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Review

Two-phase flow and pool boiling heat transfer in microgravity

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ABSTRACT

Researches on two-phase flow and pool boiling heat transfer in microgravity, which included ground-based tests, flight experiments, and theoretical analyses, were conducted in the National Microgravity Laboratory/CAS. A semi-theoretical Weber number model was proposed to predict the slug-to-annular flow transition of two-phase gas–liquid flows in microgravity, while the influence of the initial bubble size on the bubble-to-slug flow transition was investigated numerically using the Monte Carlo method. Two-phase flow pattern maps in microgravity were obtained in the experiments both aboard the Russian space station Mir and aboard IL-76 reduced gravity airplane. Mini-scale modeling was also used to simulate the behavior of microgravity two-phase flow on the ground. Pressure drops of two-phase flow in microgravity were also measured experimentally and correlated successfully based on its characteristics. 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. 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. Lateral motions of vapor bubbles were observed before their departure in microgravity. The relationship between bubble behavior and heat transfer on plate was analyzed. A semi-theoretical model was also proposed for predicting the bubble departure diameter during pool boiling on wires. 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.

1. Introduction

Two-phase gas–liquid systems have wide applications both on Earth and in space. On Earth, they occur in a variety of process equipments, such as petroleum production facilities, condensers and re-boilers, power systems and core cooling of nuclear power plants during emergency operation. The potential space applications include active thermal control system, power cycle, storage and transfer of cryogenic fluids, and so on. Reliable design of such systems requires a thorough understanding of the mechanism of two-phase flow, such as the phase distributions (flow patterns), pressure drops and heat transfer coefficients at different gas and liquid flow rates.

With the aid of numerous meticulous experiments, our present knowledge on two-phase gas–liquid systems has been built. It is, however, far from complete due to the complicate influence of gravity which is a dominant factor in normal gravity. Gravity strongly affects many phenomena of two-phase gas–liquid systems 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. Depending on the flow orientation and the phase velocities, gravity can significantly alter the flow patterns, and hence the pressure drops and heat transfer rates associated the flow. Advances in the understanding of two-phase flow and heat transfer have been greatly hindered by masking effect of gravity on the flow. Therefore, the microgravity researches will be conductive to revealing of the mechanism underlying the phenomena, and then developing of more mechanistic models for the two-phase flow and heat transfer both on Earth and in space.

Research on two-phase gas–liquid flow and 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, Hewitt (1996), McQuillen et al. (1998), Straub (2001), Di Marco (2003), Kim (2003), Ohta (2003a, b), and Gabriel (2007) summarized the experimental and theoretical works all over the world.

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Since the middle of 1990s, a series of microgravity research projects on two-phase gas–liquid flow and pool boiling heat transfer in microgravity have been conducted in the National Microgravity Laboratory/CAS (NMLC). These activities cover two parts, namely two-phase gas–liquid flows in pipelines, and heat transfer and bubble behaviors in pool boiling. In the following sections, the results obtained in these researches will be presented. In the end, some future projects for microgravity two-phase flow and boiling in China will also be introduced.

2. Two-phase gas–liquid flows in pipelines in microgravity

2.1. Microgravity flow pattern transition models

Because the influence of buoyancy is removed or weakened strongly, two-phase flows in microgravity are believed inherently simpler than those in normal gravity. For example, although other flow patterns appearing essentially in the transition zones are classified by some researchers, annular, slug, and bubble flows are usually considered as the major two-phase flow patterns in straight pipes in microgravity. Thus, there are two major transitions need to be modeled in microgravity.

For predicting the slug-to-annular flow transition in microgravity, the void fraction matched model proposed by Dukler et al. (1988) and modified by Colin et al. (1991) and Bousman (1995) is commonly used for the case of turbulent liquid and gas phases (Zhao, 2000). As shown in Fig. 1, it is possible that there will be 0, 1, or 2 solutions in this model according to the different values of the phase distribution parameter C_0 in the drift-flux model and the material parameter $\zeta = (\rho_G/\rho_L)(\nu_G/\nu_L)^{1/5}$ (here ρ and ν denote the density and viscosity, respectively, while the subscripts G and L denote the gas and liquid phase, respectively). The solutions will alter if different correlations for interfacial friction, such as those proposed by Wallis (1969) and Chen et al. (1991), are used. Furthermore, the suggestion of Dukler (1989) that the slug-to-annular flow transition will take place at the solution of smaller void fraction is not a feasible criterion. For example, such a solution may locate in bubble flow regime for the case of $\zeta = 0.001$, which approximates to the experimental condition of Dukler et al. (1988).

A semi-theoretical Weber number model was developed firstly by Zhao and Hu (2000), and later modified by Zhao et al. (2001a), which was based on the balance between the impulsive force due to the gas inertia and the surface tension force near the slug-to-annular flow transition in microgravity. As shown in Fig. 2, the model can provide an improvement of the accuracy in comparison with others (Bousman, 1995; Reinarts, 1995; Carron and Best, 1996; Jayawardena et al., 1997; Lowe and Rezkallah, 1999). It was also proved to be accurate over a rather wide range of working fluids, tube diameters, and experimental methods including both flight experiments and ground simulated tests such as capillary gas–liquid experiments and equi-density, or neutral buoyancy, immiscible liquid–liquid experiments on the ground.

