Pool Boiling on Wire in Microgravity – What Have We Learned

Jian-Fu ZHAO, Shi-Xin WAN, Shuang-Feng WANG

National Microgravity Laboratory/CAS; Institute of Mechanics, Chinese Academy of Sciences, China. jfzhao@imech.ac.cn

Abstract: In the past years, steady pool boiling of degassed R113 on thin platinum wires has been studied systematically in our lab, including experiments in long-term microgravity aboard RS-22, in short-term microgravity in the Drop Tower Beijing / NMLC, and in normal gravity on the ground. Slight enhancement of nucleate boiling heat transfer is observed in microgravity, while dramatic changes of bubble behaviors are much evident. The value of CHF in microgravity is lower than that in normal gravity, but it can be predicted well by the Lienhard-Dhir correlation, although the dimensionless radius in the present case is far beyond its initial application range. The scaling of CHF with gravity is thus much different from the traditional viewpoint. Considering the influence of the Marangoni effects, the different characteristics of bubble behaviors in microgravity have been explained. A new bubble departure model has also been proposed, which can predict the whole observation both in microgravity and in normal gravity.

Keywords: Pool Boiling, Bubble Detachment, Scaling of CHF, Microgravity

1. Introduction

Boiling is a very complex and illusive process because of the interrelation of numerous factors and effects as the nucleate process, the growth of the bubbles, the interaction between the heater's surface with liquid and vapor, the evaporation process at the liquid-vapor interface, and the transport process of vapor and hot liquid away from the heater's surface. For a variety of reasons, fewer studies have focused on the physics of the boiling process than have been tailored to fit the needs of engineering endeavors. As a result, the literature has been flooded with the correlations involving several adjustable, empirical parameters. These correlations can provide quick input to design, performance, and safety issues and hence are attractive on a short-term basis. However, the usefulness of the correlations diminishes very quickly as parameters of interest start to fall outside the range of physical parameters for which the correlations were developed. Thus, the physics of the boiling process itself is not properly understood yet, and is poorly represented in the most correlations, despite of almost seven decades of boiling research.

Among many sub-processes in boiling phenomenon, gravity can be involved and play much important roles. Since the end of 1950's, microgravity experiments were motivated by the design of space devices. On the other hand, the microgravity environment offers the ability to remove the effect of buoyancy on boiling and thus to be of advantage to reveal the physics of the boiling. On the progress in this field, several comprehensive reviews, for example, Straub[1] Di Marco[2], Kim[3], and Ohta[4] among many others, are available.

In the past years, steady pool boiling of degassed R113 on thin platinum wires have been studied systematically in our lab, including experiments in long-term microgravity aboard RS-22, in short-term microgravity in the Drop Tower Beijing/NMLC, and in normal gravity. Some of the research findings will be highlighted in the following.

2. Experimental Facility

A temperature-controlled pool boiling (TCPB) device (Fig. 1) has been developed to perform such studies both in normal gravity on Earth and in microgravity aboard the 22nd Chinese recoverable satellite. Detailed description of the experimental facility can be read in Wan et al. [5]. Therefore, only a simple description will be presented briefly here.

The boiling chamber is filled with about 700 mL of carefully degassed R113, and fixed inside an air-proof container. A bellows connected with the chamber will allow the pressure in the chamber to be approximately constant. Two platinum resistance thermometers with a range of 0~60 °C are used to measure the bulk temperature of the fluid in the boiling chamber, which are calibrated to within 0.25 °C. The absolute pressure within the boiling chamber is measured using a pressure transducer with a range of 0~0.2 MPa and an accuracy of 0.25% FS (full scale). The voltages across the heater and a reference resistance, which is used to measure the electric current through the heater, are sampled at a rate of 20 Hz in space experiment, while a much higher sampling rate of 1000 Hz is used in the ground experiments before and after the space flight. A lower sampling rate of 1/3 Hz is used for the outputs of the pressure transducer and the platinum resistance thermometers both in space and on the ground. The analysis shows that the uncertainty of the heater temperature can be significantly reduced by using high sample rate (less than 3 °C), while the influence of the sample rate on the uncertainty of heat flux is negligible. The uncertainties of heat flux are less than 24 kW/m^2 in the space experiments and 21 kW/m^2 in the ground experiments, respectively. Two LEDs (light-emitting diode) are used to light the boiling chamber through a diffusion window at the chamber bottom. A CCD video camera is used to obtain images of the motion of vapor bubble or film around the heater, which is recorded by a VCR at a speed of 25 fps. The video images are digitized and analyzed using

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the commercial software Ulead™ VideoStudio7.0.

