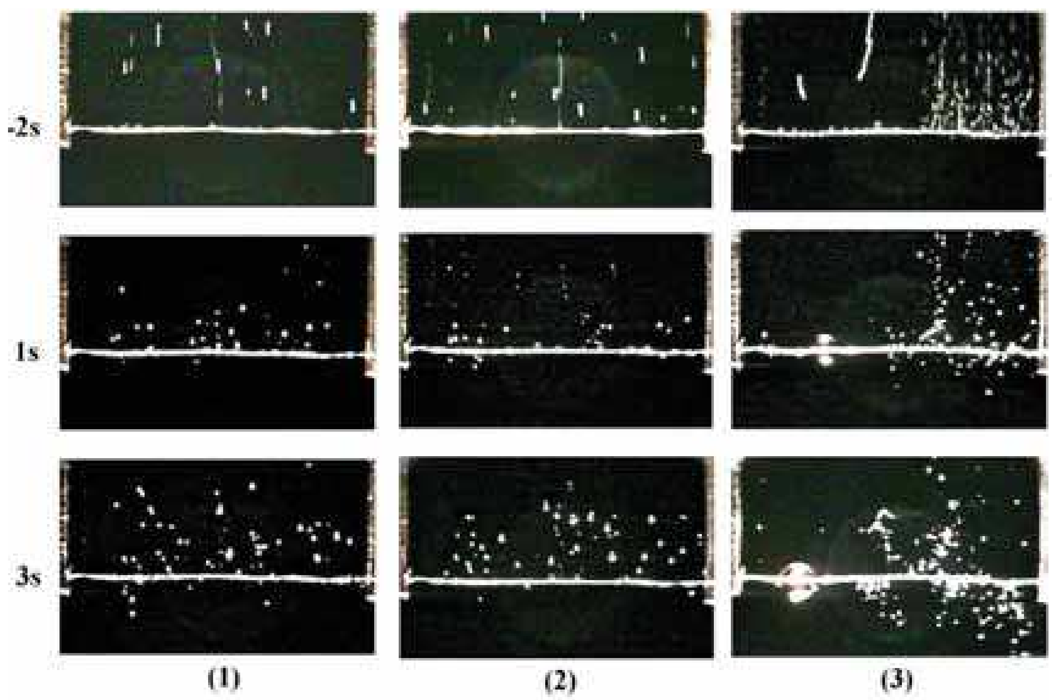


Fig. 2. Bubble behaviors on thin wire in different gravity conditions (Zhao et al., 2004).

In the drop tower tests, bubble behaviors were dramatically altered by the variation of the acceleration (Fig. 2). 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 centre of the large spheroid bubble wiggled along the wire and its size increased slowly. Sometimes, the wire near the centre 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 (Zhao et al., 2007). There existed three critical bubble diameters in the discrete vapor bubble regime in microgravity, which divided the observed vapor bubbles into four regions (Fig. 3): 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.

Fig. 3. Special bubble behaviors on thin wire in long-term microgravity (Zhao et al., 2007).

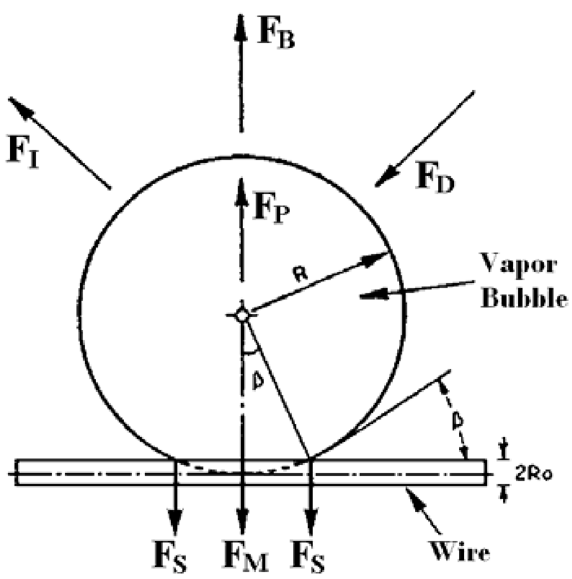


Fig. 4. Forces acted upon a vapour bubble growing on thin wire (Zhao et al., 2008).

Among the commonly used models for bubble departure, no one can predict the whole observation. A qualitative model was proposed by Zhao et al. (2008), in which the Marangoni effect was taken into account (Fig. 4)

$$f(y) = C_4 y^4 + C_3 y^3 + C_1 y + C_0 \tag{1}$$

where,

$$y = \tau^{1/2} \tag{2}$$

$$C_4 = \frac{4}{3}\pi E^3 (\rho_L - \rho_V) g \tag{3}$$

$$C_3 = -2K\pi |\sigma_T| E^2 \nabla T \tag{4}$$

$$C_1 = 4\sigma R_0 \sin^2 \beta + \frac{\pi}{3}\rho_L E^4 \tag{5}$$

$$C_0 = R_0 E^3 \rho_L \sin^2 \beta \left(\frac{1}{3} - \frac{3}{8}C_d\right) \tag{6}$$

$$E = \frac{1}{2\sqrt{\pi}} Ja\sqrt{\alpha_L} \tag{7}$$

where τ, σ_T, σ, ρ, β, α, R_0, C_d and *Ja* denote the growing time of bubble, surface tension and its temperature coefficient, density, contact angle, heat diffusivity coefficient, wire radius, drag coefficient and the Jacob number, respectively. *K* is an empirical parameter to count the departure from the linear theory for the case of finite Reynolds and Marangoni numbers. The subscripts L and V denote liquid and vapour phases, respectively.

According to Eq. (1), the following conclusion can be obtained: If $f(y)<0$, the departure force is larger than the resistant force, so the bubble will stay on the heater's surface; if $f(y)>0$, the departure force is smaller than the resistant force, so the bubble will depart from the heater's surface. Fig. 5 also shows the predictions of Eq. (1) in microgravity. 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 at $g=10^{-4}\ g_0$ with the observation, the agreement is quite evident.

