

Experimental Study on Subcooled Pool Boiling in Microgravity Utilizing the Drop Tower Beijing (NMLC)

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Abstract: A temperature-controlled pool boiling (TCPB) device was developed to perform pool boiling heat transfer studies at both normal gravity and microgravity. A platinum wire of 60 μm in diameter and 30 mm in length was simultaneously used as heaters and thermometers. The heater resistance, and thus the heater temperature, was kept constant by a feedback circuit. The fluid was R113 at 0.1 MPa and subcooled by 24 °C nominally for all cases. The results of the experiments at both normal gravity and microgravity in the Drop Tower Beijing were presented. Nucleate and two-mode transition boiling were observed. For nucleate boiling, the heat transfer was slightly enhanced, namely no more than 10% increase of the heat flux was obtained 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. A scale analysis on the Marangoni convection surrounding bubble in the process of subcooled nucleate pool boiling was also presented. The characteristic velocity of the lateral motion and its observability were obtained approximately. The predictions consist with the experimental observations.

1. Introduction

Pool boiling in microgravity has become an increasing significant subject for investigation, since many potential 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. They are authored by Straub ^[1], and Di Marco and Grassi ^[2], among many others.

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 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 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.

It is generally assumed that heat and mass transport in pool boiling process is strongly influenced by buoyancy, which is caused by the great difference in the densities between liquid and vapor at normal gravity environment. Thus, gravity is considered as an important parameter in most physically based or empirical correlations describing the heat transfer of pool boiling. However, for quite a long time, no evidence had been obtained to experimentally check whether the influence of gravity was modeled correctly. Since the end of 1950's and the middle of 1960's, microgravity experiments were initiated which was sparked by the design of space devices. These experiments provide a means to study the actual influence of gravity and to separate gravity from gravity independent factors. Furthermore, microgravity experiments offer the unique opportunity to study the complex interactions without or at least with strongly reduced external forces, such as buoyancy, which can affect the bubble dynamics and the related heat transfer.

The present work is a research effort on subcooled pool boiling on a thin wire at microgravity in the Drop Tower Beijing (NMLC), which can last for 3.6 seconds. The device was developed to perform pool boiling heat transfer studies at both normal gravity on Earth and microgravity in the Drop Tower Beijing (NMLC) and aboard a Chinese recovery satellite. Further experiments will be conducted in a long-term microgravity environment aboard the 22nd Chinese recovery satellite in the near future.

2. Experimental Facility

A temperature-controlled pool boiling (TCPB) device was developed to perform such studies both at

both normal gravity on Earth and microgravity in the Drop Tower Beijing (NMLC) and aboard a Chinese recovery satellite. Detailed description of the experimental facility can be read in Wan et al [3]. Here, only important parts related with the drop tower tests will be presented.

A platinum wire of 60 μm in diameter and 30 mm in length was 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 were 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, was kept constant by a feedback circuit similar to that used in constant-temperature hot-wire anemometry (Fig. 1). The op-amp measured the imbalance in the bridge and provided an output of whatever voltage was needed to keep the ratio R_1/R_w equal to the resistance ratio on the right side of the bridge.

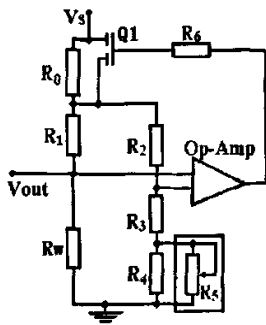


Fig 1. Schematic of the electronic feedback loop

The heater resistance, and thus the heater temperature, was kept constant by varying the resistance of the changeable resistance network (R5). This resistance network comprises 16 parallel resistors and a 16-channel analog switch, which is controlled by a SCM (single-chip-microcomputer). The output of the circuit was the voltage required to keep the heater at a set temperature. The set temperature points were located uniformly in $\log(\Delta T_{sat})$, where the wall superheat $\Delta T_{sat} = T_w - T_{sat}$, T_w and T_{sat} denote the temperature of the heater surface and the saturation temperature of the liquid.

