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Visualization study of growth of spherical bubble in He II boiling under microgravity condition

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Abstract

Under microgravity conditions, the heat transfer is considered to be different from that in normal gravity because of zero subcooling due to zero hydrodynamic pressure in saturated He II. Thus the heat transfer in He II under microgravity is an interesting research target. Microgravity experiment is expected to reveal some hidden mechanism of boiling heat transfer across the vapor-liquid interface because stable large-scale vapor bubbles are formed. In the present study, the behavior of a single spherical bubble generated by a micro heater was observed under microgravity condition during free fall in a drop tower for about 1.3 second. The visualized images taken by a high-speed camera were analyzed to examine the time variation of a large vapor bubble of the order of 10 mm. It was seen that the sizes of a single bubble increased with decreasing He II temperature for fixed heat input. The bubble size near the lambda temperature was smaller than that at 1.9 K though the effective thermal conductivity is quite small. The magnitude of the saturated vapor pressure seems to be a dominant factor to determine the bubble size. For the case of He I, the vapor bubble growth can be predicted by a simple consideration in terms of the latent heat and the gas density in film boiling state.

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Keywords: superufluid helium, microgravity, visualization, boiling, vapor bubble

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1. Introduction

Superfluid helium (He II) has been utilized for optics and detectors cooling in space. However, there are little superfluid helium experiments under microgravity condition (by Lipa (1994), Gradt et al (1986)) because the microgravity environment using parabolic flight is difficult to conduct. Thus the boiling heat transfer in He II under microgravity condition is not fully understood. The heat transfer of He II in microgravity is considered to be different from that under normal gravity condition because of zero subcooling due to zero hydrodynamic pressure. The boiling experiment in microgravity may reveal some effect on heat transfer across the liquid–vapor interface hidden by the gravity.

Our group has tried another approach to microgravity experiments such as free fall experiment using a 10 m height drop tower (by Kimura et al.(2011), Takada et al.(2013)). That can provide with a microgravity environment for about 1.3 second. In earlier reports, the behavior of film boiling around a thin heater wire of 50 micron diameter has been observed through optical windows of 20 mm in diameter. However, the observed vapor bubble grew larger than the size of the optical window even when a slightly larger current than the critical heat flux was applied. Thus the vapor size couldn't be measured and the edge effect should be taken into consideration.

In the present experiment, a single spherical bubble was generated by a micro heater in order to observe an overall shape of a small bubble significantly smaller than the vessel size.

2. Experimental Apparatus

The cryostat and the experimental set up used in this study were mostly the same as these of the previous experiments Takada et al. (2013). To generate a single spherical bubble in He II, a micro heater unit was installed in the cryostat consisting of a manganin wire, 0.05 mm in outer diameter and 2.8 mm in length, and two copper stabilized mono filament NbTi superconducting wires as shown in Fig.1. The heat generation rate of this heater unit was measured by the four terminals method. Most of the heat was generated by the manganin part even when the superconducting wire parts were in the bubble. The constant current was applied from just after free fall starting through the end of time in microgravity. In the previous experiments, the constant power supply was realized using a feedback control circuit. On the other hand, the feedback control is difficult because of the small resistance in this experiment. The applied Joule heat was not exactly constant due to the positive correlation between resistance and temperature but the variation was within a few percent. The free fall experiments were successfully conducted more than twenty times a day. For comparison, the several temperature conditions in He II and He I at about 4.2 K were tested.

3. Result and Discussion

The difference in visualization results were clearly recognized between boiling He II and He I. In the case of He II shown in Figs.2 (a)-(d), a single spherical bubble was formed and grew to about 8 mm in diameter for 14 mW at the He II bath temperature of 1.9 K. The present results were taken by a high-speed camera with a telecentric lens at

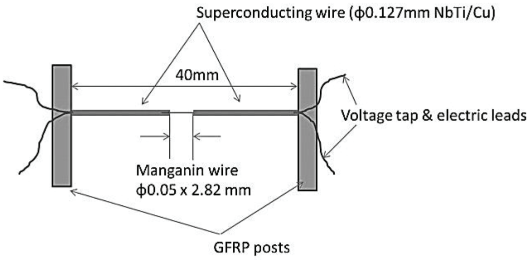

Fig.1 A schematic illustration of heater unit configuration

a frame rate of 231 fps. This visualization method has high sensitivity for density variation, covering 20 x 20 mm He II field. The spherical bubble never detached from wire heater as in boiling under normal gravity condition.

