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STUDY OF THE DRAG OF A THROTTLE IN THE FILM BOILING OF A CRYOGENIC LIQUID FLOWING IN A HORIZONTAL PIPE

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A one-dimensional model is used to calculate the parameters of a two-phase flow and generalize test data on discharge coefficients.

The flow rate of a coolant and its efficiency are determined in large part by the drag of throttling devices (rings, chokes, valves, etc.) installed at the outlet of a cryogenic system. It has been shown in cooling such systems, for example [1], that the rate of flow of the cryogen changes significantly over time. This is attributable to a change in the parameters of the two-phase flow — especially the volume and mass vapor contents — and a change in the discharge coefficient of the throttling devices during cooling. The parameters of the two-phase flow during the cooling of the pipelines of a cryogenic system can be calculated using a unidimensional mathematical model describable by the equations of hydrodynamics and closing relations on heat transfer and slip obtained for vertical pipes in [2, 3].

In the absence of control of coolant flow rate, a solution of the system of equations requires a closing relation to connect the change in the discharge coefficient with the change in the parameters of the two-phase flow. An attempt was made in [4] to obtain a relation to calculate the drag of throttling rings. However, in calculating the parameters of the flow at the ring inlet, the authors used a unidimensional flow model which did not allow for phase slip. It was shown in [2] that this model cannot be used to calculate cooling. Thus, test data on the discharge coefficients of throttling devices should be generalized using direct measurements of parameters of the two-phase flow at the device inlet or the results of calculations which take into account actual values of phase slip and heating of the liquid phase (when the temperature of the liquid is below the saturation temperature).

The present article describes results of a study of the discharge coefficients of throttles during the unsteady cooling of a horizontal pipe with hydrogen. The pipe was 70 mm in diameter and 3500 mm in length and had a wall 3 mm thick. The following parameters were recorded during cooling: the second-by-second flow rate of the liquid at the pipe inlet; the temperature of the liquid phase at four stations; the temperature of the wall of the pipe at five stations, using copper—constantin thermocouples (five thermocouples per station). We also measured the temperature at five other stations of the pipe wall on the top generatrix, using single thermocouples. Pressure in the pipe and the pressure drop at the throttle was measured with potentiometric pickups. The volume vapor content was measured by the radioisotope method at two stations 1650 and 2650 mm from the inlet. The measurement technique was described in [2].

Figure 1 shows the change in the basic parameters determined during cooling. It is apparent that the mass flow rate of the coolant changes significantly over time and depends on the pressure gradient at the throttle and the parameters of the two-phase flow.

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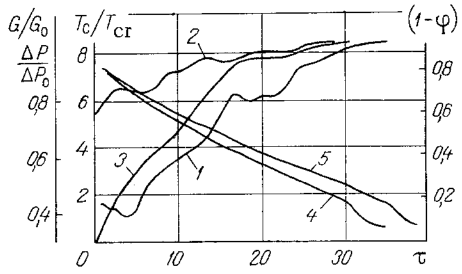

Fig. 1

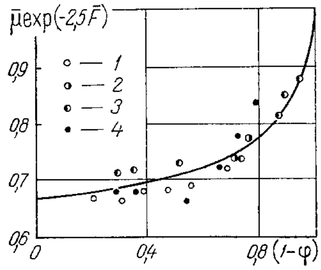

Fig. 2

Fig. 1. Change in basic parameters with time during pipe cooling: 1) flow rate; 2) pressure gradient; 3) volume content of liquid phase at the section z = 2.65 m; 4, 5) temperature of pipe wall at the section z = 2.27 m (4 — bottom generatrix, 5 — top generatrix). τ, sec.

Fig. 2. Generalizing relation for the throttle discharge coefficient: 1) $\bar{F} = 0.097$, P = 3 bars; 2) 0.097 and 6; 3) 0.053 and 5; 4) 0.027 and 7.

To determine the latter, we solved a unidimensional system of hydrodynamic equations which describes the cooling process. Based on the studies in [1], the process was broken down in time into several quasisteady sections. Also, the following assumptions were adopted in describing cooling.