A platinum wire of 60 μm in diameter and 30 mm in length is simultaneously used as heaters and thermometers, with the advantage that because of its low thermal capacity, it reacted almost without any delay on changes in temperature and heat transfer, respectively. The ends of the wire are soldered with copper poles of 3 mm in diameter to provide a firm support for the wire heater and low resistance paths for the electric current. The heater resistance, and thus the heater temperature, is kept constant by a feedback circuit similar to that used in constant-temperature hot-wire anemometry. Its adjustment is controlled by varying the resistance of the changeable resistance network. This resistance network comprises 16 parallel resistors and a 16-channel analog switch, which is controlled by a single-chip-microcomputer (SCM). Thus, 16 set-points of heater temperature can be obtained. An "up-down-up" procedure is used for the heater temperature. According to Straub[1], each state lasts about 30 seconds in order to obtain steady pool boiling. In the drop tower experiments, a special procedure was adopted due to the short duration of microgravity. Before release, a higher temperature was firstly set to initiate boiling, generally two-mode transition boiling, on the wire. Then the temperature of the wire was adjusted to the required value, and the capsule was released after about 10 seconds. When the capsule is stopped, turn off the heating power supply. Furthermore, voltage-controlled heating method was also used in the ground experiments.

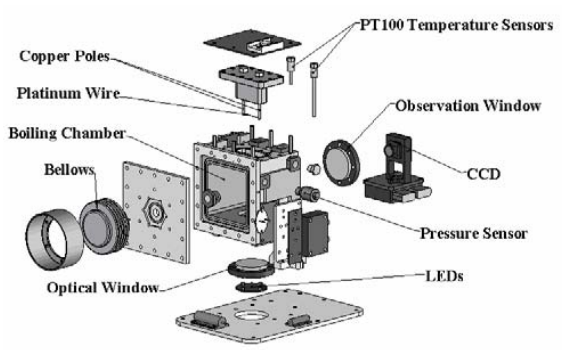

Figure 1: Diagram of boiling chamber and its accessories.

3. Results and Discussions

3.1 Heat Transfer

Fig. 2 shows the whole curve obtained in the space experiment. Similar curves can also be obtained in normal gravity, which aren't shown here. The first heat transfer mode is single-phase natural convection both in normal gravity and in microgravity. The experimental data of single-phase natural convection are compared with the prediction of commonly used correlation of Kuehn & Goldstein [6]. An agreement is quite evident in normal gravity, which warrants reasonable confidence in the data. Comparing the results of space experiments with the correlation's predictions, it's indicated that the residual gravity during the space experiment is in the range of (10^{-3} ~ 10^{-5}) g_0, which is equivalent to that given by the satellite establishment.

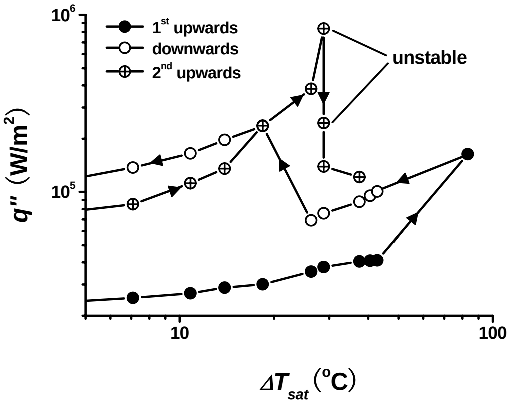

Figure 2: Heat transfer curves in microgravity.

