HEAT-TRANSFER CRISES IN THE NUCLEATE BOILING OF OXYGEN UNDER LOW-GRAVITY CONDITIONS

Yu. A. Kirichenko, G. M. Gladchenko, and K. V. Rusanov

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The correctness of certain models of the heat-transfer crisis during boiling which employ micromechanism representations is established for low-gravity conditions and different saturation pressures.

A more thorough understanding of a process as complex as heat exchange during boiling is evidently best achieved by constructing physical models based on an examination of the process at the microscopic level of individual vapor bubbles and then proceeding to macroscopic characteristics — heat-transfer coefficients, critical heat flux. There have been several examples of such an approach in recent years.

The applicability of a specific model and the theoretical formula obtained from it is obviously determined by how much it reflects the effect the basic regime parameters (pressure, acceleration, etc.) and the ranges of parameter values within which the simplifying assumptions are valid. By comparing basic principles and conclusions of the model with experimental data on both the microscopic and macroscopic level, it is possible to make a conclusion regarding the correctness of the approach — the most important moment for any model.

It is of definite interest to in this way examine certain models of the heat-transfer crisis during nucleate boiling and to check their correctness when there is a substantial change in pressure and acceleration. The Physical-Engineering Institute of Low Temperatures of the Academy of Sciences of the Ukrainian SSR studied heat transfer during the boiling of liquid oxygen in simulated weak body-force fields. Here, investigators studied both integral characteristics [1, 2] and microcharacteristics of the boiling process [3]. The study was conducted in a broad range of pressures ($P = 6\cdot10^3 - 7\cdot10^5$ Pa) and relative accelerations ($\eta = g/g_n = 0.01 - 1$). The weak body-force fields were simulated by means of an inhomogeneous magnetic field [4].

In accordance with the thermal model of the heat-transfer crisis, the transition from nucleate boiling to sheet boiling occurs as a result of the mutual contact and coalescence of vapor bubbles on the heat-emitting surface; thus, with a given R_d, the critical parameter turns out to be the density of the vaporization centers Z_{cr}. If we assume in a first approximation that growing bubbles simultaneously reach the size required for separation from the heating surface, then

$$Z_{\text{cr}} = \frac{1}{4R_{d\,\text{cr}}^2}. \tag{1}$$

Since in reality bubbles do not grow synchronously, then in the more general case

$$Z_{\text{cr}} = \frac{A}{4R_{d\,\text{cr}}^2}, \tag{1a}$$

here $A \geq 1$; $\sqrt{A} = R_d/\bar{R}$ determines how many times greater the separation size is compared to the mean bubble size on the surface. Thus, if

$$\bar{R} = \frac{1}{\tau_d}\int_0^{\tau_d} \beta\tau^{0.5}d\tau, \quad R_d = \beta\tau^{0.5}, \tag{2}$$

then $A = 2.25$.

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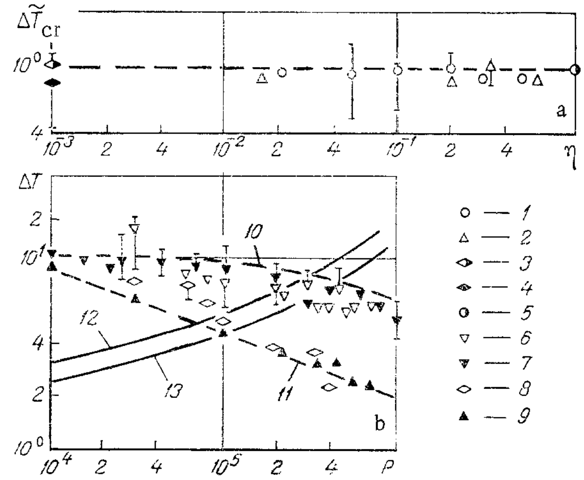

Fig. 1. Effect of acceleration and pressure on the critical temperature head: a) the function $\Delta T_{cr} = f(\eta)$: 1) oxygen (our data); 2) nitrogen [8]; 3) nitrogen [9]; 4) helium [9]; 5) $\Delta \tilde{T}_{cr} = \Delta T_{cr}$ $(\eta = 1)/$ ΔT_{cr} $(\eta = 1) \equiv 1$; b) dependence of characteristic temperature heads on pressure, ΔT_{cr}: 6) oxygen (our data); 7) oxygen [10]; ΔT_e: 8) oxygen (our data); 9) oxygen [10]; 10) calculation with (5); 11) start of oxygen boiling according to [10]; calculation with (24): 12) $B_1 = 10$; 13) $B_1 = 40$. ΔT, °K; P, Pa.

