EXPERIMENTAL INVESTIGATION OF CRITICAL HEAT-FLUX DENSITY IN OPEN CHANNELS COOLED WITH HELIUM-II

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We give the experimental values of critical heat-flux density in uniformly heated open channels cooled with He-II.

Increasing attention is being given today to the investigation of the laws governing the heat exchange taking place in the thermostating of a number of devices with helium-II, or superfluid helium, i.e., liquid helium (He_4) in the state which it assumes after λ-transition (Fig. 1). The reason for this is the need for thermostating a number of cryogenic systems operating at temperatures of T = 1.7-2°K [1, 2].

Survey publications, e.g. [2-4], have essentially generalized experimental investigations on heat exchange in a large volume and indicated the special features of heat transfer to He-II, which are due to its exceptionally high thermal conductivity, substantial heat capacity, and extremely low viscosity. The manifestation of the fundamental properties of this quantum liquid — superfluidity, thermomechanical and mechanocaloric effects, etc. — in the heat-exchange mechanism have made it necessary to use apparatus and models completely different from those used in the case of other liquids to generalize and analyze the results of the investigations. However, in order to formulate a heat-exchange theory, for example on the basis of a two-component model (a normal and a superfluid component) in this region, the experimental data obtained so far are clearly insufficient.

Since helium-II has high thermal conductivity, it provides reliable thermostating of objects at T = 1.7-2°K, and the heat removal is effectively achieved without the formation of vapors. At the same time, after a certain maximum (critical) heat flux is exceeded, the intensity of the heat exchange deteriorates sharply as a result of the transition to film boiling. Therefore, the use of He-II is advisable only in cases in which it is known with certainty that the critical heat flux density (q_{cr}) will not be exceeded.

The authors of [2-4] analyzed the effects of the liquid temperature, the dimensions of the heat-exchange surface, the depth of immersion of the specimen into the liquid, etc. on the value of q_{cr} in the case of horizontal wires and cylinders, as well as plane surfaces in a large volume. It was shown that the value of the critical heat-flux density may vary, depending on these conditions, over a wide range (essentially from $1 \cdot 10^4$ to $15 \cdot 10^4$ W/m^2), in many cases far exceeding the value of q_{cr} for He-I. There have also been a number of published studies [5-8] on the investigation of heat exchange (mainly the determination of q_{cr}) in dead-end channels and helical partially heated channels.

The investigation of heat transfer in open channels to He-II which circulates naturally is of interest today for the following reasons. A shape of this kind (an open cylindrical channel) is the most suitable for the design of a number of devices. The data obtained earlier indicate that in such channels we should expect the critical heat flux density to be substantially less than heat exchange in a large volume [2, 9].

In the present article we give some results of the investigation of the critical heat-flux density in uniformly heated open channels cooled with helium-II at T = 1.7-2.14°K. The channels were pipes made of 12Kh18N10T steel with an inner diameter of d = 0.8, 1.8, and 2.8 mm, a wall thickness of 0.1 mm, and a ratio l/d = 20.8, 44, and 85. The orientation of the channels could vary from vertical to horizontal, and the depth of immersion from 100 to 600 mm.

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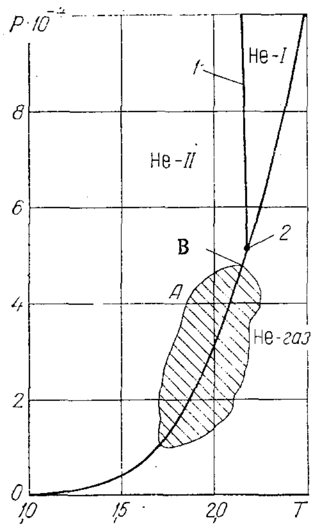

Fig. 1

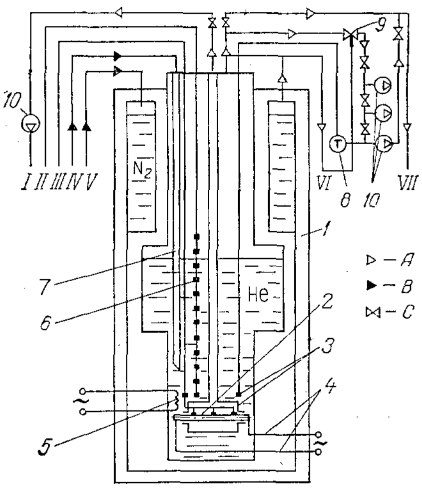

Fig. 2

Fig. 1. P–T diagrams for helium: 1) λ-line; 2) λ-point (A, region of operating pressures and temperatures; B, saturation curve). $P \cdot 10^{-4}$, Pa; T, °K.