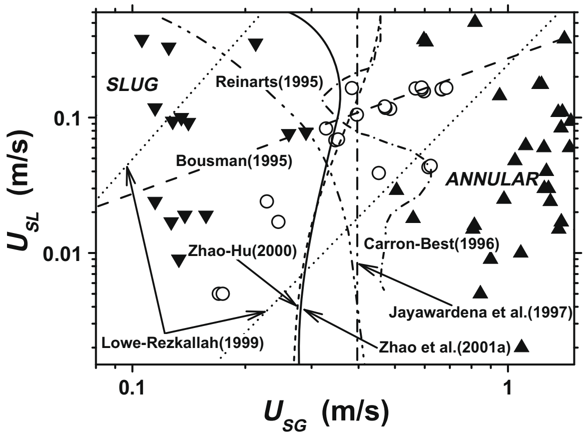

Fig. 2. Comparisons of the semi-theoretical Weber number model with the experimental data of Reinarts (1993) and other commonly used models. Symbols ▲,▼,○ denote slug, annular, and transitional flows, respectively. Re-drawing after Zhao et al. (2001a).

For predicting the bubble-to-slug flow transition in microgravity, the drift-flux model (Dukler et al., 1988; Colin et al., 1996) was commonly used in the literature. The empirical model proposed by Jayawardena et al. (1997) can also be re-written in the same form. It was, however, found that there exists an obvious difference between bubble flows in mini-scale channels in normal gravity and those in normal channels in microgravity. It may arise from the difference of the relative bubble initial size in the two cases. A Monte Carlo method was then used to simulate the influence of the initial bubble size d_b on the bubble-to-slug flow transition based on the bubble coalescence mechanism (Zhao, 2005). It was found that the dimensionless rate of collision is a universal function of the dimensionless bubble diameter d_b/D (where D denotes the pipe diameter), and that the bubble initial size can affect the bubble-to-slug flow transition when its dimensionless value locates in the range from 0.03 to 0.4. Assuming the transition void fraction α_{cr} depends only on the dimensionless collision rate, the correlation for the critical void fraction, $\alpha_{cr} = 0.60–2.32d_b/D$, was obtained,

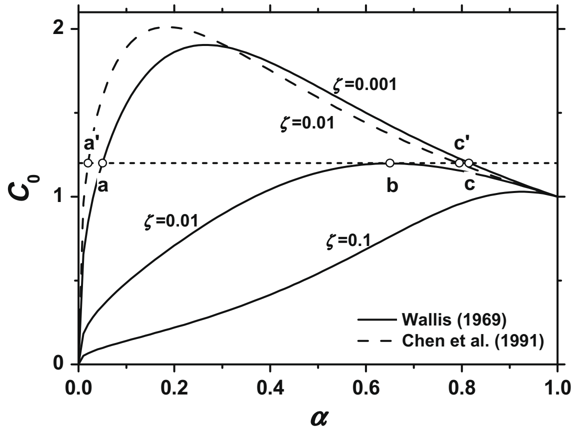

Fig. 1. Characteristics of the solution of the void fraction matched model for the slug-to-annular flow transition in microgravity. Re-drawing after Zhao (2000).

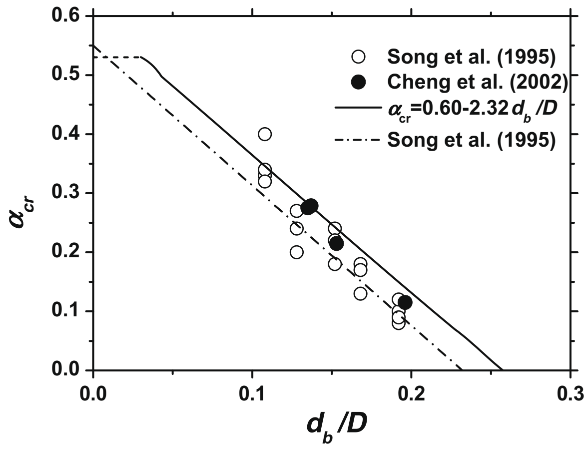

Fig. 3. The influence of bubble initial size on the transition void fraction for the bubble-to-slug flow transition. Re-drawing after Zhao (2005).

which agreed well with the experimental data (Song et al., 1995; Cheng et al., 2002) (Fig. 3).

2.2. Two-phase flow pattern maps in microgravity

Collaborating with researchers from the Keldysh Research Center of Russia, an experimental study was conducted on two-phase flow patterns in a circular pipe with an inside diameter of 10 mm and a length of 356 mm aboard the Russian space station Mir in August 1999 (Zhao et al., 2001b,c), which is the first opportunity and also the sole one up to now to have data from an experiment conducted in a long-term, steady microgravity environment. Air was used as the gas phase, while carbogal, an odorless, colorless and non-toxic liquid with a small contact angle (0–7°) with the test tube, was used as the liquid phase. Bubble, slug, and annular flow were observed as in other researches. Fine dispersed bubble flow was observed at higher liquid superficial velocity, while a wider region of slug-annular flow was also observed at moderate gas superficial velocity. A new region of annular flow with smooth interface at much lower liquid superficial velocity was discovered firstly, which can not be interpreted presently. With detailed comparisons between the reliable data obtained aboard the space station Mir and the predictions of the models proposed in the literature, it was indicated that the observed flow patterns at low gas superficial velocity should be considered to be developing ones due to the small length-to-diameter ratio (Lee, 1993). The entrance effects were much weak on the flow pattern transitions at moderate and high gas superficial velocity. A comprehensive flow pattern map (Fig. 4) was provided according to the results in the background microgravity environment aboard the space station Mir. Data in partial gravity conditions provided by rotating the experimental facility with constant velocities aboard the space station Mir were also reported by Zhao et al. (2004c).

