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Dynamics of Discrete Bubble in Nucleate Pool Boiling on Thin Wires in Microgravity

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A space experiment on bubble behavior and heat transfer in subcooled pool boiling phenomenon has been performed utilizing the temperature-controlled pool boiling (TCPB) device both in normal gravity in the laboratory and in microgravity aboard the 22nd Chinese recoverable satellite. The fluid is degassed R113 at 0.1 MPa and subcooled by 26℃ nominally. A thin platinum wire of 60 μm in diameter and 30 mm in length is simultaneously used as heater and thermometer. Only the dynamics of the vapor bubbles, particularly the lateral motion and the departure of discrete vapor bubbles in nucleate pool boiling are reported and analyzed in the present paper. It's found that these distinct behaviors can be explained by the Marangoni convection in the liquid surrounding vapor bubbles. The origin of the Marangoni effect is also discussed.

Keywords: bubble dynamics, pool boiling, microgravity, Marangoni effect

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 most correlations, despite of almost seven decades of boiling research.

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 boiling. The present work is a part of researches on pool boiling heat transfer both in normal and in microgravity. Only the lateral motion and departure of discrete vapor bubbles in nucleate pool boiling observed in the space experiment are reported and analyzed in the present paper, while the heat transfer in different gravity conditions has been presented in elsewhere [1].

Literature Review

Pool boiling in microgravity has become an increasing significant subject for investigation, since many potential

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Nomenclature

D	diameter (m)
g	gravitational acceleration ($\mathrm{ms^{-1}}$)
g_0	normal gravity on Earth (=9.8 $\mathrm{ms^{-1}}$)
P	pressure ($\mathrm{Nm^{-2}}$)
X	relative position along the wire (m)
Y	relative position departing from the wire (m)
U	lateral velocity ($\mathrm{ms^{-1}}$)
V	departure velocity ($\mathrm{ms^{-1}}$)
Ob	observability (-)
t	time (s)
R	radius (m)
E	model constant (-)
K	model constant (-)

Greek letters

β	contact angle (deg)
ΔT	temperature difference (K)
ν	kinematic viscosity ($\mathrm{m^2s}$)
ρ	density ($\mathrm{kgm^{-3}}$)
σ	surface tension ($\mathrm{Nm^{-1}}$)
σ_T	temperature gradient of surface tension ($\mathrm{Nm^{-1}K^{-1}}$)
τ	time (s)

Subscripts

0	characteristic
b	bubble or buoyancy
L	liquid

applications exist in space and on planetary neighbors due to its high efficiency. However, the investigation in microgravity suffers for unique and stringent constraints in terms of size, power and weight of experimental apparatuses, and of number and duration of the experiments. Thus, only a partial and in some aspects contradictory knowledge of microgravity boiling has been attained so far. On the progress in this field, several comprehensive reviews are available. For example, Straub [2] issued a comprehensive review of his own activity on this field from the early 1980s to date, while Di Marco [3], Kim [4], and Ohta [5] recently issued reviews of microgravity boiling researches in Europe, in US, and in Japan, respectively. Thus, only results related to the present study, namely those on pool boiling on wires and small cylinders in microgravity can shortly summarized in the following.

The first experiments of pool boiling on wires in microgravity were carried out by Siegel *et al.* [6]. They used a 2.5 m-high drop tower. They found that heat transfer is enhanced in reduced gravity (0.014 g_0, here g_0 denotes the terrestrial gravity) for pool boiling on a horizontal 0.5 mm-dia. wire in water and alcohol, and that the enhancement decreases with the increase of heat flux. No influence of gravity was observed for boiling on a horizontal 0.5 mm-dia. wire in 60% sucrose solution.

Much extensive experiments were performed by Straub and co-workers [2, 7-9] with various refrigerants (R113, R12, R134) in parabolic flights, sounding rockets and orbital flights. For nucleate pool boiling on wires, the heat transfer coefficient was found to be almost independent of gravity level in both sounding rocket and parabolic flight experiments, while a slight enhancement (15%) of heat transfer was found in the experiments on a GAS payload on the space shuttle. Generally, the heat transfer efficiency ε, *i.e.* the ratio between the heat transfer coefficient in microgravity and that in normal gravity, always decreases with increasing heat flux. It can be greater than one at low heat flux and lower than one at high heat flux. Enhancement or degradation are anyway limited (±30% max). For pool film boiling, a dependence of the heat transfer efficiency ε on $(g/g_0)^n$, with n=0.16~0.33, valid for $g/g_0>10^{-2}$, was evidenced. This is in agreement with the common used heat transfer correlations, like Bromley's [10]. For lower gravity levels, like in orbital flights, the heat transfer efficiency is higher than predicted by the above relationship. They also reported their CHF data which were consistently lower than the corresponding terrestrial values, and could be successfully correlated by the correlation of Lienhard & Dhir [11] for values of $R'=R[g(\rho_L-\rho_G)/\ \sigma]^{1/2}$ as low as 5×10^{-4}. However, no fitting of CHF values at different gravity levels was made.

