PECULIARITIES OF HEAT TRANSFER WITH HYDROGEN BOILING IN A THICK HEATER MADE OF AMg-6 ALLOY

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The authors show that there is a mixed boiling regime for hydrogen in a heater of poorly conducting material.

One must study the laws of heat transfer for boiling hydrogen in order to effectively solve the problems of retaining and using this cryogenic liquid. The known test data on boiling hydrogen in heavy copper heaters [1-4] and in thin-walled heaters made of low-conductivity alloys [5-7] show satisfactory inter-agreement and agreement with existing theoretical relations. However, it is known in the example of helium that in boiling in a thin-walled heater of steel or other material with a low value of the parameter $\varkappa_h$ an anomalous behavior of the heat transfer characteristics has been observed [8-12]. Here the value of α depends more weakly on q and the pressure than for bubble boiling: the heater temperature T_h, right up to the onset of the crisis, exceeds not only T_{lim} but also the critical liquid temperature. This is evidently due to the presence of film boiling centers for $q_{cr2} < q < q_{cr1}$ on the heat-generating surface, as well as bubble boiling. For film boiling we typically have α practically indepent of q and a comparatively small influence of p on the heat transfer coefficient. Therefore, the appearance of film centers with relative area ψ_m must lead to the existence of a type of dependence $\alpha(p, q)$ intermediate between pure bubble and pure film boiling. To a first approximation the measured mean surface temperature is [13]

$$T_h = T_s + \psi_m \Delta T_m + (1 - \psi_m) \Delta T_{bub} \tag{1}$$

and for $\psi_m > 0$ it may exceed $T_{lim} \geqslant (T_s + \Delta T_{bub})$.

For nitrogen and cryogenic liquids with higher boiling points we do not see mixed boiling, even in heavy steel heaters [14, 15]. For hydrogen, which occupies an intermediate position between helium and nitrogen, a direct check has not yet been performed. However, this is necessary, both from the viewpoint of elucidating the uniqueness of helium in this respect, and also in the interests of improving methods of computing heat transfer with hydrogen boiling in thin-walled vessels and pipes.

In the present work an experimental heater was made of AMg-6 aluminum—magnesium alloy which is widely used in cryogenic technology as a construction material. At T_h = 20 K the alloy has a low value of the parameter $\varkappa_h = 7.78 \cdot 10^2$ W·sec$^{0.5}$/(m^2·K), close to that of steel ($5.73 \cdot 10^2$ for 12Cr18Ni9Ti) and much less than for copper ($1.19 \cdot 10^4$) [16], and therefore corresponds to the problem formulated.

The tests were conducted in a cryostat [17] in the range $p = 7.2 \cdot 10^3 - 6 \cdot 10^5$ N/m^2. The structure of the heater block was analogous to that used in [10, 11]; the diameter of the heat-generating surface was 30 mm, and the thickness of the heater was 13 mm. Transparent plastic heat insulation achieved a calculated heat leakage of from 8.5% at $q = 10^3$ W/m^2 to 3% at $q = 10^5$ W/m^2. In three series of tests the heat-generating surface had a different level of treatment (class 5, 7 and 10). We also studied the influence of the surface slope angle φ .

The heater temperature in the liquid was measured with germanium resistance thermometers from the IP, Academy of Sciences of the Ukrainian SSR. Inside the heater, along the axis of symmetry there were three thermometers in drilled holes (at distances 1.5, 5.5 and 9.5 mm from the heating surface). The surface temperature T_h was determined by graphical

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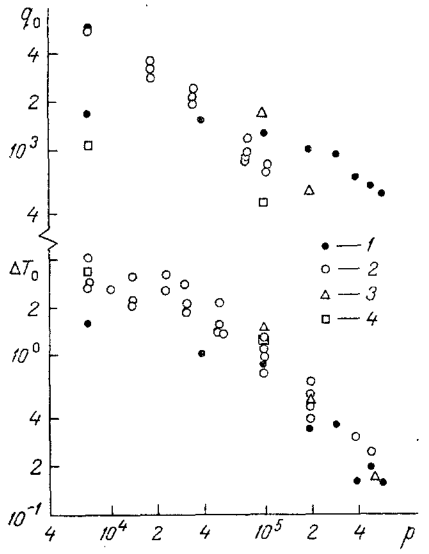

