Boiling of He-II on a cylindrical heater inside a porous shell with constant operation condition

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Abstract. This paper presents new efforts undertaken in the study of boiling in superfluid helium on the surface of a cylindrical heater located along the axis in a cylindrical cavity inside a porous shell. New experimental results are obtained with maintaining constant temperature of the helium-II and helium vapor pressure. The modernization of the experimental setup and vacuum system carried out to obtain a series of longer experiments with maintaining a stationary state are described. The basic experimental configurations are specified. Visualization of helium-II film boiling in constant operation condition is represented.

1. Introduction
The investigation of boiling in superfluid helium (He-II) is important for a number of problems of heat and mass transfer, e.g., in the development of cryostating systems for superconducting devices. Interest in studying the boiling of superfluid helium in porous structures is due to a change in the nature of heat transfer in it and a decrease in the rate of evaporation, which leads to improved performance of cryostatting equipment.

Heat and mass transfer at film boiling of helium-II and flow of He-II through porous media was investigated in many studies. For example, in paper [1] the problem of heat transfer through a porous medium saturated by superfluid helium is investigated. It was assumed that the two-fluid model of Landau describes the behavior of He II at low heat flux or small velocity in a porous medium. The method of volume averaging has been applied to the pore-scale equations. The permeability coming up in the upscaled model was calculated on an array of simple unit cells in the temperature range from 1.4 K to 2.1 K and was found to be equal to the intrinsic permeability (Stokes’ flow), independently of the heat flux and temperature. The measurements of permeability performed independently with a cold gas and in He-II were in reasonable agreement with the theoretical predictions. However, the experiments indicated an increase of the permeability with He-II as temperature decreases below 1.8 K.

Heat flux through superfluid helium contained in porous media is examined in [2]. In particular, heat transfer experiments were performed on He-II contained in a bed of polyethylene spheres of uniform size arranged in random packs. Measured results include the steady-state temperature drops across the three random packs of spheres (35, 49, and 98 microns diameter) and the associated steady heat inputs. Bath temperatures range from 1.7 to 2.1 K to help grasp the superfluid effects. Two pure flow regimes (laminar and turbulent) were decipherable from the heat flux dependence of the temperature gradient.
Heat transfer in superfluid helium in a volume of a porous medium with decreasing pressure is studied in [3]. Heat flow induced pressure drop through superfluid helium contained in porous media was examined. In this experiment, heat was applied to one side of a He-II column containing a random pack of uniform size polyethylene spheres. Measured results include steady state pressure drops across the random packs of spheres (nominally 35 lm, 49 lm, and 98 lm diameter) for different heat inputs. Laminar, turbulent, and transition fluid flow regimes were examined. Turbulent results are fitted to models with empirically derived friction factors. A turbulent model considering only dynamic pressure losses in the normal fluid yields the most consistent friction factors.

An experimental investigation of heat transfer through porous media in superfluid helium has been conducted in paper [4]. Several types of porous media with different characteristics were tested and, in particular, samples with pore size diameters of 0.1 lm, 1 lm, 2 lm, 10 lm and 20 lm. Temperature and pressure were measured between an insulating inner bath and the cryostat bath, communicating only through the porous medium. The cryostat bath is held constant all along the measurement and, for each sample, the tests are performed for bath temperature from 1.4 K to 2.1 K with 0.1 K increment. In the laminar regime, the permeability of the samples was determined and it was found that the permeability is constant for bath temperature above 1.9 K whereas it increases as the bath temperature decreases from 1.8 K to 1.4 K. For samples with a pore size diameter of 10 and 20 lm, measurement permits only to observe the turbulent regime and the analysis exhibits a constant average tortuosity for each samples, independently of the bath temperature.

Thermal measurement and visualization study results were compared for the case of the narrow parallel channel in He-II [5]. Even in the narrow channel, the several film boiling modes exist same as in open bath. 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 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.

