Comparative Study of Heat Transfer Performance and Visualization Images of Superfluid Helium Boiling in Narrow Two-dimensional channel

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Abstract. In a narrow channel, boiling heat transfer in He II is much different from that in the case of an open bath. Even under saturated pressure condition, rapid temperature rise due to the onset of film boiling is not seen when the temperature reaches the lambda temperature, but only the temperature oscillation is detected. The behaviour of this state looks like the nucleate boiling, though it is known the steady nucleate boiling state is absent in He II in open bath. The high heat transfer coefficient in this quasi-nucleation boiling state above the lambda temperature suggests the range where this advantage in heat transfer appears is wider than that based on simple prediction of He II heat transfer. The appearance of metastable states of superheated He II and superheated He I should be considered in the case of a narrow channel. In this study, the visualization experiment result using a transparent heater and the transient temperature measurement data on a copper heater surface had been compared with each other. In the case of rather high heat flux, several film boiling modes were observed in a narrow two-dimensional channel. The peak of the heat transfer coefficient appeared around the lambda pressure. In the case of low heat flux, the heat transfer coefficient variation with the pressure shows sudden rise around the lambda point. The heat transfer coefficient under nearly saturated pressure condition below the lambda pressure is larger than that above the lambda pressure.

1. Introduction

Superfluid helium (He II) is utilized as a good coolant to cool superconducting magnets. He II cooling channels are generally very narrow in the case of cooling of superconducting magnets to achieve high current density. Thus, boiling heat transfer and critical heat flux for the onset of boiling in narrow channels were important research themes in the engineering fields. He II boiling heat transfer is much different from that in the case of an open bath. In the case of the narrow parallel two-dimensional...
channel, the He I layer plays a significant role on boiling heat transfer under atmospheric pressure condition. The critical heat flux around the lambda transition is detected weakly because of the existence of He I layer [1, 2]. In the case of an open bath, the critical heat flux around the lambda transition is quite close to the value at the onset of film boiling [3]. In other words, the quasi nucleation boiling region appears only in a narrow channel, though the nucleation boiling region is absent in an open bath. Even under saturated vapor pressure condition, rapid temperature rise due to the onset of film boiling is not seen when the bath temperature reaches the lambda temperature, but, instead, only temperature oscillation is detected [4, 5]. The behaviour of this state looks like the nucleate boiling, though it is known the steady nucleate boiling state is also absent in saturated He II in open bath. Those phenomena were considered to be caused by the effect of the appearance of metastable state [4, 5]. It is well known that in a low vibration level state in a special system, the metastable state of superheating can be created [6, 7]. However, Prof. Kobayshi’s group had found these kinds of phenomena in narrow two parallel channels even in rather noisy circumstance where mechanical noise caused by a vacuum pump was not suppressed sufficiently. These conclusions [4, 5] were derived on the basis of the precise temperature measurements. On the other hand, the superheated He II– superheated He I interface could be visualized [8] in a narrow parallel transparent channel. Visualization studies demonstrated that superheated He I was created rather easily and vapor bubbles were generated inside superheated He I in a narrow gap thinner than 0.6 mm [9]. Our previous study was focused on the appearance of superheating state. In the present study, the thermal performance including film boiling region and quasi nucleation region were compared in order to understand the characteristic heat transfer mechanism in a narrow channel.

2. Experiment setup

In this study, two experimental setups were used to compare the thermal performance measurement results with visualization results. Two measurements were conducted by using two independent Claudet type cryostats that are capable of varying the pressure from atmospheric to saturated pressures. One is the normal full metal cryostat, and the other is equipped with optical windows for visualization.

2.1 Thermal measurement

The narrow parallel channel for thermal performance measurement consists of copper disk as a heater block and GFRP wall as an insulator disk as shown in Figure 1. The copper disk is contained in the vacuum can for thermal insulation. The diameter of the heater block is 20 mm. The small gap between the heater block and the GFRP insulator block was controlled with a gap spacer. The gaps tested were between 0.05 and 0.50 mm [4, 5]. In this study, only the gap thickness of 0.15 mm is selected because the corresponding visualization experiment was done by only 0.15mm case.