We will further assume that during the heat-transfer crisis all of the heat given off by the surface goes into vaporization of the liquid

$$q_{cr} = \frac{4\pi}{3} L\rho_v (f_d R_d^3 Z)_{cr}. \tag{3}$$

Inserting (1a) into (3) gives us

$$q_{cr}/L\rho_v = \frac{\pi A}{3} (f_d R_d)_{cr}. \tag{4}$$

Both parts of (4) have the dimension of rate; the left side is the corrected rate of vaporization $W_{cr} = q_{cr}/L\rho_v$; the right side is the mean rate of growth of the vapor bubbles $U_{cr} = (f_d R_d)_{cr}$ [5].

To check the correctness of the model, it is sufficient to make sure that the following equation is satisfied:

$$W_{cr} = BU_{cr} \tag{4a}$$

and that the value of $B = \pi A/3$ found from test data corresponds to the preliminary estimate ($B \approx 2.36$). The difficulty, however, lies in the fact that it is nearly impossible to find experimental values of R_d and f_d for $q = q_{cr}$; the available data corresponds to $q_e < q_{cr}$, $\Delta T_e < \Delta T_{cr}$. We will attempt to extrapolate the value of U_e to crisis conditions, using data on ΔT_{cr} and expressions for R_d and f_d corresponding to dynamic and quasistatic bubble separation regimes [6].

It should be noted that the quantity ΔT_{cr} is an important heat-transfer characteristic and that data obtained on it for different accelerations and pressures is valuable in and of itself. There is very little data in the literature for $\eta < 1$. Figure 1 shows our results: it turns out that ΔT_{cr} is practically independent of accleration at $\eta \leq 1$ (at $\eta > 1$, the dependence may be fairly strong [7]) throughout the investigated range of pressures. Figure 1a, using the relative form $\Delta \tilde{T}_{cr} = \Delta T_{cr}(\eta, P)/\Delta T_{cr}$ (1, P) also shows data from [8] (nitrogen) and [9] (helium, nitrogen) confirming this conclusion.

The critical temperature head decreases with an increase in pressure. Our data in Fig. 1b, averaged over the investigated interval of η, agrees satisfactorily with the data in [10] (oxygen) obtained for the conditions $\eta = 1$ and with data calculated from the formula

$$\Delta T_{cr} = 0.6\,(\sigma T_s/\lambda)^{1/2}\,\nu^{1/4}\,(\sigma/\rho)^{1/8}\,\{\sigma\,[kT_s \ln (NkT_s/h)]\}^{3/16} \tag{5}$$

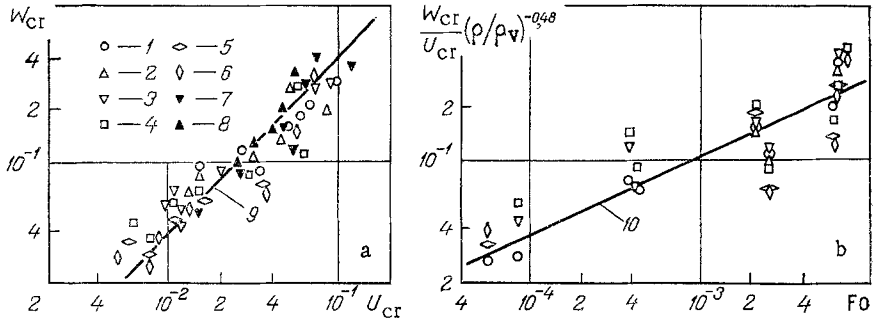

Fig. 2. Comparison of data on q_{cr} and microcharacteristics of boiling: a) thermal model; b) system of criteria of V. I. Tolubinskii; our data: 1) η = 1; 2) 0.5; 3) 0.3; 4) 0.1; 5) 0.06; 6) 0.04; 7) oxygen [10]; 8) nitrogen [10]; 9) calculation with (13); 10) calculation with (14). W_{cr}; U_{cr}, m/sec.

which was proposed in [11].