For several decades at the Low Temperature Department of the Moscow Power Engineering Institute, research teams have been conducting experiments to study the processes of heat and mass transfer during the boiling of helium-II. For example, the experiments have been performed to study the boiling of superfluid helium [6] on thin wires. These experiments were carried out under conditions of a bulk, just as subsequent experimental studies of He-II boiling on a sphere [7], where a smooth stable vapor film on the heater surface has been obtained. In addition, the dynamics of the He-II interface under confined conditions. The flow of helium-II in a capillary with vapor was observed in the presence of a longitudinal heat flux [8], where in the course of the experiments an anomalous helium-II flow to the heater was obtained, in contrast to the behavior of ordinary liquids, which was confirmed by analytical calculations [9,10].

Development of cryogenic systems for special purposes associated with a high level of heat fluxes at helium temperature level, including space applications, makes it necessary to investigate the heat and mass transfer processes at the superfluid helium in porous media and the He-II film boiling within the porous shells. In this paper the problems of experimental studies of the boiling of superfluid helium on a cylindrical heater placed in a porous body are considered. Previously, to conduct such experiments, the scientific group of the Department of Low Temperatures designed and installed an experimental cell and a stand, described in detail in the article [11]. In experiments on this stand, various boiling modes of helium were obtained, including a mode with a thin, about hundreds of microns film on a cylindrical heater inside a porous structure. The description of these experiments is presented in [12,13]. However, in these experiments, the limited rate of pumping of helium vapor from the cryostat led to an increase in pressure in the cryostat when the electrical load was supplied to the heater. As a result, an increase in temperature was observed in the entire volume of liquid helium. The duration of the experiments was limited by the time of reaching the lambda point temperature by the He-II temperature in the cryostat, since after that the superfluid helium passed into the normal fluid state.
2. Modernization of vacuum system

To obtain a series of longer experiments with maintaining a stationary state, the part of the stand responsible for the removal of helium vapor was completely modernized. A new upper flange was designed and manufactured to fixate the Dewar's helium vessel. It is made of stainless steel and had the required elements: two connectors with KF50 flanges for mounting nitrogen traps, a branch pipe for connecting a pressure sensor "Baratron" and a cup mercury pressure gauge, cylindrical sealed port with 32 contacts for connecting sensors that record the temperature, pressure and level of liquid helium inside the cryostat, a valve for a fluid transfer device connected to a transport helium vessel and an emergency pressure relief valve. All split connections are sealed with viton rings. The glass helium Dewar was clamped into a vacuum rubber ring inside the flange. This design provided sufficient tightness for experiments. In addition to improving the tightness of the cryostat, the pipeline flow rate was also increased. The circuit with a single pipeline based on KF20 connectors was replaced with two identical systems connected in parallel.

![Figure 1. Experimental setup and vacuum system.](image)

Every system consisted of a nitrogen trap with a volume of 4 liters, a ball shut-off valve, and a flexible metal pipeline with a length of 3m connected to a spool vacuum pump with a capacity of 20 l/s. The theoretical calculation of the pumping speed through this system on two branches has given a result of 39.4 l/s. This value is almost 10 times higher than that of the old vacuum system. This enables conducting the experiment for a relatively long time (about 20 minutes), holding constant operation condition.

3. Basic experimental configurations

The described experiment is conducted on a copper cylindrical heating surface with a diameter of 3 millimetres and a length of 30 millimetres, which was placed inside a cell with a porous shell. The scheme of this heater and the description methodology of experiment are described in the article [14].
However, the new heater has a higher resistance at the helium temperature level of 179 Ohms. Under the conditions of our experimental unit, it is possible to transfer a lower limit specific heat flux (up to 71 kW/m²) to helium in contrast to the previous heater (85 kW/m²), and to more precisely control the operation conditions in the experiment. Prior to the experiment, vapor is pumped out of the cryostat to a pressure of 750 Pa. If we focus on the saturation line of helium, this point equates to a temperature of 1.6 K, which is confirmed by thermoresistive sensors located in the free volume of the liquid. The level of helium above the central axis of the heater at this time is 315 mm.