The temperature of the heater could be varied by approximately 400 K. The resistor R_0 parallel-connected with a MOSFET (Q1) was used to provide a small trickle current through the heater, resulting in a voltage across the heater of about 90 mV even when the op-amp was not regulating.

The working fluid is degassed R113 with nominally

a volume of 700 ml. Two platinum resistance thermometers with a range of 0 $^{\circ}\text{C}$ ~ 60 $^{\circ}\text{C}$ were used to measure the bulk temperature of the fluid in the boiling chamber, which were calibrated to within 0.25 $^{\circ}\text{C}$. The absolute pressure within the boiling chamber was measured using a pressure transducer with a range of 0 ~ 0.2MPa and an accuracy of 0.25%FS (full scale). LEDs (light-emitting diode) were used to light the boiling chamber through a window at the chamber bottom. A CCD video camera was used to obtain images of the motion of vapor bubble or film around the heater, which was recorded by a VCR at a speed of 25 frame/s. The voltages across the heater and a reference resistance, which is used to measure the electric current through the heater, and the outputs of the pressure transducer and the platinum resistance thermometers were sampled at 50Hz. A sample rate of 200Hz was also used in some runs.

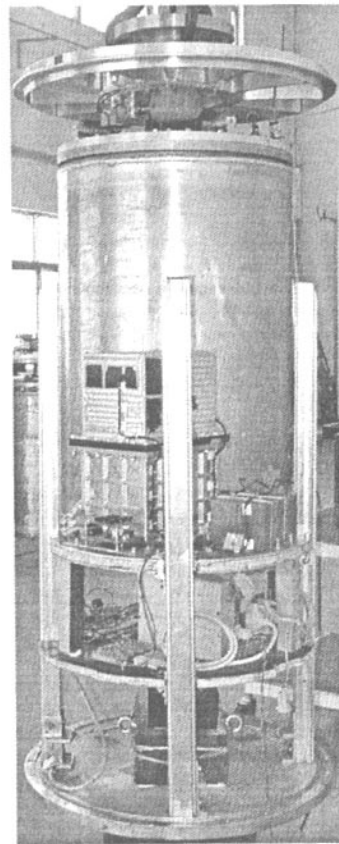


Fig 2. Photo of the experimental facility installed in the inner capsule in the Drop Tower Beijing (NMLC)

In the present study, the conditions of microgravity were provided by the free fall in the drop tower Beijing (NMLC). It is located at the area of Zhongguancun, Beijing. The Drop Tower Beijing is 116 m above the ground (including 92 m of the tower body and 24 m of

the rest parts) and 8 m under the ground. The free drop height is about 60 m, which provides a course of 3.6 s for microgravity experiments. The drop capsule is released in the atmosphere environment. To increase the microgravity level, it is designed to have inner and outer capsules with light and thin shell structure. The space between the inner capsule (experiment rig) and the outer capsule (drag shield) is evacuated to 100 Pa. Fig. 2 presents a photo of the experimental facility installed in the inner capsule in the Drop Tower Beijing (NMLC).

Due to the short duration of microgravity in the drop tower, a special procedure was adopted in the present testing. 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. Fig. 3 presents a typical course of acceleration g , electric resistance R_w of the wire, and heating power Q_E during one free fall in the Drop Tower Beijing (NMLC).

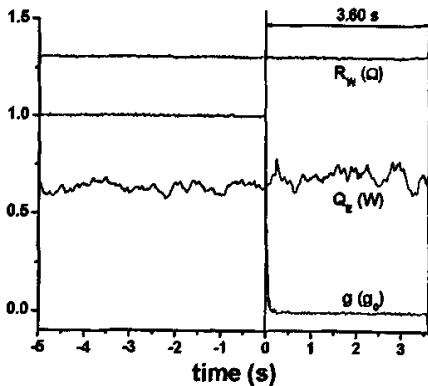


Fig. 3. Typical course of acceleration, electric resistance of the wire, and heating power during free fall in the Drop Tower Beijing (NMLC)

