Observation of various boiling states in nearly saturated He II

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He II boiling phenomenon is one of the least understood aspects of He II. In the present investigation, boiling phenomenon in He II is studied by the simultaneous measurement of the heater surface temperature and the pressure oscillation in He II bath. Several boiling states can be encountered with the variation of the immersion depth of the heater at small heat flux. The heat transfer coefficients of the various boiling states are measured. It is observed that there exists correlation between the dominant frequencies of the pressure oscillation and the heat transfer coefficient in these boiling states.

INTRODUCTION

Superfluid helium (He II) is widely utilized in many cryogenic cooling application cases for its high cooling capability, such as cooling of superconducting magnets and IR detectors in space cryogenic applications, and so on. However, its cooling performance is sometimes deteriorated by the appearance of the gas phase, and even boiling phenomena, for example, superconducting magnet quenching in He II. Boiling phenomena in He II are of both academic and applied interests, because their occurrence may lead to catastrophic events for the cryogenic systems where good heat transfer performance should be maintained and because it still remains one of the least understood aspects of He II. Obviously, film boiling is the worst situation from the heat transfer performance point of view. Recently, a lot of effort has been made to understand He II film boiling. Zhang [1] conducted film boiling experiments under different thermal conditions, and constructed a three dimensional boundary map to classify noisy film boiling, transition boiling and silent film boiling. Pressure oscillation and temperature oscillation in He II were measured by a pressure sensor and a superconducting temperature sensor, which showed strong correlation between each other. It was found from the visualization video during the experiments that the vapor bubble was oscillating on the heater surface and the size could be comparable to the heater size. It was further confirmed that every contact of the cold He II with the higher temperature heater surface would generate an audible loud noisy sound, after which noisy film boiling was named. There was another non-noisy counterpart of He II film boiling mode, which was so-called silent film boiling. The appearance of He II film boiling modes depended strongly on the thermal conditions. Although a lot of research has been carried out, the information about He II film boiling is still inadequate [2] from the heat transfer point of view. In the present study, experiments are carried out to study the heat transfer performance in different boiling states by employing a stainless steel heater.

EXPERIMENTAL SETUP AND MEASURING METHODS

A glass cryostat of 9 cm inner diameter was used in the experiments. The boiling process could be observed through the unsilvered strips along the body of the cryostat. An evacuation system was used for regulating the bath temperature. In order to measure the heater surface temperature, a stainless steel foil heater of about 10 μm in thickness was employed in the present experiments. The resistance of stainless steel foil (SUS-304) is temperature dependent, and the average temperature can be obtained by measuring the resistance. The stainless steel foil was cut into a zigzag form in order to obtain higher resistance, as shown in Figure 1. The width of the heating element was about 3.2 mm, and the width of the gap between the heating elements was about 0.8 mm. As the width of the gap was much smaller comparing to that of the heating elements, the total heating part could still be regarded as a square planar heater. After the heating part was cut out, it was pasted carefully to a FRP base plate by using a thin layer of Stycast. Total net heat transfer area of the heater in the present measurement was about 8 cm^2. A Kulite-piezoelectric pressure sensor (CCQ-093) was placed right above the heater surface to measure the pressure oscillation during film boiling. The pressure sensor was calibrated against the saturated vapor pressure of liquid helium. The experiments were conducted under nearly saturated pressure condition. The heater was mounted horizontally in the cryostat. The helium bath temperature was controlled by regulating the vapor pressure in the cryostat with the pressure controlling system. The electric voltage and the electric current applied to the heater were simultaneously measured. The signal measured by the pressure sensor was 100 times amplified by the low noise pre-amplifier. All data were recorded by a storage oscilloscope and transmitted to the computer through GPIB interface and then stored there for a further analysis.

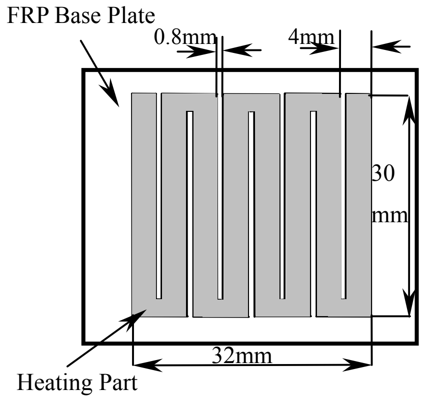

Figure 1 Schematic illustration of the stainless steel foil heater (not to scale)

RESULTS AND DISCUSSION

Shown in Figure 2 is one example of the pressure oscillation and the heater surface temperature oscillation in noisy film boiling. It is seen from the figure that the pressure spike and the temperature spike are rather strong, and there exists strong correlation between the pressure and the temperature spikes, which indicates the pressure spike results from the direct contact of He II with the heater surface. However, the hydrodynamic information reflected from the pressure and the temperature oscillations is different. The pressure oscillation displays both global and local hydrodynamic information, while the temperature oscillation displays only local hydrodynamic information [3]. The heater surface temperature drops about 10 K at the moment of the He II contacting with the heater, because the evaporation of He II is an effective way for the heat removal.

