The first results of He II boiling visualization experiment conducted under 4.7 seconds microgravity conditions

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Abstract. An experiment regarding boiling of superfluid helium (He II) has been carried out under conditions of microgravity, in order to investigate the dynamics of the phase transition. A small cryostat equipped with visualization setup has been utilized for this purpose. Presence of two orthogonal optical axes allowed for registering of 3-dimensional images of a vapor bubble induced by a micro heater. Microgravity environment has been produced for about 4.7 s using the 122 m high drop tower facility at ZARM (Center of Applied Space Technology and Microgravity), University of Bremen, Germany. The experimental campaign consisting of 32 drops has been successfully conducted, while avoiding any damage to the equipment.

1. Introduction

He II is utilized as a coolant in satellite telescopes such as X ray telescopes and infrared telescopes. Thus, it is important to become acquainted with the heat transfer mechanisms in He II under microgravity. However, only a few experiments regarding this matter have been conducted so far [1, 2]. The knowledge of the boiling phenomena in He II under microgravity conditions is necessary for a proper design of space equipment exposed to relatively high heat loads.

Furthermore, it is well known that the superfluid helium heat transfer accompanied by boiling depends on the subcooling caused by the presence of a hydrostatic pressure head. Thus, an experimental study conducted under the gravity of Earth would not be representative for a microgravity environment. Moreover, a microgravity experiment may lead to revealing the mechanisms of heat transfer in He II otherwise overshadowed by the influence of gravitational field during a ground experiment.

A series of microgravity experiments has been conducted at the drop tower of Hokkaido Center of AIST over the course of several years [3-5]. The drop tower of AIST can produce microgravity conditions only for about 1.3 s. In this study, the visualization of bubble growth was aimed at reaching a steady state, what was facilitated by longer a microgravity period of about 4.7 s.

2. Experimental set-up

2.1. Drop tower
The microgravity environment was produced using the drop tower of ZARM. The drops have been performed inside a 122 m high vacuum tube in order to ensure high quality of microgravity. Vacuum pressure inside the drop tube was being reduced to approximately 50 Pa, ensuring that the residual gravity drops below $10^{-4}$ g ($1 g$ equals the value of the standard acceleration due to gravity on ground)[6]. The duration of microgravity was about 4.7 s. The first 0.5 s just after the beginning of free fall were not considered, because of the residual acceleration due to initial vibrations. The experimental set-up as shown in Fig.1 was installed in an airtight capsule. Power for all of the experimental set-up components was supplied from a battery pack. The dropped capsule was being captured by a reciever tank filled with vast powder beads, which results in deceleration ranging up to 45 g

2.2 Cryostat

2.2-1 Safety measures
The utilized cryostat was modified in comparison with previous research [4, 5] to withstand the deceleration of 45 g. Its weakest point was the welding seal joint on the top of the neck, which may cause problems during deceleration for vertical axis. Hence, the copper radiation shield was replaced with aluminium one to reduce the weight. In addition, several G-10 supports were set to fix the lateral axis. The safety factor assumed at the design stage always exceeded 2.

The mitigation of a false safe was considered. When a sudden vacuum loss happens, harmful boiling of liquid helium occurs inside the vessel. The evaporated gas is vented out of the capsule using a feedback operation of the control valve with a pressure sensor on the vent line. In addition, numerous safety valves were set in the capsule in order to mitigate the results of the worst-case scenario when the valve control doesn’t work. On top of the cryostat a weak safety valve which opens just above atmospheric pressure was installed. In addition two safety valves were set on the boundary between the drop capsule and the vacuum drop tube. The schematic illustration of the cryostat and the valves is shown in Fig 2.

![Fig.1 A picture of the experimental set-up inside the capsule](image1)

![Fig.2 The schematic illustration of the cryostat and the valves](image2)

2.2-2 Experimental set-up and operation
The cryostat was equipped with 4 windows for visualization over two orthogonal optical axes. Two LED arrays and two small high speed cameras (Photoron Fastcam MC-2) along with a pair of telecentric lens were set to obtain a 3-dimensional image of vapor bubble boundary position. A small heater which consisting of a short Manganin wire ($\phi 0.05 \times 1.88$ mm) and two superconducting wires [4, 5] was placed vertically. Consequently the
axis of the heater is perpendicular to the plane defined by the optical axes. The heater current was supplied from a constant power supply utilizing a feedback control. The data acquisition system and all of the solenoid valves were controlled using the capsule control system provided by ZARM, which is based on Labview® and National Instruments PXI® platform.

Liquid helium was transferred before each drop prior to enclosing the capsule and launching it within the drop tube. The test vessel was pumped out using the large vacuum volume of the drop tube via the vent line across the boundary of the capsule. Prior to release of the capsule, the pressure inside the cryostat was controlled using the electric valve on the vent line. During the free fall period, all of the valves were closed to avoid a thruster effect to the capsule. If the tiny exhaust leakage exists between capsule and vacuum tower, the falling capsule must be tilted by thruster effect. Thus, the temperature of He II inside the cryostat was increasing by about several mK during the free fall. For the purpose of this study, this relatively small temperature increase may be considered negligible.