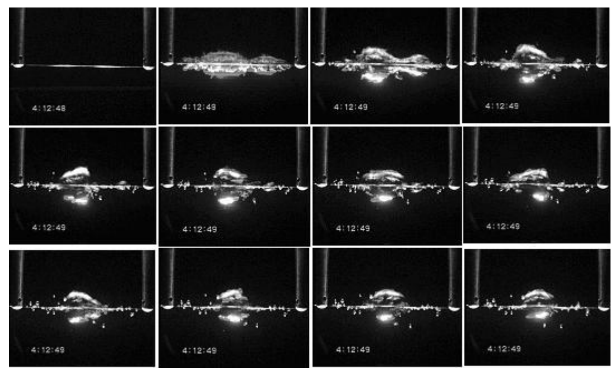

Figure 3: A sequence of pictures of bubble development after the onset of boiling in microgravity. The time interval between sequent images is 1/25 s.

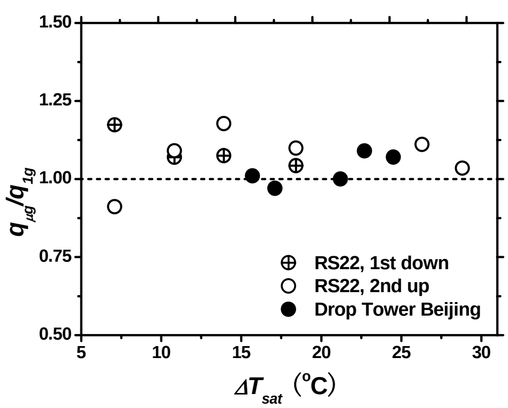

Figure 4: Microgravity efficiency on heat transfer of nucleate boiling in microgravity.

The onset of boiling occurs at the 16th step as two-mode transition boiling both in the space experiment and in ground experiments. The sequence of pictures in Fig. 3 (for magnitude estimation, the distance between the two copper poles is 30 mm) corresponds to the onset of boiling in microgravity. About 0.12 sec. after the beginning of the 16th step, a large amount of vapor springs out throughout the wire with a very irregular interface. Due to the surface tension, a large spherical bubble is eventually formed. It stays on the wire continuously without enclosing the wire in the subsequent experiments, and coalesces continually up adjacent small bubbles. The boiling reached a steady state in about 3 sec. after the beginning of the 16th step. The superheat of the onset of boiling is 83 ^{o}C, which is independent, or at least, dependent much weakly on gravity. It ought to be pointed out that the actual superheat of the onset of boiling will locate in the range between the 15th and 16th set-point, or 42 to 83 ^{o}C, due to the limitation of the present control method. The heat flux, however, decreased in microgravity to about 40% of that in normal gravity, while about 20% decrease for two-mode transition boiling was found in our preliminary experiments in the Drop Tower Beijing [7].

On the contrary, heat fluxes of nucleate boiling in microgravity are the same or only slightly enhanced comparing with those in normal gravity (Fig. 4).

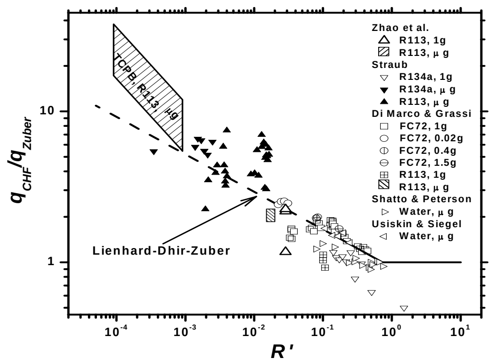

Figure 5: Scaling of CHF with gravity.

