Film Boiling Modes in Weakly Subcooled He II around Lambda Pressure

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Film boiling modes in both subcooled and saturated He II were experimentally investigated. It was found that there were two film boiling modes clearly bounded by a line just above the lambda pressure (p_). The one is a typical subcooled film boiling mode that normally appears at still higher pressure than p_. The other film boiling mode resembles noisy film boiling in saturated He II. It is found that in the vicinity of the region of the lambda point or the lower heat flux, noisy film boiling does not occur and subcooled region directly connects with silent film boiling one.

1. INTRODUCTION

For cooling of large superconducting magnets that are required for generating a high magnetic field, He II has been frequently utilized as a coolant in its subcooled state that is referred to as He II_p. When a superconducting magnet is quenched, boiling may occur in coolant as a result of large amount of heat generation due to Joule heating. It is a natural understanding that for He II in a pressurized state at a pressure higher than the lambda pressure p_ (=5.04kPa) the subcooled film boiling occurs. On the other hand, when He II is in nearly saturated state when the pressure is lower than p_, the noisy or silent film boiling occurs. In the past, studies on saturated film boiling in He II have been conducted frequently [1,2,3,4]. But little studies have been attempted to reveal the physical nature of subcooled film boiling [5,6].

In the present study the characteristics of film boiling in both subcooled and saturated He II have been experimentally investigated. It is a characteristic feature of the present study that a single cryostat was used for the measurement of the change of boiling modes in both subcooled and saturated He II. A pressurized He II cryostat was utilized, where the pressure (p_{bath}) can be set arbitrarily in a range from the atmospheric pressure (101kPa) down to the saturated vapor pressure of He II. In our previous study, it was reported that the noisy film boiling occurred even at the pressure just above p_ [7]. This result suggested that the boundary between the weakly subcooled film boiling and the noisy film boiling should be investigated in more detail. In the present study, the boiling mode map was drawn by taking the temperature (T) and the heat flux (q) as parameters. The condition for the appearance of the subcooled, the noisy and the silent film boilings in He II was investigated, and the influence of He I layer on boiling modes, which appeared in the case of subcooled film boiling was examined.

2. EXPERIMENTAL APPARATUS

The cryostat shown in Figure 1. is of a Claudet type designed for pressurized superfluid helium experiments. The detail of the cryostat system was described in Ref.[7]. The He II_p vessel is equipped with optical windows for visual observation. The visualization optical system, a compact Schlieren system, is also shown in Figure 1. The visualization image is taken by the high-speed video camera.

In the test section shown in Figure 2., the planar heater (25 mm x 25 mm) is located horizontally. The pressure and the superconductive temperature sensors are fixed at 10 mm and 5 mm above the center of the heater, respectively. For an experimental run, the planar heater is heated in the form of a square wave in time for 0.20 second.

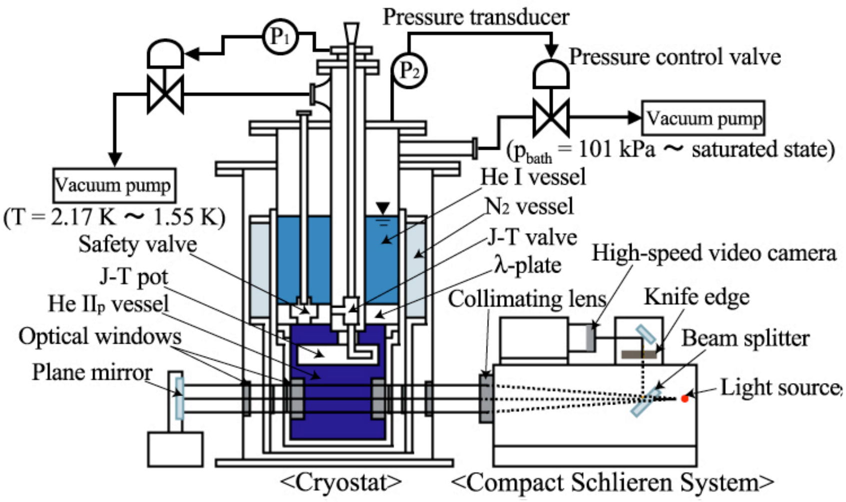

Figure 1. Schematic illustration of the pressurized superfluid cryostat system and the optics for visual study.

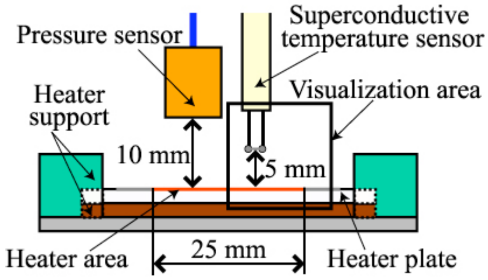

Figure 2. Schematic illustration of the test section in the He II_p vessel and the locations of the heater, and the pressure and superconductive temperature sensors.

