Thermal Dynamics of Growing Bubble and Heat Transfer in Microgravity Pool Boiling

Wangfang Du, Jianfu Zhao, Huixiong Li, Yonghai Zhang, Jinjia Wei and Kai Li

Abstract Boiling heat transfer realizes the high-performance heat exchange due to latent heat transportation, and then there are extensive industrial applications on Earth and many potential applications in space. Microgravity experiments offer a unique opportunity to study the complex interactions without external forces, and can also provide a means to study the actual influence of gravity on the pool boiling by comparing the results obtained from microgravity experiments with their counterparts in normal gravity. It 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. The present chapter summarize the up-to-date progress on the understanding of pool boiling phenomenon based on the knowledge obtained from microgravity experiments, focusing particularly on the thermal dynamics of growing bubble and heat transfer in microgravity pool boiling. The gravity scaling behavior, as well as the passive enhancement of heat transfer

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performance of nucleate pool boiling on flat plates by using micro-pin-finned surface, is presented and discussed in detail. Based on the outcome of the current trends in pool boiling research, some recommendations for future work are also proposed.

Keywords Microgravity · Pool boiling · Bubble dynamics · Heat transfer · Gravity scaling law

1 Introduction

Boiling heat transfer realizes the high-performance heat exchange due to latent heat transportation, and then there are extensive industrial applications on Earth and many potential applications in space. It is, however, also a very complex and illusive process because of the interrelation of numerous factors and effects. Such factors and effects include 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, the transport process of vapor and hot liquid away from the heater's surface, and so on. Furthermore, adding to the complexity is the randomness of the distribution and the configuration of the activated nucleation sites, around which bubbles continue to form, grow up, depart off and move on. Some macro-scale statistical average parameters are then commonly used in the boiling study to fit the needs of engineering endeavors rather than to focus upon the physics of the boiling process. As a result, our present knowledge on boiling phenomenon has been built with the aid of numerous meticulous experiments in normal gravity on Earth where gravity is a dominant factor because of large density difference between the liquid and vapour phases. The literature on boiling research has then been flooded with empirical correlations and semi-mechanistic models involving several adjustable, empirical parameters. These empirical correlations and/or semi-mechanistic models can provide quick input to design, performance, and safety issues and hence are attractive on a short-term basis. However, the usefulness of them diminishes very quickly as parameters of interest start to fall outside the range of physical parameters for which the empirical correlations and/or semi-mechanistic models were developed. In particular, although many empirical correlations and/or semi-mechanistic models include gravity as a parameter, they usually fail when extended beyond the range of gravity levels, usually the sole $1g_0$ (here g_0 denotes the normal gravity on Earth) condition, they were based on. Thus, the physics of the boiling process itself is not properly understood yet, and is poorly represented in the most of empirical correlations and/or semi-mechanistic models, despite almost seven decades of boiling research.

This chapter focuses upon the so-called pool boiling phenomenon, in which the liquid is essentially quiescent and, in normal gravity on the ground, vapor bubbles rise as a result of buoyancy forces induced by gravity. It is, thus, well known that gravity strongly affects pool boiling phenomenon in the environment of normal gravity by creating forces in the systems that drive motions, shape boundaries, and compress fluids. Buoyancy dominates the bubble dynamics, which undermines the phase change heat transfer process and local convection feature near the heater surface, particularly in the vicinity of the liquid-vapor-solid three-phase contact line, which restricts the theoretical development of boiling heat transfer. Advances in the understanding of pool 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. In microgravity, gravity effect is greatly weakened and even disappears, and some processes related to surface or interface which are ever undermined in normal gravity become very prominent. The driving force is weakened to make bubbles depart from the heater surface, and the effect of flow and heat transfer near the heater surface becomes much more prominent than that in normal gravity. The micro flow and heat transfer feature become clear near the liquid-vapor-solid three-phase contact line by excluding the buoyancy effect, which is convenient for studying the heat transfer mechanism deeply. Therefore, pool boiling in microgravity has become an increasing significant subject for investigation.

In addition, comparing the results obtained from microgravity experiments with their counterparts in normal gravity, it can also provide a means to study the actual influence of gravity on the pool boiling. 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 pool boiling heat transfer in microgravity has a history of more than 50 years with a short pause in the 1970s, and then has been advanced with the development of various microgravity facilities and with increased experimental opportunities, especially in the last three decades. On the progress in this field, many comprehensive reviews and monographs are available now. Among many others, Straub [1], Di Marco [2], Ohta [3], Kim [4, 5], and Zhao [6] summarized the experimental and theoretical works all over the world. Here, we focus particularly on the thermal dynamics of growing bubble and heat transfer of pool boiling in microgravity, and discuss in detail on the gravity scaling of bubble behaviour and heat transfer. The enhancement of heat transfer performance of nucleate pool boiling on flat plates with a passive method by using micro-pin-finned surface is also presented and discussed.

2 Pool Boiling Curve

A number of investigators have observed different regions of pool boiling heat transfer. The common-accepted pool boiling curve following Nukiyama [7] is shown, for example, in Fig. 1 for saturated water at atmospheric pressure. It incorporates a number of additional features that have been identified by later investigators. The heat flux q'' from the heater surface to the working fluid is plotted against the wall superheat $\Delta T_{\mathrm{W}} = T_{\mathrm{W}} - T_{\mathrm{SAT}}$, where T_{W} and T_{SAT} denote the temperature at the

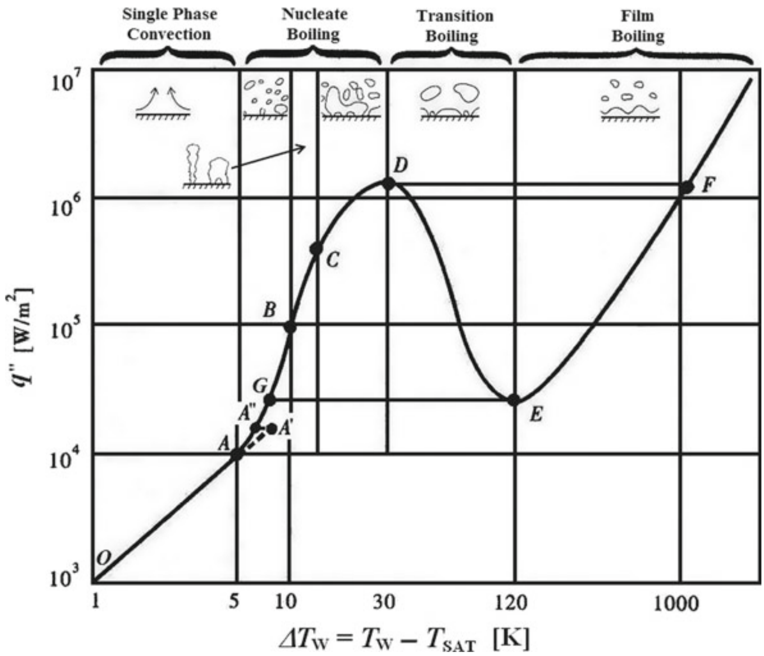

Fig. 1 Typical pool boiling curve for saturated water at atmospheric pressure

heater surface and the saturation temperature at the system pressure P, respectively. The nature of bubbles or a vapor film surrounding the heater in different regions is also depicted in Fig. 1.

