Determination of the recovery heat flux at superfluid helium film boiling in different conditions

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Abstract The calculation of the recovery heat flux density is considered for different conditions to investigate heat mass transfer processes. System of equations is based on the methods of continuum mechanics and molecular kinetic theory. Pressure distribution in the liquid is determined by the hydrostatic difference. At the vapor-liquid interface the Laplace formula is used. The vapor pressure in the film is determined by the non-equilibrium effects in the vapor near the interface. Heat transfer in a liquid is described by the Gorter-Mellink semi-empirical theory. Experimental data on the boiling of superfluid helium under various conditions are interpreted based on the formulated mathematical model. For all cases in the considered range of parameters, the qualitative and in some cases quantitative agreement between the calculated and experimental values of the recovery heat flux were obtained.

1. Introduction
Superconductor magnet is usually cooled by normal liquid helium, however higher cryostability could be obtained in superfluid (He II). Superconductor cooled by He II shows a larger critical current and recovery current than those in He I. Furthermore, pressurized superfluid helium has better cooling properties than saturated one has.

Superfluid helium (He II) is successfully used as a magnets coolant of modern particle accelerators, reactors of controlled thermonuclear synthesis and cooling of space telescopes. Two reasons determine the use of this working fluid as a coolant for superconducting devices: low operating temperature, which increases the reliability of such systems, and improved heat exchange indicators. Helium II spontaneously penetrates into various cavities of the magnet windings, while its large specific heat capacity and high heat transfer efficiency in the liquid can provide powerful stabilization from thermal interference.

Among all the equipment already in operation with He II, the largest one is the Large Hadron Collider (LHC) at CERN with thousands of superconducting magnets working around 1.9K. The scale of this project prevents the use of as many cold sources as required magnets. The thermal stability of superconducting wires depends strongly upon the heat transfer to the coolant. In fact, pressure is an important factor on the heat transfer to superfluid helium. The direct experimental data about peak and recovery heat flux and vapor film behavior can give important information about critical parameters for high field system emergency mode. Superconducting engineering still relies heavily on liquid helium heat transfer efficiency model of calculations.

The experimental data about recovery heat flux was received in [1] and presented in [2] also among others. At this the corresponding model is developed in the following part.
2. Boiling in large volume

The following problem statement of the superfluid helium film boiling in a large volume is considered (Fig.1). The boiling is silent. Cylindrical heater of radius \( R_w \) is immersed in the superfluid helium at the depth \( h \). The smooth vapor film is formed as coaxial heater. The recovery process takes place when the vapor film collapses into the liquid at the heat flux \( q_w = q_R \). Above the free surface of the liquid constant pressure \( P_b \) is maintained so the liquid is in equilibrium with the vapor \( P_b = P_S(T_b) \).

![Figure 1. Schematic diagram of the problem.](image)

The application of the model [3], which describes the method of calculating the recovery heat flux for superfluid helium boiling, to the considered problem, allows us to obtain a system of equations. The peculiarity of present paper is taking into account capillary force on the vapour-liquid interface.

The pressure in the fluid \( P' \) is determined by the hydrostatic difference:

\[
P' = P_b + \rho' g h ,
\]

where \( \rho' \) – liquid density, \( g \) – gravity acceleration.

The vapor pressure \( P'' \) in the film is determined by the nonequilibrium boundary condition obtained by solving of the kinetic Boltzmann equation for evaporation-condensation problems [4]. The relationship between the actual vapor pressure near the phase interface \( P'' \), the pressure \( P_s(T_1) \) corresponding to saturation lines of the vapour-liquid interface surface temperature \( T_1 \) and the heat flux density on it \( q_R \) is the following:

\[
P'' = P_s(T_1) + \frac{0.44 q_R}{\sqrt{2 R_h T_1}},
\]

where \( R_h \) – individual gas constant for helium.

The correlation (2) was received for absence of mass flux density on the vapor-liquid interface. The conditions which satisfy (2) must be the minimum heat flux at which film boiling can occur, a value equal to the recovery heat flux.

The Laplace formula is written on the phase boundary, taking into account the cylindrical geometry:

\[
P'' - P' = \frac{\sigma}{R_w},
\]

where \( \sigma \) – surface tension coefficient.