![Diagram of experimental set-up](image)

**Fig. 3 A top view of the experimental set-up**

### 3. Results

All of the 32 scheduled drops were successfully conducted. The experimental set-up withstood decelerations ranging up to 45 g. Typical visualization results of He II boiling under microgravity are shown in Fig. 4. Fig. 4 (a) presents an image from the camera head 1, whereas Fig. 4 (b) corresponds to the camera head 2. The shape of the vapor bubble is very close to an exact sphere. The center of the bubble is shifted from the center of wire. These characteristic features were always observed, regardless of the bulk temperature or dissipated heat flux.

Typical time distributions of the heater power and temperature are shown in Fig. 5 and Fig. 6, respectively. In this paper, the time \( t = 0 \) defines the beginning of the free fall. The heater current was applied after 0.5 s from free fall start. The dissipated power was controlled within about 2% by the feedback system, though the electric resistance of the Manganin wire varied during heating. Fig. 6 shows the calculated temperature of the heater wire, computed on the basis of its resistance. This temperature seems to oscillate depending on the distance between the heater wire and the vapor-liquid interface.

The size of the bubbles generated at 1.9 K was compared with the values previously obtained during experiments held at Hokkaido center of AIST, as shown in Fig. 7. The duration of microgravity in the previous experiments was about 1.3 s. In the previous study, the longest heating duration under microgravity condition is 1.2 s, because residual gravity is rather high during the initial 0.1 s of a drop.

The obtained values and the tendency of the present experimental results are consistent with the previous results. Thus, it can be concluded that repeatability was confirmed. In the case of the longest heating duration of 4.2 s, the bubble grows in between the bubbles for the case of 1.2 s and the calculated value of simple model of steady heat transfer across the liquid-vapor interface. The calculated steady-state bubble diameters are derived from the energy balance on the vapor-liquid interface, based on kinetic theory [7-9]:

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\[ 2\sqrt{\pi} \left(1 - \frac{0.4\beta}{\beta}\right) j - \Delta p \sqrt{2RT_i} + \frac{\sqrt{\pi}}{4} q_i = 0 \quad (1) \]

where \( j \) denotes the mass flux across the interface, \( \beta \) is the thermal expansion ratio, \( q_i \) is the heat flux across the interface, and \( T_i \) is the temperature at the interface (not the bath temperature). \( T_i = T_b \) can be assumed because the temperature difference between them is negligibly small. \( T_i - T_b \) is caused by the temperature distribution of He II and the thermal resistance between He II and He Vapor. The thermal resistance across He II-vapor interface are quite small [10, 11]. And temperature distribution should be close to zero because of zero subcooling condition realized in microgravity. Only the pressure difference due to surface tension cause slight subcooling. Even if several ten-micron bubble appears in initial phase, the possible maximum temperature difference is the order of 10 mK. Thus, the temperature difference must influence negligibly small against the calculation results.

During the steady state the mass flux \( j \) equals 0, hence the first term of Eq. (1) is excluded and \( q_i \) is obtained easily from the following expression:

\[ q_i = \frac{4}{\sqrt{\pi}} \left( \frac{4\sigma}{D} \sqrt{2RT_b} \right) \quad (2) \]

where \( D \) stands for the diameter and \( \sigma \) refers to the surface tension. The heat flux across the bubble surface can be expressed as follows:

\[ Q = q_i D^2 \pi \quad (3) \]

Hence, the diameter in a steady state equals:

\[ D = \frac{Q}{16\sigma \sqrt{2RT_b} \pi} \quad (4) \]

Since a steady state was closely approached during the 4.2 s long drops, the above formula brings valid results. In the case of a small heat current, just above the critical value of boiling onset, the bubble size doesn’t exceed the calculated one.

![Visualization results of a vapor bubble induced by the small heater; \( T_b = 1.9 \) K, \( q = 5.08 \) mW, \( t = 4.2 \) s. (a) Head 1 (b) Head 2. Visualized area is about 12.5 x 12.5 mm square.](image)
Fig. 5 Time distribution of heat current and acceleration $T_b = 1.9$ K, $q = 12.83$ mW

Fig. 6 Time distribution of heater temperature $T_b = 1.9$ K, $q = 12.83$ mW

Fig. 7 Bubble diameter as a function of heat current at bulk temperature equal 1.9 K

4. Summary

A series of 32 drops was successfully performed without any damage to the experimental set-up, using the 122 m high drop tower located in ZARM, Bremen, Germany. The center of the bubbles generated through boiling of saturated superfluid helium is always shifted away from the center of the heater. A complicated temperature distribution might exist inside a bubble, although due to the almost spherical shape of a bubble the heat flux across the interface can be assumed to be uniform. Repeatability of the performed experiment was confirmed through comparison with the previous results obtained at Hokkaido Center of AIST.

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