Fig. 5 shows the scaling of CHF with the gravity. Contrary to the traditional viewpoint on CHF, it's found that the trend of CHF in different gravity can be predicted much well by the Lienhard-Dhir-Zuber model [8], established on the mechanism of hydrodynamic instability, although the value of *R'* is far beyond the initial application range of LD-Zuber model. This observation is consistent with Straub [1]. Furthermore, comparing the trend of CHF in Fig. 5 with the common viewpoint on the scaling of CHF, it's inferred, as pointed out by Di Marco & Grassi [9], that the dimensionless radius $R' = R\sqrt{(\rho_L - \rho_G)g/\sigma}$, or the Bond number, may not be able to scale adequately the effects and to separate groups containing gravity due to complex competition of different mechanisms for small cylinder heaters. A parameter, named as "the Limited Nucleate Size d_{LN}", and a non-dimensional coefficient $\Gamma = d_{LN}/d_{wire}$ have been introduced to interpret this phenomenon, which is independent with gravity. The occurrence of the CHF will be caused by the mechanism of hydrodynamic instability if Γ is small, while it will be caused by the mechanism of local dryout if Γ is large. Further researches are needed for the delimitation of the two mechanisms.

Furthermore, it's found in normal gravity that the scaling and subcooling effects are not isolated with each other in small Bond number (Figure 6). In fact, it can be found in the book of Kutateladze [10], in which different Scaling behaviors of CHF is pointed out with respect to different subcooling if *R'* is smaller than ~0.5. You et al. [11] also pointed out that for small Bond number the subcooling can changed the CHF mechanism from dry-out to hydrodynamic situations.

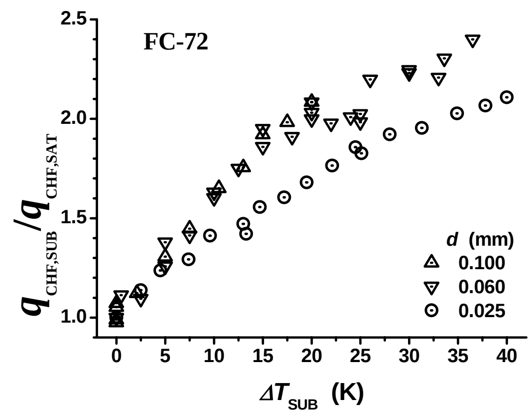

Figure 6: Influences of subcooling on CHF in pool boiling of FC-72 on thin Platinum wires with different diameters.

3.2 Bubble Behaviors

It's found that the oscillation due to coalescence of adjacent bubbles is the primary reason of bubble departure in the fully developed nucleate boiling regime in microgravity. Before their departure from the wire in microgravity, it's also observed that there exists a forward-and-backward lateral motion of discrete vapor bubbles along the wire. They could change moving direction backward when encountering with another bubble and reach a new steady velocity. Fig. 7 shows the position *X* along the wire and the lateral velocity *U* of a typical bubble of about 0.9 mm in diameter during its forward-and-backward lateral motion. The lateral velocity is about 20 mm/s, unless it comes in collision with and bounces off an adjacent bubble.

Generally, the lateral velocity increases with the decrease of the bubble size. This kind of lateral motion can lead to the lateral coalescence between adjacent bubbles, and then the new bubble detaches due to its surface oscillation. For example, the above bubble coalesces with another bubble when it moves back to nearly its initial position. The following motion after its departure is shown in Fig. 8, where *Y* and *V* denote the distance of the bubble away from the wire and its departure velocity.

A hypothesis has been proposed by Zhao *et al.* [7] that adjacent bubbles entrain each other in thermo-capillary or Marangoni flow surrounding them during nucleate boiling of subcooled liquids. The entrainment manifests itself as motion of the bubbles toward each other, which promotes their coalescence. A scale analysis on this phenomenon leads to formulas of the characteristic velocity of the lateral motion and its observability as

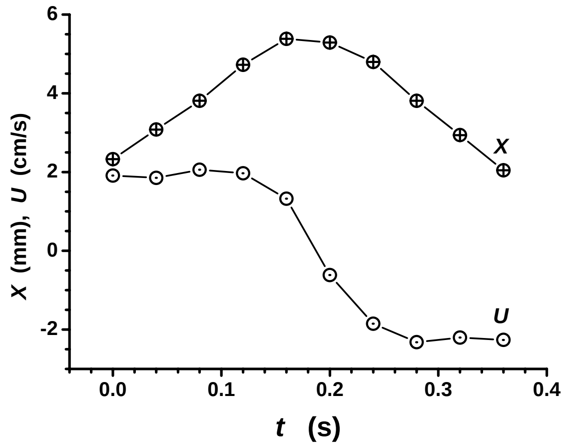

Figure 7: Lateral motion of a typical bubble.

