Experimental Study of Superfluid Helium Boiling on a Cylindrical Heater within the Porous Shell

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Abstract The problems of the carrying out experimental investigations of the superfluid helium boiling on a cylindrical heater placed in the porous body are considered. The scheme of installation is presented. The experimental cell, control and measuring devices, and devices for video recording and data processing are described. The technique of carrying out the experiments and the analysis of the obtained experimental results and their discussion are given.

1. Introduction

The interaction of the heater with cold liquid is urgent fundamental problem of the modern physics. Particular attention is paid to high-intensity heat and mass transfer processes on the interfaces that define the behavior of the two phase system as a whole. A vapor film forms on the heater surface if highly heated body contacts with the cold liquid in the case where the temperature of the object exceeds the temperature of the limiting overheating of liquid.

Further a vapor film increases and the temperature of the heater decreases. As the result, the vapor film becomes unstable and there is a contact of the hot heater and cold liquid. The subsequent impulse of pressure arising at a descent of a vapor film can destroy not only a hot object if it represents a drop of liquid, but also and to damage displacement volume. Such processes are observed experimentally.

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 (He-II) in porous media and the He-II film boiling within the porous shells. The heat transfer processes for superfluid helium dynamics in a porous body are studied in [1] with respect to a new type of superconducting cable insulation. These studies related to the improvement of the Large Hadron Collider, the increase in the power of magnets and a corresponding increase in heat capacity. Authors investigated the problem of heat transfer through a porous medium filled with superfluid helium assuming that the two-fluid model of Landau describes the behavior of He-II at low heat flux or small velocity in a porous medium.

Heat flow 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) are decipherable from the heat flux dependence of the

In paper [3] the problem of describing the helium-II film boiling process on the cylindrical heating surface in a bulk is studied. The helium-II boiling on the heater surface under various conditions is considered in paper [4]. The problem of determining dynamic characteristics in the process of the vapor film evolution on the cylindrical heater surface in the presence of a confining coaxial porous structure is set. The processes in a bulk and under constrained conditions are compared. The existing experimental data on the boiling of helium-II on the sphere surface are analyzed. The results of video filming of the helium-II boiling under zero-gravity conditions on the surface of a thin wire are interpreted.

The main aim of this paper is the investigation the helium-II film boiling on a cylindrical heater within the porous shell. Thus, the new possibilities for interpreting the effects in a quantum liquid and development of new equipment for various scientific applications will be opening up.

A typical feature of helium-II boiling is the absence of a bubble regime. It is found that in addition to the smooth stable vapor film regime, there is a so-called noise boiling regime at large immersion depths and, accordingly, at high heat flux densities. In this case, the vapor film loses its outlines and becomes substantially non-symmetric. Despite the peculiarities of heat transfer in helium-II, the shape of the boiling curve is quite traditional, where the peak heat flux corresponds to the instant of the appearance of the vapor film, and the recovery heat flux corresponds to the moment of collapse of the vapor film. To determine the latter value, a calculation method was developed [5], based on the Gorter-Mellink's equation for describing the heat transfer across a liquid, as well as the nonequilibrium boundary conditions written in the form of D.A. Labuntsov's formulae.

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. These experiments were carried out under conditions of a bulk, for example, the experiments on the boiling of helium-II on a sphere [6], where a smooth stable vapor film was obtained on the surface of the heater. Particular attention is paid to the dynamics of interface of He-II in constrained conditions. Previously, the flow of helium-II in a capillary with vapor was observed in the presence of a longitudinal heat flux [7], 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 [8, 9].

2. The experimental setup

To examine He-II boiling on a cylindrical heater within porous shell, we used an experimental setup that comprised a cryostatting system, an optical system, a video-recording system, and also a system for generating the heat flux and temperature measurement [10] (Fig. 1). The experimental assembly was a glass helium pair consisting of two Dewar vessels of different diameters: an inner Dewar vessel (whose inner diameter was 65 mm) filled by helium and an outer Dewar vessel filled by nitrogen [7]. The inner glass Dewar vessel is hermetically sealed with a cap (metal cylinder with flanges). Three pipes are welded to the cap. One of which is intended for pouring liquid helium, and through the other pipe a suspension tube is passed. On this suspension an experimental cell is fixed. The suspension is made in the form of a thin-walled copper tube with a diameter of 10 mm, inside which there are electrical wires. Third pipe was connected to the pipeline vapor evacuation. The outer Dewar vessel was opened (directly contacting the atmosphere) and was filled by liquid nitrogen serving as a protecting thermal shield. Both Dewar vessels had vision slots 20 mm wide. These slots were used for video recording of the experimental processes. The glass Dewar vessels were aligned so that the slots coincided with each other, which allowed visual observations and video recording of the experimental cell installed in the inner Dewar vessel. The cryostat was filled by liquid helium from a liquid-helium transport vessel through an overflow siphon.
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.

