EFFECT OF ORIENTING THE HOT SURFACE WITH RESPECT TO THE GRAVITATIONAL FIELD ON THE CRITICAL NUCLEATE BOILING OF A LIQUID

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Laws are established according to which the critical boiling mode changes with the orientation of the hot surface. The existence of an extremum temperature is shown. Formulas are proposed which account for the surface orientation during boiling in a free volume.

The effect which the orientation of the hot surface with respect to the gravitational field has on the critical nucleate boiling of liquids is recently becoming important from both the scientific and practical point of view.

A survey of available test data shows that studies on this subject have until now been concerned mainly with the position of the hot surface in a large boiling volume, and only very few experiments have dealt with the effect of channel orientation. These data give researchers only a qualitative notion as to how the orientation of the hot surface affects the critical thermal flux q_{cr1}. No formulas for calculating the effect of surface orientation have been proposed yet.

Styrikovich and Polyakov [1], who studied how the orientation of the hot surface affects q_{cr1} in the case of water, benzene, and various alcohols boiling in a large volume at a 5 mm thick Nichrome plate under atmospheric pressure, also noted that changing the inclination angle φ* of the hot surface from 0 to 90° causes a reduction of q_{cr1} by 8% and that at $\varphi = 180°$ the critical heat load is 40% lower than with the hot surface turned upward.

Costello and Adams [2] studied the effect of surface orientation on water boiling under conditions of simulated gravitation during the rotation of a vessel containing both the water and the hot surface. In their experiments with an 8 mm thick graphite plate, under simulating forces equal to natural terrestrial gravitation, a change of the orientation angle produced a change in q_{cr1} by 25%, while under a force of ~100 g (corresponding to a rise in water pressure to ~34 bars) the critical heat load varied as a function of the inclination angle through a factor of 5 (from $3.15 \cdot 10^6$ to $0.63 \cdot 10^6$ W/m^2). Such a reduction of the heat load, as a result of varying the inclination angle, during boiling in a large volume under atmospheric pressure was noted by many authors [3-7].

It must be pointed out that no thorough specialized research has been done concerning the effect of surface orientation on the heat transfer during the boiling of liquids with a high boiling point. Measurements of q_{cr1} during the boiling of cryogenic liquids at oriented surfaces under free-fall conditions ($g \simeq 0$) have adequately well revealed the qualitative pattern of the process, but still cannot be considered reliable as far as the absolute values of q_{cr1} are concerned – because those measurements were made during a transient boiling mode lasting only 1.3-1.8 sec [7-10]. For this reason, it becomes important to perform such measurements in orbital laboratories beyond the influence of Earth's gravitation.

Lyon [11] has carefully studied the effect of surface orientation on q_{cr1} with helium boiling in a large volume subject to terrestrial gravitation. His hot surface was a platinum disk 10 mm in diameter. He has

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*The orientation angle is defined here as the angle between the normal to the surface and the direction in which vapor bubbles depart from the surface under the influence of gravitation.

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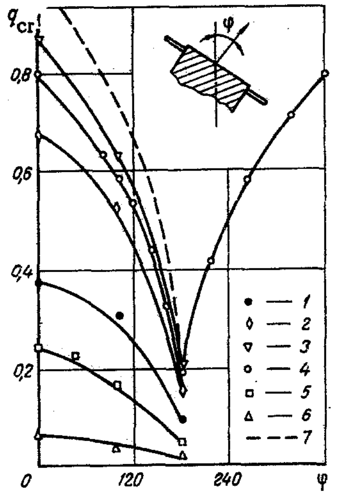

Fig. 1. Critical thermal flux q_{cr1} (W/cm^2) as a function of the inclination angle $\varphi°$ of the hot surface, during boiling of helium in a large volume [11]: 1) T = 2.26°K; 2) 2.96; 3) 3.75; 4) 4.21; 5) 4.98; 6) 5.13; 7) $T_{extr} = 4.1°K = 0.8T/T_{cr}$.

established (Fig. 1) that, under atmospheric pressure and depending on the position of the hot plate relative to the direction of Earth's gravitation vector and, therefore, also depending on the mode of vapor evacuation, the critical value of the thermal flux can vary through a factor of 4 from 0.8 W/cm^2 at a horizontal plate with the hot surface facing up to 0.2 W/cm^2 at a horizontal plate with the hot surface facing down. At a vertical surface the value of q_{cr1} was 25% lower than at a horizontal plate with the hot surface facing up.

