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EXPERIMENTAL STUDY OF HE-II BOILING ON A SPHERE

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Regimes of superfluid-helium boiling on structural-steel spheres 4.8 *and* 6.0 mm *in diameter, with heaters installed inside, are examined. Experimental data on the evolution of vapor films formed on the spherical surfaces are obtained.*

Key words: *superfluid helium, interface, film boiling, molecular-kinetic theory.*

Introduction. Knowing the features of vapor-film formation and development on heater surfaces is important both for basic research of transfer processes across interfaces and for solving many applied problems. In particular, elucidation of conditions for vapor-phase generation and development in superfluid-helium film boiling is necessary for working out measures providing for reliable cryostatting of superconducting magnets, cables, and other devices, and also for substantiating methods preventing equipment faults.

The majority of He-II boiling studies were performed on cylindrical samples and flat heaters [1–4]. On the other hand, studying the evolution of the vapor film in He-II on spherical surfaces is capable of providing useful information for further development of the theory of heat and mass transfer and for various applications.

Experimental Setup. To examine He-II boiling on a sphere, we used an experimental setup that comprised a cryostatting system, an optical system, a video-recording system, and also a system for generating the thermal load and temperature measurement (Fig. 1). The experimental assembly was a glass helium pair consisting of two Dewar flasks of different diameters: An inner flask filled by helium and an outer flask filled by nitrogen. The helium flask (whose inner diameter was 55 mm) was hermetically connected to the pipeline vapor evacuation. The outer flask was open (directly contacting the atmosphere) and was filled by liquid nitrogen serving as a protecting thermal shield. Both flasks had vision slots 20 mm wide, which were used for video recording of the experimental processes. The flasks 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 flask. The desired temperature in the helium bath was maintained by vapor evacuation. The liquid temperature was monitored on the basis of the saturation pressure measured with a mercury manometer. The cryostat was filled by liquid helium from an STG-40 liquid-helium transport vessel through an overflow siphon.

The processes on the sphere were recorded using an optical system consisting of an MBS-9 microscope placed onto the optical axis of the two Dewar flasks, a video camera coupled with the microscope eyepiece, and a videotape recorder.

The experimental sample is schematically shown in Fig. 2. A hole was drilled in a ball bearing to insert a fluoroplastic-insulated carbon heater. Samples 4.8 and 6.0 mm in diameter were used. The heat supplied to the heater was measured by a four-wire circuit. The electric current in the supply circuit was determined from the voltage drop across a reference coil with a nominal resistance of 0.1 Ω. The depth of sphere penetration below the superfluid-helium level was measured by a measuring bar graduated by 1 mm.

The sphere was suspended on the supply wire (Fig. 2) in superfluid helium. The supply wire itself was secured at the wire suspension (see Fig. 1). In calculating the interfacial heat flux toward superfluid helium, we took into account the heat flux through the supply wires made of copper, which amounted to 20% of the total heat released in the heater.

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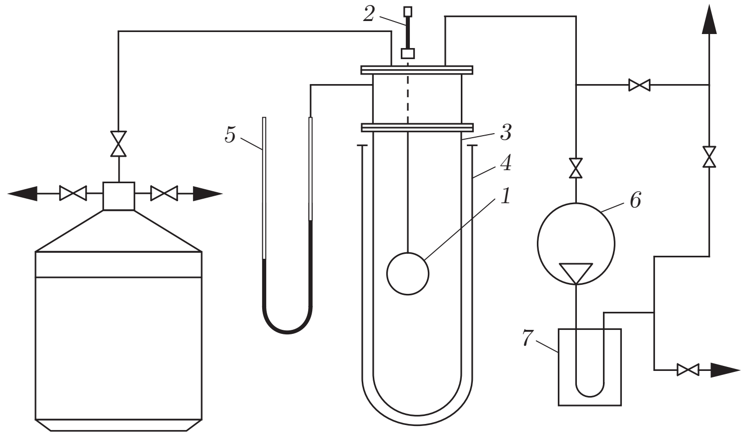

Fig. 1. Experimental setup: 1) experimental cell; 2) suspension; 3) Dewar flask with helium; 4) Dewar flask with nitrogen; 5) mercury manometer; 6) NVZ-20 vacuum pump; 7) nitrogen trap.