Another experimental research was conducted on two-phase water–air flow patterns in a 12 × 12 mm^2 square channel aboard the Russian IL-76 reduced gravity airplane in July 1999 (Zhao et al., 2001a). Bubble, slug, slug-annular, and annular flows were observed. The flow pattern map obtained in microgravity was shown in Fig. 5, while that obtained from the ground control tests in normal gravity was also shown for comparison. If the slug-annular flow is considered as no one of the major flow patterns but a transitional one between the slug and annular flows, the semi-theoretical Weber number model with the improvement about the shape influence can predict well the slug-to-annular flow transition both in normal and in microgravity. The prediction by Jayawardena et al. (1997) was also in reasonable agreement with the observed boundary between bubble and slug flows in microgravity. Furthermore, it was found that the transition void fraction for the bubble-to-slug flow transition with large Froude number in normal gravity is in direct proportion to the gas relative area in the channel cross-section and its counterpart in microgravity.

Two-phase flow patterns in a 90° bend in microgravity were analyzed by Zhao and Gabriel (2004). The experimental data were obtained by the Microgravity Research Group at the University of Saskatchewan, Canada. Three major flow patterns, namely slug, slug-annular, and annular flows, were observed in this study (Fig. 6). The transitions between adjoining flow patterns were found to be more or less the same as those in straight pipes, and can be predicted satisfactorily by the Weber number models (Zhao and Hu, 2000; Lowe and Rezkallah, 1999). Attention was also paid to the difference of the flow structure between single- and two-phase flows. The bullet-shaped bubbles in slug flow and the gas core in annular flow usually exhibited imposed rotation, which could be inferred from the obvious striations on the gas–liquid interface spreading from the inside to the outside at an acute angle to the forward direction. It may arise from the secondary liquid flow in the bend, which is modified by the presence of the gas phase. This information will be valuable for more sophisticated modeling of two-phase flow in bends in the future.

Mini-scale modeling was also used to simulate the behavior of two-phase flow in microgravity (Zhao et al., 2004a). A 1 × 1 mm^2 square mini-channel was used. A mixer with four 0.7-mm holes perpendicular to the channel axis was located before the channel. The experimental data were compared with other data in mini-channels reported in literature, and also compared with those in normal channel in microgravity, in which the Bond number had the same order of magnitude. The transition to annular flow was consistent in all cases. Comparing with the prediction of the empirical relation of Jayawardena et al. (1997), a much smaller value of the transition void fraction was obtained for the bubble-to-slug flow transition in mini-channels. Obvious difference was found between bubble flow in mini-scale experiments and that in microgravity experiments. As discussed above, it may arise from the difference of the relative bubble initial size in the two cases. Thus, the mini-scale modeling can be used to anticipate the behavior of two-phase flows with high flow rates through normal size channels in microgravity, while it can not be an effective way for simulating the behavior of microgravity two-phase bubble flows.

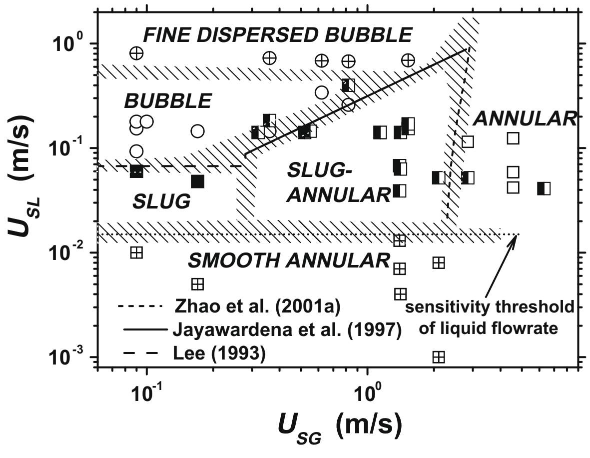

Fig. 4. Flow pattern map of two-phase flow in microgravity aboard the space station Mir. Re-drawing after Zhao et al. (2001b,c).

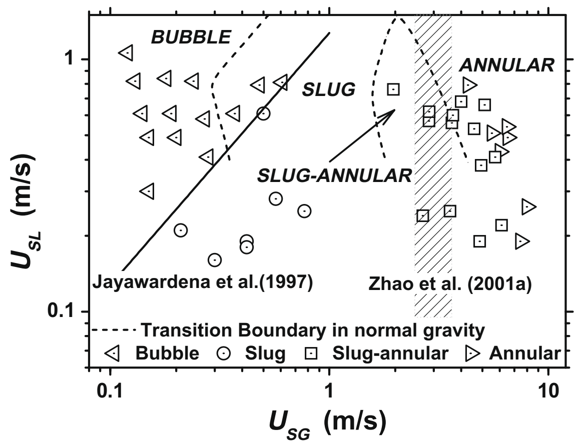

Fig. 5. Flow pattern map of water–air flow in a square channel in microgravity. Re-drawing after Zhao et al. (2001a).