Fig. 1

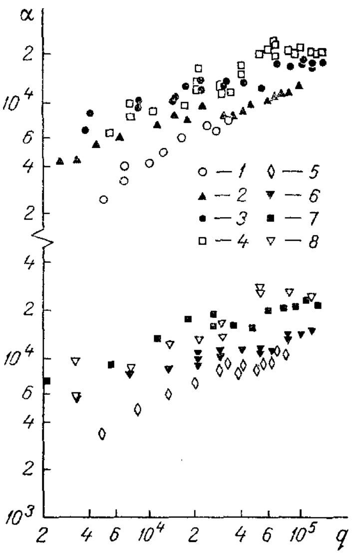

Fig. 2

Fig. 1. Dependence of the characteristics of start of boiling of hydrogen on the pressure: 1) present data; 2) cylindrical steel heater of diameter 4 mm [6, 7]; 3) planar copper heater [18]; 4) planar copper heater [2].

Fig. 2. Dependence of the heat transfer coefficient on the heat load with boiling of hydrogen on a horizontal heater: 1) $p = 7.2 \cdot 10^3$ N/m^2; 2) $1 \cdot 10^5$; 3) $3 \cdot 10^5$; 4) $5 \cdot 10^5$; 5) $4 \cdot 10^4$; 6) $2 \cdot 10^5$; 7) $4 \cdot 10^5$; 8) $6 \cdot 10^5$ N/m^2.

extrapolation from the three values of T inside the heater. It should be noted that the estimate of thermal conductivity of the metal from the values of q and the measured differences of T in the tests agree satisfactorily with the handbook data [16]; this allows us to calculate T_h by linear extrapolation from the readings of the thermometer closest to the surface. One can estimate the error in determining T_h to be ±0.2 K.

The time for the start of boiling of the liquid was fixed visually from the appearance of the first vapor bubbles. Figure 1 shows the mean values of q_0, ΔT_0 for a horizontal location of the heater ($\varphi = 0°$). We note that the reproducubility of the start-of-boiling characteristics is poor; for example, in repeat tests in conditions $p = 10^5$ N/m^2 we obtained values of ΔT_0 in the range 0.55 to 1.06 K, q_0 from 640 to 2120 W/m^2; because of this scatter of the data we did not observe the influence of roughness on q_0, ΔT_0. A comparison of the results obtained with the data of [2, 6, 7, 18] shows satisfactory agreement on the whole, both in the nature of the dependence of q_0, ΔT_0 on pressure, and in absolute magnitudes. One can thus conclude that there are no heat transfer anomalies in the low q region.

The curves of bubble boiling $q(\Delta T)$ were determined in tests on two directions of change of the heat load: with an increase from $q = 0$ (direct course) and a decrease from $q = 0.9\, q_{cr1}$ (inverse course). On the whole we obtained a small hysteresis in the boiling curves for $q_0 \leqslant q \leqslant 0{,}5\, q_{cr1}$, a maximum for a coarse surface treatment, and practically nothing on a polished surface. In general the influence of roughness on α and q_{cr1}, ΔT_{cr1} was insignificant, and is not considered below.

Figure 2 shows the test data on the dependence α(q); for clarity the figure is divided into two parts. It can be seen that, depending on the pressure, the curve α(q) has qualitatively different behavior: for $p = 7.2 \cdot 10^3 - 2 \cdot 10^5$ N/m^2 it can be approximated by a single straight line (in logarithmic coordinates):

$$\alpha = Cq^n; \tag{2}$$

for $p = (3\text{-}6)10^5$ N/m^2 the edge of the initial sloping section of the dependence is a practically horizontal ($\alpha \approx$ const) section in the precrisis region of q. The exponent n of the sloping section varies in the range 0.23-0.47, and does not show a single-valued dependence on the pressure. This is less than the value of n = 0.6-0.7 obtained for bubble