Let us return to extrapolation of data on the effect of the mean rate of bubble growth on crisis conditions. We write the relations for R_d and f_d in the dynamic separation regime [6]:

$$R_d \sim \beta^{4/3} g^{-1/3}, \;\; f_d \sim \beta^{-2/3} g^{2/3}. \tag{6}$$

Having determined the bubble growth modulus from the well-known Plesset–Zwick formula

$$\beta = 2\sqrt{3/\pi}\, \mathrm{Ja} \sqrt{a} \sim \Delta T, \tag{7}$$

we obtain

$$U_{cr} = U_e (\Delta T_{cr}/\Delta T_e)^{2/3}. \tag{8}$$

For the quasistatic vapor-bubble separation regime [6], the separation size can be expressed as

$$R_d \sim \left[\frac{R_c \sigma}{g(\rho - \rho_v)}\right]^{1/3}, \text{where} R_c = \frac{B_1 \sigma T_s}{L \rho_v \Delta T}. \tag{9}$$

We can use the bubble-growth law $R = \beta\tau^{0.5}$ to determine f_d:

$$f_d \sim \frac{1}{\tau_d} \sim \beta^2 \left[\frac{R_c \sigma}{g(\rho - \rho_v)}\right]^{-2/3}. \tag{10}$$

Having determined the growth modulus from the Labuntsov formula

$$\beta = \sqrt{12\,\mathrm{Ja}}\sqrt{a} \sim \sqrt{\Delta T}, \tag{11}$$

we obtain the following for the quasistatic regime from Eqs. (9)-(11):

$$U_{cr} = U_e (\Delta T_{cr}/\Delta T_e)^{4/3}. \tag{12}$$

It was reasoned in analyzing the data that there is a dynamic separation regime for oxygen at $P \leqslant 8 \cdot 10^4$ Pa and a quasistatic regime for oxygen at $P \geqslant 10^5$ Pa [6]. Values of ΔT_e are shown in Fig. 1b; it can be seen that the correction for U_e may be substantial, especially at high pressures.

Figure 2a shows results of calculation of W_{cr} and U_{cr} using the data in [1-3]. It can be seen that the data on oxygen boiling at $\eta \leqslant 1$ agrees satisfactorily with the data in [10] (nitrogen, oxygen, η = 1). The following empirical formula was proposed in [10]:

$$W_{cr} = 3{,}7 U_{cr}. \tag{13}$$

Although the deviation of our data from the results calculated with (13) is quite large in some cases, the overall results indicate the correctness of the above variant of the thermal model of the heat-transfer crisis. The relationship between W_{cr} and U_{cr} is close to being directly proportional, while the value of B lies within the range from 2 to 5. Considering the certain degree of conditionality in the extrapolation made, the results of the comparison of data on q_{cr} and R_d, f_d should be regarded as satisfactory.

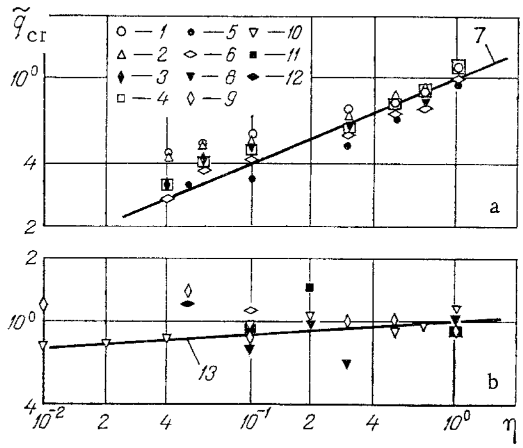

Fig. 3. Dependence of relative critical heat flux on acceleration: 1) P = 10^5 Pa; 2) 2.2; 3) 3.4; 4) 4.6; 5) 5.8; 6) 7.0; 7) calculation from (21); 8) P = $6 \cdot 10^4$ Pa; 9) $3.5 \cdot 10^4$; 10) $3 \cdot 10^4$; 11) $2 \cdot 10^4$; 12) $6 \cdot 10^3$; 13) calculation from (23). $\tilde{q}_{cr} = q_{cr}(\eta)/q_{cr}(1)$.

