An experiment on He-II film boiling inside the porous structure

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Abstract. The experiments on film boiling of superfluid helium (He-II) on the surface of a cylindrical heater inside a cylindrical porous shell are considered in this paper. The methodology and results obtained in a number of experiments, in particular, video footage of the boiling process is presented. The conclusions about the influence of the experimental cell structure on the character of boiling regimes, namely on the shape of the vapour film around the heater and its integrity are drawn. In the constrained conditions only the boiling with "open" film was implemented. While the noise film boiling with closed vapor film and boiling with "open" film were observed when the glasses on the end caps of the porous shell were removed.

1. Introduction
Superfluid helium, which received its name due to its ability to leak through the pores and capillaries of small size without revealing the properties of the viscous friction, represents one of the phases of $^4$He, which exists at very low temperatures and it is a quantum liquid, i.e. a substance in which macroscopic quantum effects are manifested. A pseudo-convective heat transfer mechanism predominates in superfluid helium. This mechanism provides a very high efficiency of heat transfer surpassing in several orders of magnitude the transfer efficiency of the ordinary diffusion mechanism which does not play a significant role in He-II. Due to these special characteristics, superfluid helium is the most appropriate medium for studying the specific features of transport phenomena, which is difficult to study using ordinary liquids. Solution to the problems related to the heat and mass transfer processes through the interface of vapor–He-II is not only of fundamental importance but also it is essential to ensure the proper functioning of the cryogenic equipment.

Opportunities to explore the process of vapor–liquid transfer through interfaces in zero gravity appear in a program for the development of the ISS Russian segment. The main result of the He-II boiling studies in microgravity conditions should become the information about the transfer processes on the interphase surface under the conditions of significant thermodynamic non-equilibrium. However, these studies become impossible without solving the problem of keeping He-II near the heating surface. On Earth, the necessary impact on the film is provided by hydrostatic pressure difference. In space, the equivalent of such impact can be created due to the peculiarities of superfluid helium behavior in microporous structures [1, 2]. The presence of a non-ideal thermomechanical effect, which consists in the fact that helium-II can flow to the heater under certain conditions, allows solving this problem by placing the heater inside the porous shell [3].
2. Description of experimental stand
2.1. Experimental stand of the Low Temperatures Department of MPEI

For the study of film boiling of He-II in a cylindrical heater, an experimental stand is assembled. It includes a cryostatting system, optical system, video-recording system, and system for generating the heat flux and temperature measurements (see fig. 1).

The cryostat providing the necessary temperature less than 2.17 K consists of an inner working vessel 65 mm in diameter filled with helium and outer vessel filled with nitrogen and serving as a protective thermal shield. Both Dewar vessels have observation ports approximately 20 mm wide. This makes possible observation and video recording of the processes in the experimental cell in the inner vessel.

The Dewar vessel filled with helium is hermetically sealed with a metal cap (a cylindrical coupling with flanges). The cap is fitted with welded tubes, one of which is used to pour liquid helium, and another encloses the suspension tube to which the experimental cell is attached. The suspension is made in the form of a 10 mm diameter thin-walled tube which houses electrical wires. The system for simultaneously moving the video camera and experimental cell allows video recording of the heater at any position of the experimental cell in the Dewar vessel.

The pressure in the inner vessel is monitored visually using an MChR-4 mercury cup manometer in a wide range of pressures (from atmospheric to operating pressure in experiments) and automatically using a capacitive pressure sensor "Baratron" (model 235). In the range from 26.66 to $10^4$ Pa, the pressure measurement error is 0.5%.

Figure 1. The scheme of the experimental stand: 1 – transport vessel; 2 – mercury manometer; 3 – capacitive pressure sensor "Baratron"; 4 – experimental cell; 5 – suspension, 6 – Dewar helium vessel; 7 – Dewar nitrogen vessel; 8 – nitrogen trap; 9 – vacuum pump.

2.2. Experimental cell

The configuration of the experimental cell is shown in fig. 2. The cell body is a cylindrical shell with an internal diameter of 38 mm, made of copper. Holes with a diameter of 3.5 mm are drilled in the side wall of the shell. The end covers having observation ports made of thin Plexiglas (1 mm thick) are screwed to the body. The cylindrical heater located on the axis of the shell is mounted on an L-shaped metal holder (curved rod), which is inserted in the shell through a hole in the end cover. The holder is insulated from the body with epoxy resin. The inner thread for the screws securing the covers is cut directly in the body of the cell.
The porous structure placed in the body and soldered to it is a thick-walled shell (7 mm thick) obtained by winding 10 layers of steel woven mesh (diameter of the warp yarns is 0.12 mm, diameter of the weft yarns is 0.1 mm, diameter of the weave is 0.44 mm). If we vary the thickness of the porous shell of woven mesh in different experiments, it is possible to achieve a steady state of the vapor film at different values of the heat flux from the heater [4]. The cell is sealed with spacers made of indium wire, which before screwing of the covers, is laid in the circumferential grooves carved in the cell body (not shown in Fig. 2).

The feed load and resistance of the heater are measured with a four-pass comparison circuit. An advantage of this circuit is that the measured voltage takes into account the voltage drop in the wires. The measuring circuit is powered by B5-43 and B5-44 direct current sources. The reference resistance is a P321 coil with the resistance of 1 Ω with an accuracy class of 0.2.

3. The experiments methodology

Preliminary flushing of the inner Dewar vessel to remove water vapor and other impurities is carried out using gaseous helium supplied from the STG-40 vessel. For this, the inner vessel is first evacuated to the pressure of $10^2$ Pa and is then filled with gaseous helium from the STG-40 vessel to atmospheric pressure. This procedure is carried out at least four times to remove water vapor from the cryostat and other condensing compounds.