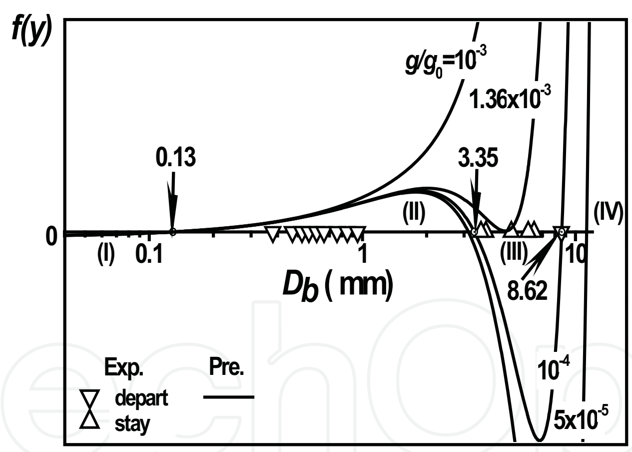


Fig. 5. Bubble departure in the discrete vapor bubble regime in microgravity. (Zhao et al., 2008).

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. 6. It was found that the Lienhard-Dhir-Zuber model (Lienhard & Dhir, 1973), established on the mechanism of hydrodynamic instability, 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 (2001).

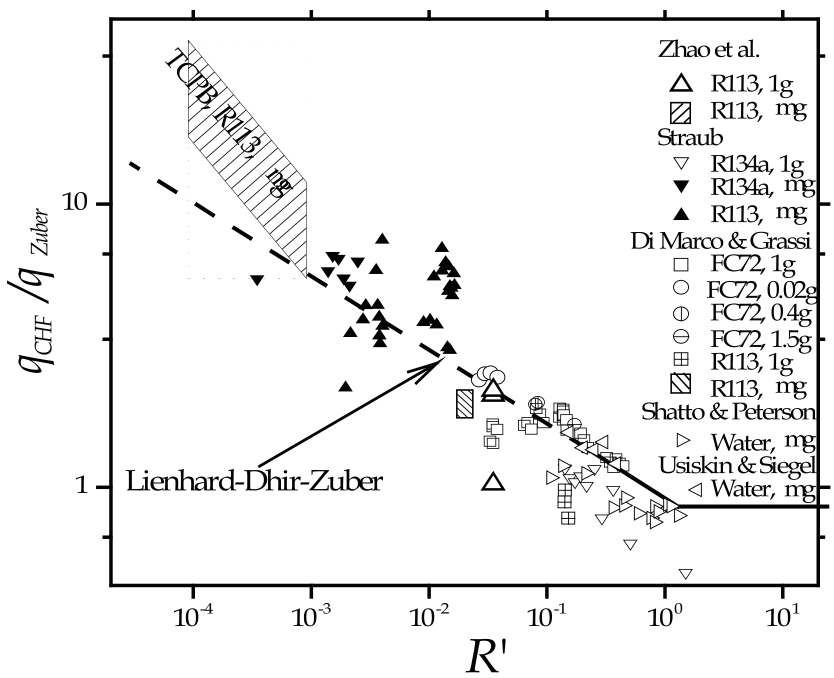


Fig. 6. Scaling of CHF with gravity (Zhao et al., 2009d).

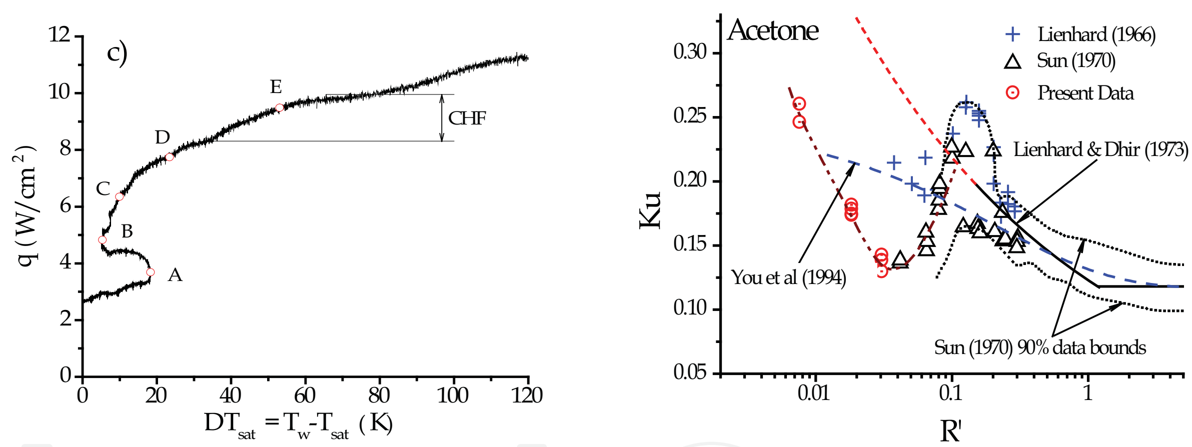


Fig. 7. Scaling behaviours of CHF on wires at saturated condition in normal gravity (Zhao et al., 2009b, c).

However, comparing the trend of CHF in Fig. 6 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 (1999), 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. Furthermore, Zhao et al. (2009b, c) revisited the scaling behaviours of CHF with respect to R' at small value of the Bond number in normal gravity conditions. It has been found that interactions between the influences of the subcooling and size on CHF will be important for the small Bond number, and that there may exist some other parameters, which may be material-dependant, in addition to the Bond number that play important roles in the CHF phenomenon with small Bond number (Fig. 7)

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 (Zhao et al., 2009b). 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 vapour 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. Pool boiling on plate in microgravity

A QSPB (quasi-steady pool boiling) device was developed to study heat transfer of pool boiling on plane plate both in normal and in microgravity, which was flown aboard the Chinese recoverable satellite SJ-8 in September 2006 (Yan, 2007).

To avoid large scatterance of data points measured in steady state boiling experiments and to obtain continuous boiling curves in the limited microgravity duration, a transient heating method was adopted, in which the heating voltage was controlled as an exponential function with time, namely

$$U = U_0 \exp(\tau/\tau_0) \tag{8}$$

where τ denotes the heating time, and the period τ_0 determines the heating rate. In the space experiment aboard SJ-8 and the ground control experiments before the space flight, the period was set for τ_0 = 80 s in order to make the heating process as a quasi-steady state, which was verified in the preliminary experiments on the ground. Furthermore, the period used in the present study was about 3~4 order of magnitude larger than those in Johnson (1971), which guaranteed the fulfillment of quasi-steady condition, though different structure of the heater and working fluid employed here.