It is interesting to similarly check the approach taken by Tolubinskii [5], in accordance with which

$$W_{cr}/U_{cr} = C\,\mathrm{Fo}^n(\rho/\rho_v)^m, \tag{14}$$

where Fo = $a/(f_d R_d^2)_{cr}$; n = m = 0.5; C = 7. We note on the basis of the preceding discussions that in the case of correctness of the approach the right side of (14) should not change with a change in pressure and acceleration and should be equal to B.

In extrapolating data on $(f_d R_d^2)$ to crisis conditions, it is not hard to obtain relations similar to (8) and (12):

$$(f_d R_d^2)_{cr} = (f_d R_d^2)_e (\Delta T_{cr}/\Delta T_e)^2 \tag{15}$$

for the dynamic separation regime and

$$(f_d R_d^2)_{cr} = (f_d R_d^2)_e (\Delta T_{cr}/\Delta T_e) \tag{16}$$

for the quasistatic separation regime.

Figure 2b shows results of analysis of data from [1-3] in the system of variables (14). Use of the least-squares method gives n = 0.47, m = 0.48, and C = 2.8; the standard deviation of the data from an approximating straight line is ±43%. Although the coefficient obtained is less than that recommended in [5], the values of the exponents are very close to 0.5.

Thus, on the basis of the foregoing we can be certain of the correctness of models of the heat-transfer crisis which derive their expression for q_{cr} from examining microcharacteristics of the process. It is also clear that such models are in need of further improvement. As an example, let us show how it is possible within the framework of the thermal model to explain the fact, noted in [1], that the dependence of q_{cr} on η changes with a change in pressure: the exponent in

$$q_{cr} \sim \eta^k \tag{17}$$

changes from $k \approx 0$ at $P \ll 10^5$ Pa to k = 0.41 at P = $7 \cdot 10^5$ Pa and is not equal to k = 0.25, as would follow from the hydrodynamic model of crisis. Let us examine the case of low pressures, in which the dynamic bubble separation regime is typical. We will assume in accordance with [12] that the critical density of the vaporization centers and the quantity $\sigma T_s/L\rho_v\Delta T$ are related as follows:

$$Z_{cr} \sim \left(\frac{L\rho_v \Delta T_{cr}}{\sigma T_s}\right)^{n_1}, \tag{18}$$

where n_1 = 3. Using (1), (6) and (7), (18), we obtain a relation for ΔT_{cr} which contains only properties of the liquid and vapor and the acceleration:

$$\Delta T_{cr} \sim \frac{(\sigma T_s)^{9/17}}{(L\rho_v)^{1/17} a^{4/17} (c_p \rho)^{8/17}} g^{2/17}. \tag{19}$$

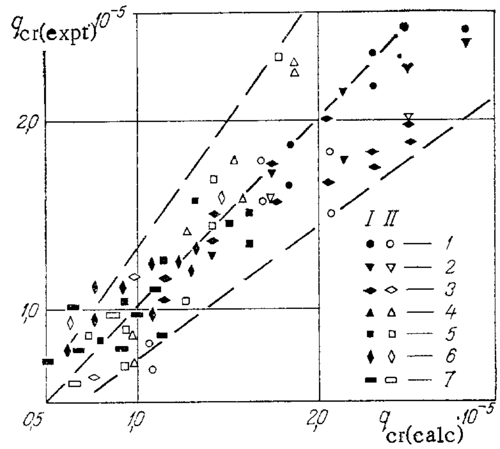

Fig. 4. Comparison of test data on q_{cr} with results calculated from (21), (23): 1) $\eta = 1$; 2) 0.5; 3) 0.3; 4) 0.2; 5) 0.1; 6) 0.06; 7) 0.04; I) $P \geqslant 10^5$ Pa; II) $P \leqslant 6\cdot 10^4$ Pa.

