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CRITICAL DISCHARGE OF A SPONTANEOUSLY EVAPORATING LIQUID FROM CYLINDRICAL CHANNELS

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A method is proposed for the calculated determination of the critical pressure in the discharge of a spontaneously evaporating saturated liquid through cylindrical channels. The results of the calculation are compared with experimental data.

The discharge of adiabatically effervescing streams through channels of constant cross section at large longitudinal pressure gradients is of considerable practical interest for a wide circle of problems of modern technology. In this case, as a rule, the pressure drop exceeds the critical value. The relationships of the crisis phenomena in spontaneously evaporating streams are very complicated. Depending on the geometrical characteristics and the initial parameters of the liquid the true flow rates vary within wide limits: from a value corresponding to isentropic discharge to flow rates corresponding to the case of the discharge of a non-effervescing liquid. As a result, all the design recommendations have a particular nature, as a rule, and are not subject to generalization [1, 2].

Below we propose a method for calculating the critical state of a spontaneously evaporating stream during discharge from cylindrical channels based on the simplified thermodynamic model of [3], the essence of which comes down to the following.

1. The effervescence of the stream takes place only at the channel walls and the penetration of the vapor into the core of the stream takes place only through the movement of bubbles formed in the boundary layer.

2. The peripheral (boundary) stream is in equilibrium and mechanical and thermal phase slippage is absent from it.

3. A jet of superheated (metastable) liquid whose temperature is taken as constant moves in the center. Thus, the motion of two one-dimensional concurrent streams is analyzed.

If one neglects the effect of frictional forces at the channel walls, a stream in a channel of constant cross section is described by the system

$$\rho_1 W_1 f_1 + \rho_2 W_2 f_2 = \Phi_0, \tag{1}$$

$$P_0 + \rho_0 W_0^2 = P + \frac{1}{\rho_1}(\rho_1 W_1)^2 f_1 + \frac{1}{\rho_2}(\rho_2 W_2)^2 f_2, \tag{2}$$

$$\left(h_0 + \frac{W_0^2}{2}\right)\Phi_0 = \left(h_1 + rx + \frac{W_1^2}{2}\right)\Phi_1 f_1 + \left(h_2 + \frac{W_2^2}{2}\right)\Phi_2 f_2. \tag{3}$$

As shown in [2], the velocity of the central metastable stream is determined by the equation

$$W_2 = \sqrt{\frac{2(P_0^* - P)}{\rho'}}, \tag{4}$$

while the mass velocity Φ_2 is equal to $\rho_2 W_2$.

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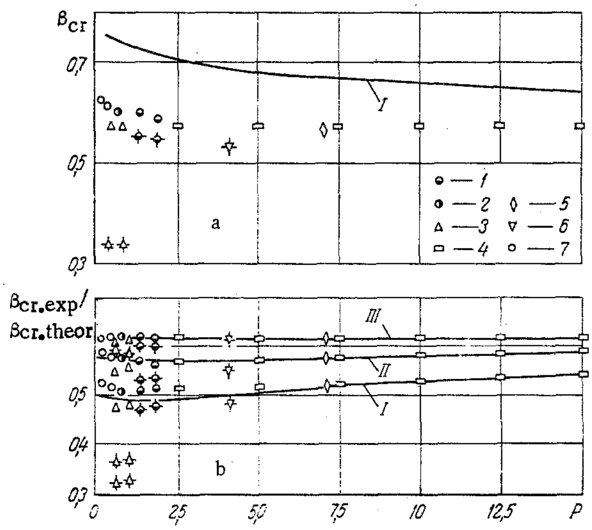

Fig. 1. Comparison of experimental results on water with data of simplified thermodynamic model based on Eqs. (1)-(3) (a) and correlation curves of convergence of experimental and theoretical data with allowance for additional factors in initial calculating model (b): 1) experimental data of [5] (l/d = 9.100); 2) [9] (l/d = 34); 3) [10] (l/d = 9.625); 4) [11] (l/d = 9); 5) [12] (l/d = 30); 6) [13] (l/d = 100); 7) our experimental data with discharge into a vacuum (l/d = 34). The points designated by circles pertain to channels with smooth entrances while those with short lines pertain to channels with $l/d > 40$. P, MPa. One should read 0.4, 0.6, 0.8 (from bottom to top) along the axis $\beta_{cr.exp}/\beta_{cr.theor}$.