This parallel channel was located horizontally. The time variation of the heat load was a triangle shape, when the total heating time was typically 2 hours.

![Figure 1](image_url)

**Figure 1.** The configuration of the narrow parallel channel (Cited from Ref. [4])
Figure 2. Configuration of the transparent two-dimensional narrow channel (cited from Ref [8])

2.2 Visualization Experiment

The transparent parallel channel was used for the visualization experiment is shown in Figure 2. The channel consists of the thick glass plate and the transparent heater made of vacuum deposited indium oxide onto glass. The heater size is 25 x 25 mm. The heater size is a little larger than that of the thermal experiment setup. The heat capacity is much smaller than the thermal experiment setup because the thickness is less than 1 μm so that the distribution of heat flux should be negligibly small in this case. The channel was set vertically to apply the shadowgraph method for the sensitivity of extremely small density variation such as across He II-He I interface. The constant heat loads were applied for 0.8 seconds with a programmed heat generation rate with the time variation of a rectangular shape controlled by a function generator, synchronized with a high-speed video camera. This heating time of 0.8 sec is good enough to reach a steady state for visualization. Each movie for visualization is taken with a frame rate of 1000 frame/s.

3. Results and Discussion

The typical boiling curve in the narrow parallel plate structure in saturated He II is shown in Figure 3. The large difference in temperature variation due to hysteresis was found between the cases of increasing and decreasing heat loads. In that transition region, the lower temperature branch could be recognized as a quasi-nucleation boiling branch. The heater temperature oscillated after the wall temperature (T1 in Figure 1.) reaches the lambda temperature [4, 5]. This quasi nucleation boiling branch is a unique feature in a narrow channel. On the other hand, the higher temperature branch must result from film boiling. In this study, the heat transfer in the transition region was focused on.

Figure 4 shows the pressure dependence of the heat transfer coefficient at two constant heat fluxes in the case on the film boiling branch. In this study, the heat flux q is calculated by the following equation,

\[ q = \frac{Q}{D \pi g} \]  

(1),

where D is the diameter of the copper disk and g is gap thickness. Around atmospheric pressure, the heat transfer coefficient slightly decreases when the pressure decreases. On the other hand, the pressure dependence becomes stronger at the pressure just above the lambda pressure. The peak heat transfer coefficient appears just at the lambda pressure. And below the lambda pressure, the heat transfer coefficient has strong positive correlation with the pressure.
Figure 3. Typical boiling curve in the narrow parallel channel under saturated pressure condition, \( T_b = 1.95 \) K

Figure 4. The variation of the heat transfer coefficient with pressure at two constant heat flux at 1.95 K on film boiling branch

On the other hand, visualization results can suggest which film boiling mode appears under each different pressure condition. Figure 5 (a), (b) shows still pictures of typical stable film boiling corresponding to the strongly subcooled film boiling mode in the case of the open bath experiment [10]. The liquid-vapor interface looks rather smooth, and the motion is slow. When the pressure decreases, the phase interfaces became sharper as shown in Figure 5 (b). Around 10 kPa, the weakly subcooled and the strongly subcooled film boiling modes occur intermittently. The weakly subcooled mode has an unstable interface as shown in Figure 6 and the interfaces were shaking, but vapor covered area were almost maintained. Below about 5 kPa, the noisy film boiling mode was observed as shown in Figure 7. In the noisy film boiling, liquid- vapor interfaces move more violently than that in the weakly film boiling so that the vapor covered area were changing. Sometimes, tiny He II droplets penetrate into the dry out area.

Figure 8 shows the boiling mode map in the narrow parallel channel on p-q diagram at \( T_b = 1.9 \) K. The stable region, that is the subcooled film boiling mode, became wider than that in the case of open bath [9]. It might be indicated that the walls suppress the unstable turbulent motion of liquid -vapor interface in a narrow channel. It is seen, according to this film boiling mode map, that the tendency of pressure dependence of the heat transfer coefficient is consistent with that in the case of open channel.
The peak heat transfer coefficient appears in the transition region in between the weakly subcooled and the noisy film boiling modes even though in narrow channel.