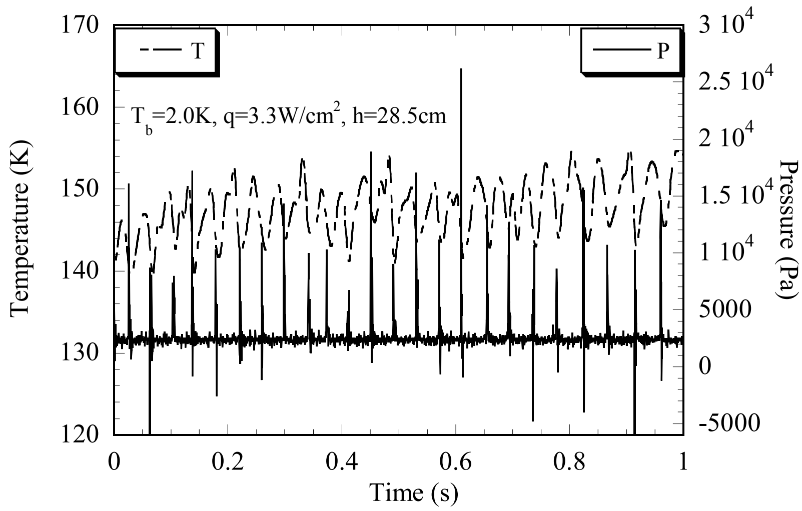

Figure 2 The pressure oscillation and the heater surface temperature oscillation in noisy film boiling

One of the interesting features of He II film boiling is that the boiling state varies with the immersion depth of the heater. In general, boiling state is noisy film boiling when the immersion depth is deep; on the contrary, boiling state is silent film boiling when the immersion depth is small. When the heat flux is moderate and the immersion depth of the heater is deep, say above 38 cm, the general outlook of the boiling state in this case is different from that in noisy film boiling or silent film boiling. It is observed that a very small vapor bubble oscillates on the heater surface and the boiling sound is fizzy and in high frequency, as shown in Figure 3 (a). (In the following figures, only the data of the pressure oscillation is shown because the fundamental frequency of the pressure oscillation and the temperature oscillation is essentially the same.) It is also seen from the figure that the amplitude of the pressure oscillation is much smaller than that in noisy film boiling, which occurs at the immersion depth below 38 cm. It could be concluded that the boiling state at deeper immersion depth is a kind of undeveloped film boiling (pre-mature film boiling state). Shown in Figure 3 (b) are the FFT analysis results of the pressure oscillation data. It is obvious that the fundamental frequency of the pressure oscillation in the undeveloped film boiling is much higher than that in noisy film boiling. When the immersion depth decreases to the range of 15-38 cm, the boiling state is noisy film boiling, in which the fundamental frequency is around 20-30 Hz. As the immersion depth further decreases to below 15 cm, the boiling state turns into an intermittent state: transition boiling, in which noisy film boiling and silent film boiling appear intermittently. And thus, the fundamental frequency is smaller. In general, silent film boiling occurs at lower immersion depth without detectable pressure oscillation. It is seen form Figure 3 (b) that the immersion depth for silent film boiling in the present case is around 4 cm.