1. The mean-mass temperature of the vapor in both the bottom and top parts of the pipe was equal to the saturation temperature, and the superheating of the vapor which occurs in reality was concentrated in a boundary layer which was much thinner than the thickness of the vapor film. This assumption gains support from measurements of the vapor temperature at high values of volume vapor content ($\varphi > 0.75$).

2. The liquid flows in the pipe in the form of a rod which is deformed in the top part and is symmetrical relative to a vertical plane passing through the pipe axis.

3. Heat flow in the axial direction and about the pipe perimeter can be ignored in view of the low temperature gradients present during cooling of the pipe from the ambient temperature to the saturation temperature of the coolant.

Allowing for these assumptions, we wrote the system of equations as follows:

the mass conservation equations for the phases of the flow

$$\frac{dx}{dz} = \frac{\pi D \bar{q}_c - \Pi_m q_m}{Gr}, \tag{1}$$

$$\frac{dx}{dz} = \frac{\Pi_m q_m}{Gr}; \tag{2}$$

the energy equations for the phases

$$q_m = \frac{(1-x)G}{\Pi_m}\frac{di_m}{dz} - \frac{q_n}{r}(i_m - i_{ms}), \tag{3}$$

$$T_h = T_s(P); \tag{4}$$

the flow-rate balance equations

$$xG = \rho_h u_h \varphi F, \tag{5}$$

$$(1-x)G = \rho_m u_m (1-\varphi) F; \tag{6}$$

the heat-balance equation

$$\pi D q_c = (q_m + q_n)\Pi_m; \tag{7}$$

the geometric relations

$$\Pi_m = (\pi - \gamma + \sin\gamma) D \sqrt{1 - \varphi_v}, \tag{8}$$

$$\varphi = \varphi_v + \frac{\gamma}{\pi} - \frac{\sin 2\gamma}{2\pi}. \quad (9)$$

Equations (8) and (9) were written on the assumption that the volume content of vapor in the layered flow can be represented as the sum of the two vapor contents — one of these contents φ_v is realized in film boiling in a vertical pipe, while the second

$$\varphi_t = \frac{\gamma}{\pi} - \frac{\sin 2\gamma}{2\pi}$$

is connected with deformation of the liquid rod. The value of φ_v was determined from the formula [2]

$$\varphi_v = \left[1 + 0.355\cdot 10^{-4}\,\mathrm{Re}^* \frac{(1-x)}{\rho_q\, x^{0,25}}\right]^{-1}. \quad (10)$$

System (1)-(10) was solved numerically for each of the quasisteady regimes with the initial conditions

$$z = 0,\ x = 0,\ \varphi = 0,\ T_m = T_{mo} \quad (11)$$

and the boundary conditions

$$q_{c1} = q_{c1}(z), \quad (12)$$

$$q_{c2} = q_{c2}(z). \quad (13)$$

Numerical solution of the system and generalization of the test data on slip at different stations, with measurement of the volume vapor content, yielded a relation which connects the amount of slip with the parameters of the two-phase flow:

$$u_h/u_m = 0.427\cdot 10^{-4} x^{0,53}\,\mathrm{Re}^*\,(\mathrm{Fr}_{m\cdot cr})^{0,4}. \quad (14)$$

Simultaneous solution of (5), (6), and (14) yielded an equation for determining the volume vapor content at any station along the pipe, including at the throttle inlet:

$$\frac{(1-\varphi)^{0,2}}{\varphi} = 1.06\cdot 10^{-4}\,\frac{\rho_{hs}}{(\rho_m)^{0,2}}\,\mathrm{Re}^*\,(l_{cr.s})^{0,4}\left(\frac{F}{G}\right)^{0,8}\frac{(1-x)^{0,2}}{x^{0,47}}. \quad (15)$$