In the first region $O-A/A'$ shown in Fig. 1 with a small ΔT_W, heat is transferred by single phase convection, or natural convection of liquid phase in normal gravity environment. The heat fluxes in the region of single phase convection are drastically reduced in microgravity compared with those in normal gravity due to great weakening of the gravity effect.

At location A' corresponding to a certain value of $\Delta T_{W,\,ONB}$, bubble nucleation is initiated on the cavities present on the heater surface, which is called onset of nucleate boiling (ONB). With the inception of nucleation, the heater surface temperature drops to A'' for a given imposed heat flux, which is termed the hysteresis effect of the onset of nucleate boiling. Beyond the ONB point, the slope of the curve increases at higher ΔT_W values as the bubbles grow and depart more rapidly in the partial nucleate boiling region (region $A/A''-B$). As heat flux is increased, more nucleation sites become active and fully developed nucleate boiling ensues (regions $B-C$). The slope of the boiling curve becomes to decrease and the heat transfer coefficient begins to decrease because the intense evaporation under the overcrowded bubble at higher heat fluxes leads to periodic dry patches on the heater surface that can be rewetted by the surrounding liquid. As the wall superheat increases further, liquid is unable to rewet the heater surface, causing a sudden formation of a dry patch that eventually covers a large region of the heater surface. A thin film of vapor eventually separates the liquid from the heater surface and leads to a large temperature excursion of the heater surface (drastic reduction in the heat transfer coefficient). The so-called the critical heat flux (CHF), q''_{CHF}, corresponding to this condition at location D represents the maximum heat flux sustained under the nucleate boiling condition. This is an unstable condition and the heater temperature jumps to point F under any small increase of the heat flux. The ensuing mode of heat transfer in which the heater is blanketed with a thin vapor film is called film boiling.

The region D–E following the CHF represents the transition boiling region, in which the heat transfer is associated with formation followed by rewetting of the dry patches in rapid successions. The transition boiling region is not accessible with the heat flux-controlled method, such as the heating with an electrical heater that imposes a constant heat flux boundary condition. It can only be traced under stable conditions by employing a constant temperature boundary condition on the heated wall. As the heater surface temperature is increased, eventually the rewetting cannot be sustained at the so-called Leidenfrost condition represented by E, and the heater is surrounded by a stable vapor film, resulting in the transition to the film boiling. The heat flux at E is called the minimum heat flux (MHF), q''_{MHF} under the film boiling condition.

Finally, the region E–F is the film boiling region in which heat is transferred by combined radioactive and convective modes across the thin vapor film. With the heat flux-controlled method, another hysteresis effect, shown as the curve *GBCDFEG*, can also be observed.

There are several factors, such as the system pressure P, the bulk liquid temperature T_{L} or the subcooling $\Delta T_{\mathrm{SUB}} = T_{\mathrm{SAT}} - T_{\mathrm{L}}$, the gravity, and so on, affecting greatly the characteristics of heat transfer and then the boiling curves in pool boiling phenomenon. The major progress on the understanding of pool boiling, particularly relevant to the influence of the gravity on nucleate pool boiling, will be presented and discussed in the following sections.

3 Onset of Nucleation Boiling

As mentioned above, the onset of nucleate boiling (ONB) refers to the transition of heat transfer mode from the single-phase liquid convection to a combination of convection and nucleate boiling. In pool boiling, it is identified by the formation of vapor bubbles on the heated wall in a pool of liquid, which is termed “heterogeneous nucleation”. Oppositely, the formation of a vapor bubble completely inside a superheated bulk liquid mass is termed “homogeneous nucleation”. Theoretically, the upper limit on the superheat for homogeneous nucleation within a liquid mass at constant pressure is very high and equal to the spinodal limit that results from thermodynamic consideration [8].

The theoretical value of the superheat required for facilitating the heterogeneous nucleation from an atomically smooth surface has been estimated to be very high,

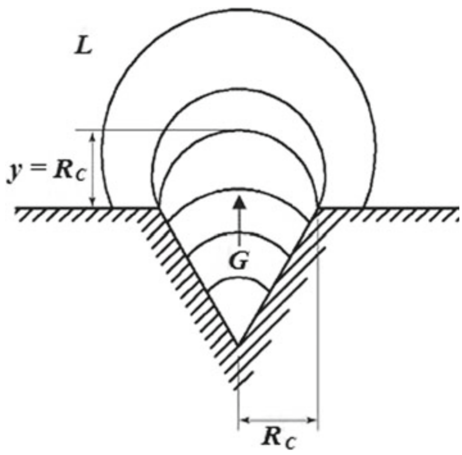

Fig. 2 Growth of a vapor bubble nucleating from a cavity

and often close to the homogeneous nucleation limit. Most experiments, however, reported a significantly lower value. This is usually explained by the fact that the heater surfaces used in practical applications are far from atomically smooth and/or the fluid is contaminated, resulting in that the surfaces are not completely wet by the liquid and there is always some entrapment of vapor/gas in the cavities or around the contaminant [9].

Small cavities trap vapor/gas and act as nucleation sites for bubbles on the heater surface. As the heater surface temperature exceeds the saturation temperature of the working fluid at the corresponding system pressure, a bubble may grow inside the cavity and appear at its mouth, as shown in Fig. 2 where L and G denote the liquid and vapor/gas phases, respectively. A certain value of the wall superheat is needed to activate the cavities depending on various factors: (1) cavity size and shape; (2) fluid properties, including surface tension and contact angles; and (3) temperature profile in the liquid immediately surrounding the heater surface. It is generally expected that the inception superheat or the superheat of ONB is independent of the gravity.

Griffith and Wallis [10] proposed firstly that incipient superheat for boiling from pre-existing nuclei corresponds to the minimum radius of curvature of the interface. The minimum radius of curvature of the interface was assumed to be equal to the radius of the cavity mouth. By replacing the pressure difference between the vapor bubble (no gas) and liquid with the liquid superheat through the use of the Clausius-Clapeyron equation, they obtained an expression for inception superheat as

$$\Delta T_{\mathrm{W,\ ONB}} = \frac{2\sigma T_{\mathrm{SAT}}}{\rho_V h_{LV} R_c} \tag{1}$$

here σ, ρ_V, h_{LV}, and R_c denote the surface tension, the vapor density, the latent heat of liquid-vapor phase change, and the cavity mouth radius, respectively. It should be noted that Eq. (1) includes neither the effect of contact angle on inception superheat nor the effect of temperature gradient that exists near a heated wall. Subsequently, Hsu and Graham [11] and Hsu [12] studied the effect of temperature profile adjacent to the heated surface on the minimum superheat needed for nucleation. In developing his model, Hsu [12] proposed that the top of a bubble embryo should be covered with warm liquid before it can grow. Since vapor in the embryo must be at saturation temperature corresponding to the pressure of vapor in the bubble (which is higher than the pool pressure by $2\sigma/R$), the liquid surrounding the bubble must be superheated to maintain the thermal equilibrium. If the required superheat does not exist, the heat transfer to colder liquid will cause the bubble embryo to shrink. Because heat is transferred from the wall, the liquid temperature decreases with distance from the wall, and the above criterion is satisfied everywhere around the embryo, if the temperature of the liquid at the tip of the embryo is equal to the saturation temperature corresponding to pressure in the bubble.