2.3. Pressure drop of two-phase flow in microgravity

In the experiment aboard the Russian IL-76 reduced gravity airplane in July 1999, pressure drops of two-phase flow in microgravity were also measured and compared with some commonly used correlations in the literature (Zhao et al., 2001d), such as the homogenous model, the Lockhart–Martinelli–Chisholm model, and the Friedel model. It was found that much large differences exist between the experimental data and the predictions. Among these models, the Friedel model provided a relative good agreement with the experimental data. A more accurate model should be developed based on a more physical analysis of flow characteristics and a large empirical database developed with the aid of numerous meticulous experiments both in normal and reduced gravity.

Based on the analysis of the flow structure of two-phase bubble flow in microgravity, it was suggested by Zhao et al. (2002) that the friction factor and the Reynolds number in this case should be defined based on the mixture velocity U_m and the properties of the liquid phase, namely $f_{TP} = [(dp/dz)_F D]/(2\rho_L U_m^2)$ and $Re_{TP}=\rho_L U_m D/\mu_L$, respectively. A semi-theoretical relationship, i.e. $f_{TP} = ARe_{TP}^{-1}$, was also proposed, in which the parameter A is dependent on the Reynolds number and should be determined empirically. Comparing the present data in the square channel with those collected by Zhao and Rezkallah (1995) and Bousman (1995) in circular pipes, little influence of the cross-sectional shape was found. Constant values of the parameter A, namely $A = 35$ for $Re_{TP} < 3000$ and $A = 120$ for $Re_{TP} > 4000$, were obtained (Fig. 7). It was indicated that there exists a transition of flow structure in the range of $3000 < Re_{TP} < 4000$, similar to the laminar-to-turbulent transition in single-phase pipe flow. A further comparison, however, with the data obtained by Colin (1990) showed that an exponent for the Reynolds number between 0 and -1 should be more suitable for the case of large Reynolds number.

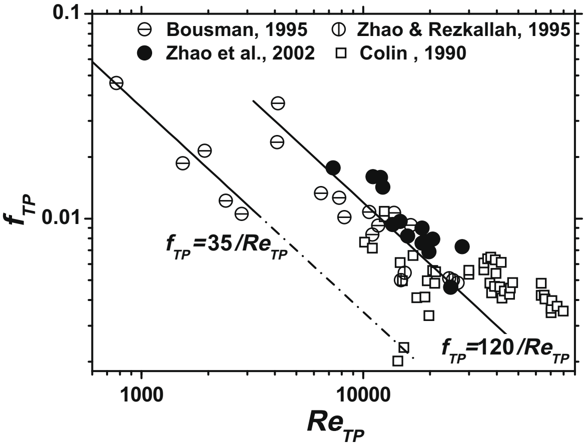

Fig. 7. Pressure drop of two-phase bubble flow in microgravity. Re-drawing after Zhao et al. (2002).

3. Pool boiling heat transfer in microgravity

3.1. 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 m 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 s 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.

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., 2004b). 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. 8), while about 20% and 40% decrease of heat flux was observed for two-mode transition boiling in short- and long-term microgravity, respectively.

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. 9. It was found that the Lienhard–Dhir–Zuber model (Lienhard and Dhir, 1973), established on the mechanism of hydrodynamic instability, can provide a relative good prediction on the trend of CHF in different gravity conditions,

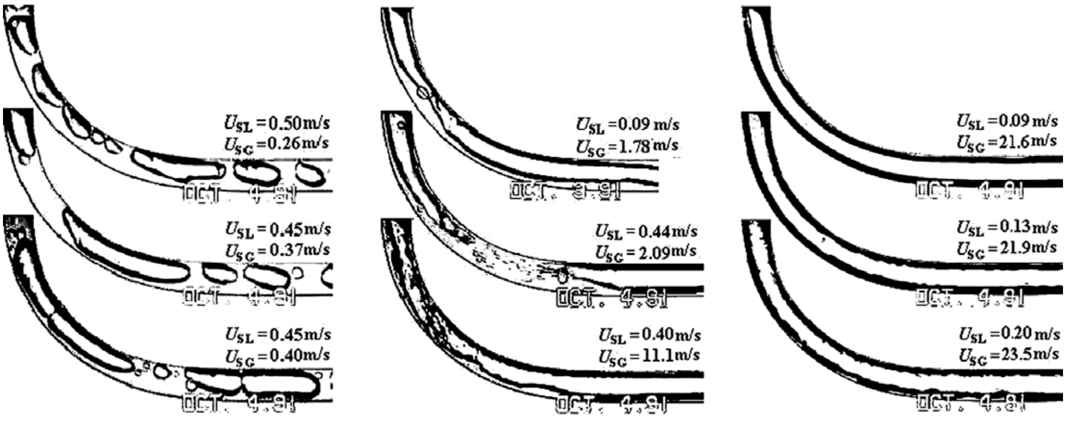

Fig. 6. Flow patterns in 90° bend in microgravity (Zhao and Gabriel, 2004).