Fig. 2. Scheme of the apparatus: 1) cryostat; 2) channel; 3) resistance thermometers; 4) current input wires; 5) heater; 6) level meter; 7) overflow device; 8) thermostabilizer; 9) electromagnetic valve; 10) vacuum pumps. The process lines are: I) evacuation of the experimental element; II) measuring the helium level in the cryostat; III) measuring the temperature of the channel wall; IV, V) overflows for liquid helium and nitrogen; VI, VII) gaseous nitrogen and helium discharges; A, B) gas and liquid streams; C) shutoff device.

The channels investigated were placed in an experimental element, which was immersed into a cryostat containing 15-100 liters of He (Fig. 2). The element was held to the lid of the cryostat by means of rods that permitted regulation of the immersion depth and orientation of the channel. The specified temperature of the liquid helium was attained by pumping out the vapors with a mechanical vacuum pump. The liquid-helium temperature was maintained during the experiment by means of a special thermostabilizer which used a resistance thermometer as the sensitive element and used an electromagnetic valve set up on the pump piping as the actuator.

The experimental element consisted of the channel under investigation, heated with alternating current, a vacuum jacket, and temperature sensors. The temperature of the outer surface of the channel was measured at three cross sections along its length (at the midpoint and at a distance of 8-10 calibers from each end) with resistance thermometers accurate to 0.01°K or less. As the heat-flux density was increased gradually (quasistationary regime), we observed a gradual increase in the temperature of the wall. When certain values of heat-flux density were reached, the wall temperature increased sharply — these values of q were taken as q_{cr}.

In addition to the experiments indicated above, two more groups of experiments were carried out on the apparatus: determination of the critical heat flux density for a horizontal cylinder with D = 3 mm and l = 42 mm made of the same material in a large volume of He-II; and determination of the critical heat-flux density in the investigated channels with natural circulation of boiling He-I (T = 2.4-4.2°K). The results of these experiments serve as auxiliary material and are of interest for direct comparison with the results of the main group of experiments, as well as for estimating the accuracy of the measurement system. (For a large volume of He-II and boiling of He-I in this region of the parameters, fairly reliable experimental data are available [2-4, 10, 11].)

In Figs. 3 and 4 and Table 1 we show the results of the experimental investigation of the effect of the temperature of the helium-II, the depth of immersion of the experimental segment into the tank of He-II, and the orientation and geometric dimensions of the channels on the

TABLE 1. Critical Heat Flux Density in Open Cylindrical Channels Placed in He-II, for Different Regime Parameters

T, K	q_{cr}, W/m^2	H, mm	φ °	d, mm	l/d
1,78	206,4	415	0	0,8	85
1,87	227,5	305			
1,98	148,9	375			
	173,2				
2,09	74,9	280			
	76,4				
1,78	354	400	90		
	383	500			
1,89	385	350			
	435	370			
2,00	422,7	410			
2,13	354	440			
1,70	380	300	0	1,8	44
	381	500			
1,80	360	300			
	363	500			
1,84	453	100			
	475	300			
	508	600			
1,90	453	100			
	462	300			
	480	600			
1,95	506	100			
2,00	271	550	0		
	313	600			
2,01	236	150			
	298	450			
2,09	127	100			
2,13	118	310			
1,70	617	100	45	1,8	44
	635				
1,80	743	100			
	789				
1,84	795	100			
	938	300			
		500			
1,90	893	100			
	899	300			
		600			
1,95	831	100			
	857				
	862				
2,01	822	100			
		300			
		550			
2,09	575	100			
	583	300			
1,70	912	100	90		
1,80	900	100			
	1005	200			
	1033	550			
		600			
1,84	990	200			
		600			
1,9	1120	170			
	1124	300			
		470			
		550			
2,01	925	100			
		600	90	1,8	44
2,02	925	450			
2,09	776	100	90	1,8	44
	833				
2,11	849	110			
		430			
		550			
2,14	849	430			
1,95	1578	100	0	2,8	20,8
	1593				
2,09	1239				
1,80	2823		45		
1,95	2952				
	3052				
2,09	2693				
1,70	2976		90		
1,80	3255				
	3307				
1,95	4118				
	4257				
2,09	3334				