The heater used in the study had an Al_2O_3 ceramic substrate with a size of 28×20×1 mm^3 embedded in a PTFE base with a thickness of 25 mm. An epoxy-bonded composite layer of mica sheets and asbestos was set between the ceramic substrate and the PTFE base to reduce the heat loss. The effective heating area with an area of 15×15 mm^2 was covered by a serpentine strip of multi-layer alloy film with a width of 300 μm and a thickness about 10 μm. The space between the adjacent parallel strips is about 70 μm. In addition, the multi-layer alloy film also served simultaneously as a resistance thermometer. The averaged temperature of the heater surface in the experiments was calculated using the correlation between the temperature and the resistance of the multi-layer alloy film, which was calibrated prior to the space flight. In the data reduction, the data of the averaged temperature of the heater surface were filtered to remove noise effects. The total heat flux was transported into both the liquid and the Al_2O_3 ceramic substrate, while the heat loss to the PTFE base and the surrounding was neglected. The filtered temperature data was used to compute the increase of the inner energy of the Al_2O_3 ceramic substrate using appropriate numerical computations. Subtracting the increase of the inner energy of the Al_2O_3 ceramic substrate from the total heat flux input provided the heat flux to the liquid and the transient mean heat transfer coefficient.

Degassed FC-72 was used as the working fluid. The pressure was controlled by a passive control method similar with that used in the TCPB device. Venting air from the container to the module of the satellite decreased the pressure inside the boiling chamber from its initial value of about 100 kPa to the same as that in the module of the satellite, i.e. 40 ~ 60 kPa. 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. Except the first run without pre-heating phase, each of the following runs consists of pre-heating, stabilizing and boiling phases, and lasts about one hour. 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. Figs. 8 and 9 show some typical processes of bubble growth, heating history, and the corresponding boiling curves in the space experiments.

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

Table 1. Space experimental conditions and the estimated CHF values (Zhao et al., 2009a).

Because of the residual gravity which was estimated in the range of 10^{-3}~10^{-5} g_0, there could exist a week single-phase natural convection before the incipience of boiling. Due to the experimental schedule, different behaviours of the incipience of boiling were observed in the space experiment. 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 of the monotonous increasing of the heating rate. On the contrary, a gradual growth of the first bubble was observed 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 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. 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 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 the detailed analyses of the video images.

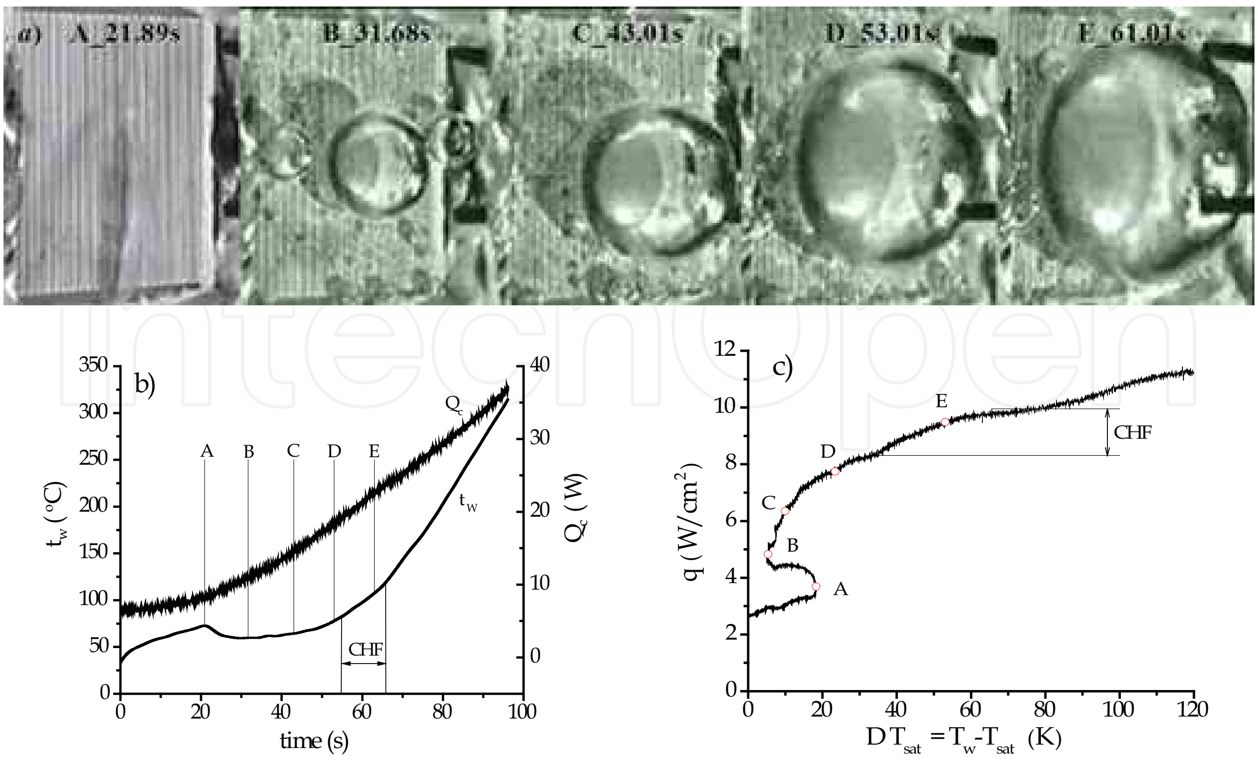


Fig. 8. Bubble dynamics (a), heating history (b), and boiling curve (c) in the run I-1 aboard SJ-8 (Zhao et al., 2009a).

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° 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. (1999), 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. (1995). 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 Fig. 8.

The bubble behaviours and the characteristics of the boiling curves at lower subcooling were different from those at higher subcooling. In these runs, *e.g.* the run I-4 shown in Fig. 9, 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.