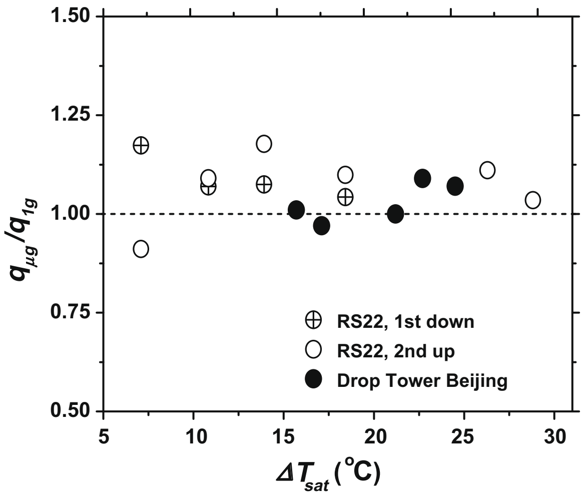

Fig. 8. Microgravity efficiency on heat transfer of nucleate boiling in microgravity (Zhao et al., 2009b).

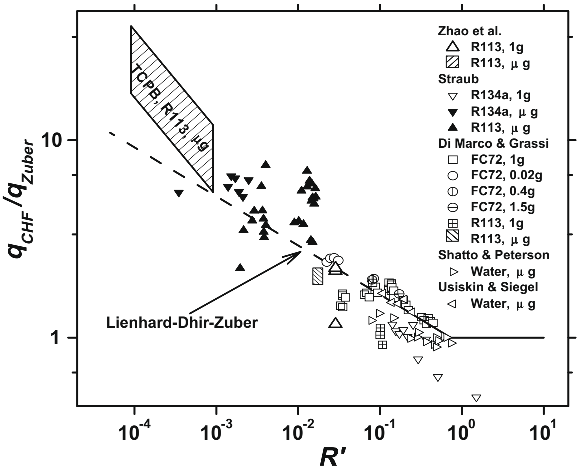

Fig. 9. Scaling of CHF with gravity (Zhao et al., 2009b).

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). Furthermore, comparing the trend of CHF in Fig. 9 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 and 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. 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, and 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.

In the drop tower tests, bubble behaviors were dramatically altered by the variation of the acceleration. 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 could not, 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 (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 (I)–(IV) (Fig. 10): 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. (2008), 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 $1.36 \times 10^{-4} g_0$, 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.

3.2. 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

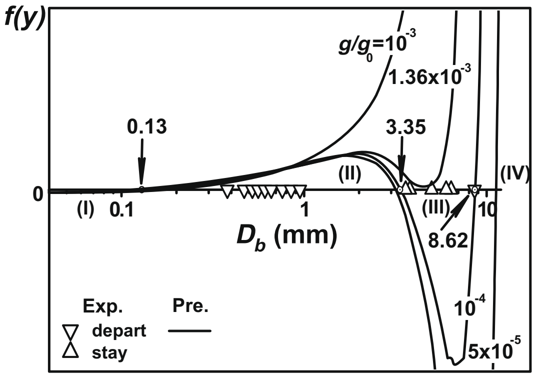

Fig. 10. Bubble departure in the discrete vapor bubble regime in microgravity. (Zhao et al., 2008).

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 $U = U_0 \exp(\tau/\tau_0)$, 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 $\tau_0 = 80$ 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 $28 \times 20 \times 1$ 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 m and a thickness about 10 m. The space between the adjacent parallel strips is about 70 m. 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 were 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.

Because of the residual gravity which was estimated in the range of 10^{-3}–$10^{-5}g_0$, there could exist a weak 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, 8.68, 8.12, 4.54, and 4.84 s, respectively. The typical process observed in the space experiments was shown in Figs. 11 and 12. 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° 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. 11. 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, e.g. the run I-4 shown in Fig. 12, 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

