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Periodic Oscillation of Liquid Helium Boiling in a Narrow Rectangular Duct

Y. Eikoku · K. Ishida · A. Iwamoto · Y. Tsuji

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Abstract Temperature fluctuations in saturated superfluid He II (at 1.9K) were measured using small thermistors operated by a lock-in amplifier. The experiments were performed in a rectangular channel ($13 \times 13 \times 200$ mm) with a heater set at the bottom. The temperature oscillated periodically and a pulsive boiling sound appeared. The two become synchronized and the oscillating frequencies strongly depend on the helium pressure and the heat flux. When the He pressure decreases, the oscillation frequency decreases. A simple model to predict the cyclic period is presented.

Keywords Helium II · boiling · periodic oscillation

1 Introduction

When the temperature of liquid helium is below 2.17K, it becomes a superfluid (He II) and exhibits unique properties. For instance, there is mass flow without friction, anomalous heat transport and quantized vortex lines in the turbulent state. These characteristics have been studied experimentally and by numerical simulations [1].

In this study, the boiling phenomena inside a small duct were investigated experimentally. A heater is attached at the bottom of a small rectangular duct. As the heat flux increases, film boiling occurs in He II. This phenomenon was found in 1960's, and has been studied extensively. In the boiling process, pressure above the lambda pressure (5kPa) is a decisive factor in the apperance

Y. Eikoku, K. Ishida, Y. Tsuji
Nagoya University, Nagoya city, Japan 464-8603
Tel.: +81-52-7894693
Fax: +81-52-7894692
E-mail: c42406a@nucc.cc.nagoya-u.ac.jp

A. Iwamoto
National Institute for Fusion Science, Japan

of the boiling mode. Above the lambda pressure, film boiling occurs with the co-existence of three phases: He II, He I and helium vapor. Below the lambda pressure, the film boiling is accompanied by only two phases: He II and helium vapor. The boiling curve for He II may be different from that of ordinary fluid, but the details remain unclear. In He II boiling, the detached vapor bubbles cannot be seen due to extremely large effective thermal conductivity, and nucleate boiling is observed only in a transitional state at the beginning of film boiling. Film boiling modes were experimentally studied in detail by Nozawa et al. [2,3] and their heat transfer coefficients were investigated by Takada et al. [4]. These previous experiments were done in boiling generated over a foil heater on the plate. There are few researches on boiling inside small rectangular small ducts, where the side walls may affect the boiling and flow conditions [5]. For earlier works on visualization of bubbles in liquid He, one may refer to Katagiri et al. [6] and Abe et. al. [7]. In this paper, the periodic temperature oscillation accompanying boiling sounds inside a small rectangular duct is studied. The two become synchronized and the oscillating frequencies strongly depend on the helium pressure and the heat flux.

2 Experimental Conditions

Figure 1 shows a schematic view of the experimental apparatus. Inside the glass dewar, a rectangular duct (cross section $S_a = 1.69$ [cm^2], length $L = 20$ [cm]) made of Glass-Fiber-Reinforced Plastics (GFRP) is installed. A heater is located at the bottom to generate a thermal counter flow. The heater power is changed from 0 to 3.4 [W/cm^2]. The temperature fluctuation inside the duct is measured by small thermistors (Lake Shore, Model CX-1030-BG), which are set at $x/L = 0.07$, $x/L = 0.73$ and $x/L = 1.00$ from the bottom. They are operated by a lock-in amplifier and data are recorded at sampling frequency of 1 [kHz]. The heat flux, carried by the normal fluid, is evaluated by these temperature gradients and is compared with the supplied heater power q [W/cm^2]. The helium pressure P [Pa] is the sum of liquid He hydraulic head pressure P_1 and gas He pressure P_2. P_2 is measured by the digital manometer (Yokogawa model-2655) at the top of the flange and the head pressure P_1 is calculated by the height level of helium in the dewar. The total pressure is then obtained by $P = P_1 + P_2$.

The liquid He temperature is controlled and kept around 1.9 [K] during the measurements. A cyclic sound occurs inside the dewar, which is caused by bubble generation due to boiling. The sound is recorded by a microphone mounted on the top the glass dewar. In order to visualize the boiling process, a duct made of acrylic resin is also used, its size is the same as that of the GFRP duct. A CCD camera (1018×1008 pixels) is used to visualize the fluid motion within an area of 47×47 [mm^2]. Temperature fluctuation and visualization images are recorded simultaneously.