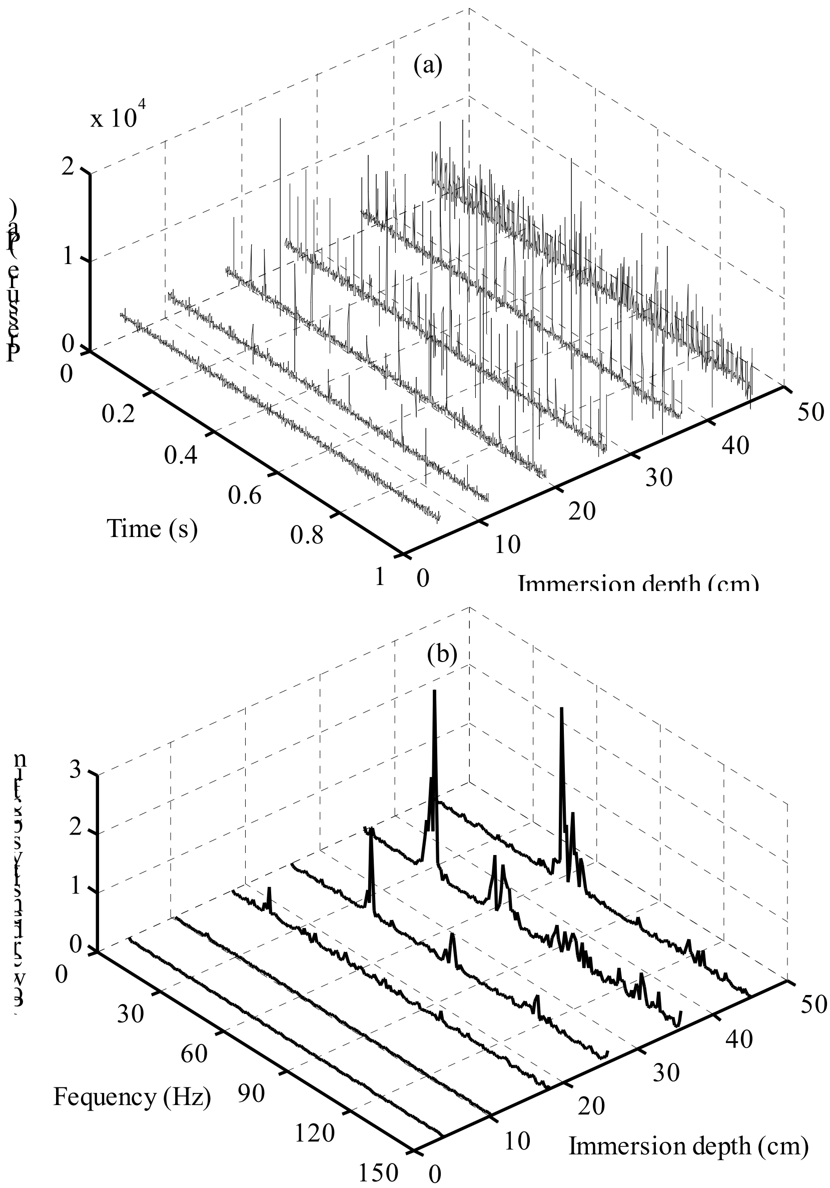

Figure 3 Variations of the pressure oscillations with the immersion depth (a) and their FFT analysis results (b), T_b=2.0 K, q=3.3 W/cm^2

Shown in Figure 4 are the variations of the heat transfer coefficient and the fundamental frequency with the immersion depth. The shadowed area indicates the transition boiling region, wherein the lightly shadowed area indicates the transition boiling dominated by noisy film boiling and the heavily shadowed indicates the transition boiling dominated by silent film boiling. It is understood from the figure that there exists some correlation between the heat transfer coefficient and the fundamental frequency. At the deeper immersion depth, the boiling state is the undeveloped film boiling and the corresponding heat transfer coefficient is also larger. The heat transfer coefficient decreases with the decreasing of the immersion depth as well as the fundamental frequency does. An interesting phenomenon is that the heat transfer

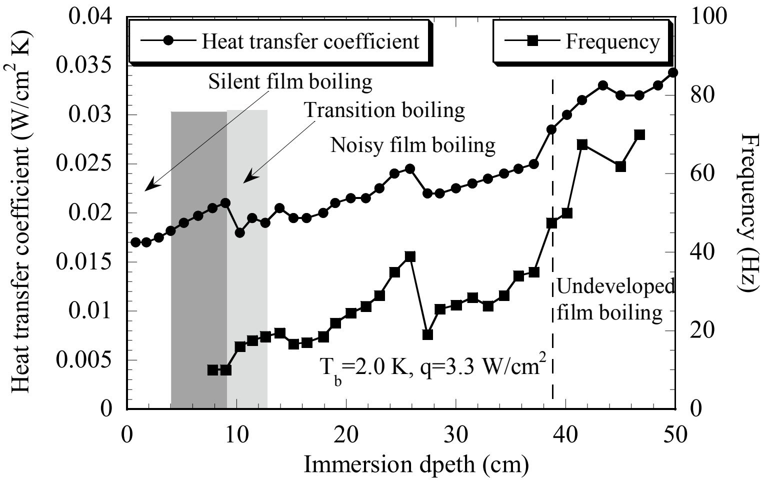

Figure 4 Variations of the heat transfer coefficient and the fundamental frequency with the immersion depth

coefficient suddenly increases when the immersion depth decreases to around 25 cm, and the fundamental frequency counterpart also shows a jump, which may be due to some resonant frequency component of the system being excited by the oscillation of the vapor bubble in noisy film boiling region and then gets sympathetic vibration. It can be further concluded that the frequent contact of He II with the heater surface may enhance the heat transfer performance. With the decreasing of the immersion depth, the boiling state turns into transition boiling in which the heat transfer coefficient shows a small jump and then decreases continuously to silent film boiling in which no obvious fundamental frequency is detected.

CONCLUSIONS:

The film boiling in He II is investigated in the present study. It is found from the experimental results that the boiling states display different features under different thermal conditions. At the immersion depth above 38 cm, the boiling state is undeveloped film boiling and it is characterized by higher fundamental frequency and larger heat transfer coefficient; as the immersion depth decreases, the boiling state is noisy film boiling in which the fundamental frequency and the heat transfer coefficient are weakly dependent on the immersion depth. It is interesting to note that there exists a correlation between the fundamental frequency and the heat transfer coefficient, and frequent contact of He II with the heater surface will enhance the heat transfer performance. The boiling state turns into transition boiling as the immersion depth decreases to the range of 15-4 cm, below which the boiling state is silent film boiling. The corresponding heat transfer coefficient displays a jump in transition boiling and decreases continuously in silent film boiling.

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