On the other hand, the nucleation boiling could be observed in He I as shown in Figs.3 (a)-(d). The small bubbles detached from a wire heater even at small heat input. It seems that small bubbles were formed with the size of sub-millimetre order and the bubbles grew larger by merging with each other. The bubbles flew downwards by the effect of residual small scale flow in the liquid vessel. For rather large heat input, film boiling state was observed. The single bubble shown in Figs 4(a)-(d) grew slower and smaller than that in He II.

Figure 5 shows the typical time variations of vapor growth, which is calculated on the basis of the measurement of the projected area of vapor from the pictures like Figs 2 (a)-(d). The calculation is based on the assumption that a bubble is regarded as a perfect sphere. It seems that the bubble volume is roughly proportional to the time in about one second and the growth rate depends on the heat input. Thus, it is shown in Fig.6 that the volume of a vapor bubble is proportional to the total applied heat. On the other hand, the vapor volume is proportional to the total applied energy for the case of He I at 4.2 K shown in Fig. 7.

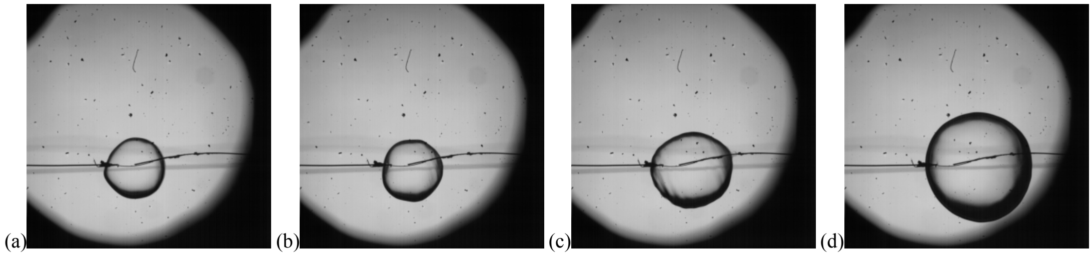

Fig. 2 A typical series of pictures of a single bubble growth in He II under microgravity for 14.02 mW at 1.9 K
(a)0.093 s (b)0.249 s (c) 0.491 s (d) 1.028s

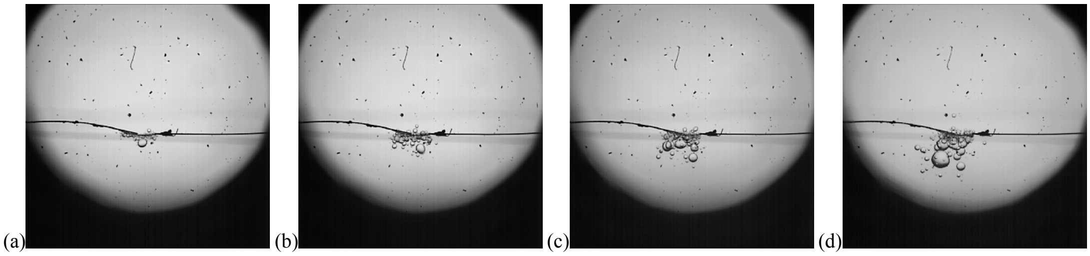

Fig.3 A typical series of pictures of a single bubble growth in He I nucleate boiling state under microgravity for 3.08 mW at 4.2 K
(a)0.093 s (b)0.249 s (c) 0.491 s (d) 1.028s

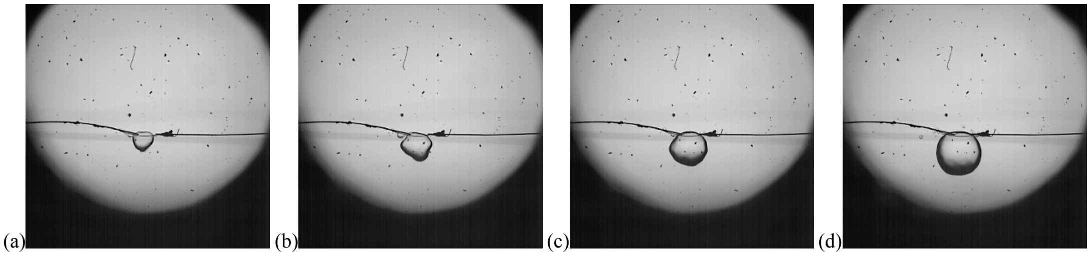

Fig. 4 A typical series of pictures of a single bubble growth in He I film boiling state under microgravity for 10.97 mW at 4.2 K
(a)0.093 s (b)0.249 s (c) 0.491 s (d) 1.028s