A general criterion of the range of the active nucleation cavities, according to Davis and Anderson [13], can be deduced as

$$\left\{R_{c,\,\mathrm{min}}, R_{c,\,\mathrm{max}}\right\} = \frac{f_1\delta_t}{2f_2}\left(1 \mp \sqrt{1 - \frac{8\sigma T_{\mathrm{SAT}} f_2}{\rho_V h_{LV}\delta_t \Delta T_{\mathrm{W}}}}\right) \quad (2)$$

In Eq. (2), the minimum and maximum cavity radii $R_{c,\,\mathrm{min}}$ and $R_{c,\,\mathrm{max}}$ are obtained from the negative and positive signs of the radical, respectively. $f_1 = \sin(\theta + \alpha_c)$ and $f_2 = 1 + \cos(\theta + \alpha_c)$, in which θ and α_c denote respectively the contact angle and the cavity mouth angle, while δ_t denotes the thickness of the thermal boundary layer before ONB.

Different investigators have used different models to relate the bubble radius R_b or height y_b to the cavity radius R_c and to the location where the liquid temperature is determined. Hsu and Graham [11] and Hsu [12] assumed that $y_b = 2R_c$, which effectively translates into a contact angle of $\theta = 53.1°$. Bergles and Rohsenow [14] and Sato and Matsumura [15] considered a hemispherical bubble at the nucleation inception with $y_b = R_c$, namely $\theta = 90°$.

Based on Eq. (2), a graph showing the active range of nucleation cavities for different thermal boundary layer thicknesses at saturated temperature is plotted for water under atmospheric pressure in Fig. 3. It is evident that a certain value of superheat is required before any cavity becomes active, corresponding to ONB (black dots marked in Fig. 3).

For a given cavity radius R_c of the nucleate site, the criterion, in term of the inception superheat, can be re-written as [12]

$$\Delta T_{\mathrm{W,\,ONB}} = \frac{2f_1\sigma T_{\mathrm{SAT}}}{\rho_V h_{LV} R_c} \Big/ \left(1 - \frac{f_2 R_c}{f_1\delta_t}\right) \quad (3)$$

For R_c much smaller than δ_t, the wall superheat varies inversely with size of a nucleating cavity, as was the case for Eq. (1). As an alternative to Hsu's criterion, Wang and Dhir [16] proposed that the instability of vapor nuclei in a cavity determines the inception superheat, namely

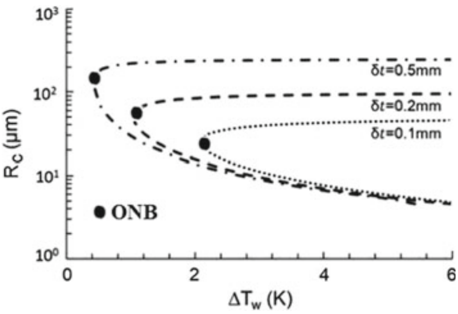

Fig. 3 Active range of nucleation cavities for different thermal boundary layer thickness during saturated boiling of water under atmospheric pressure

$$\Delta T_{\text{W, ONB}} = \frac{2\sigma T_{\text{SAT}}}{\rho_V h_{LV} R_c} K\text{max} \tag{4}$$

where $K_{mas} = 1$ for $\theta < 90^{\circ}$, while $K_{mas} = \sin\theta$ for $\theta > 90^{\circ}$. The above expression is obtained under the assumption that cavity radius, R_c, is much smaller than the thermal layer thickness. Thus, in this limit, Eq. (4) suggests that f_1 in Eqs. (2) and (3) is unity for $\theta < 90^{\circ}$ and is equal to $\sin\theta$ for $\theta > 90^{\circ}$. Or, for non-wetted surfaces, the required superheat is smaller than that given by Eq. (1) of Griffith and Wallis [10]. Wang and Dhir [16], from their experiments on surfaces with different contact angles, have shown the general validity of Eq. (4).

Straub [1] studied systematically the onset of boiling both in normal and micro-gravity conditions using wires as heating elements. The study demonstrates, as is generally expected, that the inception superheat is more or less independent of the gravity and of the subcooling if the overheating due to the saturation state is regarded. The inception superheat depends on the saturation state and decreases with increasing system pressure, which is consistent with the predictions of nucleation theory, for example, Eqs. (1), (3), and (4) mentioned above. Similar conclusions have also been obtained experimentally both for wire heater [17] and for flat plate heater [18]. Therefore, Zhang et al. [19, 20] and Li et al. [21] adopted Eq. (3) as the criterion for determining the beginning of the subsequent bubble cycle in the numerical simulation of single bubble pool boiling.

Contrary to the inception superheat, the criterion of ONB in term of the inception heat flux will be exhibited a great difference between normal and microgravity. Generally, the cooling of single phase natural convection before ONB in normal gravity can be so efficient that at high subcooling the inception superheat will not be attained. Thus, to attain the inception of pool boiling, a much higher heat flux will be needed in normal gravity than that in microgravity.

4 Bubble Dynamics During Nucleation Pool Boiling

After ONB, nucleate boiling ensues which is characterized, particularly in the partial nucleate boiling at low heat fluxes, by the appearance of vapor bubbles at discrete locations on the heater surface. A bubble continues to grow until forces causing it to detach from the surface exceed those pushing the bubble against the wall. After departure, liquid from the bulk fills the space vacated by the bubble, and the thermal layer at and around the nucleation site reforms. When the required critical superheat is attained, a new bubble starts to form at the same site, and the process repeats. It is called ebullition cycle, including the following four stages: bubble nucleation, growth period, bubble departure, and waiting period. It is believed that the quasi-periodic cycle of bubble growth, departure, and waiting processes plays a fundamental role in nucleate pool boiling.

The growth period is generally divided into inertia-controlled and thermally controlled regions. Inertia-controlled growth occurs in the first very short period of bubble growth, in which the bubble radius is proportional to the time, namely $R_B \sim t$. Superheated liquid provides the thermal energy for rapid evaporation at the interface in this region, but the bubble growth is limited by the inertia of the surrounding liquid. Subsequent to the initial rapid growth, evaporation is limited by transient conduction heat transfer. Thus, bubble growth is thermally controlled, which is commonly observed in pool boiling phenomenon.

Analytical solutions for transient heat conduction in the case of uniformly heated liquid over a spherical bubble are generally of the following form

$$R_B(t) = C(\alpha t)^{1/2} \tag{5}$$

where α is the thermal diffusivity of the liquid, and C is a function of the thermophysical properties and the wall superheat, being mostly expressed with an empirical or analytical factor and the Jakob number

$$Ja = \frac{\rho_L c_{p,L} \Delta T_W}{\rho_V h_{LV}} \tag{6}$$

here c_p is the specific heat at constant pressure. Scriven [22], for example, proposed for small superheat $C = (2Ja)^{1/2}$ and for large superheat $C = (12/\pi)^{1/2} Ja$, which corresponds to the asymptotic solution of Plesset and Zwick [23]. Ground experimental observations, for example, Dergarabedian [24], among many others, of the growth of vapor bubbles in superheated water and the calculations using the Plesset-Zwick method agree quite well, although the analytical model can only be valid under the idealized assumptions of the boundary conditions which were realizable only in microgravity. Straub [1] studied the bubble growth experimentally and numerically in microgravity in drop towers and space shuttle experiments, where a bubble was initiated by a heat pulse and grew in an overall supersaturated liquid that was generated by a pressure drop. A mean values of $C = 2.03Ja$ and for the exponent 0.43 are obtained, confirming that the analytical model of Plesset and Zwick [23] and Scriven [22] is the best to describe bubble growth in a uniformly heated liquid, or bubble growth after homogeneous nucleation.