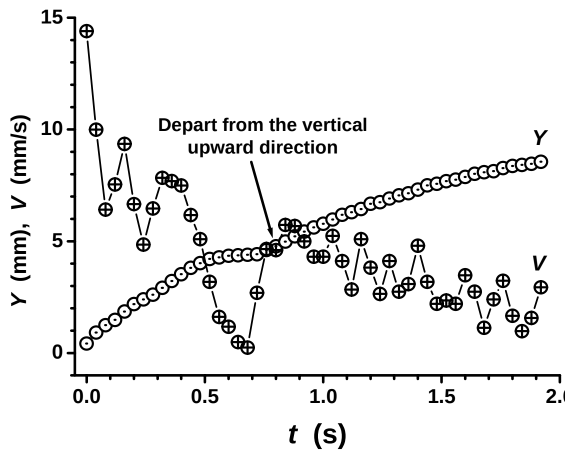

Figure 8: Departure of the former bubble.

Table 1 Bubble lateral motion and its observability

ρ_L, kg/m^3	σ_T, N/m·K	ΔT, K	ν_L, m^2/s	D_b, mm	U_0, mm/s	g/g_0	Ob
				10	10		
10^3	10^{-4}	10	10^{-6}			10^{-5}	$\sim 10^{2.5} >> 1$
				1	32	10^{-2}	$\sim 10^{-0.5} \sim 1$
						1	$\sim 10^{-2.5} << 1$
				0.1	100	1	~ 1

$$U_0 = \sqrt{\sigma_T \Delta T / \rho_L D_b} \quad (1)$$

$$Ob = \frac{U_0}{U_b} = g^{-1}\sqrt{\frac{\sigma_T \Delta T \upsilon_L^2}{\rho_L D_b^5}} \quad (2)$$

The predictions consist with the experimental observations (Table 1), and a good agreement is evident.

On the contrary, four regimes and three critical bubble diameters are observed in the case of discrete vapor bubbles in microgravity (Fig. 9). Tiny vapor bubbles form and grow on the heater surface until their sizes exceed the first critical value, and then depart slowly from the wire. Above the second critical value, however, bubble may stay on the wire, oscillate along the wire, and coalesce with adjacent bubbles, till its size exceeds the third critical value and it will depart from the wire again. The behaviors of tiny bubbles are observed both in microgravity and in normal gravity, while the last two kinds of bubble behaviors are observed only in microgravity aboard the satellite. None of the common used models, in which the Marangoni effect is neglected at all, can predict the present observation in microgravity. Recently, Zhao et al. [12] proposed a qualitative model based on the model of Lee [13] to predict the bubble departure diameter, in which the Marangoni effect is taken into account. The agreement between the prediction and observations is much satisfied (Fig. 9, where the force with positive sign is corresponding with bubble departure, while negative force is corresponding with bubble staying on the wire). In this model, the following asymptotic bubble growth relation is adopted,

$$D_B = Et^{1/2}$$
$$E = \frac{1}{2\sqrt{\pi}} Ja \sqrt{\alpha_L} \quad (3)$$

where Ja and α_L denote the Jacob number and the heat diffusivity coefficient of the liquid, respectively.

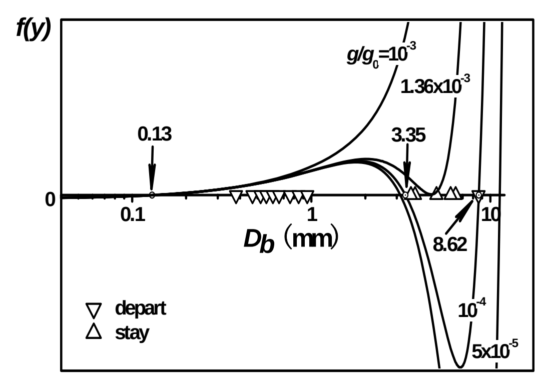

Figure 9: Bubble departure in the case of discrete vapor bubble in microgravity.

