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Dynamical behavior of He I–He II interface layer caused by forced heat flow

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The appearance and dynamical behavior of a He I–He II phase interface is experimentally investigated. The experimental mode in which nearly saturated He I initially at a little bit higher temperature than the lambda temperature is cooled by sudden evaporative cooling is primarily employed in the present experiment among several possibilities. In this mode where an interface appears and propagates downward, some dynamical aspects of an interface layer can be preferably investigated. The phenomenon is investigated by the application of Schlieren visualization method, and by measuring the temperature variation by superconductive temperature sensors and the pressure variation as well as the evaporating vapor flow rate which can be converted into the cooling rate.

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Introduction

The λ transition of liquid helium was investigated by several researchers both theoretically [1,2] and experimentally [3], in which a phase transition was supposed to be caused by heating. In the present study, the appearance and dynamical behavior of He I–He II interface generated by imposing forced heat flow as a means to create spatial inhomogeneity is experimentally investigated. A phase interface can emerge in such several modes as; i) cooling of nearly saturated He I initially at a little bit higher temperature than the lambda temperature by sudden evaporative cooling from a free surface, ii) cooling of subcooled He I by Joule–Thomson (J–T) heat exchanger during the process of phase conversion to create subcooled He II where a phase interface proceeds from below, and iii) heating of subcooled He II by a heater. The appearance of an interface was able to be visually observed in every mode. The experimental result conducted in the first mode is primarily described in the present report. Such dynamical aspects of the phenomena as the propagation speed of an interface and the dynamical stability are investigated by the application of Schlieren visualization method and by using a superconductive temperature sensor. It is visually observed that an interface appears and then propagates downward from a free surface in a cryostat if the cooling heat flux is larger than parasitic heat leak into the cryostat. The propagation speed is measured by a double probe superconductive sensor and the data is correlated with the cooling heat flux and the distance from the free surface. It is, however, suggested from the present ground experiment that the dynamical behavior, in particular the dynamical stability, as well as the appearance is affected by the such gravity effects as the natural convection and thermal stratification.

Experimental apparatus and procedure

A He I–He II phase interface was generated by a number of methods by imposing forced heat flow in this study, as mentioned in the introduction, such as; i) sudden evaporating cooling of He I, ii) cooling of subcooled He I by a J–T heat exchanger, and iii) heating of subcooled He II from a horizontal planar heater. In the first mode, of which experimental results are primarily discussed in this paper, nearly saturated He I at a little bit higher temperature than the lambda temperature is cooled by sudden evaporative cooling by evacuating vapor from a free surface with a vacuum pump. The overall view of the experimental setup for the first mode experiment is schematically given in Fig. 1. An electric valve controls quick opening of the evacuation line connected to a vacuum pump to start vapor evacuation for sudden cooling. The temperature of He I in the free surface region drops abruptly to pass the lambda point along the satu-

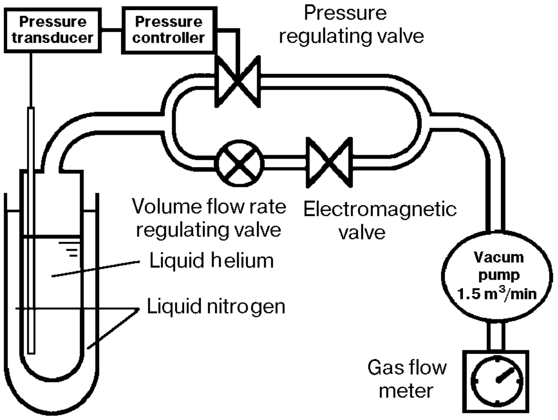

Fig. 1. Overall view of the experimental setup for the first experimental mode, evaporative cooling of He I.

rated vapor line, and then a phase interface appears and propagates downward from the free surface provided that the cooling heat flux is larger than parasitic heat leak into the cryostat. A schematic illustration of the propagation of an interface is given in Fig. 2. A well defined phase boundary layer can be observed by using high sensitivity Schlieren visualization method. The dark and white contrast in a Schlieren image is in proportion to the spatial derivative of the refractive index, or approximately of the temperature. For the measurement of the propagation speed of an interface, we utilize a superconductive sensor made of gold-tin thin film vacuum deposited on the side wall of a fine quartz rod with a diameter of 40 μm. The schematic drawing of a sensor is shown in Fig. 3. The electric resistance of a sensing element drastically changes as a function of the temperature around a super-normal transition region. The sensor has a very high sensitivity and a high time resolution as small as several μs, and the active range with a very high temperature sensitivity can be adjusted so as to cover the lambda point region by carefully controlling the thickness ratio between gold and tin films. And the minute trimming of the sensitive range can be performed by changing the bias electric current through a sensing element. The speed of interface propagation is calculated from the time interval of two onset signals of the resistance variations of two alined sensing elements, that is time-of-flight method. For this purpose, we utilized a double probe sensor of which two sensing elements are separated by about 5 mm in the direction of interface propagation. The cooling heat flux across a free surface is calculated in terms of the evaporating vapor flow rate measured with a gas flow meter and the latent heat of evaporation. Optical visualization to make the local density, or the temperature variation around an interface visible is applied to investigate the dynamical stability of it during propagation.

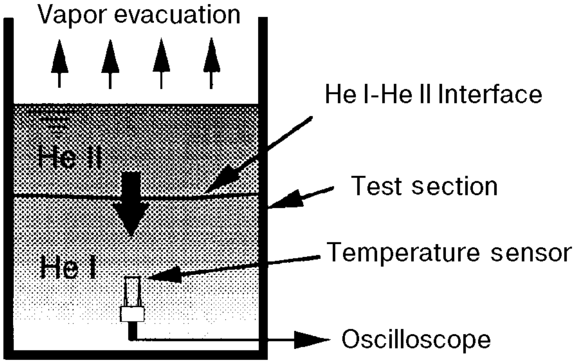

Fig. 2. Schematic illustration of a propagating interface downward and a superconductive temperature sensor.