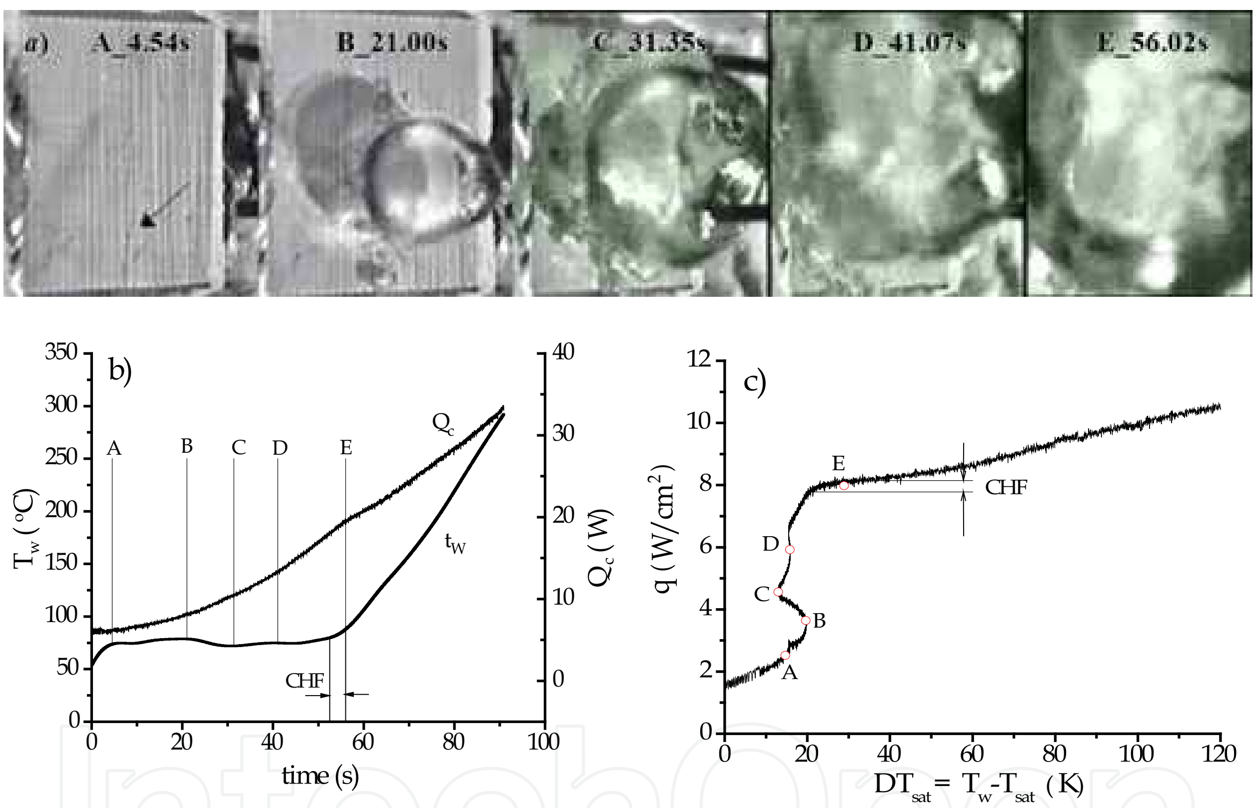


Fig. 9. Bubble dynamics (a), heating history (b), and boiling curve (c) in the run I-4 aboard SJ-8 (Zhao et al., 2009a).

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. The value of CHF in microgravity, however, was only about one third of that at the similar pressure and subcooling in terrestrial condition. 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.

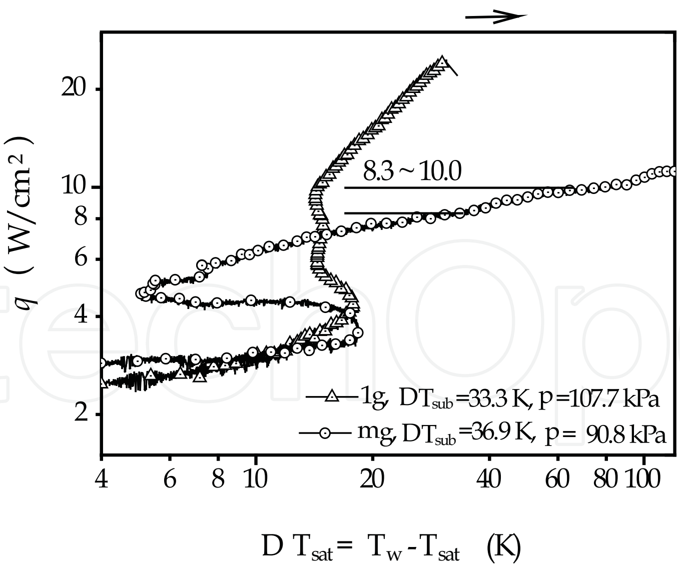


Fig. 10. Comparison of boiling curves in different gravity (Zhao et al., 2009a).

In Fig. 10, 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. 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. (1997). 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 (2001).

Recently, a new serial of experiments of pool boiling of FC-72 with non-condensable gas on smooth surface (denoted as chip S) in short-term microgravity have been conducted utilizing the drop tower Beijing (Xue et al., 2010). The boiling vessel was filled with about 3 L of FC-72 as the working liquid. The test chip was a P doped N-type silicon chip with the dimensions of 10×10×0.5 mm^3, which was set horizontally upward. The chip was Joule heated by a direct current. Two 0.25-mm diameter copper wires were soldered by a low temperature solder to the chip side surfaces at the opposite end for power supply. A programmable DC power supply was used to provide constant heating electric current for the chip. A nearly atmospheric pressure is maintained by attaching a rubber bag to the test vessel. A K-type thermocouple was used for measuring the local temperature of the test liquid at the chip level, and directly connected to a temperature display monitor for visual observation through a CCD camera. Besides, the local wall temperature at the center of the chip and the local temperature of the test liquid at about 40 mm from the edge of the chip were measured by two 0.13 mm-diameter T-type thermocouples which were connect with a data acquisition system (DI710-UHS). A high speed video camera (VITcam CTC) imaging 250 frames per second at a resolution of 1024×640 pixels with a shutter speed of 1/2000s was used along with a computar lens (MLM-3XMP) to obtain images of the boiling process. The high speed camera was installed in front of the test vessel at a direction angle of 30° with respect to the heater surface. Due to the short duration of microgravity (nearly 3.6 s), boiling was initiated before the release of the drop capsule and keep at a steady state for enough duration. Then the drop capsule released, and the experiment was run in microgravity. After the recovery of the drop capsule, this experimental run was finished.