As the temperature (pressure) of the boiling liquid varies, the effect of surface orientation varies but in a bivalent manner. Lyon's test data have been plotted in Fig. 2 in $q_{cr1} = f(T, \varphi)$ coordinates. As the boiling of the liquid rises (at a constant inclination angle φ of the hot surface), according to the graph, the value of q_{cr1} first increases and then sharply decreases. The same trend is noted also in the case of other liquids (Fig. 2b), such as water according to the tests reported by Kazakova [3]. This leads to the interesting conclusion that for every boiling liquid there is an extremum temperature at which the surface orientation has its maximum effect on q_{cr1}. For helium, at all possible inclination angles of the hot surface relative to the direction of gravitation, this extremum temperature T_{extr} corresponds to the boiling point: $T_{extr} = T_b = 4.1°K$ or $T_{extr}/T_{cr} = 0.79 \simeq 0.80$.

As the boiling point of a liquid departs from this extremum temperature toward the critical temperature T_{cr} or the λ-temperature of helium, the effect of the inclination angle of the hot surface diminishes fast down to complete degeneracy.

Several researchers [2, 7-10, et al.] have experimentally studied the effect of attenuated and amplified gravitation on the critical thermal flux during nucleate boiling of liquids. Unfortunately, these experiments were performed at only one saturation temperature and were not set up for tracking the effect of variations in the boiling temperature.

Starting with an analysis of nucleation processes, of bubble buildup and dynamics during boiling under zero gravitation (or amplified gravitation), one can derive a relation for q_{cr1} as a function of the boiling point for any given liquid. The validity of this hypothesis is confirmed by Lyon's test results with helium (Fig. 1, curve 1) [11]. With the hot surface inclined at an angle $\varphi = 180°$ under conditions of nearly zero gravitation, as is well known, the critical thermal flux depends largely on the boiling point of the liquid: at the extremum temperature of helium $q_{cr1} = 0.22$ W/cm^2, and $q_{cr1} \simeq 0$ at a temperature near T_{cr} or T_λ.

The results which all those researchers [2, 3, 11, 12] had obtained for water and helium were subsequently compared by this author under corresponding thermodynamic conditions, at T/T_{cr} temperature as proposed by Borishanskii and Novikov [13], proving convincingly that the inclination angle of the hot surface can have an appreciable effect on the absolute magnitude of the first critical thermal flux (an effect of changing that magnitude by up to 500% or more), while the relative values of q_{cr1} for both these liquids are almost the same. Such a sharp decrease (to one fifth) of q_{cr1} for water, as a result of changing the surface orientation and the boiling point, is not in agreement with most known test data and can be explained, apparently, by the fact that the effect of surface orientation during boiling was studied only under atmospheric pressure.

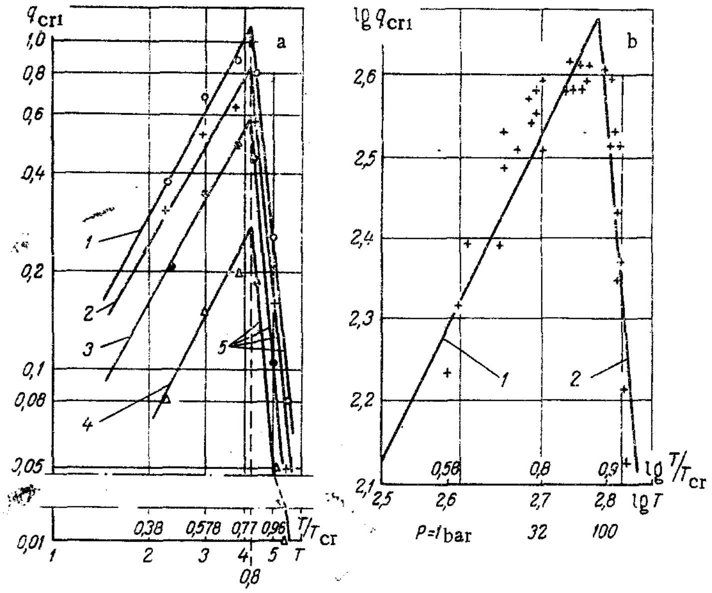

Fig. 2. Effect of the inclination angle φ of the hot surface on the critical nucleate boiling of helium and water in a large volume, in q_{cr1}, T/T_{cr} coordinates: a) boiling of helium [11] at $\varphi = 0°$ and $q_{cr1} = \chi(T)^{1.8}$ (1); $\varphi = 90°$ and $q_{cr1} = \chi(T)^{1.7}$ (2); $\varphi = 140°$ and $\bar{q}_{cr1} = \chi(T)^{1.8}$ (3); $\varphi = 180°$ and $q_{cr1} = \chi(T)^{1.9}$ (4), descending curves $q_{cr1} = \chi(T)^{9.4}$ (5); b) boiling of water [2] at $\varphi = 90°$ and $q_{cr1} = \chi(T)^2$ (1); $\varphi = 90°$ and $q_{cr1} = \chi(T)^{10.5}$ (2).