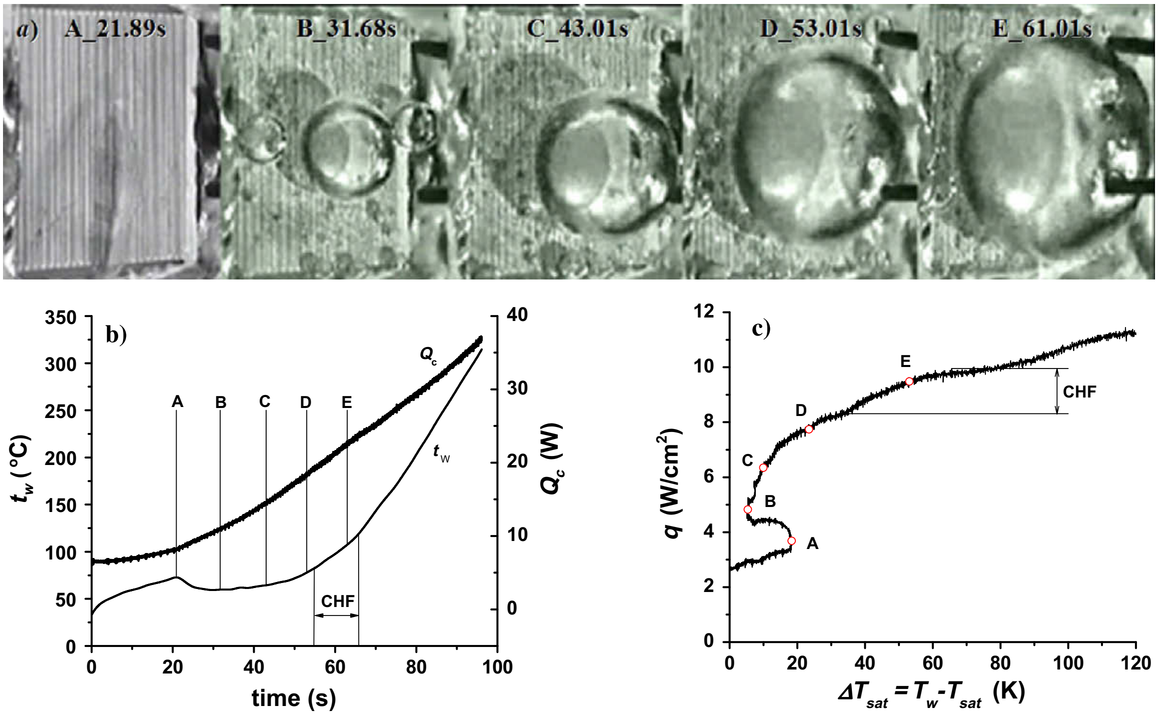

Fig. 11. Bubble dynamics (a), heating history (b), and boiling curve (c) in the run I-1 aboard SJ-8 (Zhao et al., 2009a).

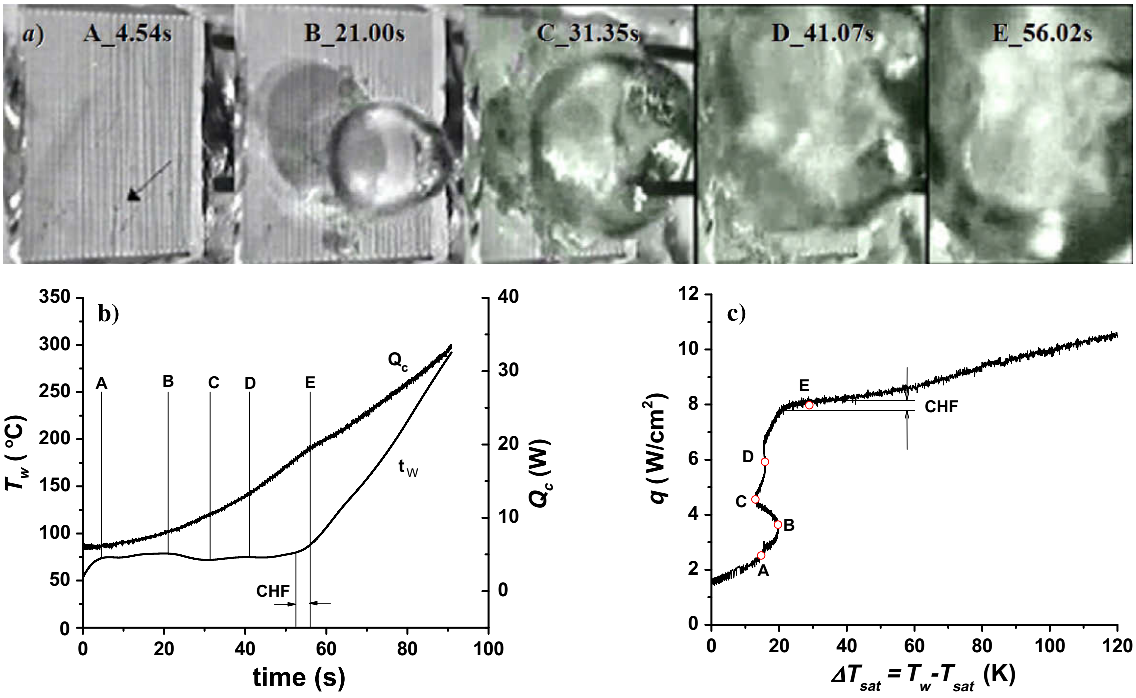

Fig. 12. Bubble dynamics (a), heating history (b), and boiling curve (c) in the run I-4 aboard SJ-8 (Zhao et al., 2009a).

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.

In Fig. 13, 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

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

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

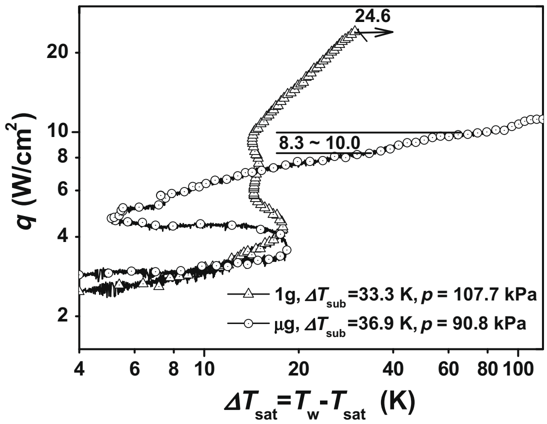

Fig. 13. Comparison of boiling curves in different gravity (Zhao et al., 2009a).

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).

4. Future projects for microgravity two-phase flow and boiling 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 and 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.

Other projects for two-phase flow and boiling in microgravity have also been proposed to study boiling heat transfer enhancement by using micro-pin-finned surface for electronics cooling (Wei et al., 2009), two-phase flows inside fuel cells (Guo et al., 2008) and/or electrolysis cells, membrane separation of two-phase air–water mixture, and so on.