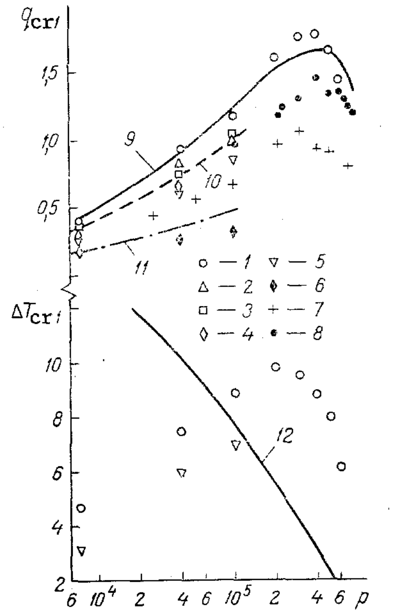

Fig. 3

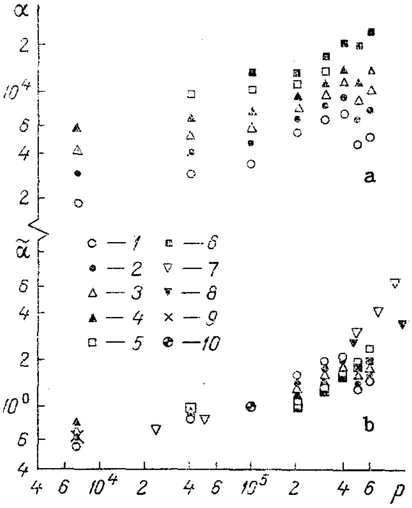

Fig. 4

Fig. 3. Dependence of the characteristics of the first boiling crisis in boiling of hydrogen on the pressure for different heater orientations: present data: 1) $\varphi = 0°$; 2) 45; 3) 90; 4) 135; 5) 160; 6) 180; 7) data of [17], stainless steel tube, $\varphi = 0°$; 8) data of [3], copper disk, $\varphi = 0°$; 9) computed using Eq. (3), K = 0.225; 10) computed using Eq. (3), for $\varphi = 90°$; 11) computed using Eq. (4), for $\varphi = 180°$; 12) line of limiting superheat – $\Delta T_{lim} = \Delta T_{lim}(p)$.

Fig. 4. Dependence of the heat transfer coefficient on the pressure for different heat loads (computed using Eq. (2)): a) $\alpha(p)$; b) $\alpha(p)/\alpha(1 \cdot 10^5\ N/m^2)$; present data: 1) $q = 2 \cdot 10^3\ W/m^2$; 2) $5 \cdot 10^3$; 3) 10^4; 4) $2 \cdot 10^4$; 5) $5 \cdot 10^4$; 6) 10^5; 7) data of [6]; 8) [3]; 9) [2]; 10) $\tilde{\alpha} = 1$; $q = 10^4\ W/m^2$.

boiling of hydrogen in [1-7] and used in the computing formulas [14, 15]. The beginning of the horizontal section corresponds roughly with $q^* = (4\text{-}6) \cdot 10^4\ W/m^2$; although there are no test data on q_{cr2} for hydrogen in the literature, one can postulate that $q^* \approx q_{cr2} \approx 0.25\text{-}0.3 \cdot q_{cr1}$ (Fig. 3). According to ΔT the region of independence of α on q begins for temperature heads of about 2-3 K, which coincides to a first approximation with the limiting overheat of the liquid ΔT_{lim}, which decreases in this range of p roughly from 4 to 1.6 K (Fig. 3). Thus, for $q^* \leqslant q \leqslant q_{cr1}$ and $\Delta T_{lim} \leqslant \Delta T \leqslant \Delta T_{cr1}$ the measured surface temperature is above T_{lim}, and as the crisis is approached, it also exceeds the critical temperature of hydrogen. It should be stressed that for q = const the temperatures of the sensors here are kept in a stable manner at a steady-state level, and do not experience "drift" with time, a matter that was checked specially in the tests. This means that the frequently expressed objection to the ideas of mixed boiling, based on the supposedly occurring centers that hinder the experimenter in determining the crisis, is untenable: at the crisis ΔT increases, and tends to ΔT_m.

To evaluate ψ_m from Eq. (1) we need to know the value of ΔT_m for $q = q_{cr1}$. Computing ΔT_m from a formula suggested in [19] and giving a good correlation of test data on film boiling of hydrogen over a wide pressure range, and taking $\Delta T_{bub} = \Delta T_{lim}$, we obtain the result that ψ_m increases from zero at $q = q^*$ to 1.3-1.6% for $q = q_{cr1}$. This is noticeably less than for helium, where ψ_m reaches 20-40% [13, 20]. This estimate is quite arbitrary, however, because the surface temperature at film boiling centers is naturally below the computed value of ΔT_m due to heat leakage, and ψ_m is greater than the computed value. The estimate was made as a qualitative illustration of the less pronounced nature of mixed boiling effects at high boiling temperature.

Figure 4a shows the data on the dependence $\alpha(p)$ for several values of q = const; it can be seen that α increases with increase of pressure. However, in comparing the present results with the data of other authors [2, 3, 6] on a relative scale (Fig. 4, b) one can note a weaker dependence $\alpha(p)$ than is usual for bubble boiling of hydrogen; the most noticeable deviation is observed for $p > 2\cdot10^5$ N/m^2. For example, for $q = 10^4$ W/m^2 in the pressure range $p = 7.2\cdot10^3\text{-}6\cdot10^5$ N/m^2 according to the data of [6] α increases a factor of 6, but only by a factor of 2.5 in our data. The latter value is rather close to typical for the dependence $\alpha(p)$ in film boiling of hydrogen [19].