The velocity and density of the peripheral vapor—liquid stream are found as follows:

$$W_1 = \sqrt{2\Delta h_s}, \tag{5}$$

$$\rho_1 = \frac{\rho'\rho''}{\rho'' + x(\rho' - \rho'')}. \tag{6}$$

The system of equations (1)-(3) uniquely determines the state of the stream regardless of the nature of the mechanical interaction between the concurrent jets. Therefore, if one assigns the state of the liquid before the channel from which the discharge occurs, one can determine all the parameters of each of the concurrent jets in the channel cross section where the pressure equals P.

Experience shows that the cutoff of spontaneously evaporating streams during discharge from cylindrical channels takes place with the condition [4, 5]

$$\frac{P_e}{P_0^*} < \frac{P_{crs}}{P_0^*} = \beta_{cr}. \tag{7}$$

Further, it has been established that in the discharge of a saturated liquid through cylindrical channels the flow rate is determined by the equation [6]

$$G = \mu F \sqrt{2(P_0^* - P_{crs})\rho'}. \tag{8}$$

Thus, in the region of the channel where $P_{cr} \leq P < P_{crs}$ the peripheral vapor—liquid jet must move with supercritical velocity, increasing its cross section, while the central jet decreases its cross section:

$$\frac{df_2}{dP} < 0, \quad \frac{df_1}{dP} > 0. \tag{9}$$

A crisis sets in when

$$\left|\frac{df_1}{dP}\right| = \left|\frac{df_2}{dP}\right|. \tag{10}$$

In fact, if one assumes the possibility of expansion into the region of $P < P_{cr}$, then the signs of the inequalities (9) change. This is physically impossible, since it would require the condensation of the peripheral jet on the central metastable jet.

The available experimental data on the critical pressure ratio β_{cr} in the discharge of saturated water through cylindrical channels of different relative lengths with rounded and sharp entrance rims are presented in Fig. 1a. Curve I, characterizing the value of β_{cr} calculated by the method described above, is also plotted here. As we can see, this curve, while in qualitative agreement with the experimental data, still gives overstated values of β_{cr}. In Fig. 1b curve I determines the ratio of the calculated and experimental values of β_{cr}. Furthermore, the pressure losses at the entrance to a channel with a sharp rim were taken into account by the well-known method [7]. Curve II in Fig. 1b corresponds to this treatment. As we can see, the disagreement between the calculated and experimental data was reduced and the scatter of the points pertaining to channels with different entrance geometries was decreased.

The remaining disagreement can be explained by the fact that the effect of the friction of the stream against the wall has not yet been taken into account. In the given case there is a high-velocity two-phase stream with a large longitudinal pressure gradient. The method of calculation of frictional losses has not been developed for these conditions. As a first approximation we calculated β_{cr} (curve III) with an estimate of the frictional losses by the method of [8], tested for nongradient flows. In the given case the frictional losses were evidently overstated. However, the departure from the average experimental values does not exceed 5%, while the relative disagreement between the experimental data of the investigators does not exceed 8%.

NOTATION

ρ, density; W, velocity; f, relative cross-sectional area of one of the component jets; h, enthalpy; Δh_s, isentropic enthalpy drop in the pressure interval $P_0 - P$; x, degree of dryness corresponding to isentropic expansion in the pressure interval $P_0 - P$; Φ, mass velocity; P, statistical pressure in a given channel cross section; P_e, exterior pressure; P_{crs}, final counterpressure at which maximum flow rate through channel is reached — critical pressure with isentropic expansion; P*, stagnation stream pressure; F, cross-sectional area of channel; μ, flow-rate coefficient. Indices: 0, initial parameters of state of stream; 1, peripheral vapor—liquid stream; 2, central superheated liquid jet; ' and ", liquid and vapor phases, respectively.

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