The above analytical model should not be applied to the growth of bubbles in boiling, because these bubbles grow in a thermal layer in which strong temperature gradient exists, and the bubbles, attached to the heater wall, are not spherical. By incorporating the shape of a bubble growing in the vicinity of a heated surface, Mikic et al. [25] derived the following equation, which covers the entire growth cycle, including the inertia-controlled region for small values of t and the thermally controlled region for large values of t.

$$R^{+} = \frac{2}{3}\left[\left(t^{+}+1\right)^{3/2} - \left(t^{+}\right)^{3/2} - 1\right] \tag{7}$$

where

$R^{+} = \frac{A}{B^2} R_B(t)$, $t^{+} = \frac{A^2}{B^2} t$, $A = \left(\frac{2\rho_V h_{LV} \Delta T_{\mathrm{W}}}{\rho_L T_{\mathrm{SAT}}}\right)^{1/2}$, $B = \left(\frac{12\alpha_L}{\pi}\right)^{1/2}\left(\frac{2\rho_L c_{p,L} \Delta T_{\mathrm{W}}}{\rho_V h_{LV}}\right)$.

Equation (7) indicates that the exponent will decrease quickly from 1 to 0.5 during bubble growth.

Straub and his colleagues observed the growth of a single bubble on a flat gold-coated heater in saturated R113 in microgravity [1]. A values of $C = 0.42Ja$ and for the exponent 0.555 are obtained. They found that the bubble grew to a radius of about 15 mm, considerably farther than the extension of the thermal layer reached, and therefore the growth rate became slower than the prediction by the analytical model of growth in a uniformly heated liquid. However, 1/2-power law of bubble growth may be available only for saturated boiling. A mean exponent of 1/3 was observed under subcooled conditions from TEXUS. The exponent depends on the bubble size and decreases with the growing bubble from 0.527 for small bubbles with $R < 1.5$ mm, up to 0.286 for $R \leq 3.5$ mm, where R is the equivalent radius of a spherical bubble calculated from the measured volume. Wan et al. [26] also observed that the exponent changes from 1/3 at the beginning with $R < 1$ mm to 1/5 for $R > 1$ mm for a single bubble growing in subcooled R113 in microgravity. For larger bubble in subcooled liquid, its growth stops when the condensation mass flow at the top reaches the evaporating one at the base. Marangoni effect, caused by un-even distribution of temperature along the interface, may affect the bubble behaviors, particularly in large subcooled boiling in microgravity. Li et al. [27] studied the growth of a single bubble on a smooth surface of a self-heating silicon chip in gas-saturated FC-72 in short-term microgravity in the Drop Tower Beijing. It is found that the bubble growth during the early period before $t = 0.04$ s can be described by $R_B = k \cdot t^{1/2}$ with an empirical value $k = 5.6$, which is consistent with the model based on classical thermal-controlled mechanism, and the empirical parameter locates in the range reported in the literature. The growth rate decreases quickly after $t = 0.04$ s, to 0 at $t = 0.1$ s, and even exhibits a slightly negative rate later.

Recently, a single bubble pool boiling on a plain plate was experimentally studied in microgravity aboard the Chinese recoverable satellite SJ-10 [28, 29]. With the benefit of frame by frame playback of the recorded video images, an axisymmetric isolated bubble is observed at the center of the top surface immediately after the activation of the bubble trigger. The bubble grows quickly both in radial and axial directions within the first 2 s, and in approximately unchanged shape in the following 6 s. After that, the bubble is observed to slide continually on the surface of the heater and merge with small bubbles appeared on the edge of the heating area. The variation of the radius is obtained by image analyses of the recorded video images from the two CCDs. The stage of steady growth of the bubble adhering to the excitation point can be divided into two sub-stages, i.e. expansion and retreat of the bubble base. During the bubble base expansion sub-stage, its radius can be expressed as an exponential function of time. The exponent decreases from 0.42 for the smaller size to 0.28 for the medium one, and finally to 0. The bubble size slightly retraces at the beginning of the bubble base retreat, and then slowly increases again until the subcooled liquid penetrated the bottom of the bubble completely, causing the bubble to detach from the heating surface and then slid on the heating surface under the external disturbance.

Furthermore, the bubble growth problem is much more complex. Most of the evaporation occurs at the base of the bubble, in which the micro-layer between the vapor-liquid interface and the heater surface plays an important role. Snyder and Edwards [30] were the first to propose this mechanism for evaporation. Subsequently, Moore and Mesler [31] deduced the existence of a micro-layer under the bubble from the oscillations in the temperature measured at the bubble release site. Cooper and Lloyd [32] further confirmed the existence of the micro-layer. Following these pioneer works, the micro-layer model is often used in analyzing the bubble dynamics and the relevant heat transfer in boiling. Later, Stephan and Hammer [33] proposed a contact line model, which is often used in the literature. One major difference between the contact line model and the micro-layer model is the wall heat flux profile which has only a peak at the triple-phase-line in the contact line model whereas it exhibits a peak at the triple-phase-line followed by a plateau along the micro-layer in the micro-layer model. This difference is caused by the different assumptions on the size of the liquid film (thicker than molecular level) underneath the growing bubble. In the micro-layer model, the liquid film, or micro-layer, exists in the nearly entire region underneath the growing bubble, while in the contact line model just in a tiny space, or micro region, adjacent to the bubble base. Experimental evidences of the transition between contact line and micro-layer regime have been reported recently for a configuration involving a liquid meniscus moving on a heated wall [34]. Further progress has been obtained most recently by numerical simulations [35–37] comparing with the latest experimental data. There are, however, remaining gaps in building a generally applicable model for the formation and depletion of the micro-layer during boiling process.

As the bubble grows, it experiences forces causing to detach from the surface or pushing it against the wall. As a result of all these forces, a bubble departs from the heater surface after attaining a certain size. The diameter to which a bubble grows before departing is dictated by the balance of forces acting on the bubble.

Fritz [38] correlated the bubble departure diameter by balancing buoyancy, which acts to lift the bubble from the surface, with the surface tension force, which tends to hold the bubble to the wall, so that

$$D_d = 0.0208\theta\sqrt{\frac{\sigma}{g(\rho_L - \rho_V)}} \tag{8}$$

where, θ is the contact angle measured in degrees. It provides a correct length scale for the boiling process, though significant deviations of the bubble diameter at departure have been reported in the literature. Several other expressions that are obtained either empirically or analytically by involving various forces acting on a bubble have also been reported in the literature, which are not always consistent with each other. Generally, these models predict an n-power scaling behavior of the departure bubble diameter related to gravity with a wide range of the exponent n from 0 to $-1/2$.