Taking account of the feature's mentioned above, the growth rates are compared for several temperature conditions. The growth rate is expressed as a ratio of the amount of vapor volume generated to the applied energy in m^3/J. For the bubble in He II, the growth rate was calculated using the instantaneous volume data of vapor bubble at the time 0.6 sec when the volume and applied energy are clearly linear to each other. On the other hand, for the case of He I, the growth rate was calculated by using all data of Fig. 7. The growth rate of the vapor bubble has strong dependence on the temperature as shown in Fig. 8, where the calculated value based on the property of the gas density and the latent heat on the saturated vapor line is also compared to the experimental result. The volume of the vapor bubble in He II under microgravity is not determined predominantly by the effective thermal conductivity, which is different from that under normal gravity condition. Under normal gravity, the film thickness around a thin wire heater in film boiling depends on the critical heat flux related to the effective thermal conductivity (Takada S.,et al., 2010). Fig. 8 indicates that the dominant factor in determining the volume of the vapor bubble in He II is indeed the latent heat and the gas density because the pressure difference caused only by surface tension is quite small so that the resulting temperature difference between the interface and the bath is as same as the order of 10^{-8} K. The growth rate of a vapor bubble has similar tendency to the calculated value though the gas density inside the bubble must be lower than that of saturated vapor at the bath temperature because the heater temperature is rising in fact. Thus, calculated line in Fig.8 is rather small estimation. Some of the applied heat must be transported to the liquid phase in addition to the vaporization of He II. Furthermore, the heat transfer across the liquid-vapor interface has to be considered in He II. For the case of He I, it can be said that most of the applied energy is expended in vaporization. In other words, vapor volume for film boiling state in 4.2 K can be predicted easily in 90 % because the product of the gas density and the latent heat at 4.2 K is rather large.

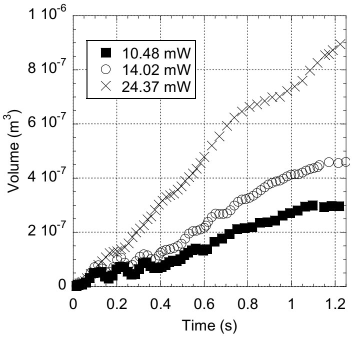

Fig. 5 Time variation of volume of vapor bubble on the several heat input in He II at 1.9 K.

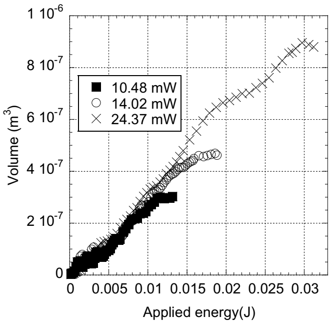

Fig. 6 Correlation between applied energy and volume of vapor bubble at 1.9K

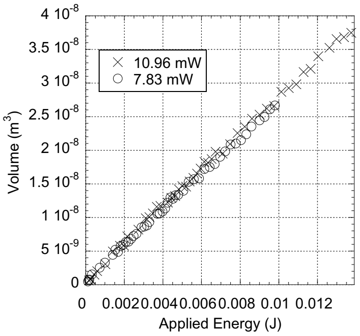

Fig.7 Correlation between applied energy and volume of vapor bubble for He I film boiling at 4.2 K.

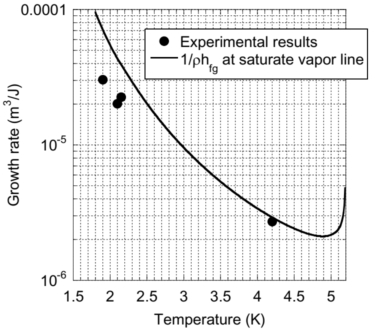

Fig.8 Comparison between the experimental results of growth rate and the simple assumption that all heat expend as latent heat with the gas density on saturated vapor pressure

4. Summary

In the present experimental study, He II boiling phenomena around a small heater were investigated with visualization in microgravity environment by using a drop tower. A single spherical vapor bubble could be created by the small wire heater in He II and He I. Some features from visualization results were summarized as follows.

The volume of the vapor bubble has a linear relation to the applied energy only in about 1 second in He II. On the other hand, the volume of the vapor bubble in He I is always proportional to the applied energy. It is found that the growth rate as a function of the applied energy is mainly determined by the latent heat and the gas density. For the case of He I, most of the applied energy is expended in vaporization. In the case of He II, the dominant factor determining the volume of vapor bubble is also latent heat and gas density. The role of superfluid super thermal conductivity is small for the bubble in He II under microgravity condition. However, it is clear that some of the applied heat is transported to the liquid phase in addition the vaporization in He II.

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