Heat transfer in a liquid is described on the basis of the theory of mutual friction. [5]:

\[
q_R^3 = \frac{2}{f(T) R_w} (T_1 - T_b),
\]
where \( f(T) \) is the empirical Gorter-Mellink mutual friction parameter average in the temperature range \( T_b \sim T_1 \).

Equation from (2) to (4) is transformed using Clapeyron-Clausius equation:

\[
P_b(T_1) - P_b = P_s(T_1) - P_s(T_b) = \frac{f(T)}{2} q_R^2 R_w R_n T_b,
\]

where \( r \) is phase transition heat for helium.

The system of equations (1) - (5) is reduced to the following equation for \( q_R \):

\[
\frac{f(T)}{2} q_R^2 R_w R_n T_b^2 + \frac{0.44q_R}{\sqrt{2R_b \left( T_b + \frac{f(T)}{2} q_R^2 R_w \right)}} = \rho' gh + \frac{\sigma}{R_w},
\]

If we accept that the change in temperature of superfluid helium can be neglected, then equation (6) is reduced to the next form:

\[
q_R = 2.27 \sqrt{2R_b T_b \left( \rho' gh + \frac{\sigma}{R_w} \right)},
\]

The differences in the calculations results of the vapor film thickness \( \delta \) according to equations (7) and (6) is a few percent (1-3%), therefore, the formula (7) can be recommended for practical use.

The calculations results of the recovery heat flux \( q_R \) for the experimental data [1] with different heater sizes \( d_w \) and different immersion depth \( h \) show that agreement is achieved quite satisfactory. The dependencies of recovery heat flux \( q_R \) on immersion depth \( h \) is presented on fig. 2 for two size of heater. Points for experimental data good enough correspond with calculation lines which is linear as follows from (7). The deviation is not exceeded 7% for higher immersion depth \( h \). As the heater diameter \( d_w \) is more than recovery heat flux \( q_R \) is less.

**Figure 2.** Comparison of experimental and calculation data (\( T_b = 1.92 \)K)
(points – experiments, lines – calculations): 1 – \( d_w = 1.5 \) mm; 2 – \( d_w = 0.05 \) mm

The dependencies of recovery heat flux for two different temperatures are presented on fig. 3. As we can see from the points to experiments and lines for calculations the difference between data is much more than in fig. 2. At low immersion depth \( h = (3 \pm 10) \) cm the difference is insignificant (1\%10)\%. But at high value of immersion depth \( h = 25 \) cm, the differences can be estimated as 25% for \( T_b = 2.07 \)K and 80% for \( T_b = 1.92 \)K. It can be explained by the influence of hydrostatic pressure through vapor film from the one hand and appearance of noise film boiling from the other hand. The different constructions of the heater may also influence. Nevertheless the presented model is rather good described experimental data in the some range of the parameters.
3. Boiling of superfluid helium in microgravity

In experiments [6], the conditions of microgravity are ensured by the free fall of the container in a pipe with a height of 122 m, the pressure in which is at the level of 50 Pa. The experiment lasts approximately 4.7 s, during which the level of microgravity is \( g_0 = 10^{-5} \text{g} \).

To create a single bubble in helium-II, a microheater of manganine wire with an outer diameter of 0.05 mm and a length of 1.88 mm is placed in the cryostat. Heater is fixed on both sides by two superconducting monofilaments. The heat load of the heater was measured by a four-wire circuit. Most of the heat was released in the manganin part, even when the superconducting wires were partially in the vapor bubble. The direct current is switched on simultaneously with the onset of free fall and remains on during the entire time of microgravity (until the start of braking).

During the experiment, a single vapor bubble was formed on the heater surface, which grew to a size of \((6\sim10)\) mm in diameter at a bath temperature of 1.9K. The size dependence of the vapor film on the time was calculated by the area occupied by the vapor in the frames of the video.

The problem of superfluid helium boiling in microgravity corresponds to Fig. 1. However, vapor film on the heater surface is formed in ideal spherical shape as shown by experimental data [6]. But the recovery heat flux can be estimated for cylindrical geometry.