It should be noted that the differences obtained from the usual type of dependence $\alpha(q, p)$ for bubble boiling occur not just in the region $q^* \leqslant q < q_{\mathrm{cr1}}$ and $\Delta T_{\mathrm{lim}} \leqslant \Delta T \leqslant \Delta T_{\mathrm{cr1}}$ which formally bound the conditions for the existence of mixed boiling, although expressed here at the maximum level. However, in spite of certain qualitative indications of film boiling, the absolute values of the heat transfer coefficient are quite large, and considerably closer to pure bubble boiling than pure film boiling.

The heat transfer crisis was determined in the tests from the sharp and irreversible increase of the heater temperature upon a small (2-5%) increment of q. To generalize the dependence $q_{\mathrm{cr1}}(p)$ for $\varphi=0°$ (see Fig. 3) we used the well-known Kutateladze formula

$$q_{\mathrm{cr1}} = KL\sqrt{\rho_v}\,\sqrt[4]{\sigma g(\rho-\rho_v)}. \tag{3}$$

It was found that for $K = 0.225$ the maximum deviation of the points from the theoretical curve did not exceed 9%. The decrease of q_{cr1} with increase of the angle φ from 0 to 180 deg can be described by the relation [21]

$$\tilde{q}_{\mathrm{cr1}} = \frac{q_{\mathrm{cr1}}}{q_{\mathrm{cr1}}(\varphi=0°)} = \left(\frac{D}{2b}\right)^m, \tag{4}$$

where $m = \ln\sqrt{(190°-\varphi)/190°}/\ln 25$ and $q_{\mathrm{cr1}}(\varphi=0°)$ was determined from Eq. (3). Although the absolute values q_{cr1} obtained in this work are somewhat higher than for other authors (see Fig. 3), the nature of the dependence $q_{\mathrm{cr1}}(p, \varphi)$ does not exhibit any deviation from normal.

The dependence $\Delta T_{\mathrm{cr1}}(p)$ based on the present data is qualitatively similar to the dependence $q_{\mathrm{cr1}}(p)$, i.e., it has the form of a curve with a maximum at $p \approx 2\cdot10^5$ N/m^2. For cryogenic liquids one more frequently has a monotonically decreasing dependence [14, 15]. In a comparison of absolute values of ΔT_{cr1} with the data of [6], for example, it turns out that in the case $p < 10^5$ N/m^2 the critical temperature heads differ slightly, but as pressure increases the value of ΔT_{cr1} in a thin-walled tube decreases significantly more rapidly than in the AMg-6 alloy, remaining less than ΔT_{lim}. The values of ΔT_{cr1} found in the present work exceed for $p \geqslant 10^5$ N/m^2 the value of ΔT_{lim}, and for $p > 3\cdot10^5$ N/m^2 the value of $T_{\mathrm{h\,cr1}}$ is larger than the critical temperature of hydrogen.

In [14] the empirical relation

$$\Delta T_{\mathrm{cr1}} = A\left(1+\frac{B}{K_\varkappa}\right), \tag{5}$$

was suggested to describe the dependence of ΔT_{cr1} on the properties of the material of a heavy heater with $p = 10^5$ N/m^2, where for helium $A = 0.5$, $B = 1.82$; and for nitrogen $A = 4.5$, $B = 10$. From the values of ΔT_{cr1} with boiling of hydrogen in copper (4.52 K from the data of [4]) and AMg-6 alloy one can obtain $A = 4.2$ and $B = 2$. It is interesting that for nitrogen the condition $\Delta T_{\mathrm{cr1}} \geqslant \Delta T_{\mathrm{lim}}$ must hold for Eq. (5) with $K_\varkappa \leqslant 1.76$. The available data on ΔT_{cr1}, on which the correlation was based, were obtained in the range $K_\varkappa = 6.0-60$ [14]. Thus, the absence of mixed boiling in tests in nitrogen can be explained logically by the inadequately low values of $\varkappa_{\mathrm{h}}$, even for steel.