The vapor pressure in the inner vessel is controlled both visually by the mercury manometer attached to the vessel, and in automatic mode capacitive pressure sensor "Baratron" (235). The accuracy of the measured pressure in the range of 0.2 mm Hg to 75 mm Hg is 0.5% measurable quantities.

For video recording of processes in the experimental cell, the video module PixeLink PL B954HU with the optical zoom system Navitar 6000 is used, which provides a 12x magnification and gives the possibility of obtaining an image of high quality and ultimate clarity.

To measure the heat flux and the resistance of the heater, a four-wire circuit is used. The electric current in the supply circuit was determined from the voltage drop across a reference coil with a nominal resistance of 1.0 Ohm (accuracy class 0.2). The supply of the measuring circuit is provided by source of direct current.

3. The experimental cell

Figure 2. The scheme of the experimental cell: 1, 2, 8 – the covers; 3 – a branch pipe; 4 – the holder; 5 – stem; 6 – porous shell; 7, 9 – glasses of the viewing windows; 10 – heater; 11 – body of the cell.
The cell body is a cylindrical shell with a length of 50 mm made of copper. In the side surface of the shell, holes are drilled with a diameter of 3.5 mm. End covers, having inspection windows are made of thin Plexiglas (1 mm thick), are screwed to the body. Located on the axis of the shell, the cylindrical heater is attached to a L-shaped metal holder (curved rod), which is inserted through the hole in the end cover. The holder is insulated from the cover by epoxy resin.

The porous structure, placed inside the cell body and soldered to it, is a thick-walled shell (7 mm thick and an inner diameter of 38 mm), which is obtained by winding ten layers of steel wire gauze. To seal the cell, indium wire spacers are used.

The heater is a cylindrical copper rod with a diameter of 3 mm and a length of 38 mm, on which an insulated thin (diameter 50 μm) copper wire several meters long is wound. Due to the small area of the cross section and the long length, the resistance of the heater at helium temperatures is sufficient to obtain the required heat flux. The heater is also a resistance thermometer.

4. The experiments methodology

The temperature of λ-transition is achieved by pumping the helium vapor with a vacuum pump. The series of experimental measures starts when the heater is turned on. At this time all the characteristic parameters in the system (the vapor pressure in the cryostat, the heat flux, the temperature of the heater) are controlled. Videography occurs simultaneously with synchronous recording of the received information in the form of a spreadsheet file. When the heat load is supplied to the heater then a vapor film is formed on the heater surface and the vapor comes out in the inner Dewar vessel through the porous wall of the experimental cell. This process leads to increasing of the vapor pressure above the free interface in the inner Dewar vessel and because of this reason the pumping of helium vapor continues during the experiment, which in turn lowers the liquid level in the inner Dewar vessel. The series of the experimental measures was considered to be completed after achievement of stationary boiling regime. Liquid helium fills again the cavity within the cell after turning off the heater, and the vapor film gradually collapses, and the liquid comes into contact with the heater.

5. Results of experiments

In experiments on the boiling of helium-II on a thin wire, regimes of a closed smooth stable vapor film were observed [11]. At great depths of immersion, vapor film symmetry was violated, and a transition to a noise boiling regime occurred. A preliminary calculation analysis showed that for the boiling of helium-II inside a porous shell the same boiling regime is possible, but the thickness of the vapor film should be less than for the case of boiling in a bulk. However, experiments carried out at various depths of immersion of the experimental cell in a liquid show that within the porous shell, which limits the processes of heat and mass transfer, the helium-II boiling regime changes in principle.

Figure 3. Video recording frames, \( q_w = 3.7 \text{ kW/m}^2 \). The interval between frames is 0.67 s.
When the heat load is supplied, the following stages of the boiling process develop:

1. Visible to the naked eye objects appear on the surface of the heater, similar to vapor formations.

2. The increase in the volume occupied by the vapor phase leads to the formation of a vapor film with a visible vapor-liquid interface.

3. The apparent cross-section of the vapor film takes a drop-like shape, which then turns into an inverted bell-shaped one.

4. The volume of vapor in the upper part of the internal cavity of the shell increases, the liquid is displaced by vapor from the cell.