These projects will be helpful for the development of space systems involving two-phase flow and boiling phenomena, as well as for the improvement of understanding of such phenomena themselves.

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References

Bousman, W.S., 1995. Studies of two-phase gas–liquid flow in microgravity. Ph.D. Thesis, Univ. of Houston, TX.

Carron, I., Best, F., 1996. Microgravity gas/liquid flow regime maps: can we compute them from first principles. In: AIChE Heat Transfer Symp., Nat. Heat Transfer Conf., August, Houston, TX.

Chen, I., Downing, R., Keshock, E., Al-Sharif, M., 1991. Measurements and correlation of two-phase pressure drop under microgravity conditions. J. Thermophys. 5, 514–523.

Cheng, H., Hills, J.H., Azzopardi, B.J., 2002. Effects of initial bubble size on flow pattern transition in a 28.9 mm diameter column. Int. J. Multiphase Flow 28, 1047–1062.

Colin, C., 1990. Ecoulements diphasiques à bubbles et à poches en micropesanteur. Thesis, Institut de Mécanique des Fluides de Toulouse.

Colin, C., Fabre, J., Dukler, A.E., 1991. Gas–liquid flow at microgravity conditions – I. Dispersed bubble and slug flow. Int. J. Multiphase Flow 17, 533–544.

Colin, C., Fabre, J., McQuillen, J., 1996. Bubble and slug flow at microgravity conditions: state of knowledge and open questions. Chem. Eng. Commun., 155–173.

Di Marco, P., 2003. Review of reduced gravity boiling heat transfer: European research. J. Jpn. Soc. Microgravity Appl. 20, 252–263.

Di Marco, P., Grassi, W., 1999. About the scaling of critical heat flux with gravity acceleration in pool boiling. In: Proc. of the XVII UIT Nat. Heat Transfer Conf., Ferrara, pp. 139–149.

Dukler, A.E., Fabre, J.A., McQuillen, J.B., Vernon, R., 1988. Gas–liquid flow at microgravity conditions: flow patterns and their transitions. Int. J. Multiphase Flow 14, 389–400.

Dukler, A.E., 1989. Response. Int. J. Multiphase Flow 15, 677.

Gabriel, K.S., 2007. Microgravity Two-phase Flow and Heat Transfer. Springer, Berlin.

Guo, H., Zhao, J.F., Ye, F., Wu, F., Lv, C.P., Ma, C.F., 2008. Two-phase flow and performance of fuel cell in short-term microgravity condition. Microgravity Sci. Technol. 20, 265–270.

Hewitt, G.F., 1996. Multiphase flow: the gravity of the situation. In: Proc. of the 3rd Microgravity Fluid Physics Conf., July 13–15, Cleveland, OH, USA.

Jayawardena, S.S., Balakotaiah, V., Witte, L.C., 1997. Flow pattern transition maps for microgravity two-phase flows. AIChE J. 43, 1637–1640.

Johnson, H.A., 1971. Transient boiling heat transfer to water. Int. J. Heat Mass Transfer 14, 67–82.

Kim, J., 2003. Review of reduced gravity boiling heat transfer: US research. J. Jpn. Soc. Microgravity Appl. 20, 264–271.

Lee, H.S., Merte Jr., H., Chiaramonte, F., 1997. Pool boiling curve in microgravity. J. Thermophys. Heat Transfer 11, 216–222.

Lee, J., 1993. Scaling analysis of gas–liquid two-phase flow pattern in microgravity. In: Proc. of the 31st Aerospace Sci. Meeting Exhibit, Jan. 11–14, Reno, NV.

Lienhard, J.H., Dhir, V.K., 1973. Hydrodynamic prediction of peak pool boiling heat fluxes from finite bodies. J. Heat Transfer 95, 152–158.

Liu, G., 2006. Study of subcooled pool boiling heat transfer on thin platinum wires in different gravity conditions. M.Sc. Thesis, Institute of Mechanics, Chinese Academy of Sciences, Beijing, China.

Lowe, D.C., Rezkallah, K.S., 1999. Flow regime identification in microgravity two-phase flows using void fraction signals. Int. J. Multiphase Flow 25, 433–457.

McQuillen, J., Colin, C., Fabre, J., 1998. Ground-based gas–liquid flow research in microgravity conditions: state of knowledge. Space Forum 3, 165–457.

Oka, T., Abe, Y., Mori, Y.H., Nagashima, A., 1995. Pool boiling of *n*-pentane, CFC-113 and water under reduced gravity: parabolic flight experiments with a transparent heater. J. Heat Transfer Trans. ASME 117, 408–417.

Ohta, H., 2003a. Review of reduced gravity boiling heat transfer: Japanese research. J. Jpn. Soc. Microgravity Appl. 20, 272–285.

Ohta, H., 2003b. Microgravity heat transfer in flow boiling. Adv. Heat Transfer 37, 1–76.

Ohta, H., Kawasaki, K., Azuma, H., Yoda, S., Nakamura, T., 1999. On the heat transfer mechanisms in microgravity nucleate boiling. Adv. Space Res. 24, 1325–1330.