To obtain a relation for q_{cr}, we need to use (4). Here, it will be taken into account that in this case $\tau_w \gg \tau_d$ and the frequency $f_d = \tau_w^{-1}$, which was confirmed for oxygen by the data in [10]. We evaluate τ_w on the basis of [13]:

$$\tau_w \sim \left(\frac{\sigma T_s}{L\rho_v \Delta T}\right)^2 \frac{1}{a}. \tag{20}$$

Inserting R_d from (6), (7), f_d from (20), and the temperature head from (19) into (4), we find

$$q_{cr1} = A_1 (\sigma T_s \lambda)^{4/17} a^{47/51} (L\rho_v)^{25/17} g^{1/17}, \tag{21}$$

where A_1 =const.

For high pressures, we take $n_1 = 2$ in (18), in accordance with [14]. Using (1), (6), (11), and (18), we obtain

$$\Delta T_{cr} \sim \frac{(\sigma T_s)^{0.6}}{(L\rho_v)^{0.2}\lambda^{0.4}} g^{0.2}. \tag{22}$$

Then inserting R_d and f_d from (6), (11), and ΔT_{cr} from (22) into (4), we find

$$q_{cr} = A_2 (\sigma T_s \lambda)^{0.2} (L\rho_v)^{0.6} g^{0.4}, \tag{23}$$

similar to the formula obtained earlier in [1].

The use of expression (6) for R_d for the case of high pressures requires special validation. The point is that an increase in q (or ΔT) should shift the boundary between the quasistatic and dynamic bubble-separation regimes obtained for small amounts of superheating in the direction of higher pressures [15]. In fact, if the boundary corresponds to the condition $F_I = F_\sigma$, where $F_I = \frac{\pi}{3}\beta^4\rho$ is the inertial force associated with the reaction of the liquid and $F_\sigma = 2\pi R_c \sigma$ is the surface tension, then we can obtain an expression for ΔT_{br} by inserting R_c from (9) and β from (7):

$$\Delta T_{cr} = \left[\frac{24 B_1 \sigma^2 T_s (L\rho_v)^3 a^2}{(2\sqrt{3/\pi})^4 \lambda^4 \rho}\right]^{1/5}. \tag{24}$$

Curves calculated for oxygen with Eq. (24) for $B_1 = 10$ and 40 are shown in Fig. 1b. It is apparent that at overheatings corresponding to the beginning of boiling of the liquid (at which point bubbles are usually filmed) the boundary is located in the region $(0.7 - 1)\cdot 10^5$ Pa. If $\Delta T = \Delta T_{cr}$, then the boundary is shifted to $4\cdot 10^5$ Pa. Thus, almost all of the values of q_{cr} obtained in [1] correspond to the dynamic regime.

Figures 3 and 4 show results of generalization of data from [1] in accordance with (21), (23). It is apparent that at $P \leqslant 6\cdot 10^4$ Pa the dependence of q_{cr} on η corresponds roughly to that following from (21); here, $A_1 = 25$. Similarly, with an increase in pressure $P \geqslant 10^5$ Pa, the dependence of q_{cr} on η approaches k = 0.4 in accordance with (23); A_2 = 1500. The standard deviation of the test data from the calculated data is ±18%.

NOTATION

A, A_1, B, B_1, constants; a, diffusivity; g, acceleration; g_n = 9.81 m/sec^2, acceleration due to gravity; R, radius; Z, density of vaporization centers; τ, time of bubble growth; q, heat flux; L, heat of vaporization; ρ, ρ_V, density of liquid and vapor; f, frequency; ΔT, temperature head; T_S, saturation temperature; σ, surface tension; N, Avogadro's number; h, Planck's constant; k, Boltzmann's constant; c_p, specific heat at constant pressure; indices: d, bubble separation; e, experimental; cr, critical; br, boundary; Ja = $\lambda \Delta T / L \rho_V a$, Jacobi criterion; $\tilde{q}_{cr} = q_{cr}(\eta, P)/q_{cr}(\eta = 1, P)$.

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