During the experiment, an electrical load was gradually applied to the heater. The starting voltage value at the conditional zero point of the time scale was 5 V. Then, within four minutes, the voltage gradually increased to a value of 25 V. Then this value was held constant, providing a constant specific heat flux from the heater equal to 12 kW/m².

After the load was applied to the heater, the evaporation from the surface of the entire volume of helium inside the Dewar intensified. At the same time, since the vapor pumping rate did not change throughout the experiment, the saturated vapor pressure in the cryostat increased to a constant level of 4200 Pa (see figure 2.). The temperature of liquid superfluid helium also gradually increased to an average value of 2.12 K. (see figure 3.)

![Figure 2. Pressure change during the experiment.](image)

![Figure 3. Saturation temperature during the experiment.](image)
Thus, the operation conditions were kept constant inside the cryostat: vapor pressure, liquid temperature, and specific heat flux from the heater. However, due to the method of cooling helium by pumping out its vapor, there was a constant decrease in the liquid level relative to the center of the heater axis. The process behavior is represented in the figure 4.

4. Experimental results
During the experiment, the readings of the thermoresistive sensor installed on the lower part of the heater were recorded and the area inside the cell was captured on video to record the moments of the steam film appearance. As a result, we obtained data on the temperature of the heating surface, as well as an array of frames from which we can draw conclusions about the boiling modes of superfluid helium at constant medium parameters, but decreasing hydrostatic pressure. At the initial stages (up to 600 seconds), with a gradual increase in the voltage and the transition to constant operation conditions, no signs of boiling were observed (see Fig 5.a). Then, when applying 25 V, the temperature of the heater increased to 5.5 kelvins and after a while, a closed vapor film with capillary waves on its surface with a thickness of 400 microns began to form shortly (for fractions of seconds) on its surface (see Fig.5.b).

Figure 4. Decrease in helium levels with time.

Figure 5. Film change: (a) absence; (b) generation; (c) noise boiling.
At the time of the film appearance, the heater temperature increased slightly, but after rapid collapse it returned to the level of 5.5 K. This effect was observed at intervals of 2-14 seconds and continued until the helium level inside the cryostat fell to values of about 110 mm. After this point, presumably due to a decrease in the pressure of the liquid column, the steam film no longer collapsed, but began to grow. The developed boiling was observed with the formation of a film in the form of an elongated drop (the radius of the measured part was 1.99 mm) with intensive vapor separation into the upper part of the experimental cell (see Fig. 5. c). In the continuation of the experiment, with a further decrease in the level of helium, the film ruptured, and the vapor region increased in size, displacing the liquid from the cavity inside the cell. The experiment was terminated at a critically low level of liquid helium in the cryostat, when the heater was completely dry.

Conclusions
A new experiment on the boiling of a superfluid He-II on a cylindrical heater inside a porous structure is presented. For its implementation, the vacuum system of the stand was upgraded, and the pumping speed was calculated to confirm the possibility of maintaining the constant operation conditions. Generalized data on the basic experimental configurations are given: vapor pressure, liquid temperature, and specific heat load and immersion depth of the heater. Based on the experimental video frames of the film boiling, it can be concluded that the developed boiling with the formation of a vapor film in the form of an elongated drop occurs despite the constancy of the constant operation conditions. Thus, the transition to the noise film boiling regime and the “opening” of the vapor film observed in previous experiments cannot be considered a consequence of the instability of the operation conditions in these experiments. At low immersion depths with a constant value of the heat flux from the heater, the film quickly goes into a noisy film boiling regime and it becomes impossible to keep a certain constant size of the vapor film. While at "large" immersion depths and a constant value of the heat flux, no boiling is observed.

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