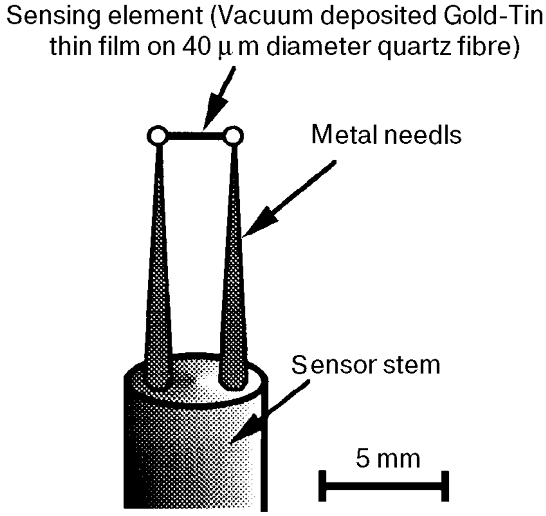

Fig. 3. Schematic drawing of a superconductive temperature sensor (single probe type).

Each experimental run begins with the production of a thermal equilibrium state at a prescribed temperature, usually only slightly higher temperature than the lambda temperature, with the vapor pressure control valve system. Just before the start of evaporative cooling, the vapor control valve is closed for the following measurement of the vapor flow rate. Then the measurements of the flow meter, the vapor pressure sensor and the superconductive sensor are started in response to the start of evaporative cooling. Visual observation is also carried out through a pair of optical windows of the cryostat.

Results and discussion

The data acquisition starts in response to the signal of quick valve opening. A typical example of the data is shown in Fig. 4, where the variation of the vapor pressure and the data from the superconductive sensor located at 10 cm below a free surface are plotted against the time. It is seen from the figure that the vapor pressure once drops upon the start of the evacuation and then further decreases very slowly during an experimental run for about 20 s. This result indicates that the temperature of a free surface once drops down to the lambda point to result in generating a phase interface and then continuously decreases a little below the lambda point through the period of evacuation. It should be noted that data from the superconductive sensor does not exactly indicate the temperature variation in particular in the region across an interface. The data should be rather considered to be subject to both effects of the heat transfer coefficient between the sensing element and surrounding medium (He I or He II) and of the temperature. The reason for this is that the sensor generates small amount of heat due to Joule heating, and thus the temperature of the element itself must be higher than that of surrounding medium when a sensor is immersed in He I because of poor heat transfer coefficient between the sensing element and He I. The element temperature rapidly drops down to the surrounding temperature in He II because of so called super thermal conduction in He II. Thus, the variation of the superconductive sensor output shown in Fig. 4 is much exaggerated as compared with that of the temperature in particular in the transition region. It is, however, fair to consider that the variation of the data except in the transition region is that of the temperature. It is seen that the temperature little drops before the arrival of an interface and it further drops quite slowly behind the interface in He II phase. The latter seems to indicate that He II behind an interface layer is in the superfluid breakdown state where small temperature gradient develops due to the effect of tangled mass of quantized vortices. Thus, we reached some conclusion as follows: Heat transfer toward an interface is highly confined within a narrow region just in front of an interface in He I. There exists a very small temperature gradient in He II phase behind an interface and the temperature of a free surface also drops quite slowly during an experimental run.

Fig. 4. Typical example of the experimental data; the time variations of the vapor pressure and the output from the superconductive sensor located at 10 cm below a free surface. $T_i = 2.18$ K, $q = 0.0177$ W/cm^2.

Fig. 5. Variation of the interface propagation speed with the net cooling rate. $T_i = 2.18$ K.

The variation of the interface propagation speed with the cooling rate is shown in Fig. 5. Here, the cooling rate is corrected to compensate the parasitic heat leak into the He II bath in the following manner as the cooling rate converted from the vapor flow rate minus the parasitic heat leak. This means that there exists a minimum cooling rate, equal to the parasitic heat leak, below which no interface appears. The propagation speed is measured by a double probe sensor located at 20 or 8 cm from a free surface, respectively. It is confirmed that a He I–He II interface propagates downward with a speed of several centimeters per second in direct proportion to the cooling heat flux and the speed varies with the distance from a free surface. In Fig. 6 the interface speed is plotted as a function of distance from a free surface for two cases of the cooling rates. It is seen that the interface speed decreases approximately in inverse proportion to the distance from a free surface except in the very initial phase of propagation near a free surface. It is experimentally suggested that the propagation speed is finite at the beginning of propagation from a free surface and then it approaches to the inversely proportional law.

Fig. 6. Interface speed as a function of distance from a free surface. $T_i = 2.18$ K, $q = 0.0166$ W/cm^2 and 0.0302 W/cm^2

It is found from Schlieren visualization pictures that a phase boundary layer propagates quite stably provided that the cooling rate is larger than a critical value. In the case of small cooling rate an interface layer once appeared is found to terminate propagation halfway in the Dewar and then gradually to disappear remaining stationary. The thickness of an interface layer seems to increase as the propagation with the lapse of time.

A phase boundary is also observed through high sensitivity Schlieren visualization in the case of cooling of subcooled (pressurized) He I by a J–T cooler in the subcool cryostat, where subcooled He II develops from the bottom of the test section. It is found that after the J–T cooling is stopped a phase boundary turns into an unsteady irregular pattern and then gradually disappears as a result of temperature rise due to parasitic heat input.

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