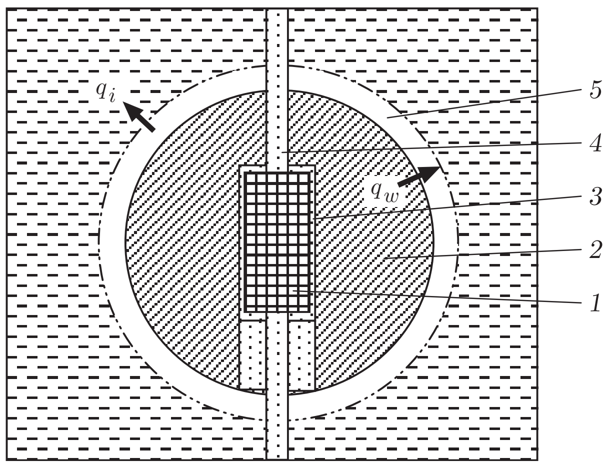

Fig. 2. Experimental sample with the vapor film: 1) heater; 2) sphere; 3) fluoroplastic insulation; 4) supply wires; 5) vapor region.

Experimental Data. A typical feature of superfluid-helium boiling is known to be the absence of the bubble regime. In turn, the film boiling regime, observed under a critical thermal load, can be either noisy or noiseless. The noisy regime is accompanied by interface vibrations (Fig. 3a) and by audible noise that can be perceived by human ear. In the noiseless regime, the interface between the phases is stationary (Fig. 3b).

The studies of superfluid-helium boiling on wires [5] revealed a domain of the noiseless boiling regime with parameters dependent on the bath temperature and immersion depth.

The experiment was aimed at obtaining a stable vapor film in the interval between the beginning of film nucleation and the transition into the noisy boiling regime. The critical heat fluxes corresponding to incipience of He-II film boiling reach 10^4–10^5 W/m^2. Under a thermal load necessary for the vapor film to be formed (approximately 0.7 and 1.1 W for spheres 4.8 and 6.0 mm in diameter, respectively), liquid helium contained in the cryostat vaporized, and the immersion depth of the sphere decreased. The average rate of variation of the immersion depth in our experiments was approximately 0.4 mm/sec. As a result, the depth changed by 4 mm during 10 sec, i.e., by 5% of its initial value. The data plotted in Fig. 4 refer to a constant (within 5%) immersion depth and to steady-state regimes observed under a constant thermal load. In the course of the experiment, the vapor pressure in the cryostat increased; hence, the He-II temperature also increased. The data in Fig. 4 actually refer to the time dependences of R_i and T_{bath}; as the time passes, the immersion depth h of the sphere decreases, and the pressure of saturated vapors in the cryostat increases. Figure 4 also shows the liquid-helium temperature.

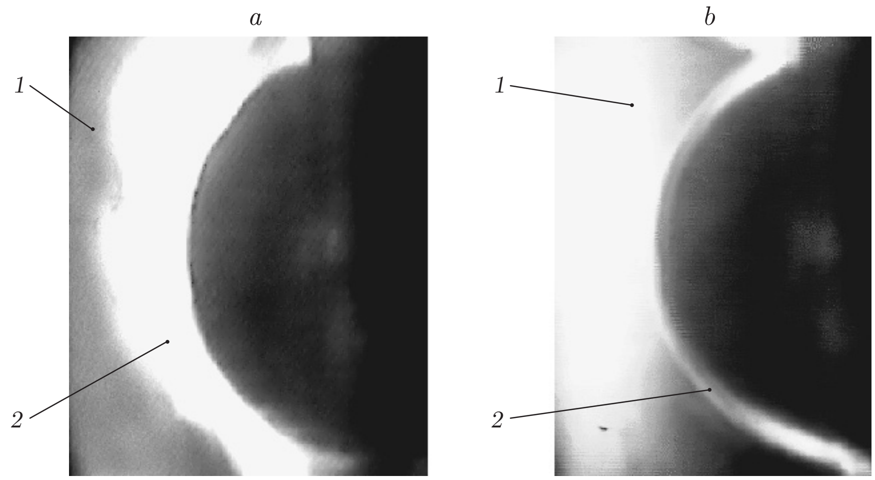

Fig. 3. Superfluid-helium boiling regimes: (a) noisy regime; (b) noiseless regime; 1) liquid; 2) vapor.