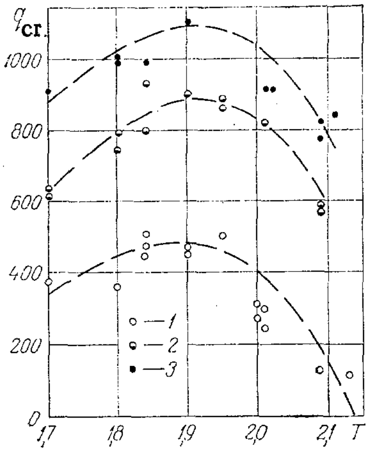

Fig. 3

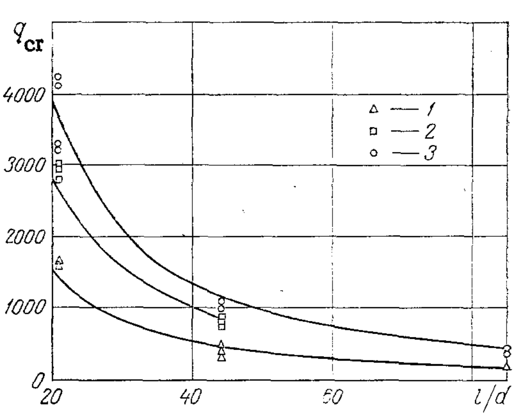

Fig. 4

Fig. 3. Critical heat-flux density in the channel, d = 1.8 mm, $l/d = 44$ for different channel orientations: 1, 2, 3) φ = 0, 45, 90°.

Fig. 4. Critical heat flux density in channels with different values of l/d for T = 1.8-1.95°K: 1, 2, 3) φ = 0, 45, 90°.

critical heat flux density. This is the first time that such data have been published in the literature. In later publications we shall give a more detailed discussion of the results obtained, the theoretical analysis, and a comparison of the results with data for different conditions.

First of all, we must note the practically instantaneous propagation of the heat-transfer crisis over the entire length of the channel containing the He-II, so that the value of q_{cr} is the same for all segments of the channel. In addition, the experimental data obtained (see Table 1) convincingly show that the immersion depth of the channels has no effect on the critical heat flux density. In many investigations in a large volume of He-II [2-4] it was observed that the depth of immersion of the specimen has a substantial effect: as H was increased, the critical heat-flux density increased considerably. This increase in q_{cr} was usually attributed to the manifestation of a thermomechanical effect and to an increase in the underheating of the He-II to the saturated state under the influence of the hydrostatic column of liquid. In the conditions we considered, this explanation is not correct.

Figure 3 shows the value of q_{cr} for a channel with d = 1.8 mm, l = 79.5 mm as a function of the temperature of the tank of He-II. For vertical (φ = 90°), inclined (φ = 45°), and horizontal (φ = 0°) positions of the channel the critical heat-flux density, as the temperature increased from 1.7°K, was found to increase, reach a maximum, and then decrease. The maximum q_{cr} value was attained for all three cases in the temperature region near 1.9°K. This is in good agreement with the data of other investigations [2-4] on heat exchange in a large volume of He-II and in dead-ended insulated channels [8], which is usually explained by the suggestion that the maximum effective thermal conductivity of He-II is reached at the indicated temperature. However, the values of q_{cr} for uniformly heated open channels are much lower (by approximately one order of magnitude) than the values obtained for a large volume, while the calculations of q_{cr} by the formulas obtained for channels with adiabatic walls and a heater at the dead end [8] are nonuniform for our case. The values of q_{cr} for the vertical position of the channel are 1.2-1.5 times as high as for a channel at a 45° angle, and ≈2.5 times as high as for a horizontal channel. Such an influence of the channel orientation on the bubble-boiling crisis in saturated He-I under conditions of natural circulation was explained by the hydrodynamics of the vapor—liquid stream [10, 11]. Naturally, such an approach is completely inapplicable to the results we obtained in our experiments with He-II.

Figure 4 shows the influence of the relative length of the channel on the value of q_{cr}. For any orientation of the channels, an increase in their relative length leads to a decrease in the critical heat flux density. The approximate relation is $q_{cr} \sim (l/d)^{-1.5}$.

The laws indicated above are characteristic for all the channels investigated. The main experimental data, in addition to those given in Figs. 3 and 4, are shown in Table 1.

The substantial difference between the results obtained by investigating the critical heat-flux density in a large volume of He-II and those obtained in channels can apparently be explained on the basis of the mechanism of interaction and motion of the normal and superfluid components of the He-II.

In the channels the superfluid component moves into the interior of the channel, toward the heated walls, and the normal component flows out of the channel. Since the motion of the superfluid component takes place without friction, the rate of "renewal" of the liquid and, consequently, of heat removal in the channel is determined by the rate of outflow of the normal component, which depends on the forces that arise: the frictional force and the lifting force. Qualitatively this situation is most clearly confirmed by the results of the investigation of the influence of the relative length of the channel on the critical heat flux density. Evidently these same considerations can explain the influence of the channel orientation and the lack of influence of the depth of immersion on the value of q_{cr}.

NOTATION

q, q_{cr}, density and critical density of the heat flux, W/m²; T, temperature, °K; d, D, inner and outer diameters, mm; l, length, mm; l/d, relative length; φ, angle of inclination, deg; H, depth of immersion, mm.

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