The mechanism of mixed boiling has received practically no study as yet. The cause of the stable existence of film boiling centers ($\psi_m > 0$) and their propagation to the entire surface ($\psi_m \neq 1$) is evidently associated with the low thermal conductivity (which decreases to very small values at the temperatures of boiling helium and to a lesser extent of boiling hydrogen) and substantial heater thickness. In fact, it was shown in [22] that the rate of propagation of a change of boiling regime front over the heat generating surface is proportional to the group $\sqrt{\lambda_{\mathrm{h}}}/(c_p\rho)_{\mathrm{h}}\sqrt{\delta_{\mathrm{h}}}$. According to test data this decreases even with a pressure increase. One can postulate that for certain conditions this rate is equal to zero, and a film boiling center will not vanish or expand. On the other hand, this rate is determined by the ratio between q_{cr1} and q_{cr2}, and also by the values of α for bubble and film boiling, and it decreases as the pairs approach one another. In heavy steel heaters the difference $q_{cr1}-q_{cr2}$, as is known, is considerably less than in copper [14]. Evidently, the coming together of the values q_{cr1} and q_{cr2}, α_{bub} and α_m with increase of the heat load is the cause of the existence of the mixed boiling regime for helium and in a copper heater in the strong field of centrifugal force [23].

NOTATION

$b=\sqrt{\sigma/g(\rho-\rho_v)}$, Laplace constant, m; c_p, specific heat, J/(kg·K); D, heater diameter, m; g, acceleration due to gravity, m/sec^2; $K_\varkappa=\varkappa_h/\varkappa$; L, heat of evaporation, J/kg; m, n, exponents; p, pressure, N/m^2; q, heat flux density, W/m^2; T, temperature, K; $\Delta T = T_h - T_s$, temperature head, K; α, heat transfer coefficient, W/(m^2·K); δ_h, heater thickness, m; $\varkappa=\sqrt{\lambda c_p\rho}$, coefficient of heat assimilation, W·sec$^{0.5}$/(m^2·K); λ, thermal conductivity, W/(m·K); ρ, ρ_v, density of liquid and vapor, kg/m^3; σ, surface tension, N/m. Subscripts: cr1, cr2, first and second heat transfer crises; h, heater; 0, start of boiling; lim, limiting superheat of liquid; bub, bubble boiling; m, film boiling; s, saturation.

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A SELF-CONSISTENT METHOD FOR THE DESCRIPTION OF THE GENERALIZED CONDUCTIVITY OF HETEROGENEOUS SYSTEMS

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A generalization is presented of the self-consistent field method for the determination of the effective conductivity of heterogeneous materials based on simultaneous utilization of the field balance and flux equations. Generality of the approach being proposed and its relation to many formal solutions of the problem being discussed are illustrated.

One of the promising paths to the improvement of the exploitational characteristics of articles is related to the extensive utilization and optimization of heterogeneous material properties that are often microinhomogeneous media with inhomogeneity dimensions significantly less than the characteristic quantities for the specimen or article. Many important physical properties of similar materials such, for instance, as the kinetic, magnetic, and dielectric, can be investigated theoretically from a single aspect because of the mathematical equivalence of their description. The problem of finding regularities of the change in the heterogeneous system characteristics being discussed has received the designation of the problem of generalized conductivity [1, 2] for which a number of fundamental generalizations has been established in investigations (see [2], say). By virtue of the sufficient complexity of the problem all the known solutions have been obtained under definite simplifying assumptions of a physical or mathematical nature whereupon the equivalence of the mathematical and physical models utilized in describing the generalized conductivity has often been lost. A generalization of the known self-consistent field method [3] is presented below, that permits setting up a connection between solutions obtained under different assumptions, as well as a deeper comprehension of their physical meaning without relying here on a complex mathematical apparatus.

The crux of the self-consistent field method in the establishment of effective heterogeneous material characteristics is the equalization of the mean field in particles of a multiphase system placed alternately in a homogeneous medium with effective properties to a microscopic field. The field balance equation is the self-consistent condition (while the flux balance equation is satisfied automatically) in this method that has received extensive application in the description of statistical mixtures of particles of equally likely phases. Generalization of the result obtained in such a manner can be obtained because of the introduction of an additional conductivity parameter for the heterogeneous system with simultaneous utilization of the field and flux balance equations.

To clarify the features of the method it is expedient first to examine the solution of an auxiliary problem on determining the characteristics of a uniform homogeneous medium in which upon placement of a single spherical inclusion with i-th phase conductivity σ_i and application of an external field $\langle E \rangle$ the field in the inclusion will agree with the mean in the corresponding phase in the heterogeneous system E_i. We call this homogeneous system the comparison body and denote its conductivity by σ_c.

Using the solution of the problem of polarization of a sphere in a homogeneous infinite field [4], and taking account of the mathematical equivalence of its description and that inherent to the problem under consideration, we obtain

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