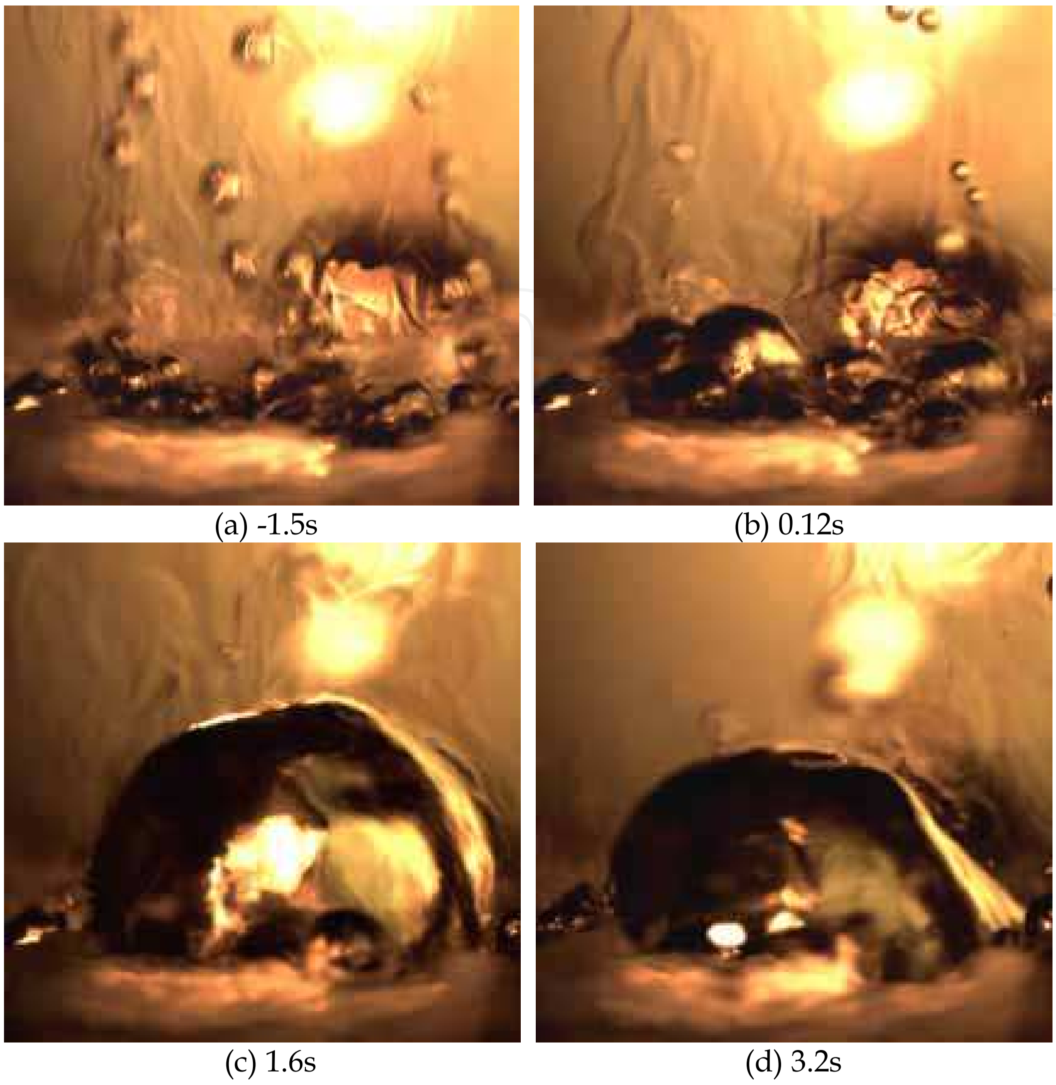


Fig. 11. Bubble behaviors on chip S (Wei et al., 2010).

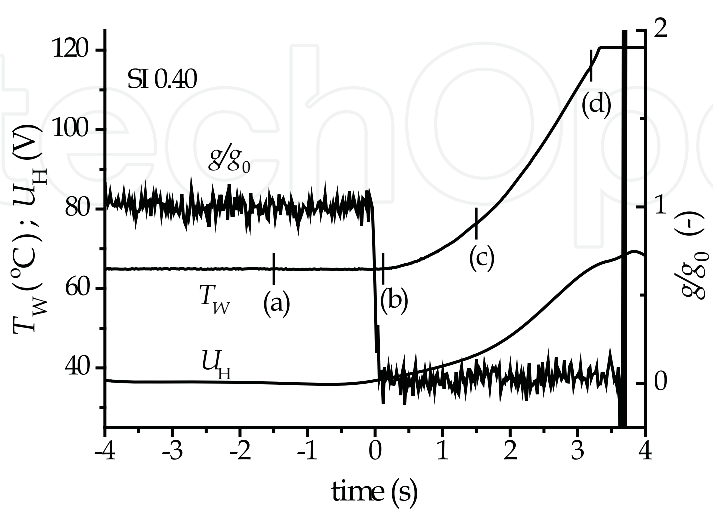


Fig. 12. Variations of surface temperature, heating voltage, and gravity for chip S (Wei et al., 2010).

Steady- or quasi-steady nucleate pool boiling was observed in the experiments for low and intermediate heat flux in the short-term microgravity conditions. At low heat fluxes in microgravity condition, the vapor bubbles increase in size but little coalescence occurs among bubbles due to large space between adjacent bubbles on the heater surface, thus the steady nucleate pool boiling can be obtained. As the heat flux increases, the vapor bubbles number as well as their size significantly increase in microgravity. Coalescence occurs continuously among adjacent bubbles. Departure of the coalesced bubbles from the heater surface caused by the surface oscillation of the coalesced bubble in lateral direction results in a constant heater temperature and heat flux in microgravity compared to that in normal gravity. The steady-state pool boiling still can be maintained. At high heat fluxes, a large coalesced bubble forms quickly and covers the heater surface completely in microgravity, followed by shrinking to an oblate in shape and smooth in contour due to the highly subcooled condensation (Fig. 11). An obvious increase of the heater temperature (Fig. 12), which indicates deterioration of boiling heat transfer, is then observed. Furthermore, the wall temperature exceeded the upper limit cutoff of the thermocouple instrument near the end of the short-term microgravity. It is possible for the occurrence of local dry-out or transition to film boiling at the bottom of the large coalesced bubble.

