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CRITICAL DISCHARGE OF SATURATED AND SUBCOOLED WATER THROUGH CHANNELS OF DIFFERENT SHAPES

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A complex experimental investigation of the outflow of saturated and subcooled water through channels of different forms has been carried out in the pressure range of 5-20 bar; the investigation included the measurements of the discharge, static pressure curves, moisture content field of the two-phase flow, and the photographic recording of the evaporation process. Empirical equations are proposed for determining the critical discharge.

The outflow of liquid into a medium with small counterpressure leads to the formation of a very moist two-phase flow. In the general case this process occurs with the violation of the thermodynamic equilibrium and the vapor – liquid flow thus formed is characterized by a structural inhomogeneity [1,2]. All this makes it difficult to use analytical methods for determining the maximum discharge of the evaporating liquid and forces one to take recourse to experiments. In the experimental respect the most completely investigated flow is the flow of water through diaphragms and cylindrical channels and there are practically no investigations of the flow of an evaporating liquid to channels of variable cross section, as can be seen from comprehensive reviews [3,4].

We made an attempt to study the effect of the geometry of the channel on the critical phenomena in a two-phase flow and on the critical discharge. The experiments were conducted on a device which was made according to the closed scheme and is described in [5]. As the operating substance we used clean deaerated water from the main supply to the boilers of the Kazan' TÉTs-2 thermoelectric power plant. Before the experimental segments the water parameters were measured in the pressure range of 5-20 bar and temperature range of 100-200°C. The geometry of the experimental channels is shown in Fig. 1. They include Laval nozzles with opening angles of 2-30°, diverging channels with a sharp-edged entrant orifice and opening angles of 4-30°, and channels of constant cross section. In all, 23 plane channels were tested. The dimensions of some of these are given in Table 1. The static pressure distribution along the length of the experimental channels was measured with the use of a tension probe placed in the plane wall of the channel. The fields of the phase concentrations in the flow were obtained by the radiographic method described in [2] by illuminating the two-phase flow with x-ray beams.

A combined analysis of the static pressure curves, the moisture content field, and the discharge characteristics of the channels, for which the typical results of measurements are given in Figs. 2, 3, and 4, showed that the establishment of the maximum discharge is related to the formation of a zone of intense

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TABLE 1

Type of channel	Dimensions of channel, nm						
	l	l_α	a	h	b	R	α, deg
L-2	135	80	9,5	7,0	10	45	6°30′
L-3	135	83	9,5	6,35	7	45	11°
L-4	135	85	9,5	6,2	5	45	17°40′
L-5	135	85	9,3	7,0	5	45	30°
K-2	118	—	8,9	7,1	—	—	12°
K-3	112	—	9,0	7,1	—	—	30°
S-2	90	—	9,25	5,8	—	0,1	—

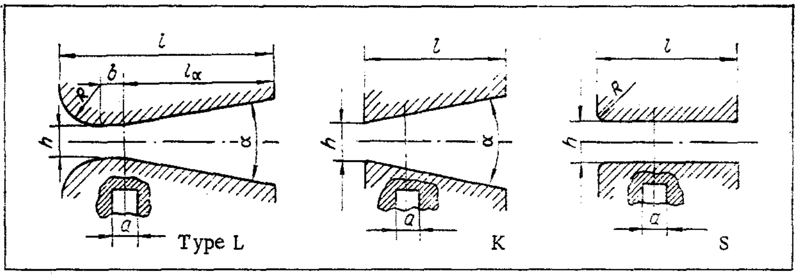

Fig. 1. Experimental channels.

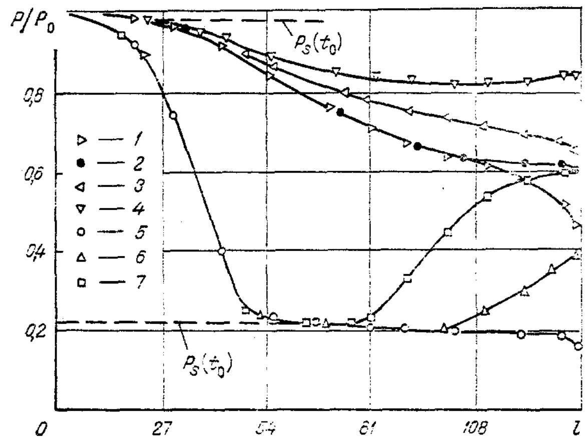

Fig. 2. Static pressure distribution along the length of the L-2 channel: for $P_0 = 13.2$ bar, $t_0 = 191.6°C$: 1) $P_{cp} = 5$ bar; 2) 7.9; 3) 8.5; 4) 11.1 bar; for $P_0 = 13.2$ bar, $t_0 = 131.6°C$: 5) $P_{cp} = 1.2$ bar; 6) 5.1; 7) 8.1 bar.

evaporation in which the flow structure changes from liquid-drop type to a form dispersed across a small transition region having bubble-type structure. In L-type channels the zone of intense evaporation is behind the throat of the nozzle, as shown in Fig. 3; in K and S type channels, where the process of evaporation is initiated by the sharp edge, this zone is formed in the entrance segment of the channel.