Sitter *et al.* [12] studied the effect of acoustic fields during nucleate boiling on a 0.25 mm-dia. platinum wire in FC-72 using a 2.1 s drop tower. Without acoustic field, decrease of heat transfer was evidenced. The heat transfer for a given wall superheat was always higher with the high-intensity acoustic field than without, and the highest heat transfer occurred with the heater placed at the antinode for both terrestrial and microgravity boiling. Acoustic streaming was observed to bring colder ambient liquid to the wire, enhancing heat transfer.

Shatto & Peterson [13] studied CHF using a cylindrical cartridge heater (9.4 mm-dia. and 44.5 mm-length) immersed in slightly subcooled water at about 1/4 atm aboard the NASA KC-135 airplane. In their study, $R'<0.4$, indicating that the cylinder was a small one. The values of CHF increased with gravity during the nominally “zero-g” parabola, and were lower than the predictions by Lienhard & Dhir’ correlation by an average of 40%. They argued that this difference is caused by thermocapillary effect. Following the work of McGillis & Carry [14], they derived an empirical correlation with an adjustable constant, which gave a good agreement with their data.

Di Marco et al. [3, 15] conducted experiments of pool boiling of R113 and FC-72 on a 0.2 mm-dia. platinum wire both in parabolic flight and in sounding rocket, in the presence of an electric field or less. Data at enhanced gravity and at Martian gravity level ($0.4g_0$) were also collected. Despite a very evident change in bubble behavior, no influence of gravity level was found on heat transfer coefficient in nucleate boiling on a wire without electric field. CHF was found to be reduced of about 50% in low gravity. For $R'>0.08$, the CHF data lie in the range of most of the other experimental data. On the contrary, for $R'<0.04$, the data obtained in microgravity are very well separated from those of thinner wires obtained in normal gravity, corresponding to the same values of R'. The authors suggested that the parameter R' is no more suitable to scale CHF for low values of R', and that the effects of gravity and size have to be accounted for separately. The imposition of a cylindrical electrostatic field was found to have no significant effect on nucleate boiling heat transfer coefficient, but to be effective in reducing bubble size and increasing CHF in microgravity. For film boiling, the variation of the oscillation wavelength of the vapor film due to gravity and electric field was evidenced: a reduction of gravity caused an increase of the oscillation wavelength and a decrease of heat transfer, while the reverse occurred by applying the electric field. Beyond a threshold of electric field, the film boiling heat transfer coefficient became insensitive to gravity level.

Zhao et al. [16] studied nucleate and two-mode transitional boiling on an electrically heated wire in different gravity conditions utilizing the Drop Tower Beijing (NMLC). The experimental device is similar as that used in the present study. They reported that the heat transfer was slightly enhanced for nucleate boiling in microgravity, while the bubble pattern is dramatically altered by the variation of the acceleration. For two-mode transition boiling, about 20% decrease of the heat flux was obtained, although the part of film boiling was receded in microgravity. It ought to be pointed out that this work is a preliminary study before the flight of the present device.

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. [17]. Therefore, only a simple description will be presented here briefly.

A platinum wire of 60 μm in diameter and 30 mm in length is simultaneously used as heaters and thermometers, with the advantage of its low thermal capacity, it reacted almost without any delay on changes in heat transfer and temperature, respectively. The ends of the wire are soldered with copper poles of 3mm 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 SCM (single-chip-microcomputer). Thus, 16 set-points of heater temperature can be obtained. An “up-down-up” procedure is used for the heater temperature. According to Straub [2], each state lasts about 30 seconds in order to obtain steady pool boiling.

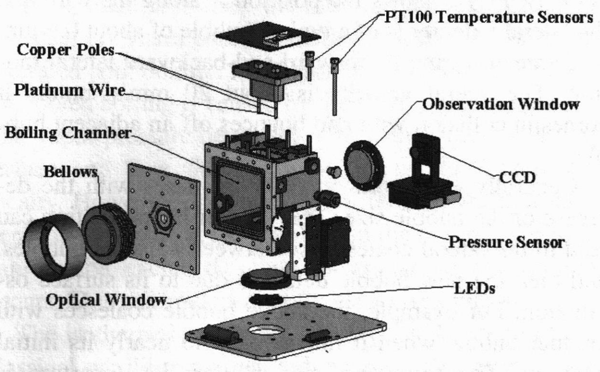

Fig. 1 Diagram of boiling chamber and its accessories.

The boiling chamber is filled with about 700 ml of degassed R113, and fixed inside an air-proof container. A bellow 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℃ are used to measure the bulk temperature of the fluid in the boiling chamber, which are calibrated to within 0.25 ℃. 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 voltage 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 output 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℃), while the influence of the sample rate on the uncertainty of heat flux is negligible. The uncertainty of heat flux is less than 24 kW/m^2 in space experiment and 21 kW/m^2 in 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 the commercial software Ulead™ VideoStudio7.0.