3. RESULTS AND DISCUSSION

3.1 Two boiling modes just above p_

Two boiling modes appeared at the pressure just above p_. One mode is observed even at relatively higher pressure than p_. We understand this boiling mode is classified into the weakly subcooled film boiling in He II. A very thin vapor layer weakly oscillates only at the vapor-liquid interface. And the pressure oscillation is also very weak with a frequency around one thousand Hz, but the temperature variation is not detected. This film boiling mode is referred to as A-mode for the present. The other boiling mode appears when the pressure is slightly decreased below the A-mode state but still higher than p_. This mode change between the two is rather drastic. This mode is now identified to the noisy film boiling in saturated He II, which is characterized by a large vapor bubble to repeat formation and crush, and accompanied with loud noise and hard vibration with a frequency of several hundred Hz. As for the pressure and the temperature variation data compared with the A-mode boiling, the amplitude of the pressure oscillation is increased tremendously and the frequency is rather decreased. The temperature oscillation is also very large in magnitude and the frequency is just the same as the pressure oscillation. It is confirmed from the visualization study that the frequency just corresponds to the vapor bubble cycle to repeat formation and crush. It is reported that in the noisy film boiling in saturated He II the condition of the vapor layer is quite unstable and the vapor layer does not always exist on the heater [2]. Nevertheless, this boiling mode is referred to as B-mode boiling for the present.

3.2 Boiling mode map

The boundary dividing the two boiling modes is examined in detail. Figure 3. shows the boiling mode map plotted on a pressure-temperature (p-T) diagram, which is experimentally obtained. It is found that the boundary between A-mode and B-mode always exists at the pressure a little higher than p_, and the pressure value of the boundary increases as the drop of He II temperature. The boundary line adjacent to the saturated vapor pressure line (S.V.P) is the boundary between the noisy film boiling and the silent film boiling [8], which is designated as the lower boundary. The silent film boiling is characterized by the fact that significant pressure and temperature variations are not detected and by quite a weak thin vapor layer oscillation [3]. In this sense, the A-mode boiling is regarded as identical to the silent film boiling. On the other hand, when the upper and lower boundary lines are extrapolated toward high temperature, the two boundary lines seem to meet at a little lower temperature than _-point. In fact, in the experiment in the vicinity of the _-point, the noisy film boiling never arose, and the regions of the weakly subcooled and the silent film boiling modes are regarded as directly connected. Therefore, it is indicated that A-mode boiling and the silent film boiling are identical.

Figure 4. shows the boiling mode map plotted on a pressure-heat flux (p-q) diagram at He II temperature of 1.9 K. It is seen that the pressure value of the upper boundary increases with the heat flux. On the contrary, if the boundary line is extrapolated to the lower heat flux, it is, however, seen that the pressure value of the upper boundary will reach p_ at the heat flux of about 5 W/cm^2 at 1.9 K. It is experimentally confirmed that the film boiling occurs when the heat flux is larger than about 5 W/cm^2 at 1.9 K. Therefore, it is thought that the pressure value of the upper boundary is certainly p_, for the case of small heat flux. However, the noisy film boiling, which is a kind of noise-induced instability, occurs even at higher pressure than p_ due to a non-ideal effect of large heat flux. Shown in Figure 5. is the enlarged diagram around the lower boundary between the noisy and the silent film boilings as shown in Figure 4. It is indicated that the pressure of the boundary is the lowest for the heat flux about 10 W/cm^2, and it increases as the heat flux decreases. So, it is natural to consider that around the heat flux at which the film boiling begins to occur, 5 W/cm^2 at 1.9 K, the upper and the lower boundaries are connected.

From the discussion mentioned above, some suggestion for the nature of each boiling mode is given. The condition that fixes the upper boundary is whether the influential He I layer exists to the degree being decisive of the boiling mode adjacent to the heater. The noisy film boiling is a strongly unstable film boiling mode of which thermo-fluid dynamic state is determined exclusively by He II and helium vapor. However, when the heat flux is large, the noisy film boiling occur even at the pressures just above p_. In this state, He I certainly exists between helium vapor and surrounding He II, but the influence of He I on