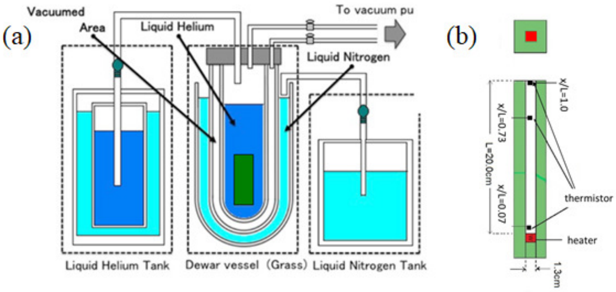

Fig. 1 (a) Schematic view of experimental apparatus. (b) rectangular duct

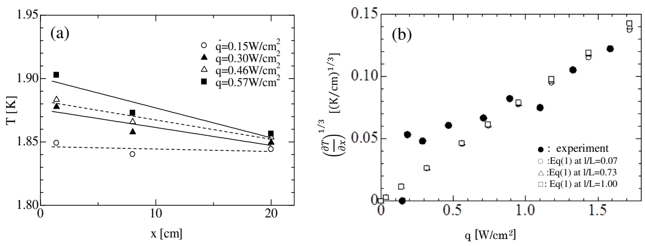

Fig. 2 (a) temperature distribution inside the duct, (b) relation between temperature gradient and the heat flux supplied to the heater.

3 Results and discussions

The mean temperature distribution inside the duct is plotted in Fig. 2(a). The distance from the heater is defined as x. The heater power is changed from 0 to 0.57 [W/cm^2] and the bath temperature is kept at 1.85 [K]. The temperature is high near the heater and decreases toward the duct exit. From the Gorter-Mellink equation [1], the heater power q is related to the mean temperature gradient dT/dx as

$$\frac{dT}{dx} \simeq \frac{A\rho_n}{S^4\rho_s^3T^3}q^3\,, \tag{1}$$

where ρ_n and ρ_s are normal and superfluid density, respectively. S is entropy and A is a constant. In the steady flow condition, the relation $dT/dx \propto q^\alpha$ is assumed, and the exponent α varies in the range of $3 \leq \alpha \leq 3.4$ [1]. In Fig. 2(b), the heat flux calculated from the temperature gradient is compared with Eq.(1). Experimental data, indicated by the solid circles are obtained from the heater power. They agree with the heat flux calculated by Eq.(1). A small difference is due to the calibration accuracy of each thermistor. From this result, we emphasize that the heat flux is carried through the duct without any loss to the outside.

As the heat flux increases, both silent film boiling and noisy film boiling are observed. The bath temperature is kept at 1.9 [K]. Based on the measured

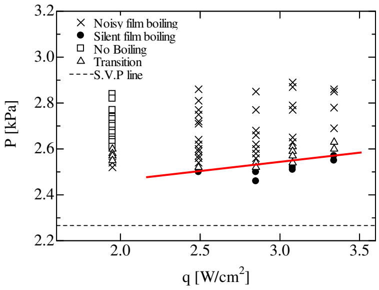

Fig. 3 Phase diagram of boiling in the present experimental setup. Solid red line is boundary of noisy film boiling.

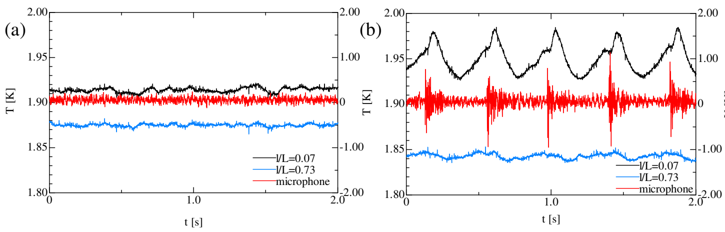

Fig. 4 Temperature fluctuations inside the duct are plotted. The solid black line is the temperature near the heater $x/L = 0.06$, and the blue one is temperature at the exit $x/L = 0.73$. The sound inside the dewar is plotted by red solid line. (a) silent film boiling, (b) noisy film boiling.

temperature fluctuation, sound generation and visualized images, the boiling modes are classified into three categories: no-film, silent film and noisy film boiling. A phase diagram of the boiling phenomena as a function of pressure and heater power is shown in Fig. 3, in which each mode is plotted by different symbols. There is a boundary between noisy film boiling and silent film boiling, which is plotted with a red solid line. Above this solid line, noisy film boiling occurs. It is clear that the boiling process is strongly dependent on both the pressure and heat flux. The duct geometry is another factor that affects the boiling. If the duct shape and size change, this diagram would be different.