Bubble Lateral Motion and Its Scale Analyse

It's observed that there exists a forward-and-backward lateral motion of discrete vapor bubbles along the wire before their departure from the wire in microgravity. They could change moving direction backward when encountering with another bubble and reach a new steady velocity. Fig. 2 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. 3, where *Y* and *V* denote the distance of the bubble away from the wire and its departure velocity.

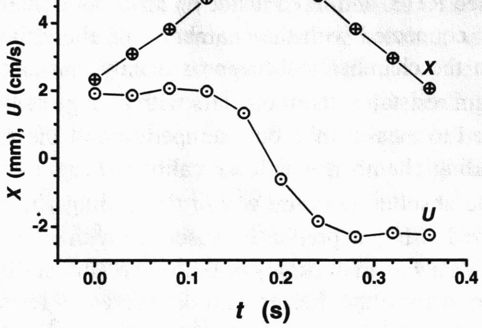

Fig. 2 Lateral motion of a typical bubble.

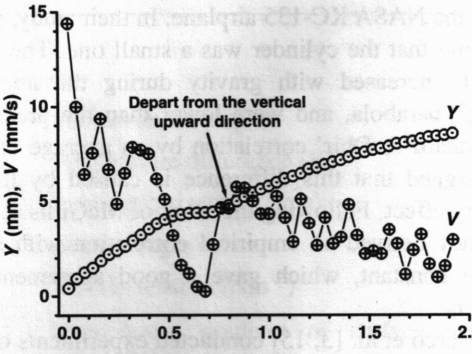

Fig. 3 Departure of the former bubble.

A hypothesis has been proposed by Zhao *et al.* [16] that adjacent bubbles entrain each other in thermocapillary 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

$$U_0 = \sqrt{\sigma_T \Delta T / \rho_L D_b} \tag{1}$$

$$Ob = \frac{U_0}{U_b} = g^{-1}\sqrt{\frac{\sigma_T \Delta T v_L^2}{\rho_L D_b^5}} \tag{2}$$

The predictions consist with the experimental observations (Table 1).

Table 1 Bubble lateral motion and its observability

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

Bubble Departure and Its Mechanism

It is found that the vibration due to coalescence of adjacent bubbles is the primary reason of bubble departure in microgravity in this regime. On the contrary, four regimes and three critical bubble diameters are observed in the case of discrete vapor bubbles in microgravity (Fig. 4). 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. [18] proposed a qualitative model based on the model of Lee [19] 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. 4, 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,

$$D_B = Et^{1/2}$$

$$E = \frac{1}{2\sqrt{\pi}} Ja\sqrt{\alpha_L} \tag{3}$$

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

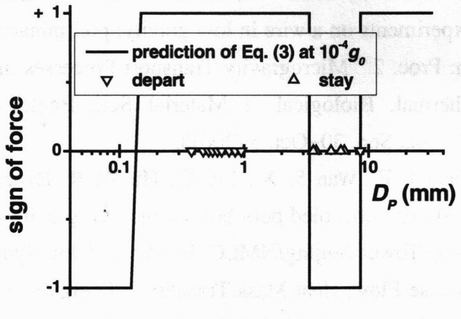

Fig. 4 Bubble departure in the case of discrete vapor bubble in microgravity.

Bubble Growth Rate

Fig. 5 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.

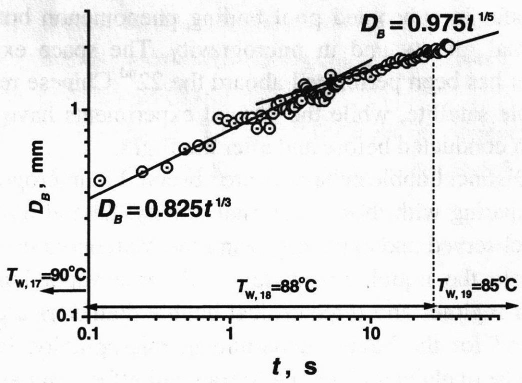

Fig. 5 Typical growth process of a discrete bubble.

Origin of the Marangoni Effect

The models mentioned above imply an assumption that 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 [2, 20]. 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 [20] 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.

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. [21], Margerit et al. [22], Ward & Duan [23], and Sefiane [24]. Li et al. [25] made a comprehensive review on the interfacial conditions with phase change. It's pointed out that none of non-equilibrium interfacial conditions has received common acceptance presently. Much more works is needed.

Summary

A temperature-controlled pool boiling (TCPB) device has been developed to study the bubble behavior and heat transfer in subcooled pool boiling phenomenon both in normal gravity and in microgravity. The space experiment has been performed aboard the 22nd Chinese recoverable satellite, while the ground experiments have also been conducted before and after the flight.

Distinct bubble behaviors are observed in microgravity, comparing with those in normal gravity. Lateral motions are observed and explained using the Marangoni convection in the liquid surrounding a discrete vapor bubble. Four regimes and three critical bubble diameters are observed for the bubble departure in microgravity. It can also be explained using the Marangoni effect, and even a quantitative prediction with good agreement can be acquired. The origin of the Marangoni effect in pool boiling, however, remains an open question.

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