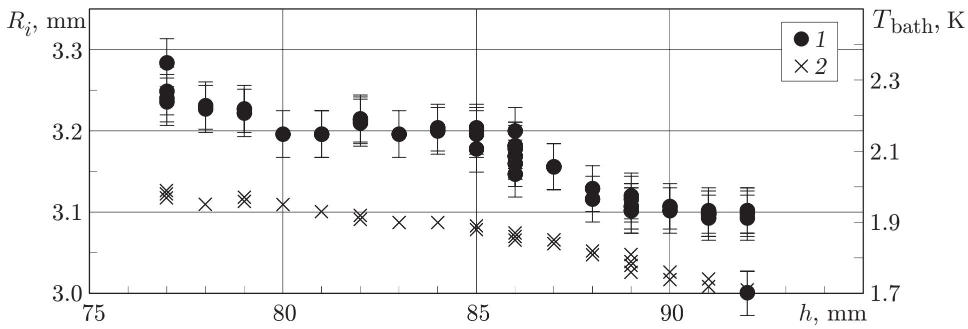

Fig. 4. Vapor-film radius R_i (1) and bath temperature T_{bath} (2) versus the immersion depth h for a sphere 6 mm in diameter.

Particular attention was given to studying the increasing thickness of the vapor film at a constant bath temperature and decreasing immersion depth. The experimental data for the sphere 6 mm in diameter are plotted in Fig. 5.

In addition, patterns of vapor-film evolution in time under the load q_w were obtained in the present experiments (Fig. 6).

Data Analysis. In the case of spherical geometry, the specific heat flux across the liquid–vapor interface can be expressed as

$$q_i = q_w(R_w/R_i)^2 \tag{1}$$

(q_w is the specific heat flux at the spherical surface and R_w is the sphere radius). Equation (1) implies that the vapor mass contained in the film is low and the amount of heat spent to heat this mass is insignificant. The specific heat flux at the interface between the phases is determined by the thermodynamic parameters of the system, the saturation temperature, and the depth to which the heater is immersed into the liquid.

A calculation procedure for the recovery thermal load in superfluid helium was proposed in [6]; this load is the minimum heat flux q_R in the boiling regime where the direct contact between the heater surface and He-II is established. The specific heat flux at the vapor–liquid (He-II) interface is calculated on the basis of data obtained in studying transfer processes by methods of the molecular kinetic theory. A formula relating the interfacial vapor pressure p and the specific heat flux q_i across the interface between the phases with the temperature T_i and the corresponding saturation pressure $p_s(T_i)$ was derived in [7]:

$$p = p_s(T_i)\Big(1 + \frac{\sqrt{\pi}}{4}\,\frac{q_i}{p_s(T_i)\sqrt{2R_\mu T_i}}\Big). \tag{2}$$