A qualitative model for bubble departure from cylindrical heating surface was proposed by Zhao et al. [39], in which the Marangoni effect was taken into account (Fig. 4)

$$f(y) = C_4 y^4 + C_3 y^3 + C_1 y + C_0 \tag{9}$$

where,

$$y = \tau^{1/2}, \quad C_4 = \frac{4}{3}\pi E^3(\rho_L - \rho_V)g, \quad C_3 = -2K\pi|\sigma_T|E^2\nabla T, \quad C_1 = 4\sigma R_0 \sin^2\theta + \frac{\pi}{3}\rho_L E^4,$$
$$C_0 = R_0 E^3 \rho_L \sin^2\theta\left(\frac{1}{3} - \frac{3}{8}C_d\right), \quad E = \frac{1}{2\sqrt{\pi}} Ja\sqrt{\alpha_L}$$

where τ, σ, σ_T, R_0, C_d and denote the growing time of bubble, surface tension and its temperature coefficient, wire radius, and drag coefficient, respectively. K is an empirical parameter to count the departure from the linear theory for the case of finite Reynolds and Marangoni numbers, and the function $f(y)$ denotes the sign of the resultant force acting on a growing discrete vapour bubble. If $f(y) < 0$, the departure

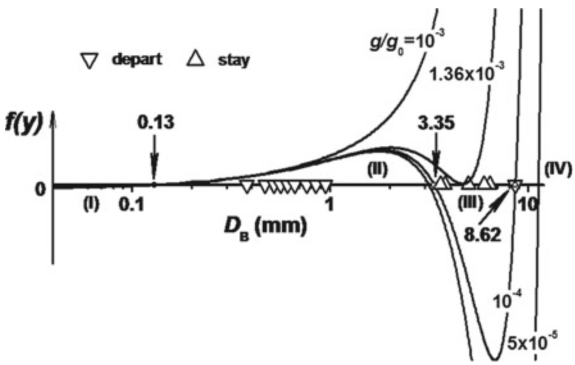

Fig. 4 The sign of the resultant force acting on a growing discrete vapour bubble in different gravity levels

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.

The predictions by Eq. (9) are plotted in Fig. 4 at different gravity. In normal gravity, the function for the resultant force 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 1.36×10^{-4} g_0, the second and third zero-value points will be predicted by the new model. It is consistent with the observation of special bubble behaviors in long-term microgravity during the TCPB (Temperature-Controlled Pool Boiling) experiment aboard the 22nd Chinese recoverable satellite RS-22 [40]. It is observed that there exist three critical bubble diameters in microgravity, which divided the observed vapor bubbles into four regions: 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. Comparing the prediction of Eq. (9) at $g = 10^{-4}$ g_0 (the level of residual gravity was estimated in the range of 10^{-3} to 10^{-5} g_0) with the observation, the agreement is quite evident.

Knowing the growth rate and the diameter to which a bubble grows before departing, the growth time, t_g, can be calculated. After bubble departure, cooler bulk liquid fills the space vacated by the bubble. The thermal layer reforms over the area surrounding the nucleation site, and then a new bubble at this location will form and grow if the superheated liquid layer is re-established and the inception criterion is satisfied. The time taken by the thermal layer to develop prior to inception is termed the waiting period, t_w. Conceivably, a theoretical evaluation of the bubble release frequency can be made from expressions for the waiting time and the growth time. Such an approach, however, meets with little success comparing with experimental data because of the extreme complexity of ebullition cycle. Thus, correlations, including both the bubble diameter at departure and the bubble release frequency f, have been reported in the literature, usually in the following form

$$f D_d^n = const \tag{10}$$

The constant parameter may be gravity-dependent, resulting in an m-power scaling behavior of the bubble release frequency with a range of the exponent m from 1/4 to 1.

One of the most comprehensive correlations of this type is given by Malenkov [41] with the value $n = 1$, while $n = 2$ is another alternative commonly used in the literature [42]. Besides, Di Marco and Grassi [43] suggested the following correlation for the bubble release frequency at different gravity

$$\frac{f_a}{f_0} = \left(\frac{a}{g_0}\right)^{3/4} \tag{11}$$

where f_0 is the bubble release frequency in normal gravity, and a is residual gravity.

Numerical simulation is a powerful alternative of experimental study for understanding bubble dynamics in pool boiling. Zhao et al. [44] studied numerically the growth processes of a single bubble on a fixed single site and the relative heat transfer in different gravity for saturated water at 0.1 MPa including the contact line model [33]. The Level Set Method and constant superficial contact angle are used to capture the interface between the vapor and liquid phases and the motion of contact line on the heating wall, respectively. The numerical results indicate that the equivalent diameter is proportional to about (1/3–1/2)-power of the growing time in spite of whatever gravity levels. But gravity has great influences on both the departure diameter and the growing time. The bubble departure diameter is proportional inversely to about 1/3-power of gravity, while the growing time is proportional inversely to about 4/5-power of gravity. The area-averaged heat fluxes are approximately proportional to the 3/2-power of the wall superheat when the number density of active nucleation sites fixes, which is consistent with the hypothesis proposed by Zuber [45] for small superheat. Furthermore, this trend has no change with the decrease of gravity, which is also confirmed later for the case including the influence of heater thermal capability [19–21].

By using the Ghost Fluid Method for sharp interface representation, Zhang et al. [19, 20] and Li et al. [21] extended the above numerical simulation to include the influence of heater thermal capability on nucleate pool boiling. Multi-cycle simulations are carried out to eliminate the influence of unreal initial conditions. Equation (3) was adopted for determining ONB. A constant and uniform temperature is fixed on to the bottom surface of the solid wall in the simulations, and thus, both the spatio-temporal averaged heat flux and superheat on the top surface, which contacts the working fluid directly, are dependent variables instead of controllable ones. They found that the surface temperature of solid wall can vary both temporally and spatially and solid wall thickness and material properties are observed to affect waiting time significantly, and the heater thickness will also affect the surface temperature recovery during nucleate boiling. Additionally, highly conductive materials are able to recover faster than poorly conductive materials. A slight dependence of the superheat related to gravity, i.e. $\Delta T_W \sim g^{-0.05}$ in the range of (10^{-2} to 10^0) g_0, is observed in the case of single bubble boiling of saturated FC-72 on SiO_2 solid wall. The departure diameter of bubbles is proportional to $g^{-0.5}$, while the bubble release frequency is proportional to g^1. Thus, fD_d^2 can keep constant, which agrees with the experimental observations by Siegel and Keshock [42].

Zhang et al. [19, 20] and Li et al. [21] analyzed in detail the transient heat conduction inside the solid wall. A sharp drop of the wall temperature is evident in the vicinity of the contact line due to violent evaporation in this tiny region. The area of the temperature drop moves with the contact line, resulting in a pseudo-periodical process of heat storage and release inside the solid wall, which exhibits a coupling effect with bubble dynamics and heat transfer. The thermal penetration depth caused by the processes of bubble growth and departure in a single bubble cycle is about 0.5 mm in both steady and quasi-steady cases, which is much smaller than the heater thickness. Based on the analysis of the thermal penetration depths caused by the processes of bubble growth and departure, a suitable thickness of about 2 mm is proposed for the substrate of the integrated micro heater used in the SOBER-SJ10 experiment aboard the Chinese recoverable satellite SJ-10 [46, 47].

Based on the measured local temperature data underneath a single growing vapor bubble of FC-72 on a flat heater surface in microgravity obtained from the SOBER-SJ10 experiment, the spatio-temporal evolution of the temperature on the heated surface (Fig. 5) is reached under the axisymmetric hypothesis [29]. A narrow superheat region corresponding to the local superheat process can be observed. Several discrete cold points, instead of continuous low temperature line due to limited spatial resolution of local temperature measurement, are also observed, which indicates the location of the trajectory of the contact line on the heated surface. A dashed line is drawn in Fig. 5 according to these cold spots to show the possible trajectory of the contact line moving on the heated surface. Furthermore, the variation of the radius is also shown in Fig. 5 for comparison. These data provides a benchmark for the validation and verification of the bubble growth models.

