a single-phase turbulent flow; q, specific heat flux; P, static pressure; ΔP, pressure drop in a channel; $\bar{U}$, velocity mean liquid over a cross section; d, L, equivalent diameter and channel length; ρ, c_p, ν, Pr, density, heat capacity, kinematic viscosity, and Prandtl number for a liquid; δ, δ_1, thicknesses of quasilinear dynamic and temperature boundary layers; α, η, parameters of Pohlhausen's solution for a laminar boundary layer.

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METAL BOILING UNDER THE ACTION OF AN ELECTRON-BEAM HEAT SOURCE

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The dynamics of vapor bubble growth in a metal alloy under the action of a volume heat source are considered. The possibility of existence of a threshold superheating value below which the boiling process is impossible is demonstrated.

It is well known that the action of an electron beam on a metal specimen forms a significant volume heat source (for U ~ 100 keV, electron path length $r_0 \sim 10^{-2}$cm) with a maximum in the interior [1, 2]. Such a mode of energy liberation significantly increases the heating zone (in comparison to a laser beam), creates conditions for heating in a volume below the surface, and thus stimulates volume boiling of the material. Thus in studying the process of mass loss under electron-beam action two possible mechanisms must be considered: 1) boiling of material from the surface; 2) volume vapor formation at artificial centers. Matter evaporation from the surface has been examined in detail in a number of studies [3, 4].

We will consider the second mechanism. It should be noted that formation of vapor at centers arising because of density fluctuations will not be considered, since in experiments on electron-beam action on metals the intense volume vapor formation process is observed at temperatures of 3000-4000°K, while fluctuations begin to play a significant role only at temperatures $T \sim T_{cr}$, significantly higher [4].

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Under usual conditions, (i.e., at a fixed external pressure) a liquid boils when the vapor saturation pressure p_s becomes equal to the external fixed pressure p_{ext}. In the case of boiling into a vacuum the external pressure is a function of the surface temperature, i.e., varies during the heating process. It is simple to show that

$$0.5\,p_s(T_\infty) < p_{ext} < p_s(T_\infty). \tag{1}$$

In order to determine the dependence of output pressure on surface temperature more accurately it is necessary to solve the complex problem of heat transfer in the liquid-metal volume and vapor dynamics. In the one-dimensional case vapor escape into a vacuum was considered in [3]. There it was shown that

$$p_{out} \sim 0.56\,p_s(T_\infty). \tag{2}$$

However, when vapor condensation in the expansion process is considered, the difference between output pressure and $p_s(T_\infty)$ is reduced significantly. Thus it will be assumed below that

$$p_{out} = p_s(T_\infty). \tag{3}$$

It should be noted that in electron-beam heating there is always a region where $T > T_\infty$. However, at low temperatures ($T \sim T_f$), boiling does not occur: The liquid metal is able to accommodate much superheating, since under conditions of ideal liquid contact (superheated zone) with the "vessel" (alloy of the same metal) the boiling initiators are nuclei present in the liquid volume. Experiments performed with potassium in contact with a very pure surface [5] have shown that this metal can maintain a superheating of $\sim$100°C.

In the case considered here it is assumed that the liquid metal (Al) can maintain a superheat of the order of 10-100°C without volume vapor formation.

The system of equations, boundary and initial conditions, describing the dynamics of vapor growth in a nonviscous incompressible liquid have the form [6]

$$\rho\left[R\frac{d^2R}{dt^2}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2\right]+\frac{2\sigma}{R}-p_s(T_\infty)\left[\exp\left(\frac{LA}{\tilde{R}T|_{r=R}}\cdot\frac{T|_{r=R}-T_\infty}{T_\infty}\right)-1\right]=0, \tag{4}$$

$$\frac{\partial T}{\partial t}+\frac{R^2}{r^2}\cdot\frac{dR}{dt}\cdot\frac{\partial T}{\partial r}=a\Delta T+\frac{Q(z)}{c\rho}, \tag{5}$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=\infty}=0, \tag{6}$$

$$R|_{t=0}=R_0=\frac{2\sigma}{p_s(T_\infty)\left[\exp\left(\frac{LA}{\tilde{R}T|_{r=R}}\cdot\frac{T|_{r=R}-T_\infty}{T_\infty}\right)-1\right]}, \tag{7}$$

$$T|_{t=0}=T_0, \tag{8}$$

$$\left.\frac{dR}{dt}\right|_{t=0}=0, \tag{9}$$

$$\lambda\left.\frac{\partial T}{\partial r}\right|_{r=R}=(\rho_v L+p_l)\frac{dR}{dt}, \tag{10}$$

$$\rho_v=\frac{P_s(T|_{r=R})}{\tilde{R}T|_{r=R}}, \tag{11}$$

$$p_s(T)=\exp\left(26.2-\frac{LA}{\tilde{R}T}\right), \tag{12}$$

$$p_l=p_s(T_\infty)\exp\left(\frac{LA}{\tilde{R}T|_{r=R}}\cdot\frac{T|_{r=R}-T_\infty}{T_\infty}\right)-\frac{2\sigma}{R}. \tag{13}$$