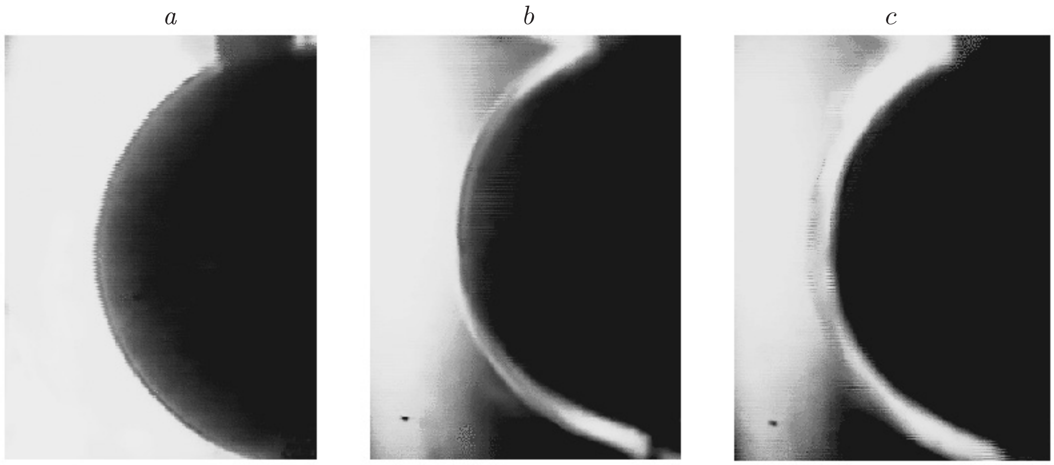

Fig. 5. Variation of the vapor-film thickness δ with decreasing immersion depth of the sphere below the He-II level: $\delta = 0.1$ (a), 0.2 (b), and 0.3 mm (c).

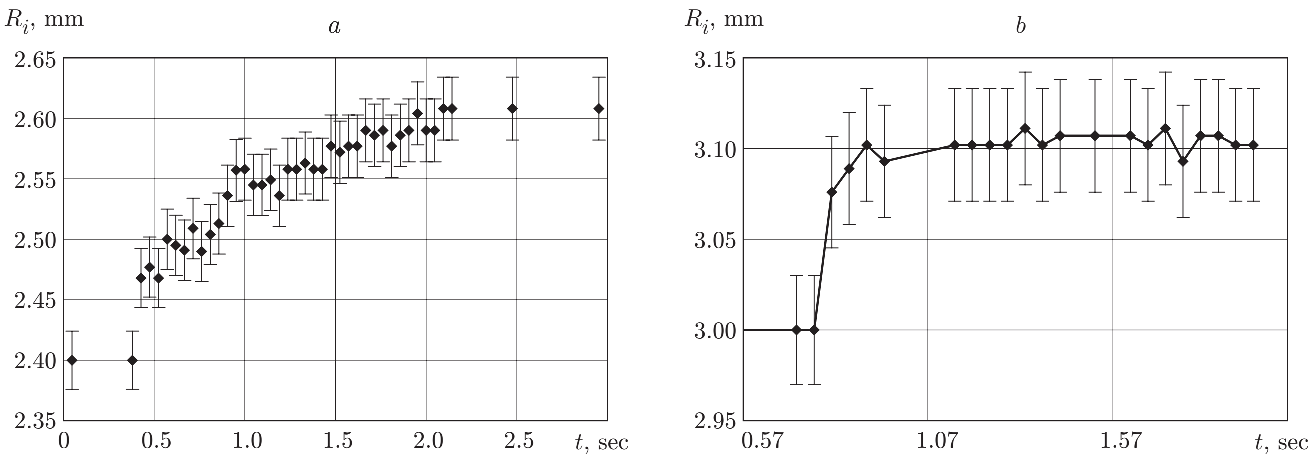

Fig. 6. Evolution of the vapor-film radius on spheres of different diameters ($T_s = 1.68$ K): (a) $2R_w = 4.8$ mm ($q_w = 12.7$ kW/m^2 and $h = 30$ mm); (b) $2R_w = 6.0$ mm ($q_w = 30.5$ kW/m^2 and $h = 90$ mm).

Formula (2) is valid provided that

$$\frac{q_i}{p_s(T_i)\sqrt{2R_\mu T_i}} \ll 1.$$

For an arbitrary value of q_i, the relation given, for instance, in [8] can be used instead of Eq. (2). It should be noted that expression (2) is valid for all steady-state boiling conditions in He-II with the vapor-film thickness δ showing no time variations, i.e., not only in determining the recovery heat flux with the film thickness tending to zero. For hydrostatic equilibrium of the liquid bed over the vapor film to be achieved, the following equation must be fulfilled:

$$p = p_s(T_b) + \rho g h.$$

Owing to the highly efficient heat transfer in liquid helium, the temperature difference across the interface between the phases near the heater and at the free surface is low; hence, the maximum heat flux can be estimated in the first approximation as

$$q_i = 2.27 \rho g h \sqrt{2R_\mu T_b}. \tag{3}$$

The difference between the fluxes q_i calculated by formula (1) on the basis of experimental values of vapor-film radii and the fluxes q_i calculated by Eq. (3) was found to be 23–25 and 9–13% for the spheres 4.8 and 6.0 mm in diameter, respectively.