5. In fact, the vapor film is the deflection of the vapor-liquid interface in the internal cavity of the cell.

In Fig. 3 shows the frames obtained during one of the sessions of switching on the heater in the experiment. The heat flux density for all the frames was about 3.7 kW/m$^2$, the vapor pressure in the cryostat varied within 3195 – 3232 Pa, gradually increasing. The immersion depth of the cell in this experiment at the initial time was about 5 cm and slowly decreased with time as the vapor was pumped from the inner Dewar vessel. The temperature of the heater was about 37.4 K and changed very slightly.

After the heater is turned on, the resulting vapor displaces a large part of the liquid helium from the internal cavity of the cell so that the vapor volume can occupy more than half the volume of this cylindrical cavity. The vapor film, which initially has a drop-like shape, communicates with the vapor volume in the upper part of the internal cavity with the thin streams (Fig. 3a). Then the vapor film increases so much in thickness (Fig. 3b), that becomes part of the vapor volume formed inside the porous shell (Fig. 3c-d). The temperature of helium-II in the cryostat increases insignificantly with time. This temperature increase is associated with an increase in vapor pressure above the free vapor-liquid interface in the cryostat (by 37 Pa) due to the evaporation of helium-II in the cell under the action of the heat flux.

The video footage in Fig. 4 show the film boiling observed in four different sessions of switching on the heater in the experiment.

![Video recording frames](image)

**Figure 4.** Video recording frames: a) $q_w = 9820$ W/m$^2$, $P_b = 2598$ Pa, $h = 25$ cm; b) $q_w = 9749$ W/m$^2$, $P_b = 4029$ Pa, $h = 25$ cm; c) $q_w = 8716$ W/m$^2$, $P_b = 4408$ Pa, $h = 10$ cm; d) $q_w = 8647$ W/m$^2$, $P_b = 4473$ Pa, $h = 5$ cm.

The heat flux density in these switching sessions remains approximately the same ($\sim 10^4$ W/m$^2$), so the thickness of the vapor film depends on the depth of immersion and the vapor pressure in the inner Dewar vessel. In the first case (Fig. 4a), the depth of immersion of the experimental cell $h$ is maximal, while the vapor pressure over the liquid in the vessel $P_b$ is inversely minimal. An increase in the pressure above the vapor-liquid interface in inner vessel, and as a consequence an increase in the equilibrium temperature of the liquid, leads to an increase in the thickness of the vapor film (Fig. 4b).
A decrease in the depth of immersion also leads to an increase in the thickness of the vapor film (Fig. 4c), since the value of the hydrostatic pressure difference decreases. In these series of experiments (Figs 4a-c), the temperature of the heater was approximately 37 K, as indicated by the resistance thermometer. In some experiments, a temperature increase of up to 80 K was observed when the vapor volume occupied more than half the internal cavity of the porous shell (Fig. 4d). This situation is possible when the immersion depth of the experimental cell is minimal.

In all series of experiments, a vapor film with an open interface was observed when the vapor film was in communication with the vapor volume in the upper part of the internal cavity of the experimental cell. In contrast to the experimental results obtained previously in the boiling of helium-II in bulk, in the constrained conditions the boiling of superfluid helium becomes like the film boiling of ordinary liquids. Convective flow of vapor in a film is visually observed, which is typical for the film boiling of nonquantum liquids, but not superfluid helium, for which, on the contrary, the contribution of convection to heat transfer with noiseless boiling is insignificant, convection is practically irrelevant, heat transfer at the vapor film takes place due to thermal conductivity. Thus, the effect of a change in the heat and mass transfer processes character during the helium-II film boiling on a cylindrical heater placed in a cavity inside a porous body was observed.

6. Conclusion

Experiments were carried out on the boiling of helium-II on a cylindrical heater located inside the porous body, and the video was taken from the end of the heating element. Previously, a mathematical model was developed for the case of a closed vapor film on the surface of a spherical heater [6]. And a preliminary analysis based on a similar model for a cylindrical heater allows to assume the possibility of existence a smooth stable vapor film on the heater surface [11]. But the experimental results show that at different depths of immersion of the experimental cell into the liquid, the boiling pattern characteristic of helium-II was not observed. Instead, the vapor film remained open in all experiments, and the vapor accumulated in the upper part of the internal cavity of the experimental cell.

Thus, the helium-II film boiling in the constrained conditions was like the film boiling of ordinary liquids in a bulk. Therefore, in the future, it is proposed to carry out an analysis of heat and mass transfer processes, leading to a violation of the integrity of the vapor film and the accumulation of vapor in the upper part of the internal cavity of the cell. For the same purpose, it is planned to conduct experiments at lower liquid temperatures in a cryostat.

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