In the outflow of both saturated water and water subcooled to the saturation temperature with respect to the pressure at the entrance into the channel with enhanced counterpressure, the discharge of the liquid through the channel remains constant until the perturbation connected with the increased counterpressure reaches the zone of intensive evaporation. Different flow regimes of saturated and subcooled waters are observed. In the outflow of saturated water or water with parameters close to saturation the absolute magnitude of the pressure gradient in the diverging part of the nozzle decreases with the increase of P_{cp}; as seen from Fig. 2, the vapor content of the flow decreases, but no qualitative changes in the flow structure are observed. Similar flow regimes were obtained in [6].

In the case of the flow of subcooled water with counterpressure $P_s/P_0 < P_{cp}/P_0 < 0.6$ a condensation jump appears in the two-phase flow, which is followed by a vapor condensation front. With the increase of the counter-

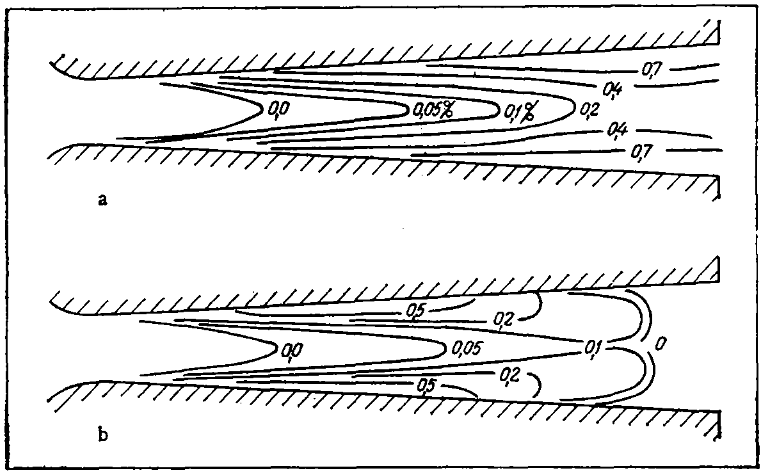

Fig. 3. Local values of the true volumetric vapor content of the two-phase flow in an L-2 channel: a) $P_0 = 13.2$ bar, $t_0 = 131.6$°C, $P_{cp} = 1.1$ bar; b) $P_0 = 131.2$ bar, $t_0 = 131.6$°C, $P_{cp} = 8.0$ bar.

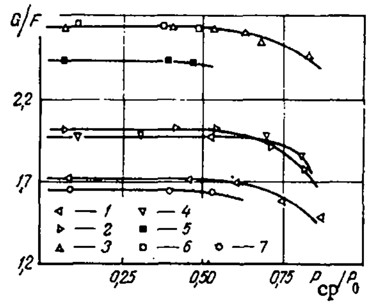

Fig. 4. Dependence of the discharge on the geometry of the channel and counter-pressure: for $P_0 = 13.2$ bar, $t_0 = 191$–191.6°C: 1) L-2; 2) L-3; 3) L-4; 4) L-5; 5) K-2; 6) K-3; 7) S-2, G/F, kgf/(sec·cm^2).

pressure the perturbation and the condensation front following it are displaced up the flow, and the two-phase region of the flow can be localized between the evaporation front and the condensation front as shown in Fig. 3. For $P_{cp}/P_0 > 0.6$ a purely hydraulic flow regime is realized. The flow regimes of saturated and subcooled water, described above, occurred in a Laval nozzle as well as in K and S channels.

The critical pressure drop, at which the discharge reached its maximum value, had a very weak dependence on the geometry of the channel; in the investigated range of P_0 and t_0, $\beta_{cr} = 0.5$–0.65. The critical discharge is substantially affected by the shape of the channel, other conditions remaining constant. The discharge of saturated and subcooled water through a Laval nozzle increases with the increase of the aperture opening angle α and reaches the maximum value for $\alpha = 17°14'$, as seen from Fig. 4. A subsequent increase of α results in a decrease of the discharge of liquid through the channel; this is probably explained by the break in the flow.

In K-type channels a noticeable effect of the opening angle α on the critical discharge appears only for small subcooling. With the increase of subcooling the effect of the opening angle on the discharge decreases and for relative subcooling $1 - P_s/P_0 > 0.4$ the discharge of the liquid through K channels remains practically constant with the increase of α.

As a result of a generalization of the experimental data on the outflow of saturated and subcooled water the following equation is proposed for determining the critical discharge:

$$G = \mu F_{\min} \sqrt{2\rho' [P_0 - C_t C_\alpha P_s(t_0)]} \quad (1)$$

The coefficients C_t and C_α occurring in (1) take account of the effect of the initial subcooling of the liquid and

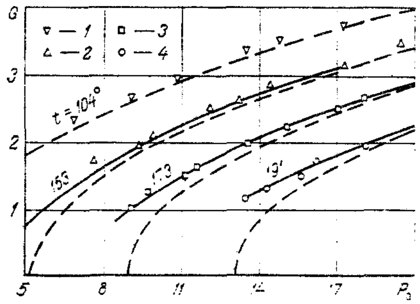

Fig. 5. Dependence on the critical discharge of water through the L-2 channel on the initial parameters of the flow: 1) t_0 = 104°C; 2) 153; 3) 173; 4) 191. Continuous curve) computation from Eq. (1) for μ = 0.98; dashed curve) computation from (6) for μ = 0.98. G, kgf/(sec · cm²); P, bar.

the geometry of the channel on the discharge. For the coefficients C_t and C_α we have derived the following empirical equations.