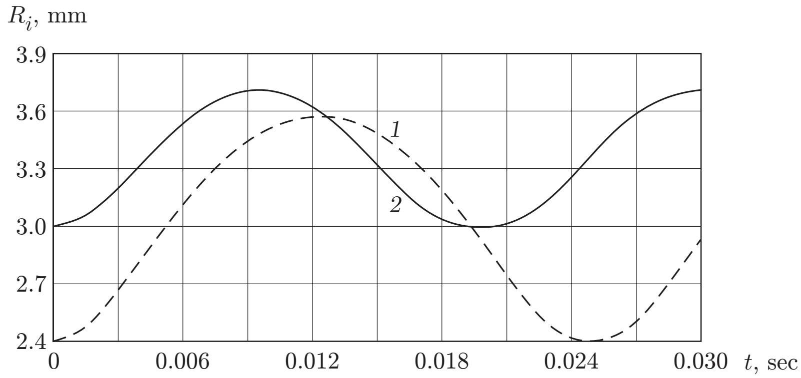

Fig. 7. Vapor-film radius versus time for $F = 0$ and $2R_w = 4.8$ (1) and 6.0 mm (2).

The heat flux supplied to the interface between the phases heats the liquid. The problem of unsteady heat transfer in He-II is rather complicated. To be solved accurately, this problem requires superfluid turbulence hydrodynamics to be invoked [9, 10]. The temperature difference $T_i - T_b$ that arises in liquid helium can be evaluated using the Gorter–Mellink semi-empirical theory. For the present test conditions, the maximum difference between T_i and T_b calculated by the Gorter–Mellink theory with allowance for the spherical geometry of the problem was several thousandths of a degree, making it possible to adopt, in the first approximation, the model of a constant liquid temperature.

The growth of the vapor film on the heater can be described by solving the Rayleigh equation [11, 12]. With allowance for the normal-motion viscosity in superfluid helium with heat transfer, the Rayleigh equation acquires the form

$$R\,\frac{d^2R}{dt^2} + \frac{3}{2}\Big(\frac{dR}{dt}\Big)^2 = \frac{p - p_s(T_b) - \rho g h - F}{\rho}, \tag{4}$$

where $F \approx (K/R)\,dR/dt$, $K = 4\eta_n$, η_n is the normal-motion viscosity of He-II, the vapor pressure p is given by formula (2), and $p_s(T_b)$ and h are known quantities.

The numerical solution of Eq. (4) for $F = 0$ is plotted in Fig. 7, which shows one period of vibration of the interface between the phases. These vibrations are seen to be nondecaying.

According to the analysis given in [11], the numerical solution of the full ($F \neq 0$) Eq. (4) predicts decaying vibrations of the interface under thermal loading, followed by the vapor-film thickness reaching a steady-state value. This pattern was not observed in our experiments with spherical heaters.

For the sphere 4.8 mm in diameter, the calculated steady-state radius of the vapor film is 3 mm, whereas the experimental value is $R_i = 2.61$ mm (see Fig. 6a). For the sphere 6 mm in diameter, the calculated steady-state radius of the vapor film is 3.41 mm, and the experimental value is $R_i = 3.1$ mm (see Fig. 6b).

Conclusions. The data obtained in our experiments show that the features of film boiling on a spherical heater can be adequately described by the approaches proposed and developed in [6, 7, 11].

The numerical solutions of the equation of interface motion prove that interface vibrations are possible. Such oscillations, however, were not registered in our experiments, possibly, because of the low frequency of video recording.

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