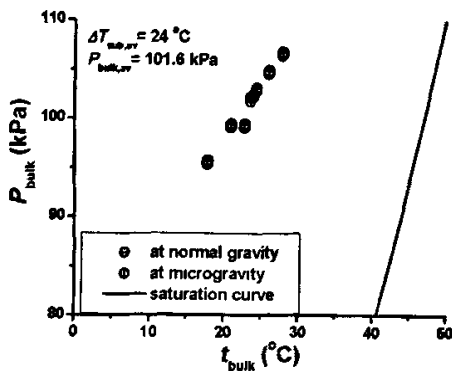


Fig. 4. Experimental conditions in the present study

3. Experimental Results

10 experimental runs have been conducted in the Drop Tower Beijing (NMLC). However, due to some error occurred during the free fall, only 8 data were collected in the present study. The nominal pressure in the boiling chamber P_{bulk} was 101.6 kPa, and the subcooling temperature ΔT_{sub} was nominally 24.0 °C (Fig. 4). The results obtained before and after release are listed in Table 1.

Table 1. Results of pool boiling heat transfer in different gravity

P_{bulk} kPa	t_{bulk} °C	ΔT_{sub} K	t_w °C	ΔT_{sat} K	mode	q''_{1g} kW/m ²	$q''_{\mu g}$ kW/m ²	$\alpha_{\mu g}/\alpha_{1g}$
99.2	22.8	24.1	62.6	15.7	N	139	140	1.01
102.2	24.0	23.7	64.8	17.1	N	140	137	0.97
102.8	24.4	23.6	69.1	21.2	N	149	149	1.00
104.6	26.1	22.4	71.2	22.7	N	144	157	1.09
95.4	17.9	27.8	70.2	24.5	N	210	225	1.07
101.8	23.6	24.0	99.7	52.1	T	406	327	0.81
99.2	21.0	25.9	151.2	104.3	T	405	338	0.83
106.5	28.0	21.0	270.1	221.1	T	474	391	0.83

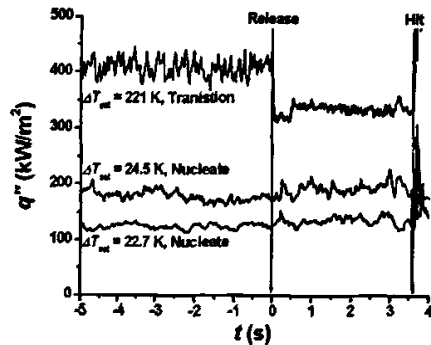


Fig. 5. Heat fluxes response to variation of gravity

Nucleate and two-mode transition boiling regimes were observed. The measured heat fluxes during some typical runs are shown in Fig. 5, which show that the heat fluxes statistically maintain constant during the free fall, and steady boiling in microgravity can be presumed in the present drop tower testing. Fig. 6 presents some typical bubble dynamic patterns in different gravity before and after release.

For nucleate boiling, the heat transfer was slightly enhanced, namely no more than 10% increase of the heat flux was obtained in microgravity, while the bubble pattern is dramatically altered by the variation of the acceleration. It was found that from some cavities on the wire surface tiny bubbles spout continuously and form a zigzag strip of fog in normal gravity. This phenomenon is not altered till an adjacent larger bubble sweeps the cavity in microgravity. On the contrary, the larger bubble

ripens until detachment in microgravity, as pointed out by Straub [1]. During its ripening, lateral oscillation along the wire is always observed, which can lead to the lateral coalescence between adjacent bubbles, and then detaches the new bubble and pushes it from the wire into the liquid. Sometimes, the new bubble formed by the lateral coalescence cannot depart from the wire immediately. It may encircle the wire and a bright spot will appear there. However, it cannot last long period and the boiling continues as nucleate boiling.