The temperature gradient of the liquid in the direction of motion was calculated from the formula

$$\frac{dT_m}{dz} = \frac{q_m \Pi_m}{Gc_{pm}(1-x)} - \frac{i_m - i_{ms}}{(1-x)\,c_{pm}}\,\frac{dx}{dz} \quad (16)$$

using an empirical relation for the density of the thermal load that went to heat the liquid:

$$\frac{q_m}{q_c} = \begin{cases} 0.49\,f(K_m) & \text{at } x \leqslant 5.62\cdot 10^{-3}, \\ 1.45\,x^{0,21} f(K_m) & \text{at } x > 5.62\cdot 10^{-3}. \end{cases} \quad (17)$$

The latter was obtained by generalizing measurements of liquid temperature and is distinguished from the equation in [2] by the fact that the mass vapor content exerts an effect when it has values $x > 5.62\cdot 10^{-3}$.

The gradient of the mass vapor content is calculated as follows.

$$\frac{dx}{dz} = \frac{\pi D \bar{q}_c - q_m \Pi_m}{Gr}. \quad (18)$$

The value of x at the throttle inlet was determined by successive integration along the pipe using Eq. (18) to calculate the gradient. The throttle discharge coefficient was calculated from the formula

$$\mu = \frac{G}{F_w \sqrt{2\,[\rho_m(1-\varphi) + \varphi\rho_{hs}]\,\Delta P}}, \quad (19)$$

in which φ was taken from the solution of (15).

Analysis showed that the main parameter affecting the value of the ratio μ/μ_0 is the volume vapor content. It was also observed that the test data stratify relative to the area of the through cross section of the throttle. The lower the vapor content, the closer the ratio μ/μ_0 to unity. Given identical values of volume vapor content, this ratio increases with an increase in the relative area of the throttle $\bar{F} = F_t/F_e$.

The test data were generalized in the form of the dependence of the complex ($\bar{\mu}\exp(-2.5\bar{F})$) on the volume content of the liquid phase in the flow. This dependence is shown in Fig. 2 and can be represented by the equation

$$\bar{\mu}\exp(-2.5\bar{F}) = 0.738\,[1 + 0.355\exp(-5.1\varphi^{0.7}) - 0.09\bar{F}]. \tag{20}$$

It can be seen from Fig. 2 that the spread of empirical points relative to Eq. (20) is no greater than ±10%.

The above generalization is valid within the following range of regime parameters and geometric dimensions: p/p_{cr} = 0.22-0.44; φ = 0-0.8; x = 0-0.45; T_m/T_{cr} = 0.60-0.90; $\bar{F}$ = 0.207-0.099.

It should be pointed out that determination of the discharge coefficient from Eq. (19), i.e., with allowance for the actual value of volume vapor content, gives values of $\bar{\mu}$ which are close to unity ($0.7 < \bar{\mu} \leqslant 1$) throughout the entire range investigated. This fact can be used to perform approximate calculations of the mass flow rate through the throttle.

More accurate calculations must be performed by solving system (1)-(9) using (10)-(13), (15), and (17) and the equation obtained in the present study — Eq. (20).

NOTATION

K_m, dimensionless subheating of the liquid; $l_{cr.s} = 2\pi[\sigma/g(\rho_m - \rho_{hs}]^{1/2}$, critical length of capillary wave on the boundary; $Fr = u^2/lg$, Froude number; $\bar{F} = F_t/F_e$, ratio of area of through cross section of throttle and cross-sectional area of pipe; $Re^* = Gl_{cr.s}/F\mu_{hs}$, Reynolds number (modified); c_p, specific heat at P = const; D, diameter; F, area; G, second-by-second mass flow rate; g, acceleration due to gravity; i, enthalpy; ρ, density, γ, angle between vertical and phase boundary; μ, absolute viscosity, discharge coefficient, φ, volume vapor content; x, mass vapor content; r, specific heat of vaporization; σ, surface tension; P, pressure; T, temperature; u, velocity; Π, perimeter; q, density of thermal load (heat flux); z, coordinate in direction of motion. Indices: 1, in lower part of pipe; 2, in upper part of pipe (occupied by vapor); v, vertical; t, throttle; m, liquid; n, evaporation; cr, critical; s, parameter on saturation line; o, single-phase liquid; h, vapor; c, on wall.

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