The formation of a closed vapor film during boiling of helium II on a cylindrical heater inside the porous structure

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Abstract. The results of experimental studies superfluid helium (He-II) film boiling are presented. Experimental studies of the He-II boiling on the surfaces of the cylindrical heaters in a bulk of He-II and under constrained conditions are described. Visualization of helium-II film boiling was first performed when observed from the end of a cylindrical heater. The scheme of the experimental facility, work cell and heater are given. The data in the form of files with visualization obtained from the experiments allow us to determine the outlines and the characteristic sizes of the films formed during boiling for different initial conditions.

1. Introduction
At Low Temperatures Department of National Research University «MPEI» experimental studies of the heat and mass transfer processes at superfluid helium (helium-II) boiling are carried out for several decades. For these purposes the experimental facility with a work cell was designed and constructed. At this experimental facility, data were previously obtained on the boiling of helium-II on a cylindrical heater in a bulk of He-II (in a "free volume"), under constrained conditions in a cavity inside a porous shell, as well as in a cell partially contacts the volume of helium-II in the Dewar vessel. The experiments to study the boiling of superfluid helium on thin wires under free volume conditions are performed in 1981 [1]. The experimental studies of He-II boiling on a sphere are conducted in 2005-2006 and a smooth stable vapor film on the spherical heating surface is obtained for the first time [2]. Process of helium-II boiling in the constrained conditions is described in [3, 4]. The results of He-II boiling experiments in a cell partially contacts the bulk (when the glasses on the end caps of the porous shell were removed) are presented in [5]. Recently, the experimental facility for studying the boiling of superfluid helium in free conditions and in constrained conditions have been fundamentally modernized. The new heaters of other sizes and designs were manufactured and installed in the work cell. In addition the calibrated temperature sensors based on the TVO resistors were purchased and installed in the cell for temperature measurement.

2. Design of the heating elements and calibrated temperature sensors
A detailed description of the experimental setup is given in [3]. The experimental cell was upgraded. The first variant of the new design heater is a thin-walled (wall thickness less than 0.5 mm) copper pipe outer diameter of 4 mm and length 30 mm (see figure 1.). A ceramic rod with a diameter of 2.8 mm is inserted inside the tube and coiled with a thin (diameter 50 microns) insulated nichrome wire about a meter long. The wire is limited by a heat-shrink sealing material, which ensures the density of
the wire turns and stable contact of the wire with the outer tube. This ensures uniform distribution of heat flux along the surface. From the ends of the tube is insulated with epoxy. The resistance of the heater at room temperature is 140 Ohms. Such resistance is sufficient to produce a heat flux density of up to 50 kW/m² at the helium temperature level. The temperature measurement of the new heating element in the first of the experiments described here are carried out by means of a thermoelectric sensor (thermocouple) copper+iron+lithium – copper. The thermocouple crown is glued to the outer surface of the copper tube (heater) near its (tube) end, which is attached to the L-shaped metal holder.

![Figure 1. Heater design: 1 – copper tube; 2 – sealing material; 3 – ceramic rod; 4 – end plug; 5 – nichrome wire.](image)

The second variant of the new design heater differs from the first in geometric dimension: the diameter of the thin-walled copper tube is 3 mm (but the length is also 30 mm). The resistance of this heater is 106 Ohms at room temperature. This heater produces a heat flux density of up to 85 kW/m² at the helium temperature level.

The heater with a diameter of 4 mm is installed outside the experimental cell horizontally on a special holder attached to the outer side of the experimental cell. In this case, the heater is located under the cell in the inner Dewar vessel filled with He-II. Thus, the experimental cell allows to study the boiling of helium-II on a heater inside a porous shell and on a heater hanging in a bulk.

For temperature measurements, calibrated T-sensors based on the TVO resistors are purchased. Sensitive part of the composite TVO sensor consists of ~20 nm size carbon grains (~4%) embedded in of aluminum-oxide matrix/filler (~90%), the rest is boron-lead binder (~6%). This is a semiconductor with a hopping type of conductivity. Such T-sensors are selected not only based on the results on thermal cycling of TVO resistor temperatures but also taking into account the calibration and fitting characteristics, and post-calibration [6].

The temperature of the second heater is measured by a calibrated cryogenic temperature sensor. This temperature sensor is attached to the outer side surface of the heater near the L-shaped metal holder. In the place of mounting the sensor, the surface of the heater is made flattened and slightly sanded. The temperature sensor is pressed to the surface of the heater with a miniature console.

A second calibrated cryogenic temperature sensor is mounted on the inner surface of the porous shell. A third temperature sensor is mounted on the outside of the experimental cell. The fourth temperature sensor is floating in the inner Dewar vessel. The fifth temperature sensor is mounted on the outer side surface of the heater located in the Dewar vessel.

### 3. Film boiling on a cylindrical heater in a bulk

The experimental study of film boiling on a heater in a bulk i.e. in the inner Dewar vessel filled with He-II were carried out. In this experiment visualization of helium-II film boiling was first performed when observed from the end of a cylindrical heater. Information about other experiments in which the observation was made in such manner is not known to the authors.
The procedure for conducting the experiment did not differ from that used in previous experiments [3]. The experimental session started when the heater was turned on. At this time, the controlled parameters in the system were: pressure in the Dewar vessel, heater load, heater temperature. At the same time, video shooting was performed with synchronous recording of the received information in the form of a table file.

