NOTATION

h, channel width; L, channel length; $\delta = h/L$, the relative channel width; ℓ, thickness of the walls; $\beta = \ell/L$, relative wall thickness; S, relative area of the outlet cross section; p, gas pressure; p_{ex}, pressure outside the slot; p_{in}, pressure at the nozzle inlet; p_e, saturation pressure; T, temperature; T_0, evaporation surface tenperature; Q, heat of evaporation; $\bar{Q} = Q/RT$, dimensionless heat of evaporation; μ, gas viscosity; λ, gas thermal conductivity; λ_s, solid-phase thermal conductivity; q, heat flux; M, Mach number; Re, Reynolds number; Kn, Knudsen number; J, evaporation rate; and G, mass flow rate per unit slot area.

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COLLAPSE TIME OF VAPOR BUBBLES

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A formula is obtained for the collapse time of a vapor bubble with sharp pressure increase, taking account of the heat transfer between the bubble and the liquid.

Consider the action of a sharp change in external pressure from p to $p_0 + \Delta p$ at a spherical homogeneous vapor bubble in an infinite liquid medium. If Δp is not too large, the process of pressure equalization in the system and establishment of thermodynamic equilibrium inside the bubble, including the vapor–liquid interface, occur relatively rapidly [1-3]. The heat transfer from the bubble to the liquid determines the condensation rate of the vapor, and the time dependence of the bubble radius may be found by solving the system of equations [1, 4]

$$\frac{\partial T}{\partial t} + \frac{dR}{dt}\frac{R^2}{r^2}\frac{\partial T}{\partial r} = \frac{a}{r}\frac{\partial^2 (Tr)}{\partial r^2}; \quad (1)$$

$$T(R,\ t) = T_0 + \Delta T;\ T(\infty,\ t) = T(r,\ 0) = T_0;$$

$$\frac{dR}{dt} = \frac{c\rho_L a}{h\rho_V}\frac{\partial T}{\partial r}\Big|_{r=R};\ R(0) = R_0. \quad (2)$$

Here T(r, t) is the spherically symmetric temperature field in the liquid ($r \geqq R$). The vapor temperature is constant over the time of collapse, and is $T_0 + \Delta T$, where ΔT is the change in boiling point of the liquid with increase in pressure by Δp. The collapse time t_c is determined by the condition $R(t_c) = 0$.

The well-known – see [1], for example – estimate of t_c is obtained on substituting the temperature field into Eq. (2) in the form $T = T_0 + \Delta T\ \mathrm{erfc}[(r - R)/2(at)^{1/2}]$, i.e., an accurate solution of the plane thermal problem. This estimate is expressed as follows

$$\tau_c = 4\mathrm{Ja}^2 a t_c/\pi R_0^2 = 1. \quad (3)$$

Here $\mathrm{Ja} = c\rho_L \Delta T/h\rho_V$ is the Jacob number, which is the only defining criterion of thermohydrodynamic similarity in Eqs. (1) and (2) (for water at 100°C, $\mathrm{Ja} \approx 100\ \Delta p/p_0$).

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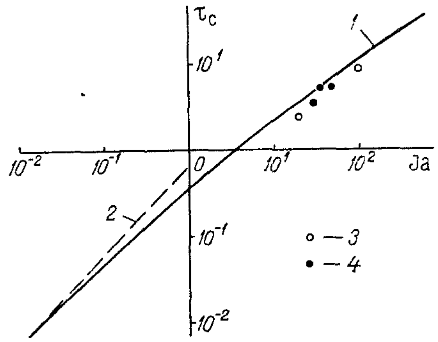

Fig. 1. Dependence of the dimensionless collapse time τ_c on the Jacob number: 1) numerical solution; 2) $\tau_c = 2\ \mathrm{Ja}/\pi$; 3) data of [1]; 4) [5].

In fact, the dimensionless complex τ_c is not constant, but depends on Ja. Numerical solution of Eqs. (1) and (2) shows that τ_c increases from $6 \cdot 10^{-3}$ to 50 with variation in Ja from 10^{-2} to 10^3, i.e., differs considerably from the estimate in Eq. (3), which is only valid when Ja ≈ 5. The dependence τ_c (Ja) obtained numerically (Fig. 1) is well described by the formula

$$\tau_c = 0{,}5\mathrm{Ja}\,(0{,}7 + \mathrm{Ja}^{1/2})^{-2/3}. \tag{4}$$

As Ja → 0 (small pressure differences or high density of the vapor), Eq. (4) transforms to the analytical estimate $\tau_c = 2\mathrm{Ja}/\pi$ corresponding to the quasisteady temperature field $T = T_0 + \Delta TR/r$. The time dependence of the bubble radius as Ja → 0 tends to the limiting function $\alpha = (1 - \tau/\tau_c)^{1/2}$, where $\alpha = R/R_0$.

As Ja → ∞, Eq. (4) gives $\tau_c \sim \mathrm{Ja}^{2/3}$. The limiting dependence $\alpha(\tau)$ takes the form [5]

$$\tau = 2/3\alpha + \alpha^2/3 - 1. \tag{5}$$

Substituting $\alpha = 0$ into Eq. (5) gives $\tau_c = \infty$, which agrees with the behavior of the function in Eq. (4) in this limit: $\tau_c \to \infty$ as Ja → ∞.

Note that the initial conditions of the problem in Eqs. (1) and (2) do not correspond to an initial unperturbed state of the bubble. Increase in pressure is accompanied by compression of the bubble, associated principally with increase in saturated vapor pressure. Therefore, R_0, which appears in the dimensionless complexes Ja, τ, α, is less than the initial bubble radius by an amount ΔR_0 [4]. For the estimate it may be supposed that $\Delta R_0/R_0 \approx \Delta p/3p_0$.

The results of calculation by Eq. (4) are in good agreement with the values of τ_c determined from the experimental dependences R(t) from [1, 5]. In the experiments, the bubbles did not collapse completely because of the presence of air, and τ_c was determined approximately by extrapolating the experimental dependences R(t) to R = 0. As is evident from Fig. 1, the experimental points lie slightly below the theoretical curve, as a rule. The probable reason for the overestimation of τ_c is the disregard of the motion (floating up) of the bubbles, which accelerates the heat transfer. The experimental data in Fig. 1 are characteristic of bubbles with small velocities of motion. If the velocity of bubble motion is close to its rate of collapse dR/dt, however, t_c may be reduced by a factor of 2-3.

NOTATION

Ja, Jacob number; c, a, specific heat and thermal diffusivity of liquid; ρ_L, ρ_V, density of liquid and vapor, respectively; h, heat of vaporization; $\tau \equiv 4a\ \mathrm{Ja}^2 t/\pi R_0^2$, dimensionless time.

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