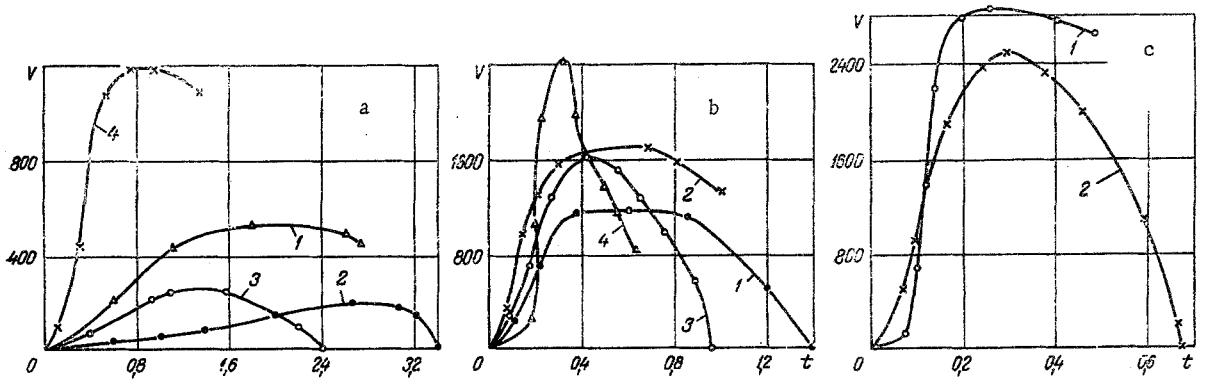

Fig. 1. Bubble-growth rate (cm/sec) versus time (μsec): a: 1) g = $1.53 \cdot 10^6$, T_∞ = 3176°K, ΔT = 83°K; 2) $1.53 \cdot 10^6$, 3101, 62; 3) $3.06 \cdot 10^6$, 3075, 51; 4) $3.06 \cdot 10^6$, 3300, 123; b: 1) $7.6 \cdot 10^6$, 3316°K, 130°K; 2) $7.6 \cdot 10^6$, 3412, 173; 3) $15.3 \cdot 10^6$, 3286, 142; 4) $15.3 \cdot 10^6$, 3420, 240; c: 1) $30.6 \cdot 10^6$, 3480°K, 382°K; 2) $30.6 \cdot 10^6$, 3289, 285.

The equations assume spherical symmetry and unlimited extent of the surrounding liquid phase. The initial temperature field T_0 and plane surface temperature $T_\infty(t) = T(t, 0)$ are determined by solution of the one-dimensional problem of thermal conductivity with evaporation, which is written in a coordinate system moving with velocity v(t) in the form [3]

$$\frac{\partial T}{\partial t} = a\,\frac{\partial^2 T}{\partial z^2} + v(t)\,\frac{\partial T}{\partial z} + \frac{Q(z)}{\rho c}, \tag{14}$$

$$\lambda \frac{\partial T}{\partial z}\Big|_{z=0} = \rho L v(t), \tag{15}$$

$$T(\infty,\ t) = T(z,\ 0) = 0, \tag{16}$$

$$v(t) = c_{so} \exp\left(-\frac{LA}{\tilde{R}T}\right). \tag{17}$$

The number of bubbles in the liquid metal having a radius equal to the critical is set arbitrarily. Each critical nucleus is surrounded by a sphere of radius equal to the mean internucleus distance b. Thermal source densities in cells Q(z) are calculated from data of [2]. Bubble growth is considered until the bubble's radius becomes equal to the mean distance between bubbles. It is assumed that at that point (R = b) the liquid boils. The basic difference between this formulation and those used previously [7] is that here the external pressure, being a function of the boiling process at the surface, changes together with the bubble growth. It is for just this reason, as calculations have shown, that for each flux value q within the interval 10^6-10^8 W/cm^2, there exists some threshold superheat $(\Delta T)_{th} = T_{max} - T_\infty$ below which the boiling process is impossible. Nucleus dimensions extending to the cell surface correspond to the threshold superheat in every cell.