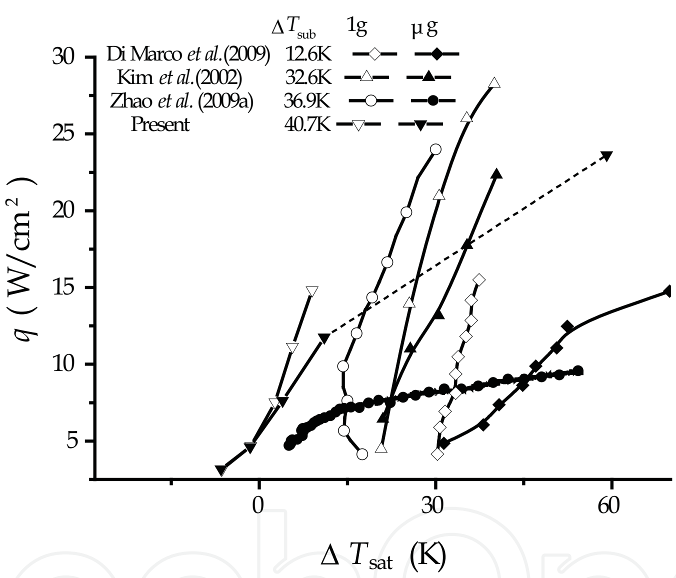


Fig. 13. Comparisons of pool boiling curves of FC-72 on plate of the present results with other data reported in the literature (Xue et al., 2010).

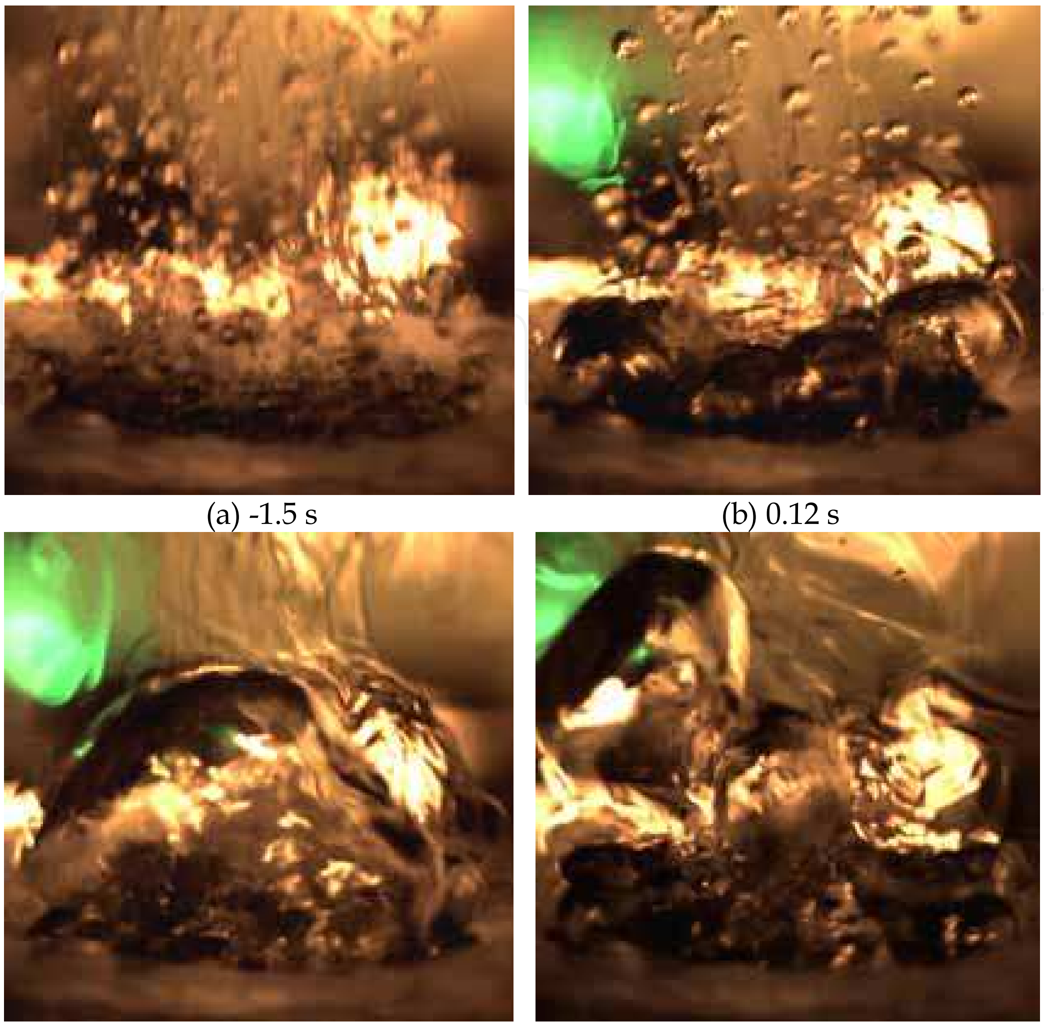
Figure 13 plots the heat transfer data of FC-72 on plate for the present results and other data reported in the literature under microgravity together with the pool boiling curves obtained under normal gravity. The last data point with the highest heat flux is not the value of the steady state due to the short duration of microgravity, and then a dashed line was used to connect it with the other data points. It can be clearly see that the influence of subcooling on nucleate pool boiling heat transfer in microgravity appears similar to that in earth gravity, *i.e.* the heat transfer increase distinctly as the subcooling increases. This agrees with the results of studies made by Lee et al. (1997). But, since the gravity level also greatly influences the average heater surface temperature, especially in the high heat flux region, the tendency of the influence of subcooling on nucleate pool boiling in microgravity is still required to further investigate. In particular, the results of Zhao et al. (2009a) in microgravity changes greatly from that in normal gravity and the value of CHF is only about one third of that at the similar pressure and subcooling in terrestrial condition. Besides, the trend of the present data result is consistent with that the Di Marco & Grass (2009), and the slopes of the heat transfer curves decrease in the high heat flux region in microgravity. However, the result of Kim et al. (2002) in microgravity changes slightly from that in normal gravity, which is different from the present and other studies. Thus, it can be inferred that the heat transfer of nucleate pool boiling in microgravity is related with the liquid subcooling, the size of the heater, the heating method, content of non-condensable gas, and so on.