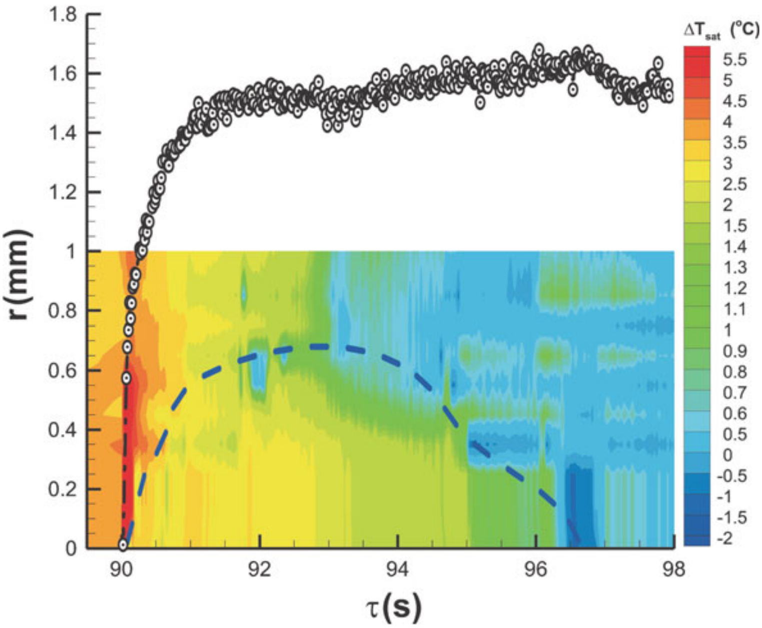

Fig. 5 The spatio-temporal evolution of local temperature on the heated surface

5 Gravity Scaling of Heat Transfer in Nucleation Pool Boiling

With high efficiency of boiling heat transfer due to the release of latent heat, nucleate pool boiling allows transferring high heat fluxes at moderate wall superheats, and then is widely used in industry. To meet the demands of industrial applications, numerous heat transfer correlations have been developed theoretically, semi-empirically, or empirically in the past decades, and are still subject of many ongoing research activities all over the world. A successful correlation must be built on a reliable physical concept and mechanisms of the phenomenon. Particularly, for space applications, the correlation must correctly represent gravity as a real parameter, not just an irrelevant constant in classical boiling study which is based on experiments performed in normal gravity on the ground.

It has been recognized that the heat transfer during nucleate pool boiling is closely related to the bubble activity over a heater surface. In principle, the heat transfer rate can be predicted by knowing the bubble frequency, active nucleating cavity site density (per unit heater surface area), and heat transferred during each bubble ebullition cycle. However, empirical correlations are commonly used in fact. The well-known and often-used one is the semi-empirical model developed by Rohsenow [48], namely

$$q'' = \mu_L h_{LV} \left[\frac{g(\rho_L - \rho_V)}{\sigma}\right]^{1/2} \left(\frac{c_{p,L}\Delta T_w}{C_{sf} h_{LV}\,\mathrm{Pr}_L^n}\right)^3 \tag{12}$$

where μ is the dynamic viscosity, and the Prandtl number $Pr = \nu/\alpha = \mu c_p/k$, in which ν and k denote the kinematic viscosity and thermal conductivity, respectively. Rohsenow introduced an empirical constant C_{sf} to account for the fluid-surface effect on nucleate boiling, while the parameter n depends on the working fluid. Rohsenow model is based on assumptions for forced convection caused by the motion of the detached bubbles which depends on the buoyancy force exerted on the bubbles, resulting in the heat transfer intensity being a function of gravity. It implies a scaling exponent $m = 1/2$ related to gravity for the same superheat, namely

$$\frac{q''}{q''_0} = \left[\frac{a}{g_0}\right]^{1/2} \tag{13}$$

Consequently, at a given superheat, the heat flux and heat transfer coefficient would be reduced by a factor of 10^{-2} to 10^{-3} if the gravity were reduced to the level of 10^{-4} to 10^{-6} g_0. Fortunately, it is not confirmed in microgravity experiments.

Generally, it is believed that the pool boiling curve near the ONB is independent of the acceleration level, i.e., m approaches zero. On the other hand, at higher superheat approaching CHF, the power law coefficient approaches a value of 0.25, as what is predicted by the CHF correlations of Kutateladze [49] and Zuber [50]. There is, however, a wide range from -0.35 to 1 for the gravity scaling exponent according

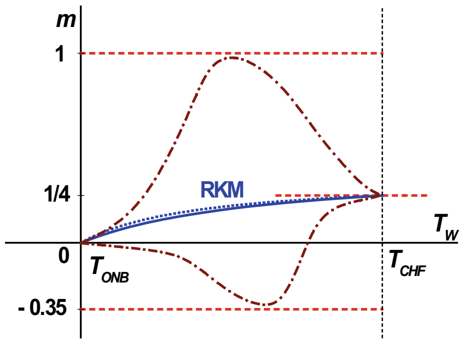

Fig. 6 A schematic of gravity scaling exponent of heat transfer in nucleate pool boiling

to the existing correlations of heat flux in nucleate pool boiling. There may exist numerous possible trajectories of gravity scaling exponent of heat transfer in nucleate pool boiling (Fig. 6). No common trend concerning the gravity scaling behavior of nucleate pool boiling could be achieved now.

Raj et al. [51, 52] observed a sharp transition in the heat transfer mechanism at a threshold gravity level a_{tran} $(=4.41\sigma/[L_h^2(\rho_{L-}\rho_V)]$, here L_h is the characteristic length of the heater) based on quasi-steady pool boiling experiments over a continuous gravity range of (0–1.8) g_0. Below this threshold (surface tension dominated boiling, or SDB, regime), a non-departing primary bubble governed the heat transfer and the effect of residual gravity was small. Above this threshold (buoyancy dominated boiling, or BDB, regime), bubble growth and departure dominated the heat transfer and gravity effects became more important. A gravity scaling model in the BDB regime was developed, namely

$$\frac{q''_{BDB}}{q''_0} = \left(\frac{a_{BDB}}{g_0}\right)^m, \quad m = \frac{0.9T^*}{1 + 2.6T^*} \quad \text{for} \quad \frac{L_h}{L_0} \geq 2.1 \tag{14}$$

where

$$T* = \frac{T_{\text{W}} - T_{\text{ONB}}}{T_{\text{CHF}} - T_{\text{ONB}}}, \quad L_0 = \sqrt{\frac{\sigma}{a(\rho_L - \rho_V)}} \tag{15}$$

The dimensionless wall temperature T^* is defined based on the assumption that CHF for all gravity levels occurs at the same wall superheat and ONB is independent on gravity. In Eq. (14), q''_0 denotes the heat flux of nucleate pool boiling at the reference gravity level, usually at the normal gravity g_0.