If for a constant external pressure nuclei of a radius greater than critical must grow, then in the given case with increase in surface temperature (i.e., external pressure) both the bubble radius and the critical radius corresponding to the current superheating [the latter may be termed the current critical radius $R_{cr}(t)$] change. If during the growth process the bubble radius remains larger than the current critical radius all the way to cell size, then it attains the limits of the cell; if at some moment the current critical radius exceeds the bubble radius, the velocity of the latter decreases (Fig. 1) and under some conditions may become negative, i.e., the bubble collapses. In the earlier stages of heating the rate of surface temperature growth is higher, i.e., conditions for the current critical radius to exceed the bubble radius are more favorable, therefore at $\Delta T < (\Delta T)_{th}$ nuclei of radii greater than the threshold which commence growing at lower superheat do not reach the cell boundaries (they collapse).

TABLE 1. Characteristic Aluminum Boiling Parameters versus Electron-Beam Power

$q \cdot 10^{-6}$ W/cm^2	$(\Delta T)^0_{th}$	T^0_∞, K	$\left(\frac{T_{max}}{T_\infty}\right)_{st}$	τ, μsec	Δt, μsec
1,53	80	3170	1,08	14,0	16,8
3,06	120	3300	1,08	4,1	5,5
7,6	140	3340	1,49	2,4	3,4
15,3	230	3400	1,74	1,3	1,9
30,6	380	3480	2,05	0,7	1,2

If the superheat is higher than the threshold value ($R < R_{th}$) the bubble reaches the limits and liquid boiling commences. From the highest (quasistable) superheat for a given flux q it is simple to determine the smallest dimensions of nucleus appearing at the surface (Table 1). Thus for a given flux q superheats in the range $\Delta T_{th} < \Delta T < \Delta T_{st}$ in the presence of nuclei of radii $R_{st} < R < R_{th}$ are capable of initiating metal boiling. With increase in power the threshold superheat value increases (Table 1). In fact, if the flux q_1 corresponds to a threshold superheat ΔT_1, then at $q_2 > q_1$ this superheat is attained earlier, i.e., at a stage where $R(t)_{cr}$ may exceed R. The lowest flux capable of producing boiling can be determined from the condition that for that value $R(\Delta T_{th})$ is of the order of the superheat zone dimensions. In the given case (Al, given heat-source distribution) $q_{min} \sim 10^5$ W/cm^2.

Boiling occurs quite rapidly (explosively) over the course of ~0.1-10 μsec. The time between two successive boilings (energy accumulation time) can be easily evaluated from the following considerations. The process encompasses that portion of the liquid where $T > T_\infty$. This comprises ~5-10% of the volume of the intense electron braking zone. If it is assumed that in one explosion all the superheated alloy is expelled outward, then after the explosion the liquid-metal surface descends to the depth of the superheated zone. At the initial moment after the expulsion the temperature within the liquid metal is lower than the new surface temperature. With passage of time, due to intense heating and evaporation from the surface there again develops a superheated (metastable) zone which exists (Table 1) until the superheat reaches the threshold value, after which the following explosion occurs, etc. Consequently, the energy accumulation time Δt is equal to the time needed to attain the threshold superheat plus the time for bubble exit to the surface. The dependence of Δt on power for corresponding threshold superheats is presented in Table 1.

NOTATION

ρ, c, λ, density, specific heat, and thermal conductivity of liquid metal; L, specific heat of vaporization of liquid metal; R, universal gas constant; Q(z), specific volume electron-beam power; σ, surface-tension coefficient of liquid metal; R(t), bubble radius at time t; T_∞, temperature of plane surface of liquid metal; $T|_{r=R}$, bubble wall temperature; $p_s(T)$, pressure determined by liquid metal–vapor phase equilibrium curve; p_l, pressure on bubble wall from liquid; v(t), evaporation rate from liquid-metal surface; c_{so}, velocity of sound in metal; ρ_v, vapor density in bubble; $(\Delta T)_{th} = T_{max} - T_\infty$, threshold superheat; $(\Delta T)_{st}$, maximum superheat (corresponding to stationary boiling); R_{th}, R_{st}, critical bubble radius for threshold and maximum superheat, respectively; T_f, fusion temperature.

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