4. Pool boiling on micro-pin-finned surface in microgravity

Very recently, a serial of experiments on boiling enhancement in microgravity by use of micro-pin-fins which were fabricated by dry etching have been performed in the drop tower Beijing (Wei et al., 2010). This project was motivated by the following observations in space experiments of boiling. Vapour bubbles cannot depart easily from the heater surface in microgravity, and then can grow attaching to the surface and coalesced with each other. As the increase of their sizes, the coalesced bubbles can cover the heater surface and prevent the fresh liquid from moving to the heater surface, thus local dryout may occur, resulting in deterioration of heat transfer. On the contrary, if plenty of fresh liquid can be supplied to the superheated wall for vaporization, the efficient nucleate pool boiling can be maintained and then no deterioration of heat transfer can occur. Following the enhanced boiling heat transfer mechanisms for the micro-pin-finned surfaces (Wei et al., 2009), it is supposed that although the bubbles staying on the top of the micro-pin-fins can not be detached soon in microgravity, the fresh bulk liquid may still access to the heater surface through interconnect tunnels formed by the micro-pin-fins due to the capillary forces, which is independent of the gravity level.

The experimental facility and schedual are similar with those used in Xue et al. (2010). The test chip was a P doped N-type silicon chip with the dimensions of $10\times10\times0.5$ mm^3. Micro-pin-fins were fabricated on the chip surface for enhancing boiling heat transfer. The fin thickness is 50 μm and fin height is 60 μm (denoted as chip PF50-60). The test chip was heated by setting a constant electric current for the desired heat flux to initiate boiling on the heater surface. After the heat transfer reached a steady state in about two minute, the free falling of drop capsule started which could provide approximately 3.6 s effective microgravity environment. The high-speed video camera could work for a duration time of 8 s, which was divided into two half sections by an external trigger signal. The bubble behaviours in normal gravity before the release of the drop capsule was recorded in the first half section, while those in microgravity after the release was recorded in the other one. Moreover, the data measurement and the video recording were operated simultaneously.

The transition of vapor bubble behaviors and the mean surface temperature of the micro-pin-finned chip responding to the variation of gravity level for the heating current of 0.42 A (corresponding to a heat flux of 19.4 W/cm^2), similar to that shown in Figs. 11 and 12, are shown in Figs. 14 and 15, respectively. The positions of Fig. 14 a-d are marked on the curves of the mean temperature of Chip PF50-60 shown in Fig. 15. The liquid subcooling keeps at about 41K, also as the same as that shown in Figs. 11 and 12.



(a) -1.5 s (b) 0.12 s

(c) 1.6 s (d) 3.2 s

Fig. 14. Bubble behaviors on chip PF50-60 (Wei et al., 2010).

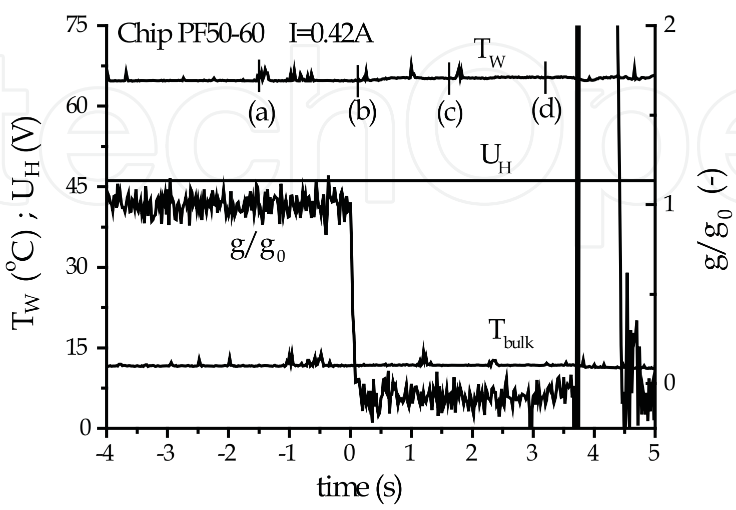


Fig. 15. Variations of surface temperature, heating voltage, and gravity for chip PF50-60 (Wei et al., 2010).

Just as the case of smooth chip, the bubbles generate and departure continuously from the heating surface caused by buoyancy forces in normal gravity before the release of the drop capsule (Fig. 14a). However, the bubble number are much larger than that for the smooth chip, indicating that the micro-pin-finned surface can provide larger number of nucleation sites for enhancing boiling heat transfer performance. At about 0.12 s after entering the microgravity condition, the vapour bubbles begin to coalesce with each other to form several large bubbles attaching on the chip surface (Fig. 14b). Some small bubbles are in the departure state when entering the microgravity condition, so we can still see them departing from the heater surface at this time. With increasing time, the bubbles coalesce to form a large spherical bubble (Fig. 14c). However, the large bubble covering on the heater surface does not cause obvious increase of wall temperature (Fig. 15).

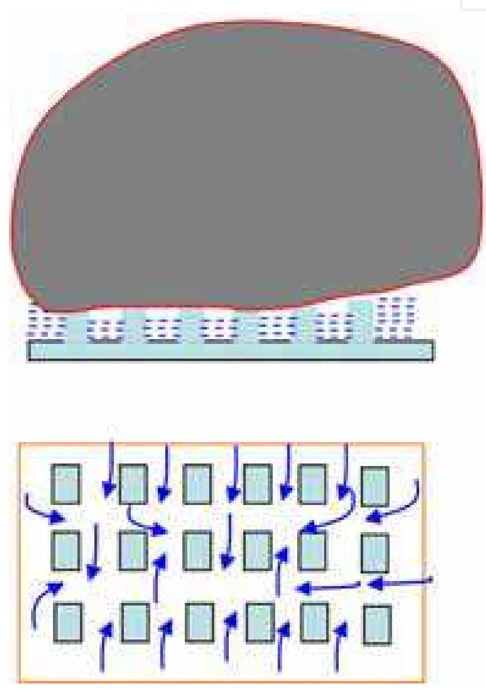


Fig. 16. Bulk liquid supply and micro-convection caused by capillary force (Wei et al., 2009).