The temperature of helium-II before turning on the heater in our experiments was 1.6 – 1.8 K. The immersion depth ranged from a few centimeters to a few tens of centimeters. When a heat load was applied to the surface of a heater immersed to a certain depth in a bulk of superfluid helium, a vapor film of finite thickness appeared (see figure 2.). After the heater was turned on, the vapor film increased in size for tens of seconds while maintaining its outline. At the same time the liquid-vapor interface remained smooth. This film growth was caused by an increase in the temperature of helium-II due to an increase in pressure in the cryostat (from ~1.2 to ~4.6 kPa) due to evaporation of He-II and a corresponding insignificant decrease in the liquid helium level. At the same time, the processes of heat and mass transfer in the vapor film and in the surrounding liquid can be considered as quasi-stationary, as the changes of parameters were much slower than the establishment of a new steady (stationary) state inside the vapor film. After the film reached a certain size, there was a breakdown of the noiseless film boiling regime and a transition to noise boiling: the film lost smooth outlines and convective liquid flows were observed around it.

![Figure 2. Stages of vapor film growth in the bulk: a) 2 s; b) 5s; c) 11 s; d) 36 s.](image)

Thus a new experiment aimed at studying the He-II film boiling on the cylindrical heater hanging in a bulk allowed to observe a stable vapor film from the end of the cylinder for the first time ever. It
was possible to see the formation of the smooth film, its growth and the disruption of its stable state, i.e. the change of the boiling regime.

4. Boiling on the heater in a cavity inside a porous shell.

The second experiment was performed for heater located along the axis of the cylindrical porous shell. After loading the heater, the vapor pressure in the cryostat, the current and voltage, the heater temperature, the porous shell inner surface temperature, the temperature of outer surface of the shell, and the temperature of liquid helium in the Dewar vessel were recorded. In cases when the heat flux density was less than the peak heat flux value, a slight increase in the temperature of the heater was observed, but boiling of helium-II did not occur. When the load are increased to a certain value corresponding to the peak heat flux, which depends on the immersion depth of the heater in helium-II, the following picture of the development of events appears. Vapor bubbles forms on the surface of the heater. The increase in the volume occupied by the vapor phase lead to the formation of a closed vapor film. Then the vapor film increases in size by remaining closed and maintaining a coaxial shape (see figure 3 a). After a significant increase in the temperature of the heater, the visible cross-section of the vapor formation take a drop-like shape, which is converted into an inverted bell-shaped one. Then vapor congregated in the upper part of the inner cavity of the porous shell gradually displacing liquid helium from the cavity (see figure 3 b). In this case the heater has to be turned off. Thus, the picture of the boiling process completely differs from that observed in previous experiments.

![Figure 3. Helium-II boiling on the cylindrical heater in a cavity inside a porous shell.](image)

In these experiments the temperature of the heater increases up to 20–25 K, as indicated by the temperature sensor (see Figure 4.). In some experiments a maximum heater temperature of 130 K was
achieved. The temperature of helium-II near the inner surface of the porous structure and the temperature of helium in the free volume also increased.

In these cases it is reasonable to allow the transition of superfluid helium in normal state near the heater surface and the subsequent boiling with the formation of bubbles. This assumption in some cases is almost confirmed by the readings of temperature sensors: the temperature of liquid helium near the inner surface of the porous shell sometimes reach the $\lambda$-transition temperature (see Figure 4.). Hence the temperature of the interface separating the vapor from the liquid helium can be higher than the $\lambda$-transition temperature. It can be assumed that the hydrodynamic resistance of the porous shell significantly interferes with the normal flow. In accordance with two-liquid model of L.D. Landau [7–9] heat is transferred in helium-II by normal flow i.e. flow of normal component of He-II. The porous shell prevent the heat transfer from heater. For this reason the liquid helium overheat near heater surface. Perhaps the permeability of the porous structure in our experimental cell is too small to support a stable heat transfer and film boiling.

If the heater was not turned off the pressure in the Dewar vessel began increasing quite rapidly and the temperature of saturated liquid helium was rising. The transition of liquid helium in the Dewar vessel from superfluid in normal state is occurred at the temperature 2.17 K and this temperature was observed at that time according to the readings of the temperature sensor freely hanging in the He-II. Thus, in some cases all superfluid helium filling the cryostat passed into the normal state.

![Figure 4](image)

**Figure 4.** The temperatures of the heater and liquid helium in a free volume and near the inner surface of the porous shell when observing boiling.

**Conclusions**
The recent experimental study of helium-II boiling on cylindrical heaters immersed in a bulk or located in the cavity inside a porous body and new experimental results are described. These experiments show that the noiseless film boiling is observed in a free volume and in the constrained conditions. In the last occurrence the both regime of boiling occurred. Preliminary analysis indicates
the existence of a smooth stable vapor film on the heater placed in a cavity inside a porous shell. But the experimental results show that at different depths of immersion of the experimental cell into the He-II, the boiling pattern characteristic of helium-II is not usually observed. Instead, the vapor film remain open in the major part of our experiments, and the vapor accumulate in the upper part of the internal cavity of the experimental cell. Thus, the helium-II film boiling in the constrained conditions comparable to film boiling of ordinary liquids in a bulk. Presumably, the superfluid helium transition in normal state near the heater surface was occurred. Perhaps in our experiments the porous shell hydrodynamic resistance significantly interfered with the normal flow. This effect prevented heat transfer from a heater and the liquid helium overheating near heater surface. Hence the boiling of normal liquid helium has observed.

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