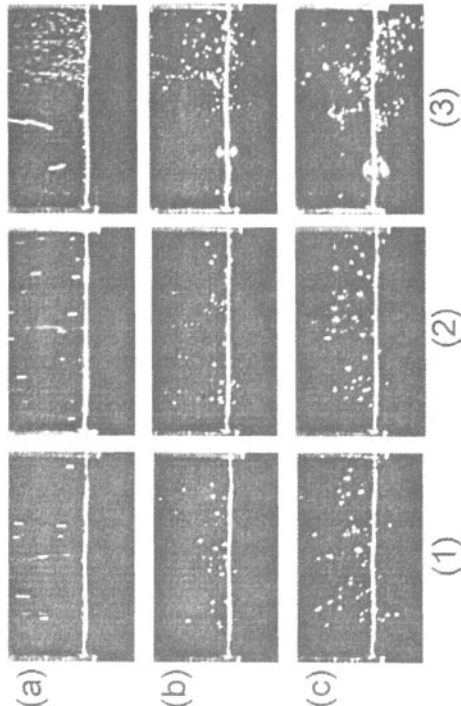


Fig 6 Bubble patterns in different gravity. (1) Nucleate boiling ($\Delta T_{sat} = 22.7$ K), (2) Nucleate boiling ($\Delta T_{sat} = 24.5$ K), (3) Two-mode transition boiling ($\Delta T_{sat} = 22.1$ K). (a) $t = -2$ s, (b) $t = 1$ s, (c) $t = 3$ s

For two-mode transition boiling, about 20% decrease of the heat flux was obtained, although the part of film boiling was receded in microgravity. In normal gravity, the vapor surrounding the wire undergoes the Taylor instability, and forms a wavy film. Vapor departs from the nodes of the wavy film as large bubbles. However, the Taylor instability disappears in microgravity. Then the surface tension reforms the shape of the film to a large spheroid bubble encircling the wire. Due to insufficiency of vapor, the part of film boiling will recede, while the part of nucleate boiling will advance. In this process, the position of the center of the large spheroid bubble wiggles along the wire and its size increases slowly with a decreasing velocity.

4. Thermo-capillary Convection Analysis

Here, we propose a hypothesis about a transport mechanism that promotes coalescence of bubbles during subcooled nucleate boiling mentioned above. The hypothesis is that adjacent bubbles entrain each other in thermo-capillary 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 (Fig. 7).

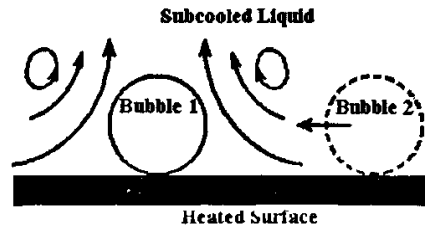


Fig 7. Lateral migration of bubbles caused by the Marangoni convection in the process of subcooled nucleate pool boiling

A scaling analysis of the equations of motion including both diffusion and convection of momentum is presented as follows for the purpose of estimation of the strength of the flow and hence the potential lateral migration velocity of the bubble. Since the lateral migration of bubbles is often observed in the range of isolated bubble, the interaction among bubbles will be neglectable. Thus, in order for conciseness, we here consider a vertical mobile interface in cylindrical coordinates, as shown in Fig 8 instead of Fig. 7. The direction along the interface is the z direction and the direction away from the interface is the r direction. The length scale along the interface is taken as the bubble diameter d . The characteristic velocity along the bubble surface is the thermo-capillary velocity [5, 6]

$$W_0 = \sigma_T \Delta T / \mu_L \quad (1)$$

where, $\sigma_T = |d\sigma/dT|$, $\Delta T = T_w - T_{bulk}$, and $\mu_L = \rho_L \nu_L$ denote the variation of surface tension with temperature, the temperature difference over the length scale d , and the liquid viscosity, respectively

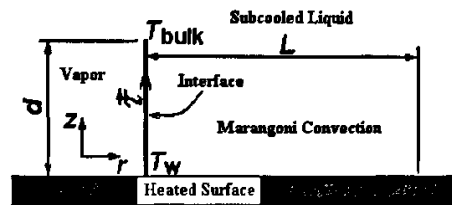


Fig. 8. A sketch of the simplified geometry for scaling analysis of the Marangoni convection surrounding a vapor bubble in the process of subcooled nucleate pool boiling