Type-S channels of constant cross section with the rounding angle of the entrance edge R ≤ 0.1 mm:

$$C_{\alpha S} = 1.0;\ C_{tS} = 1.0169 - 0.0806\left[0.3038 - \ln\left(1.063 - \frac{P_s}{P_0}\right)\right]^{0.5}. \quad (2)$$

Diverging type-K channels with sharp entrance edge:

$$C_{tK} = C_{tS};\ C_{\alpha K} = 0.7008 + \frac{8.0872}{\alpha + 27.0297}. \quad (3)$$

Laval nozzle:

$$C_{tL} = 0.9705 + 0.0196 \ln\left[1.0588 - \frac{P_s}{P_0}\right], \quad (4)$$

$$C_{\alpha L} = 1.0333 - (0.3367\alpha + 4)^{5.96} \exp(-15.8216 - 0.3078\alpha). \quad (5)$$

A comparision of the computation of the critical discharge using Eq. (1) with the experimental results for the L-2 channel is shown in Fig. 5. The results of the computation of the critical discharge from the simplified equation

$$G = \mu F_{\min} \sqrt{2\rho' [P_0 - P_s(t_0)]}, \quad (6)$$

where it is assumed that the critical cross section coincides with the minimum cross section of the channel and the pressure in this cross section equals the saturation pressure corresponding to the initial pressure of the liquid, are also shown in Fig. 5. As seen from Fig. 5, Eq. (6) gives a satisfactory description of the experimental values of the discharge only for the flow of strongly subcooled water. For small subcooling, Eq. (1), which takes account of the real characteristics of the outflow of evaporating liquid, i.e., the overheating of the liquid ahead of the evaporation front and the effect of the geometry of the channel on the flow parameters in the zone of intense evaporation, gives better results.

NOTATION

α, opening angle of the channel, deg; P_0, pressure at the entrance to the channel; P_{cp}, counterpressure; P_s, saturation pressure; t_0, water temperature at entrance to the channel; F_{min}, area of the minimum cross section of the channel; G, discharge; C_t, C_α, coefficients; ρ', density of saturated liquid.

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A PECULIARITY IN MEASURING THE DISPERSE DROP COMPOSITION IN A TWO-PHASE STREAM

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The paradox of repeated drop breakup in a two-phase stream is considered. A method of measuring their slip coefficients is proposed.

The criterial condition for stability of drops [1]

$$\frac{2r\rho_g u^2}{\sigma} \leqslant \frac{10.6}{\sqrt{1-\frac{r_{\min}}{r}}} \tag{1}$$

is known in computations of the heat and mass transfer associated with air atomization of fluids.

The existence of a limit drop size $r \leq r_{\min}$ which is stable in any high-speed stream dictated the mutual influence of aerodynamic forces and inertia and deformability of the drops [1]. For water $r_{\min} = 23\ \mu$. At the same time, it has been detected in [2] that the maxima of the mass spectra of water drops determined by the method of light scattering in the cylindrical part of a Venturi tube (throat) shift toward smaller sizes as the checked section is removed from the entrance into the throat. The authors interpreted this fact as the result of repeated breakup of the drops of turbulent gas pulsations, which contradicts (1). Indeed, according to the test conditions in [2], the velocity of blowing the coarsest $u_0 = 120$ m/sec in the first checking section ($x_1 = 30$ mm) for $u_0 = 120$ m/sec was known to be less than 120 m/sec, and therefore [according to (1)] drops of radius $\leq 50\ \mu$ should be stable under subsequent transportation.

The continuous breakup of drops in a turbulent stream observed in [3] does not contradict (1), but also does not confirm the deduction in [2], since the immiscible fluids in [3] possessed the identical density and surface tension (fine-scale turbulent pulsations were studied), while $\rho_g \ll \rho_f$ in [2].

We tried to show the presence of another, purely kinematical, reason for the transformation of the size spectrum observed in the section of drop acceleration by the gas stream. We have in mind one peculiarity in measuring the disperseness in a two-phase stream, which has still not received a clear exposure in the literature.

As is known, the mass spectrum $g(r, x)$ in a two-phase stream is understood to be the mass fraction of drops supplied by unit volume of gas. Hence, the flow rate of drops, whose radii lie in the interval dr, in a section x is

$$dq(r, x) = Q_f\, g(r, x)\, dr = mg(r, x)\, v(x)\, S(x)\, dr, \tag{2}$$

since $m = Q_f/Q_g$ and $Q_g = v(x)S(x)$.

If the drops being transported in the interval $\{x_1 - x_2\}$ retain their size (no coagulation or breakup), then $g(r, x_1) = g(r, x_2)$.

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