Reinarts, T.R., 1993. Adiabatic two phase flow regime data and modeling for zero and reduced (horizontal flow) acceleration fields. Ph.D. Thesis, Texas A&M Univ., TX.

Reinarts, T.R., 1995. Slug to annular flow regime transition modeling for two-phase flow in a zero gravity environment. In: Proc. of the 30th Int. Energy Conversion Eng. Conf., July 30 – August 4, Orlando, FL.

Song, C.H., No, H.C., Chung, M.K., 1995. Investigation of bubble flow developments and its transition based on the instability of void fraction waves. Int. J. multiphase Flow 21, 381–404.

Straub, J., 2001. Boiling heat transfer and bubble dynamics in microgravity. Adv. Heat Transfer 35, 57–172.

Wallis, G.B., 1969. One-dimensional Two-phase Flow. McGraw-Hill, New York.

Wan, S.X., Zhao, J.F., 2008. Pool boiling in microgravity: recent results and perspectives for the project DEPA-SJ10. Microgravity Sci. Technol. 20, 219–224.

Wan, S.X., Zhao, J.F., Liu, G., Li, B., Hu, W.R., 2003. TCPB device: description and preliminary ground experimental results. In: Proc. of the 54th Int. Astronautical Cong., Sept. 29 – Oct 3, Bremen, Germany.

Yan, N., 2007. Experimental study on pool boiling heat transfer in microgravity. M.Sc. Thesis, Institute of Mechanics, Chinese Academy of Sciences, Beijing, China.

Wei, J.J., Zhao, J.F., Yuan, M.Z., Xue, Y.F., 2009. Boiling heat transfer enhancement by using micro-pin-finned surface for electronics cooling. Microgravity Sci. Technol. 21, S159–S173.

Zhao, J.F., 2000. On the void fraction matched model for the slug-to-annular transition at microgravity. J. Basic Sci. Eng. 8, 394–397.

Zhao, J.F., 2005. Influence of bubble initial size on bubble-to-slug transition. J. Eng. Thermophys. 26, 793–795.

Zhao, J.F., Gabriel, K.S., 2004. Two-phase flow patterns in a 90 (bend at microgravity. Acta Mech. Sinica 20, 206–211.

Zhao, J.F., Hu, W.R., 2000. Slug to annular flow transition of microgravity two-phase flow. Int. J. Multiphase Flow 26, 1295–1304.

Zhao, J.F., Xie, J.C., Lin, H., Hu, W.R., 2001a. Experimental study on two-phase gas–liquid flow patterns at normal and reduced gravity conditions. Sci. China E 44, 553–560.

Zhao, J.F., Xie, J.C., Lin, H., Hu, W.R., Ivanov, A.V., Belyeav, A.Yu., 2001b. Microgravity experiments of two-phase flow patterns aboard Mir space station. Acta Mech. Sinica 17, 151–159.

Zhao, J.F., Xie, J.C., Lin, H., Hu, W.R., Ivanov, A.V., Belyeav, A.Yu., 2001c. Experimental studies on two-phase flow patterns aboard the Mir space station. Int. J. Multiphase Flow 27, 1931–1944.

Zhao, J.F., Xie, J.C., Lin, H., Hu, W.R., Lv, C.M., Zhang, Y.H., 2001d. Experimental study on pressure drop of two-phase gas–liquid flow at microgravity conditions. J. Basic Sci. Eng. 9, 373–380.

Zhao, J.F., Xie, J.C., Lin, H., Hu, W.R., 2002. Pressure drop of bubbly two-phase flow through a square channel at reduced gravity. Adv. Space Res. 29, 681–686.

Zhao, J.F., Liu, G., Li, B., 2004a. Two-phase flow patterns in a square micro-channel. J. Thermal Sci. 13, 174–178.

Zhao, J.F., Wan, S.X., Liu, G., Hu, W.R., 2004b. Subcooled pool boiling in microgravity: results of drop tower testing. In: Proc. of the 7th Drop Tower Days, Sept. 12–25, Bremen, Germany.

Zhao, J.F., Xie, J.C., Lin, H., Hu, W.R., Ivanov, A.V., Belyeav, A.Yu., 2004c. Study on two-phase gas–liquid flow patterns at partial gravity conditions. J. Eng. Thermophys. 25, 85–87.

Zhao, J.F., Liu, G., Li, Z.D., Wan, S.X., 2007. Bubble behaviors in nucleate pool boiling on thin wires in microgravity. In: Proc. of the 6th Int. Conf. Multiphase Flow, July 9–13, Leipzig, Germany.

Zhao, J.F., Liu, G., Wan, S.X., Yan, N., 2008. Bubble dynamics in nucleate pool boiling on thin wires in microgravity. Microgravity Sci. Technol. 20, 81–89.

Zhao, J.F., Li, J., Yan, N., Wang, S.F., 2009a. Bubble behavior and heat transfer in quasi-steady pool boiling in microgravity. Microgravity Sci. Technol. 21, S175–S183.

Zhao, J.F., Wan, S.X., Liu, G., Yan, N., Hu, W.R., 2009b. Subcooled pool boiling on thin wire in microgravity. Acta Astronaut. 64, 188–194.

Zhao, L., Rezkallah, K.S., 1995. Pressure drop in gas–liquid flow at microgravity conditions. Int. J. Multiphase Flow 21, 837–849.