If we define the characteristic pressure as $\rho_L W_0^2$, the z component dimensionless equation of motion appropriate for this case is

$$\frac{U_0 d}{W_0 L} u \frac{\partial w}{\partial r} + w \frac{\partial w}{\partial z} = -\frac{\partial p}{\partial z} + \frac{\nu_L d}{W_0 L^2} \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial w}{\partial r} \right) + \frac{\nu_L}{W_0 d} \frac{\partial^2 w}{\partial z^2} \quad (2)$$

For deducing the above dimensionless equation, it is needed the fact that convection of momentum in the direction parallel to the interface is obviously an important term. The Marangoni flow at the interface is extended into the bulk fluid by diffusion of momentum, so the second term on the rhs is important. Scaling it to $O(1)$, one obtains a formula for a characteristic distance in the lateral direction

$$L = \sqrt{\nu_L d / W_0} \quad (3)$$

Now, insert the reference velocities and distances into the continuity equation, one can obtained

$$\frac{U_0}{L} \frac{\partial u}{\partial r} + \frac{W_0}{d} \frac{\partial w}{\partial z} = 0 \quad (4)$$

The balance condition between terms is

$$U_0 / L = W_0 / d \quad (5)$$

Considering Eq (1) and (3), the characteristic length perpendicular to the interface can be deduced as

$$U_0 = \sqrt{\sigma_T \Delta T / \rho_L d} \quad (6)$$

Eq. (6) indicates that liquid flows toward the interface of Fig. 8, and similarly toward a single bubble, at a rate proportional to the square root of the temperature gradient in the direction of flow. The velocity is independent of viscosity because viscosity both produces and impedes the secondary flow toward the bubble.

The observability of motion due to thermo-capillary pumping is given by the velocities ratio between the Marangoni and buoyant motion of the bubble, which is read as

$$Or = \frac{U_0}{U_b} = g^{-1} \sqrt{\frac{\sigma_T \Delta T \nu_L^2}{\rho_L d^5}} \quad (7)$$

where,

$$U_b = (\rho_L - \rho_V) g d^2 / \mu_L \approx g d^2 / \nu_L \quad (8)$$

is the characteristic velocity of the motion of bubbles caused by buoyancy.

Generally, the variation of surface tension with temperature for most liquids is $\sigma_T \sim 10^{-4}$ N/(m·K).

Assuming $\Delta T = T_w - T_{bulk} \sim 10^1$ K and $\rho_L \sim 10^3$ kg/m³, one can obtained the characteristic velocity of the

Marangoni motion will be the order of $10^{-3/2}$ m/s, which is consistent with the observation by Merte et al. [7]

For most liquid, the viscosity is the order of 10^{-6} m²/s. Then the observability will be

$$Or \approx 10^{-3/2} g^{-1} \quad (9)$$

where g denotes the residual gravity, which is in the range of $g/g_0 = 10^{-2} \sim 10^{-5}$. Then the order of Or will be close to 1, or more than 1. therefore, the Marangoni convection will be an important factor in the subcooled pool boiling process at microgravity.

5. Conclusions

The present study focuses on subcooled pool boiling heat transfer and the dynamics of vapor bubble at a short-term microgravity condition. Nucleate and two-mode transition boiling were observed. For nucleate boiling, the heat transfer was slightly enhanced, namely no more than 10% increase of the heat flux was obtained 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.

The lateral motion of adjacent bubbles during pool nucleate boiling of subcooled liquids is also studied in the present paper. It is assumed that adjacent bubbles entrain each other in Marangoni convection surrounding them due to the temperature difference acting on the interface between vapor and liquid, resulting in lateral motion of the bubbles toward each other, which promotes their coalescence. A scale analysis on such flow is presented. The characteristic velocity of the lateral motion and its observability are obtained approximately. The predictions consist with the experimental observations.

More experimental runs in the drop tower Beijing (NMLC) and a space flight aboard the 22nd recovery satellite of China are going to be conducted in the near future.

Acknowledgements

The present study is supported financially by the National Natural Science Foundation of China under the grant of 10432060, and the Chinese Academy of Sciences under the grant of KJCX2-SW-L05. The authors wish to acknowledge the fruitful discussion with Prof. H. Ohta (Kyushu University, Japan) and the high quality work of the entire staff of the Drop Tower Beijing (NMLC).

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