The capillary force generated by the interface between the large bubble and the liquid of the micro-layer beneath the bubble drives plenty of fresh liquid to contact with the superheated wall for vaporization through the regular interconnected structures formed by the micro-pin-fins, as well as improves the micro-convection heat transfer by the motion of liquid around the micro-pin-fins, as shown schematically in Fig. 16. The sufficient supply of bulk liquid to the heater surface guarantees the continuous growth of the large bubble. Therefore, contrary to boiling on chip S, there is no deterioration of boiling heat transfer performance for the micro-pin-finned surface in microgravity, and the heater surface temperature can keep almost constant in both gravity and microgravity conditions.

In summary, the micro-pin-fined surface structure can provide large capillary force and small flow resistance, driving a plenty of bulk liquid to access the heater surface for evaporation in high heat flux region, which results in large boiling heat transfer enhancement. Since the capillary force is no relevant to the gravity level, the micro-pin-fined surface appears to be one promising enhanced surface for efficient electronic components cooling schemes not only in normal gravity but also in microgravity conditions, which is very helpful to reduce the cooling system weight in space and in planetary neighbors.

5. Future researches on boiling in microgravity in china

A new project DEPA-SJ10 has been planned to be flown aboard the Chinese recoverable satellite SJ-10 in the near future (Wan & Zhao, 2008). In the project, boiling at a single artifical cavity will be used as a model for studying subsystems in nucleate pool boiling of pure substances. Transient processes of bubble formation, growth and detachment will be observed, while the temperature distribution near the active nucleation site will be measured at subcooling and saturated conditions. The main aim is to describe bubble behavior and convection around the growing vapor bubble in microgravity, to understand small scale heat transfer mechanisms, and to reveal the physical phenomena governing nucleate boiling.

Numerical simulation on single bubble boiling has also been proposed, in which the single bubble boiling is set as a physical model for studying the thermo-dynamical behaviors of bubbles, the heat transfer and the corresponding gravity effect in the phenomenon of nucleate pool boiling (Zhao et al., 2010). According to some preliminary results, it was indicated that the growing bubble diameter is approximately proportional to the 0.4-th power of the growing time. The detach diameter of bubble is proportional to the -1/3-th power of the gravity, while the growing period to the -4/5-th power of the gravity. The heat flux is approximately proportional to the 1.5-th power of wall superheat with a fixed number density of active nucleation sites in all the studied gravity levels. The heat transfer through the micro-wedge region has a very important contribution to the whole performance of boiling.

Further experimental investigation on the performance of micro-pin-finned surface has also planned to be conducted in the drop tower Beijing, which aims to study the behaviour at very high heat flux around the critical heat flux phenomenon, as well as to determine the optimal structure of the micro-pin-fins.

These projects will be helpful for the improvement of understanding of such phenomena themselves, as well as for the development of space systems involving boiling phenomenon.

6. Conclusion

Nucleate pool boiling is a daily phenomenon transferring effectively high heat flux. It is, however, a very complex and illusive process. Among many sub-processes in boiling phenomenon, gravity can be involved and play much important roles, even enshroud the real mechanism underlying the phenomenon. 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 other hand, since many potential applications exist in space and in planetary neighbors due to its high efficiency in heat transfer, pool boiling in microgravity has become an increasing significant subject for investigation.

In the past decade, two research projects on nucleate 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. The major findings are summarized in the present chapter.

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. Considering the influence of the Marangoni effects, the different characteristics of bubble behaviors in microgravity have been explained. A new bubble departure model has also been proposed, which can predict the whole observation both in microgravity and in normal gravity.

Slight enhancement of heat transfer on wires is observed in microgravity, while diminution is evident for high heat flux in the plate case. These different characteristics may be caused by the difference of liquid supply underneath the growing bubbles in the above two different cases. It is then suggested that a high performance of heat transfer will be obtained in nucleate pool boiling in microgravity if effective supply of liquid is provided to the bottom of growing bubbles. A series of experiments of pool boiling on a micro-pin-finned surface have been carried out utilizing the drop tower Beijing. Although bubbles cannot detach in microgravity but stay on the top of the micro-pin-fins, the fresh liquid may still access to the heater surface through interconnect tunnels formed between micro-pin-fins due to the capillary forces, which is independent of the gravity level. Therefore, no deterioration of heat transfer in microgravity is observed even at much high heat flux close to CHF observed in normal gravity.

The value of CHF on wires in microgravity is lower than that in normal gravity, but it can still be predicted well by the correlation of Lienhard & Dhir (1973), although the dimensionless radius in the present case is far beyond its initial application range. The scaling of CHF with gravity is thus much different from the traditional viewpoint, and a possible mechanism is suggested based on the experimental observations.

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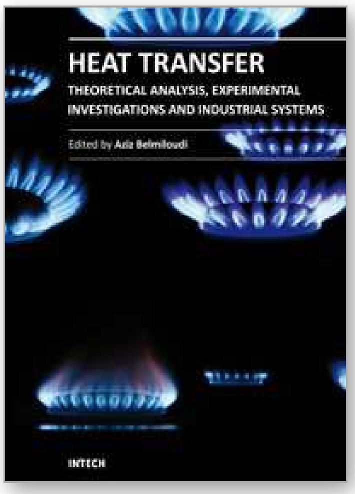

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Over the past few decades there has been a prolific increase in research and development in area of heat transfer, heat exchangers and their associated technologies. This book is a collection of current research in the above mentioned areas and discusses experimental, theoretical and calculation approaches and industrial utilizations with modern ideas and methods to study heat transfer for single and multiphase systems. The topics considered include various basic concepts of heat transfer, the fundamental modes of heat transfer (namely conduction, convection and radiation), thermophysical properties, condensation, boiling, freezing, innovative experiments, measurement analysis, theoretical models and simulations, with many real-world problems and important modern applications. The book is divided in four sections : "Heat Transfer in Micro Systems", "Boiling, Freezing and Condensation Heat Transfer", "Heat Transfer and its Assessment", "Heat Transfer Calculations", and each section discusses a wide variety of techniques, methods and applications in accordance with the subjects. The combination of theoretical and experimental investigations with many important practical applications of current interest will make this book of interest to researchers, scientists, engineers and graduate students, who make use of experimental and theoretical investigations, assessment and enhancement techniques in this multidisciplinary field as well as to researchers in mathematical modelling, computer simulations and information sciences, who make use of experimental and theoretical investigations as a means of critical assessment of models and results derived from advanced numerical simulations and improvement of the developed models and numerical methods.

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