**Figure 2.** Scheme of the experimental cell: 1 – housing, 2 – heater holder, 3 – a branch pipe with a sealing insulation in the holder hole heater, 4 – glass rear viewing Windows, 5 – retaining glass lid, 6 – front cover, 7 – glass front viewing window, 8 – porous shell, 9 – hollow metal rod, 10 – heater, 11 – back cover.

The next step is filling the outer vessel with liquid nitrogen. The pressure drops because of helium cooling in the inner vessel. It is controlled by a mercury cup pressure gauge.

The final stage is filling the inner vessel with liquid helium from the transport vessel STG-40 with the help of an overflow siphon. The temperature of $\lambda$-transition is achieved by pumping helium vapor through the vacuum post. The transition of helium in a superfluid state is visually observed after cessation of liquid boiling.
The operating temperature range in the Dewar helium vessel is achieved by continuous pumping of vapors. The experimental session begins when the heater is switched on. At this time the following parameters in the system are controlled: pressure in the cryostat, load of the heater, temperature of the heater. At the same time, there is video recording with synchronous recording of information in the form of a tabular file. The supply of load to the heater leads to formation of a vapor film on the heater and output of vapor through the wall of the porous shell from the experimental cell to the cryostat. This process is accompanied by an increase in pressure over the mirror of liquid, so the continuous pumping of helium vapors continues during the experiment, which leads to the decrease in the liquid level in the cryostat. After reaching the quasi-stationary boiling condition, the experimental series can be considered completed. After the thermal load is turned off, the liquid helium fills again the cavity inside the cell, the vapor film gradually collapses, and the liquid encounters the heater. To prepare the next experiment, it is necessary to pump out the helium vapor to the desired level (3100 Pa or lower) and, in some cases, to immerse the cell completely into the liquid in the cryostat. [5].

4. Results of experiments
Several experiments were conducted in a sealed cell (with screwed end glasses). The following stages of the boiling process are developed when the heat flux is applied:

1. Visually distinguishable objects similar to vapor microbubbles are formed on the surface of the heater.
2. Increase in the volume occupied by the vapor phase leads to formation of a vapor film with a vapor–liquid interface.
3. The visible cross-section of the vapor film takes a drop-shaped form, which is converted into an inverted bell-shaped one.
4. The volume of vapor in the upper part of the inner cavity of the shell increases, the liquid is displaced from the cell by vapor.
5. In fact, a vapor film is a deflection of the interface of the liquid-vapor in the inner cavity of the cell, which is analogous with the study about defining the shape of interface in a substantially non-equilibrium conditions [6, 7] with the difference that in our experiments all heat and mass transfer processes occur in the inner cavity of the porous shell [5].

In other experiments, glasses from the end covers of the experimental cell were removed. In these cases, boiling with an open vapor film was observed at relatively large immersion depths and large values of the heat flux from the heater ($5\times10^4$ W/m$^2$). The appearance of the cylindrical heater from the end with a film of vapor around it is shown in fig. 3.

![Figure 3. Boiling with a "open" vapor film.](image-url)
At low immersion depths, the heater was supplied with a lower load, and short-time boiling with a complete vapor film was observed (see fig. 4.).

Figure 4. Boiling with "closed" vapor film.

In both variants of the experiment the pressure in the Dewar vessel began increasing quite rapidly just after the heater was turned on that is why the temperature of saturated liquid helium was rising. Then, there was a short-time noise film boiling, after which the closed vapor film "opened" and there was a mode "with an open vapor film" (see fig. 3.). Thus, there was a breakdown of the "usual" noise film boiling of He-II. Probably, such a boiling condition stems from the changes in the properties of He-II due to the temperature increase, but the mechanism of the rupture of the originally closed film remains unclear for us.

The "usual" noise film boiling and boiling "with open film" were observed when the glasses on the end caps were removed. When the glasses on the end caps of the cell were present, only the boiling condition "with an open film" was implemented (see fig. 5.).

Figure 5. Boiling with "open" vapor film under closed end covers (a heat flux of about $8.7 \times 10^3$ W/m$^2$).
It should be mentioned that a heater with a rough surface was used in these experiments.

In the experiments with the removed glasses, a heater with a smooth surface was used, but, apparently, the nature of the heater surface is not a decisive factor determining the boiling condition in the described experimental cell. For the final conclusions, it is necessary to conduct experiments on the heater with a smooth surface in a closed cell (i.e., in a cell with glasses on the end caps). If in such experiments, there is no closed vapor film, it will be possible to make a conclusion about the cardinal impact of the porous shell on the heat exchange in boiling He-II and absence of connection between the roughness of the heating element and the "opening" of the vapor film.

5. Conclusion

The processes of hydrodynamics and heat transfer which occur at film boiling of superfluid helium on a cylindrical heater in constrained conditions are considered. It is expected that such conditions will allow the solution to the problem of He-II retention near the heating surface in microgravity. The Low Temperatures Department of MPEI has been undertaking researches for a long time to verify this hypothesis. The recent experiments with superfluid helium and new experimental results are described. In the constrained conditions the boiling "with open film" was invariably implemented. I.e. the visible cross-section of the vapor film was a drop-shaped or bell-shaped form. In the latter case a vapor film was a deflection of the interface of the liquid-vapor in the inner cavity of the cell. When the glasses on the end caps of the porous shell were removed the noise film boiling with closed vapor film and boiling "with open film" were observed. The conclusions about the possible reasons for the unforeseen boiling conditions are drawn.

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