**Figure 5.** The strongly subcooled film boiling in narrow channel at 2.0 K (a) pressure $p = 101.3$ kPa, heat flux $q = 9.68$ W/cm$^2$ (b) pressure $p = 9.2$ kPa, heat flux $q = 35.48$ W/cm$^2$

**Figure 6.** Typical image of the weakly subcooled film boiling mode in the narrow channel, pressure $p = 9.2$ kPa, subcooling temperature $T_b = 2.0$ K, heat flux $q = 35.48$ W/cm$^2$

**Figure 7.** Typical image of the noisy film boiling in narrow parallel channel, pressure $p = 5.6$ kPa, subcooling temperature $T_b = 1.9$ K, heat flux $q = 11.21$ W/cm$^2$
Figure 8. Boiling mode map drawn on the $p$-$q$ diagram in the case of the narrow channel with a gap thickness of 0.155 mm at 1.9 K.

A unique mode appears around the lambda pressure in narrow channels where the vapor bubble repeats generation and collapse intermittently. It was confirmed that generated vapor is accompanying with superheated He II and superheated He I [8]. This mode should be the quasi-nucleation boiling state. Figure 9 shows the pressure dependence of the heat transfer coefficient along the quasi-nucleation boiling branch in the case of increasing heat input such as the lower branch in Figure 3. In this region, the heat transfer coefficient was much higher compared with the film boiling region because the vapor expansion occurs throughout outer liquid which has large heat capacity including the specific heat anomaly. The heat transfer coefficient has positive correlation with the heat flux, and the jump of the heat transfer coefficient can be seen at the lambda pressure. According to the visualization results, the frequency of bubble generation and collapse increases with the increase of the heat flux in this region as shown in Figure 10. When the frequency increases, the time duration when vapor is covering the heater surface should be increased. That might be why the heat transfer coefficient has positive correlation with heat flux. In fact, the data at the pressure close to saturation line indicates an opposite correlation. As this phenomenon could not be explained on the basis of the visualization, further investigation is required. On the other hand, the jump of the heat transfer coefficient could occur because of the difference in the vapor expansion in liquid He I and in superheated He I. The vapor expansion speed at the pressure above the lambda pressure was smaller than that below the lambda pressure as shown in Figure 11. The general tendency of the shrinking speed and the frequency were similar. When the vapor expanded, the nucleated small bubble pushed out He I layer accompanied with viscos friction above the lambda pressure. However, below the lambda pressure, vapor is generated in the metastable state of superheated He I. The metastable state readily occurs on phase transition. Thus, the vapor expands faster than that in the case of above the lambda pressure. On the other hand, after vapor covered the whole narrow channel, the outside of the liquid-vapor interface must change to bulk He II which has extremely high heat transport capability, and thus the vapor must condense into He II. Thus, during shrinking, the situations across a liquid-vapor interface and the outside became similar under both pressure conditions.
Figure 9. The pressure variation of the heat transfer coefficient for two fixed heat fluxes at 1.95 K on quasi-nucleation boiling branch.

Figure 10. Frequency of vapor generation and collapse as a function of heat flux at 2.1 K (Replotted from Ref [8])

Figure 11. The comparison of time variations of the vapor covering rate at the pressures of both sides of the lambda pressure.
4. Conclusion
In this study, thermal measurement and visualization study results were compared for the case of the narrow parallel channel in He II. In the film boiling region, the heat transfer coefficient affected the film boiling mode change. Even in the narrow channel, the several film boiling modes exist same as in open bath. And the tendency of pressure dependence of the heat transfer coefficient varies corresponding to which film boiling mode appears. In the narrow channel, the unstable film boiling mode region of the weakly subcooled and the noisy film boiling was smaller than that in open bath. The peak heat transfer coefficient of film boiling region appears at the transition pressure between the strongly subcooled, the weakly subcooled and the noisy film boiling, which pressure is about the lambda pressure.

The unique boiling state in the narrow parallel channel is the quasi-nucleation boiling state. According to the visualization results, the vapor repeats generation and collapse intermittently appears around the lambda pressure. In this boiling mode, the heat transfer coefficient of the case below the lambda pressure is higher than that above the lambda pressure. It cloud be considered on the basis of the visualization experiments that the difference of heat transfer coefficient is caused by the difference of vapor expanding speed.

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