Later, Raj et al. [53] slightly modified the expression of the exponent m in the BDB regime as

$$m_{BDB} = \frac{0.65T^*}{1 + 1.6T^*} \tag{16}$$

and proposed $m_{SDB} = 0.025$ in the SDB regime. A general for the scaling behavior in the SDB regime including the jump in heat flux ($\Delta q''$) due to subcooling and dissolved gas is developed as follows

$$\frac{q''_{SDB}}{q''_0} = \left(\frac{a_{tran}}{g_0}\right)^{m_{BDB}} K_{jump}\left(\frac{a_{SDB}}{a_{tran}}\right)^{0.025}, \quad \text{for} \quad \frac{L_h}{L_0} < 2.1 \tag{17}$$

where

$$K_{jump} = 1 - e^{-CMa}, \quad \text{and} \quad Ma = \frac{\sigma_T \Delta T_{SUB} L_h}{\mu_L \alpha_L} \tag{18}$$

In the above equation, $\sigma_T = -d\sigma/dT$ denotes the temperature coefficient of surface tension. The value of the empirical parameter C for FC-72 was found to be 8.3×10^{-6}.

The heat transfer, however, measured in the SDB regime is likely to be artificially high as the bubble responds to the g-jitter in the aircraft data which is on the order of $10^{-2}\ g_0$, and then it is observed that the power law coefficient for gravity obtained in the SDB regime ($m_{SDB} = 0.025$) had much scatter. Based on experimental data obtained in the true microgravity environment provided by the ISS, a modified power law coefficient of $m_{SDB} = 0$ in the SDB regime is proposed by Raj et al. [54]. A schematic of heat flux versus acceleration is shown in Fig. 7. It is physically reasonable. Once in the SDB regime where a non-departing, coalesced bubble covers the heater, a small change in the gravity level would only change the bubble shape without affecting the steady state value of heat transfer significantly.

The trajectories of the gravity scaling exponent m_{BDB} in the above model, namely Eqs. (14) and (16), are plotted in Fig. 6, labeled as "RKM". They show a monotonically increasing trend from 0 at ONB to 1/4 at CHF. Many unexplained trends in boiling literature can be explained and modeled using this scaling framework, which demonstrates its robustness in predicting low gravity heat transfer [54–56]. Further endeavors, however, are needed because of the following questions.

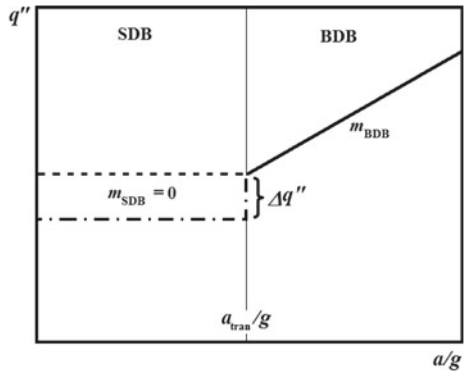

Fig. 7 A schematic of the gravity scaling model proposed by Raj et al. [54]

At first, the gravity scaling model of Raj et al. [54] is developed mainly based on the naturally transient data obtained from the pool boiling experiments aboard parabolic aircrafts, in which a continuous gravity change occurs from 0 (or 1.8 g_0) to 1.8 g_0 (or 0) in a very short period of about 5 s. As the gravity changes, time is required for the flow field and heat transfer profiles to develop and achieve steady state. Before the transition from high-g to low-g, the natural convection flow field was fully developed. During the transition from high-g to low-g, the flow field required more time to achieve steady state than was available, resulting in higher heat transfer than the expected quasi-steady value. Similarly, during the transition from low-g to high-g, the heat transfer was lower than the expected quasi-steady value. It is assumed that if there is no difference in the two curves of heat flux versus acceleration during the transition from hypergravity to low-g and vice versa at the same superheat, the flow field and heat transfer profiles may have sufficient time to achieve steady state at each acceleration level. However, a hysteresis in the heat flux curve is present at the lower superheat whenever the superheat was not sufficient to initiate nucleation, and heat transfer was by natural convection in high-g condition. If the superheat is large enough, and the heat transfer is independent of the direction of transition, the heat transfer during the transitions when boiling occurs will be considered as in quasi-steady state. At present, there are no real steady data of pool boiling in long-term partial gravity regime, even the data regarding pool boiling in the partial gravity regime are very scarce.

Secondly, the assumption that CHF for all gravity levels occurs at the same wall superheat is questionable. Recently, Ma et al. [57] simulated numerically pool boiling heat transfer from a horizontal hydrophilic surface under constant wall temperature in different gravity levels based on an improved liquid-vapor phase-change lattice Boltzmann method with the imposition of a conjugate thermal boundary condition at solid/liquid interface. It is shown that gravity has significant effects on pool boiling curves. In contrast to the assumption of constant CHF superheat, the critical heat flux occurs at a lower wall superheat and is lower in microgravity than in normal gravity. Similar experimental observations have also been reported in the literature. The same observations have also been obtained by Feng et al. [58].

Thirdly, the influence of heater geometry is not taken into account. Drastically different behaviors have been observed between pool boiling on flat plates and on cylinders in microgravity. For example, Zhao et al. [17] reported a slight enhancement of heat transfer of nucleate pool boiling on thin wires in short- and long-term microgravity comparing with that in normal gravity. On the contrary, boiling heat transfer on plates in microgravity was generally deteriorated comparing with that in normal gravity, particularly at high superheats or heat fluxes [18, 55, 59]. The deterioration of heat transfer of nucleate pool boiling on plates may be characterized by the gravity scaling model of Raj et al. [54], but it never was for the enhancement on wires.

Finally, the 1/4-power scaling law of CHF with the gravity is not always maintained. For CHF on cylinders, Zhao et al. [17] found that the Lienhard-Dhir-Zuber model [60], 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 $R' = R[(\rho_{L-}\rho_V)g/\sigma]^{1/2} = Bo^{1/2}$ was far beyond the initial application range of the model. This observation was consistent with Straub [1]. Furthermore, it was inferred, as pointed out by Di Marco and Grassi [61], 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. Zhao et al. [62] revisited the scaling behaviors 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.

A parameter, named as the limited nucleate size d_{LN}, and a corresponding dimensionless coefficient $\Gamma = d_{LN}/d_{\text{wire}}$ were introduced to interpret this phenomenon [17]. 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.

6 Enhancement of Pool Boiling Heat Transfer in Microgravity

The loss of buoyancy in microgravity has been found to change the nature of terrestrial nucleate boiling, which is driven primarily by the gravity on Earth. It is found that the boiling process in microgravity appears to be strongly dependent on heat flux and subcooling levels. For the boiling heat transfer in microgravity, the diminished buoyancy effect results in a longer stay time for the bubble departure, which prevents the effective access of fresh bulk liquid to the heater surface in time, and then leads to a lower boiling heat transfer performance and a strong increase of the heater temperature as with film boiling at high heat flux. How to improve boiling heat transfer effectively in microgravity is an important issue. A straightforward solution is to impose another force on the boiling process in microgravity to replace the buoyancy force. Sitter et al. [63, 64] and Moehrle and Chung [65] examined boiling on a wire in the presence of an acoustic field in terrestrial and microgravity experiments and found that the acoustic actuation led to an increase in the heat transfer coefficient on the wire by directly coupling with the natural oscillations of vapor bubbles through the action of the primary Bjerknes force. Complete boiling curves are presented to show how the applied acoustic field enhanced boiling heat transfer and increased critical heat flux in the terrestrial environment, while in microgravity the acoustic field was found to be capable of filling the role of terrestrial gravity in maintaining nucleate boiling. Applying a static electric field [66–71] or a magnetic field [72] can also provide additional volume forces able to replace buoyancy, to reduce the size of detaching bubbles and to lead them away of the surface, restoring efficient heat transfer conditions in microgravity.