The curves in Fig. 1 of q_{cr1} as a function of the inclination angle of the hot surface and as a function of the boiling point T of the liquid can be described by the following parabolic equation:

$$\varphi = -c_0 q_{cr1}^2 + \varphi_0 \quad \text{or} \quad q_{cr1} = \left(\frac{\varphi_0 - \varphi}{c_0}\right)^{0.5}, \tag{1}$$

where coefficient c_0 is a function of the temperature and $\varphi_0 = 190°$.

According to Fig. 2, for a boiling point $T < T_{extr}$

$$c_0 \sim T^{-2}; \tag{2}$$

while for boiling modes where $T > T_{extr}$

$$c_0 \sim T^{10}. \tag{3}$$

Inserting expressions (2) and (3) into (1), we obtain for boiling modes at $T < T_{extr}$

$$q_{cr1} = c(\varphi_0 - \varphi)^{0.5}\, T/T_{cr}; \tag{4}$$

and for boiling modes at $T > T_{extr}$

$$q_{cr1} = c_1(\varphi_0 - \varphi)^{0.5}\, (T/T_{cr})^{-5}. \tag{5}$$

Lyon's test data [11] for helium (Fig. 1), which have been plotted in Fig. 3 in coordinates of expressions (4) and (5), fit the following equations:

for boiling modes at $T < T_{extr}$

$$q_{cr1} = 0{,}085\,(190 - \varphi)^{0.5}\, T/T_{cr}\ \text{W/cm}^2; \tag{6}$$

and for boiling modes at $T > T_{extr}$

$$q_{cr1} = 0.02\,(190 - \varphi)^{0.5}\, (T/T_{cr})^{-5}\ \text{W/cm}^2. \tag{7}$$

The introduction of parameters T and T/T_{cr} into these formulas, instead of P/P_{cr}, is dictated by the low boiling pressure (40-1700 mm Hg) of liquid helium He_1^4.

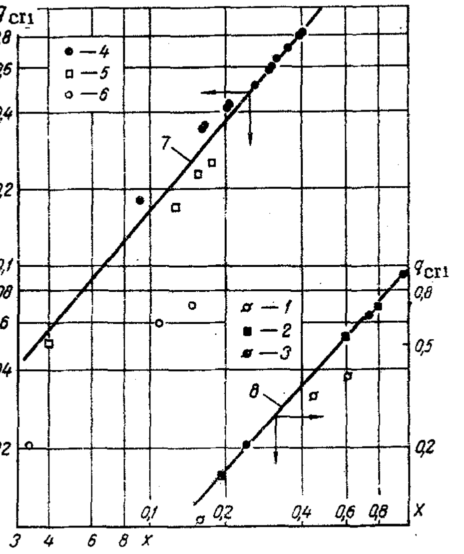

Fig. 3

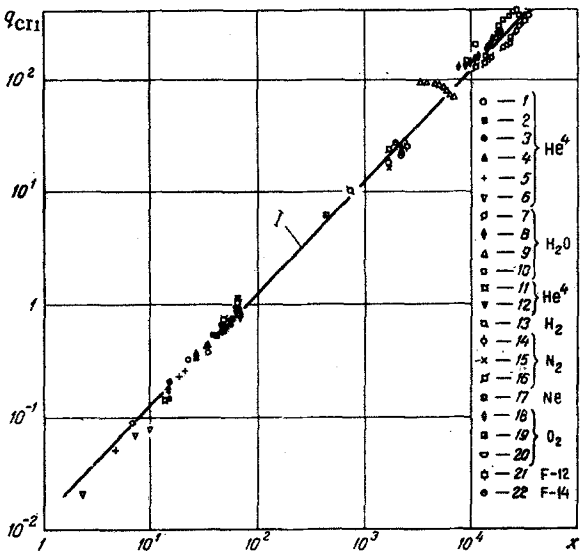

Fig. 4

Fig. 3. Critical thermal flux q_{cr1} as a function of the inclination angle of the hot surface and as a function of the relative boiling temperature [11], for helium: $(190-\varphi)^{0.5}(T/T_{cr})^{-5}$ along the x-axis; $(190-\varphi)^{0.5}T/T_{cr}$ along the X-axis: T = 2.26°K and T/T_{cr} = 0.436 (1); 2.98°K and 0.571 (2); 3.75°K and 0.723 (3); 4.21°K and 0.812 (4); 4.98°K and 0.96 (5); 5.13°K and 0.99 (6); $q_{cr1} = 0.02(190-\varphi)^{0.5}(T/T_{cr})^{-5}$ (7); $q_{cr1} = 0.085(190-\varphi)^{0.5}T/T_{cr}$ W/cm² (8).