The temperature fluctuations measured inside the duct are plotted in Fig. 4. The solid black line is the temperature near the heater, $x/L = 0.07$, and the blue line is the temperature at the exit, $x/L = 0.73$. The sound measured at the top of dewar is plotted with a red solid line. Typical cases of silent film boiling and noisy film boiling are plotted in Fig. 4(a) and (b), respectively. The silent film boiling does not show any typical sound fluctuation, but small temperature fluctuations are confirmed. In the noisy film boiling, however, periodic temperature oscillation is clearly observed near the heater, but it disappears at the exit of the duct. These temperature and sound oscillations are due to the film boiling of He II. Calculating the spectrum of

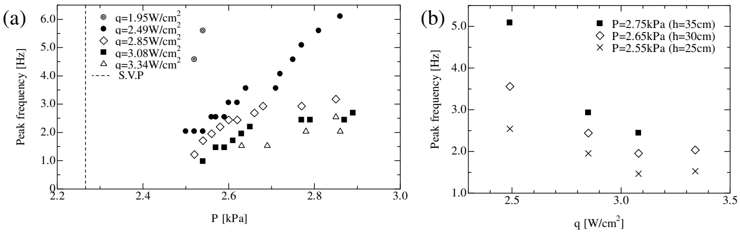

Fig. 5 Peak frequency of temperature fluctuation in noisy film boiling. Peak frequency is plotted against Helium pressure in (a) and heater power in (b).

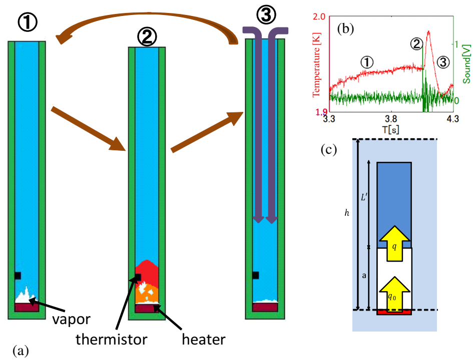

Fig. 6 Schematic view of periodic boiling process and its corresponding temperature and sound fluctuations. (a) schematic image of cyclic oscillation, (b) typical example of temperature (red) and sound (green) fluctuation, (c) simple model of oscillation.

temperature fluctuation, the peak frequency f_p [Hz] which corresponds to the cyclical period of oscillation is studied in detail. For a fixed heater power, the peak frequency is plotted against helium pressure P (which is the sum of liquid He hydraulic head pressure and gas He pressure) in Fig. 5(a). The heater power is changed from 1.95 to 3.34 [W/cm^2]. The peak frequency gradually increases with higher pressure and smaller heater power. That is, the boiling tends to occur frequently in a high pressure condition. For a fixed pressure, the peak frequency decreases as the heater power increases, as plotted in Fig. 5(b). Therefore, the film boiling is strongly affected by the helium pressure and heater power.

In the film boiling, a cyclic sound also appears. The sound is associated with the bubbles in boiling. A schematic image obtained from observations is shown in Fig. 6(a). The orange region represents the contamination of vapor and normal fluid. The red area indicates HeII at higher temperatures, and the blue represents He II in the bath. We measured the sound inside the dewar using a microphone mounted on the top of dewar flange. Typical examples of the measured signals are plotted in Fig. 6(b). The solid green line indicates the sound oscillations and the red line is the temperature fluctuation measured at

$x/L = 0.07$. It is clear that the temperature and sound oscillations are synchronizing with each other. The boiling process is visualized with a high-speed camera using a transparent duct made of acrylic resin. The temperature is also measured simultaneously. Analyzing the image and temperature fluctuations, we found that the sound is generated just after the bubbles appear. The bubbles cannot survive for long nor reach the exit of the duct. They condense in a short time and disappear, and sound is not generated at this time. These processes are schematically shown in Fig. 6(a). Heat flux is supplied to the helium from the bottom heater. In period ①, the vapor phase grows above the heater surface. When the vapor phase appears, it generates sound and the normal fluid component moves upward and transfers heat ordinarily in period ②. The He II flows into the duct from the bath at ③. This cycle transfers the heat from the heater and generates the noisy sound.