The level of microgravity in experiments [6] was \( g_0 = 10^{-5} \text{g} \). The estimate shows that the hydrostatic pressure difference can be neglected \( \rho' g_0 h \approx 7 \cdot 10^{-4} \text{ Pa} \). The capillary pressure difference is \( \frac{\sigma}{R_w} \approx 6.2 \text{ Pa} \) at the heater radius \( R_w \approx 5 \cdot 10^{-5} \text{ m} \).

Then equation (7) with the assumption of neglected temperature difference in the liquid is transformed to the following

\[
q_r = 2.27 \sqrt{2R_b T_b} \left( \frac{\sigma}{R_w} \right),
\]

At this we can conclude that recovery heat flux is determined by the capillary force in microgravity instead of laboratory conditions where the hydrostatic pressure plays main role. For experiment [6] recovery heat flux \( q_r = 1250 \text{ W/m}^2 \). This value is quiet less than for full gravity. As we can see from fig. 2-3 the corresponding values for free volume lies in the range of \((1\sim7) \text{ W/cm}^2 \), that in \(8\sim56 \) times more than in microgravity. Therefore corresponding values of peak heat flux should be also less for microgravity. In experiments [7] heat flux density for vapor film growing was \((1.7\sim5.5) \text{ W/cm}^2 \). This value is consistent in order with data [1] presented on fig. 2-3.
4. Superfluid helium boiling in confined volume

The superfluid helium boiling on the cylindrical heater inside porous shell can be described as presented in [7]. At this the recovery heat flux $q_R$ depends on permeability of porous structure $k_p$

$$q_R = \frac{\rho'gh + \sigma}{0.44 - \frac{\eta'}{k_p \rho' ST_b} \ln \left( \frac{R_0 + L}{R_0} \right)},$$

(9)

where $\eta'$ – viscosity of normal component, $S$ – entropy of liquid, $R_0$ – inner radius of porous tube, $L$ – the thickness of porous layer.

The equation (9) was received with the assumption of neglected temperature difference in the liquid. So the behavior of superfluid helium inside porous body differs from the free volume [8]. At this the corresponding comparison between free volume and confined state is presented on fig. 4. The heater radius was $R_w = 4$ mm, bath temperature $T_b = 2K$. The dependencies of recovery heat flux $q_R$ on immersion depth $h$ are plotted for two values of permeability $k_p$.

![Graph](image)

**Figure 4.** The dependence of recovery heat flux on immersion depth:
inside porous shell 1 – $k_p = 10^{-12}$ 1/m$^2$, 2 - $k_p = 10^{-11}$ 1/m$^2$, 3 – free volume

As we can see from the fig.4 recovery heat flux for free volume differs from confined conditions moreover as the permeability is less, as the recovery heat flux is larger. But at the value of permeability $k_p = 10^{-11}$ m$^2$ and higher the difference between free volume and confined condition is neglected. As for free volume the dependence is linear. From equation (9) the following conclusion follows. At the $k_p^{cr} = \frac{\sqrt{2RT_b}}{0.44} \frac{\eta'R_w}{\rho'ST_b} \ln \left( \frac{R_0 + L}{R_0} \right)$ recovery heat flux seeks to infinity, that’s mean that boiling cannot occurs at this value and higher independent of heat flux. For initial data from Fig. 4 this value of permeability is $k_p^{cr} = 3.3 \times 10^{-13}$ 1/m$^2$. However it needs to remember that equation (9) was formulated with assumption of neglected temperature difference in liquid. But at high heat flux this difference influences on heat mass transfer processes. At last, if temperature exceeds $T_c$ superfluid helium transforms into normal state.

5. Conclusion

The calculation method for recovery heat flux at film boiling of superfluid helium is developed based on continuum mechanics and molecular kinetic theory. The peculiarity of the model is taking into account the surface tension. The different experimental data were analyzed. Comparison of calculation
and experimental data is good enough. At this, presented method is satisfactory described the known experimental data.

Recovery heat flux at microgravity is determined by the capillary force and smaller by an order than for full gravity.

The method of recovery heat flux calculation at the superfluid helium boiling inside porous structure is developed taking into account peculiarities of heat transfer in porous shell. At this the permeability of porous structure influences strongly on the value of recovery heat flux.

Acknowledgments
This work was supported by the Russian Science Foundation (project No. 19-19-00321).

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