Fig. 4. Critical thermal flux q_{cr1} during nucleate boiling of liquids in a large volume, as a function of the inclination angle, of the gravity forces, and of the physical properties of the liquids: $(190-\varphi)^{0.5}r[\eta g\sigma(\rho'-\rho'')\rho''^2]^{0.25}$, W/cm² along the x-axis: helium [11]: 1) T = 2.26°K, φ = 0.90, 180°; 2) T = 2.96°K, φ = 0.90, 180°; 3) T = 3.75°K, φ = 0.90, 180°; 4) T = 4.21°K, φ = 0.40, 70, 90, 110, 140, 160, 180, 220, 270, 320, 360°; 5) T = 4.98°K, φ = 0, 40, 90, 180°; 6) T = 5.13°K, φ = 0, 90, 180°; [12]; 11) T = 4.21°K, φ = 0, 90, 180°; [19]: 12) T = 4.21°K, φ = 0°, copper, tin, brass, stainless steel; water [2]: 7) φ = 0°, η = 1-100; 8) φ = 135°, η = 1-100; 9) φ = 180°, η = 1-100; [3]: 10) φ = 90°, η = 1, P/P_{cr} = 0.004-1; hydrogen [18]: 13) T = 20.4°K, φ = 0°; nitrogen [18]: 14, 15, 16) T = 77.3°K, φ = 0°; neon [18]: 17) T = 27°K, φ = 0°; oxygen [18]: 18, 19, 20) T = 19°K, φ = 0°; Freon-12 [11]: 21) T = 243.3°K, φ = 0°; Freon-14 [11]: 22) T = 94°K, φ = 0°; I) $q_{cr1} = 0.0125(190-\varphi)^{0.5}r[\eta g\sigma(\rho-\rho'')\rho''^2]^{0.25}$.

Kruzhilin [17] and Kutateladze [14] have studied the boiling of liquids and proposed a rather accurate physical model of critical nucleate boiling at a horizontal surface. Kutateladze, while deriving a system a system of fundamental equations with boundary conditions describing the process of fully developed nucleate boiling, obtained the following relation:

$$q_{cr1} = k_1 r \sqrt{\rho''}\sqrt[4]{g\sigma(\rho'-\rho'')},$$

where K_1 is the stability factor.

It has been established experimentally that the stability factor for various liquids with high boiling points is constant, equal to 0.15-0.19 according to [14], equal to 0.17 according to [3], and equal to 0.16-0.19 according to Chickelly and Bonille. Borishanskii [15] has added some significant refinement to this physical model of critical nucleate boiling by deriving the fundamental equations of the process and has shown that the stability factor is a function of the viscosity of the liquid:

$$k_1 = 0.13 + 0.4N^{-0.4}. \tag{8}$$

An evaluation of test data on critical nucleate boiling of cryogenic liquids under atmospheric pressure at horizontal plates has yielded the values of the stability factor k_1 given in Table 1.

Tests show that the values obtained for k_1 at horizontal and, particularly, at vertical or inclined surfaces [2, 11, 12] may differ appreciably from the theoretical value $k_1 = \pi/24 = 0.13$ [16]. This indicates that the physical model of critical nucleate boiling conceived and developed by Kruzhilin [17], Kutateladze

[14], Borishanskii [15], Zuber [16], et al. for a horizontal surface does not, apparently, account for the effect of certain important aspects of surface orientation and should be still further refined.

One may hypothesize that the physical effect which the orientation of the hot surface has on critical nucleate boiling in a free volume (Fig. 1) is, in addition to other factors, also due to a distortion of the bubble shape at the hot surface, due to a change in the wetting angle, and due to a change in the amount of energy used up on merging deformed bubbles into a vapor film. At the instant preceding the critical boiling mode, a vapor bubble at an inclined surface is not exactly spherical in shape, as has been assumed earlier, but is, instead, distorted by various acting forces.