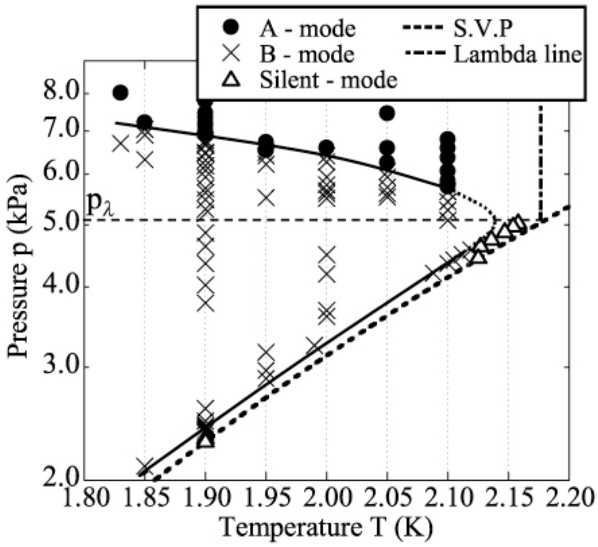

Figure 3. Boiling mode map on p-T diagram. q = 15 W/cm^2, planar heater of 25 mm x 25 mm.

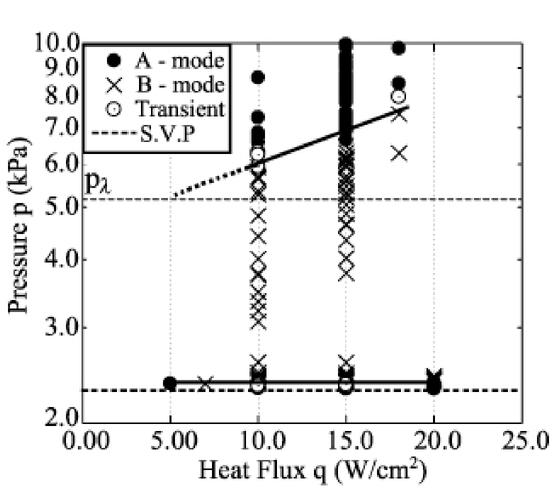

Figure 4. Boiling mode map on p-q diagram near critical q for the appearance of film boiling. T = 1.9 K.

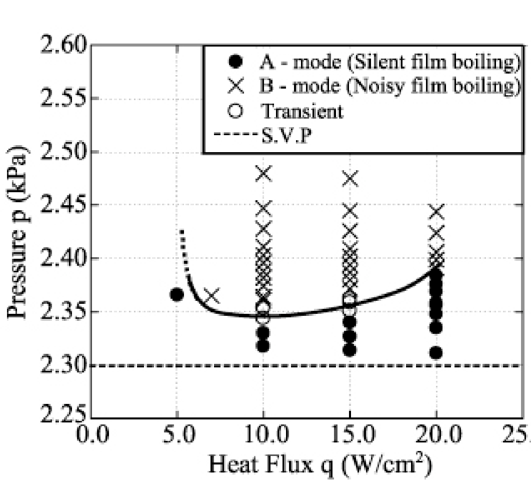

Figure 5. Detailed boiling mode map on p-q diagram near S.V.P. curve for the data presented in Fig.6. T = 1.9 K.

the boiling condition is quite a little. It is assumed that in the regions adjacent to the _-point and of the small heat flux which gives the onset condition for film boiling where the A-mode boiling and the silent film boiling are connected, the boiling is in a normal film boiling mode that occurs in common fluids. In the A-mode boiling including the silent film boiling, unstable behavior is recognized only on the surface of vapor film. On the other hand, in the B-mode boiling, that is to say the noisy film boiling, the vapor violently repeats the formation, growth and crush. In this sense, the noisy film boiling is a kind of large-scale unstable phenomenon that generates the large oscillation of the heater temperature and the heat transfer coefficient.

4. CONCLUSIONS

The variation of the film boiling mode at the pressure around the p_ or lower was investigated in detail. The following conclusions are drawn.

1. The subcooled and the silent film boiling are the same boiling mode and these film boiling modes are identical to the normal film boiling that occurs in common fluids. And the noisy film boiling is a kind of large-scale unstable phenomenon that generates the large oscillation in the heater temperature and the heat transfer coefficient, and it is the characteristic boiling mode in He II
2. In the regions very close to the _-point and of the small heat flux which gives the onset condition for film boiling, the noisy film boiling does not occur.
3. The boundary between the weakly subcooled and the noisy film boilings in He II exists just above p_. This boundary increases as the He II temperature decreases or the heat flux increases.

ACKNOWLEDGEMENT

The authors would like to thank Cryogenics Science Center and Mechanical Engineering Center at KEK for their professional support and assistance during this work.
This study was partially supported by the Japan Society for the Promotion Science, Grant-in Aid for Science Research and the auspices of the NIFS Collaborative Research Program.

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