Here we present a simple model to predict the cyclic frequency f_p in Fig. 5 and the boiling process in Fig. 6(a). In this simple model, we assume there are two fluid states: the HeII and vapor phases. The vapor phase increases to height a from the heater, as shown in Fig. 6(c). The vapor height a is evaluated based on the assumption that the vapor region grows until the height where the heat flux q is equal to the heat flux q_0. Here, q_0 is the heat flux from the bottom and q is the heat flux from the vapor region to the helium bath calculated with Eq. (1) as follows.

$$q(L,h)^3 = \frac{1}{L}\int_{T_b}^{T_b+\Delta T(h,a)} \frac{S^4\rho_s^3 T^3}{A\rho_n} dT\,, \tag{2}$$

where q is a function of L and h. T_b is the bath temperature and $\Delta T(h,a)$ is the increment inside the vapor region. From the saturated vapor pressure curve, the pressure difference between T_b and $T_b + \Delta T$ corresponds to the pressure difference ΔP. This pressure difference is caused by the growth of the vapor region, which is equal to the liquid helium head pressure $\Delta P = \rho g(L - a) = \rho g L'$. From these relations, we can obtain the vapor height a. The period of vapor region growth is calculated by $T_1^* = a/V$. The upward vapor speed V is estimated by the time lag of the temperature fluctuation between the two thermistors located at $x/L = 0.07$ and $x/L = 0.73$. This time lag is obtained by the two-point correlation of the temperature measured by the thermistors. Therefore, the period of ① + ② is modeled as $T_1^* = a/V$. The normal fluid including the vapor phase moves up and reaches the maximum height $x = a$. Then it condenses and HeII falls into duct, as is expressed in process ③. In the period of process ③, T_2^*, is modeled as a free fall, $T_2^* = \sqrt{2a/g}$. The period of process ① + ② and process ③ are expressed as T_1 and T_2, respectively. They are measured directly from the time signals (see Fig. 6(b)). We compare these periods with the simple model described above. T_1 and T_2 are plotted against T_1^* and T_2^* in Figs. 7(a) and (b), respectively. Period T_1 is close to T_1^*. Periods T_2 and T_2^* are of the same order but they have different trends. That is, process ③ is not a free fall but the motions might be complex. The total time $\tau = T_1 + T_2$ and $\tau^* = T_1^* + T_2^*$ are plotted in Fig. 7(c). The model can

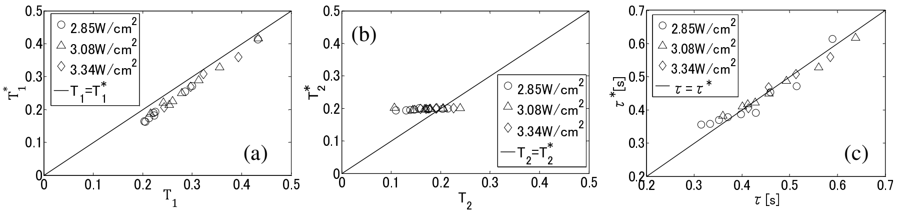

Fig. 7 Period of boiling process in ①, ② and ③. They are expressed as T_1, T_2 and T_3. Simple model predict these periods as T_1^*, T_2^* and T_3^*, respectively. (a)comparison of T_1 with T_1^*, (b)comparison of T_2 with T_2^*, (c) comparison of $\tau = T_1 + T_2$ with $\tau^* = T_1^* + T_2^*$.

predict the experimental data well. It is noted that the peak frequency f_p is equal to $1/(T_1 + T_2)$.

4 Summary

Noisy film boiling was found to occur in a small rectangular duct with periodic oscillation of temperature and sound generation. We predict the boiling process inside the duct from the temperature fluctuations, sound generation, and visualization. The periodic oscillation strongly depends on the helium pressure and the heat flux. It becomes smaller with higher heat power, and larger with higher pressure. A simple model to predict the periodic oscillation is presented. The periodic frequencies with this model are close to those of experiments in the present system.

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