On the basis of the physical model of the process developed by this author, we will analyze the given system of fundamental equations describing the heat transfer during nucleate boiling [14] (equation of heat conduction in the liquid, equations of thermal and mechanical interaction at the interphase boundary, equations of motion and continuity in the liquid and in the vapor phase, and the initial as well as the boundary conditions). By using certain well-known procedures for solving systems of equations [20, 14] and by grouping the governing referred parameters into dimensionless complexes, we obtain the following formula for calculating the critical thermal fluxes during nucleate boiling of liquids at variously oriented surfaces in a large volume:

$$q_{\mathrm{cr1}} = z(190 - \varphi)^{0.5}\, r\left[\eta g\sigma(\rho' - \rho'')\rho''^{2}\right]^{0.25}\ \mathrm{W/cm^2},$$

where $z = 0.0125$ and φ is the relative inclination angle of the hot surface.

Formula (9) approximates the test data obtained for helium and water [2, 3, 11, 12] (Fig. 4) at various inclination angles of the hot surface, also data obtained for nitrogen, oxygen, hydrogen, neon, Freon-14 at $\varphi = 0°$ [18, 19]. Lyon's data are approximated within 5-10%, except for the tests performed at temperatures close to T_{cr} or T_{λ}.

Formulas (6), (7), and (9) are applicable to any inclination angle of the boiling surface (from 0 to 360°). Angle $\varphi = 0$ refers to a horizontal surface from which bubbles depart. For angles larger than 180°, φ must be replaced by the difference $360-\varphi$. Formula (9) is valid for overloads from 0.1 g to 2500 g. It is quite evident that the product $z(190-\varphi)^{0.5}$ in (9) is equivalent to some stability factor k_1 [14]. This product does not remain constant as the inclination angle of the hot surface varies: for a horizontal surface facing up $z(190-\varphi)^{0.5} = 0.17$, for a vertical surface $z(190-\varphi)^{0.5} = 0.125$, and for a horizontal surface facing down $z(190-\varphi)^{0.5} = 0.04$.

TABLE 1. Values of Stability Factors

Indicator	Cited reference	Ne	He^4	H_2	N_2	O_2
Criterial N number in (8)		$2.3 \cdot 10^5$	$4.26 \cdot 10^5$	$1.53 \cdot 10^6$	$3.35 \cdot 10^7$	$4.7 \cdot 10^7$
k_1 according to formula (8)		0.1319	0.1322	0.1313	0.1304	0.1303
k_1 according to tests	Biveloga [18]	0.192				
The same	Lyon [11] platinum, diameter 10 mm		0.170			
" "	Lyon [18] platinum, diameter 63 mm				0.16	0.16
" "	Jergel [12] copper, diameter 15 mm		0.243			
" "	Cummings [19] copper, diameter 15 mm		0.252			
	tin		0.192			
	brass		0.175			
	stainless steel		0.175			
" "	Jefferson [19] tubing, diameter 2.5 mm copper		0.19			
	stainless steel		0.132			
" "	Rubo [18]			0.186	0.21	
" "	Brentair [18]			0.186	0.137	
	Blangero [18], tubing, diameter 19 mm					0.141
	Hodja [18]					0.148

In view of the insignificant amount of available data on the effect of surface orientation on q_{cr1} during boiling, especially for liquids with high boiling points, it is very worthwhile to further continue research in this area. It is important, moreover, that the experiments at various boiling temperatures (pressures), surface orientations, and gravitation levels be performed on standard plate specimens. As such a standard for boiling a liquid in a large volume we recommend a flat disk 10-15 mm in diameter, which will avoid distorting the test results by the effect of one of the surface dimensions; this happens often in tests where hot wires and hot long tapes are used.

NOTATION

q_{cr1}	is the critical thermal flux during nucleate boiling;
φ	is the inclination angle of the hot surface, i.e., angle between the normal to the surface and the direction of bubble departure from the surface ($\varphi_{rel} = \varphi/\varphi_1$, where $\varphi_1 = 1°$);
T	is the boiling point of the liquid;
T_{cr}	is the thermodynamic critical temperature of the substance;
T_λ	is the temperature corresponding to the λ-point of helium;
P_{cr}	is the critical pressure;
z	is the stability factor of nucleate boiling;
r	is the heat of evaporation;
ρ'	is the density of liquid;
ρ''	is the density of vapor;
σ	is the surface tension;
$\eta = a/g$	is the overload factor;
g	is the acceleration of Earth's gravity.

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