On the other hand, drastically different heat transfer performances were observed between pool boiling on flat plates and on cylinders in microgravity, which is caused by the possible fresh liquid supply. In nucleate pool boiling on cylinders (Fig. 8a), bubble grows on a side of the cylindrical surface, and the bubble, even very bigger than the cylinder diameter, may not enwrap the cylinder, resulting in a plenty supply of fresh liquid from other sides to the heater surface to maintain the same heat transfer efficiency of microgravity nucleate pool boiling as that in normal gravity, or even to obtain a higher efficiency due to the advantage of sustained phase change on the heated surface in microgravity comparing with convection driven by the rising of detached bubbles in normal gravity. On the contrary, vapor bubbles cannot depart easily from the smooth surface of a flat plate in microgravity (Fig. 8b), 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. These observations inspire us to propose a new passive method for nucleate boiling heat transfer enhancement (Fig. 8c): A reasonable design of the micro-structure of the heater surface can form effective path of fresh liquid supply to ensure that even if bubbles staying on the top of the heater surface can not be detached in microgravity, the fresh bulk liquid may still access to the heater surface through interconnect tunnels formed by the micro-structure due to the capillary forces, which is independent of the gravity level.

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 [73–78]. Unlike much obvious deterioration of heat transfer of nucleate pool

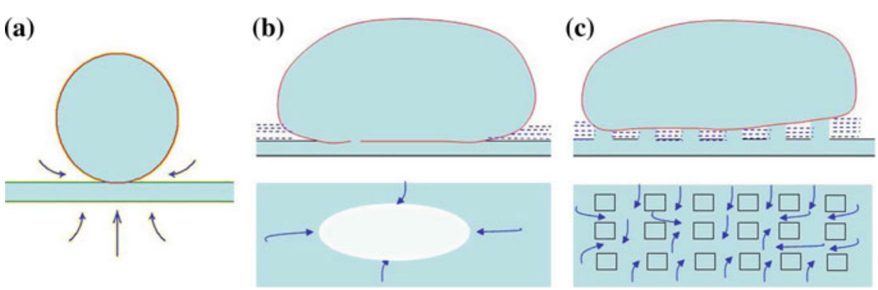

Fig. 8 Schematic path of fresh liquid supply to the heater surface underneath the growing bubble on different heater geometries: **a** cylinder, **b** smooth flat plate, and **c** flat plate with micro-structure surface

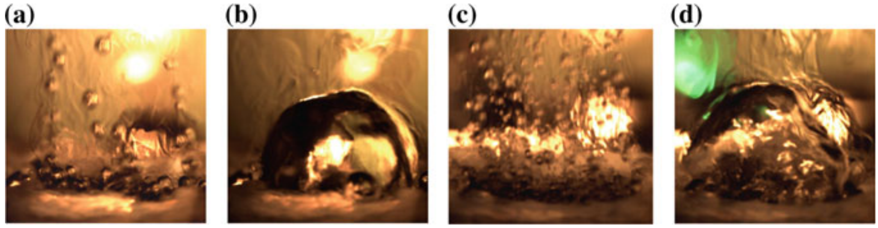

Fig. 9 Bubble behaviors in nucleate pool boiling on smooth and micro-pin-finned surfaces in normal and microgravity. **a** 1 g, smooth surface; **b** μg, smooth surface; **c** 1 g, micro-pin-finned surface; **d** μg, micro-pin-finned surface

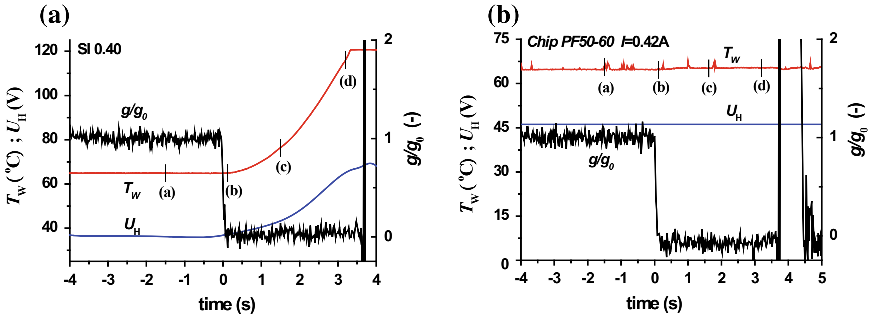

Fig. 10 Heat transfer performances of nucleate pool boiling on smooth and micro-pin-finned surfaces in normal and microgravity. **a** smooth surface; **b** micro-pin-finned surface

boiling on the smooth surface in microgravity, constant heater surface temperature of nucleate pool boiling for the micro-pin-finned surface was observed, even though a large coalesced bubble completely covered the surface under microgravity condition (Figs. 9 and 10). The critical heat flux on micro-pin-finned surface in microgravity can reach about two-thirds of that in normal gravity, but almost three times as large as that for the smooth surface in microgravity. It is also found that the fin pitch and configuration have significant effects on the boiling heat transfer coefficient as well as critical heat flux.

Therefore, it is confirmed that the micro-pin-finned surface 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-finned 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.

Further study on the enhancement of the micro-pin-finned surfaces combined with forced convection has also been performed in the drop tower Beijing [79], and long-term microgravity experiments are also proposed, which will be conducted on board the Chinese Space Station (CSS) in future.

7 Conclusion Remarks

Pool boiling is a daily phenomenon transferring effectively high heat flux, and then is widely used in industrial processes. It is, however, a very complex and illusive process due to interrelation of numerous factors and effects. Among many sub-processes in boiling phenomenon, gravity can be involved and play much important roles, even enshroud the real mechanism underlying the phenomenon. The detailed knowledge of the mechanisms underlying this phenomenon is important and essential for industrial applications. 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, and provide an effective means to study the actual influence of gravity on the boiling phenomenon. Furthermore, many potential applications exist in space and in planetary neighbors due to its high efficiency in heat transfer. Thus, pool boiling in microgravity has become an increasing significant subject for investigation.

Up to now, great progress on understanding of pool boiling phenomenon has been achieved based on a substantial amount of solicited experiments both in normal and microgravity. Based on the outcome of the current trends in pool boiling research, some recommendations for future work, particularly on resolving many outstanding issues related to gravity effect on boiling and building a comprehensive database for the development of a pool boiling regime map, can be summarized as follows:

(1) Visualization of pool boiling in various gravity levels, particularly in long-term partial gravity regime, and successful development of a gravity scaling model reflecting the actual mechanism underlying this phenomenon.
(2) Verification of the heat transfer enhancement of nucleate pool boiling by micro-pin-finned surface in long-term microgravity environment, and optimization of the micro-structure parameters to obtain highly efficient heat transfer capability in various gravity levels.
(3) Research with high spatial resolution heaters at smaller scales of both length and time in normal gravity on Earth and in partial and microgravity in space to reveal micro-convection mechanism in the immediate vicinity of growing bubbles during single- and/or multiple-bubble pool boiling experiments.
(4) Extension of single bubble boiling models to actual experimental conditions with multiple bubbles using a fractal pattern approach, and corresponding numerical studies with a moving liquid-vapor interface including the transient thermal response of the solid wall.

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