Fig. 10 shows the typical growth process of a discrete vapor bubble observed in the space experiment. It is obtained in the second stage (step-down of the heater temperature). There exists some oscillation at the beginning due to sudden change of the heater temperature from 90 °C to 88 °C. It is found that the bubble growth rate can be written as

$$D_B = Ct^n \tag{4}$$

where C and n are empirical parameters. According to the present measurement, the exponent could change from 1/3 at the beginning to 1/5 when the oscillation diminished. It means that the vapor bubble grows more slowly than the expectation of Eq. (3) and the growth rate could decrease with its size increase. It suggested that further revision for the above bubble departure model is needed.

The models mentioned above imply an assumption that the temperature distribution along the vapor bubble is not affected by evaporation and condensation, just like the case of Marangoni migration of gas bubbles in bulk liquid with temperature gradient. This is in contrary to Straub [1, 14]. In his opinion, the kinetics of evaporation is strong enough to keep the interface almost isothermal and then no Marangoni convection could be observed in saturated pool boiling. Marangoni convection observed at subcooled boiling is caused by the inert gas accumulation. The vapor pressure decreases at the upper part of the interface and then the saturation temperature decreases locally. However, Straub [1, 14] also pointed out that temperature gradients at the interface in the thin microwedge can not be excluded, where much strong evaporation occurs. This contradicts directly his above opinion.

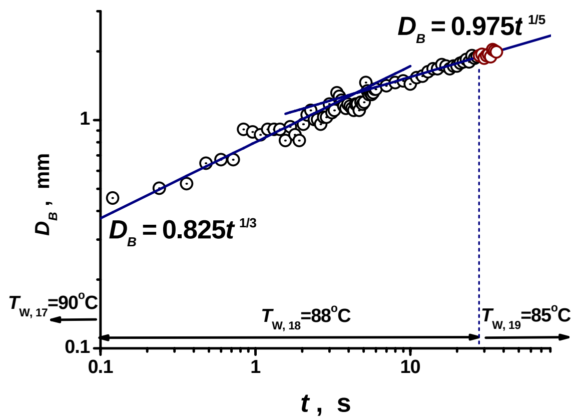

Figure 10: Typical growth process of a discrete bubble.

The isothermal condition, however, is the result of the classical equilibrium thermodynamics. The evaporation and condensation are typically non-equilibrium processes. Recently, non-equilibrium interfacial conditions have been adopted by many researchers to describe the interface of a liquid with phase change, for example, Oron et al. [15], Margerit et al. [16], Ward & Duan [17], and Sefiane [18]. Li et al. [19] made a comprehensive review on the interfacial conditions with phase change. It's pointed out that none of non-equilibrium interfacial conditions has been received common acceptance presently. Much more works is needed.

4. Summary

In the past years, steady pool boiling of degassed R113 on thin platinum wires have been studied systematically in our lab, including experiments in long-term microgravity aboard RS-22, in short-term microgravity in the Drop Tower Beijing / NMLC, and in normal gravity. Temperature-controlled heating method is used in the experiments. Slight enhancement of nucleate boiling heat transfer is observed in microgravity. The value of CHF in microgravity is lower than that in normal gravity, but it can be predicted well by the Lienhard-Dhir correlation, although the dimensionless radius in the present case is far beyond its initial application range. The scaling of CHF with gravity is thus much different from the traditional viewpoint. On the contrary, dramatic changes of bubble behaviors are much evident in different gravity conditions. Three critical diameters are observed for bubble departure in long-term microgravity. Considering the influence of the Marangoni effects, the different characteristics of bubble behaviors in microgravity have been explained. A new bubble departure model has also been proposed, which can predict the whole observation both in microgravity and in normal gravity.

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