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PHASE SLIP AND HEAT TRANSFER TO THE LIQUID IN FILM BOILING OF A CRYOGENIC LIQUID IN PISTON FLOW

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UDC 536.24

Published data are examined and results are given from a survey of experiments on phase slip and heat transfer to liquids.

It is now firmly established that heat transfer and hydraulic resistance in film boiling in a pipe are substantially dependent on the structure of the two-phase flow.

When a pipe is cooled by a cryogenic liquid in a heat-transfer device in a power plant, one usually finds [1-3] piston and dispersed modes of flow. These have been examined [1, 2] for liquid nitrogen, while dispersed flow has been examined [4] for hydrogen, nitrogen, and argon. It has been shown [1-4] that the speeds of liquid and vapor differ substantially in the dispersed mode, i.e., slip occurs for the two-phase flow. In the piston mode, it is assumed [1, 2, 5] that the phase speeds are equal, i.e., that the slip ratio is $u_v/u_l = 1$.

In most instances, the dispersed mode arises by decomposition of the piston mode in parts of the pipe fairly far from the inlet. Therefore, we assume that slip in the dispersed mode is one of the reasons for slip arising in piston mode, since sudden change in the phase velocities is unlikely when piston flow breaks up in a real process. It is necessary to assume constant slip in piston mode because the available studies [1, 2, 5] included no measurements of the volume vapor content, while the latter cannot be determined by solving a system of one-dimensional conservation equations written for each of the phases without the assumption of slip.

The difference between the mass-mean phase speeds explains why the few available measurements [6] on heat transfer to flowing hydrogen in pipes were not included in [1, 2, 5]. The results of [6] were also not incorporated in studies on dispersed flow. In [6] there were high mass flow speeds, and in most instances the flow was of piston type. One therefore concludes that the piston-flow models of [1, 2, 4] are rarely applicable, while the correct choice of slip is of primary importance in the analysis of data and in deriving general relationships.

The system of one-dimensional conservation equations for the piston model for steady-state flow takes the following form provided that the mass-average vapor temperature is equal to the saturation temperature (any superheating of the vapor is localized in a narrow layer near the wall, whose thickness is much less than the thickness of the vapor film):

$$\frac{dx}{dz} = \frac{\pi d}{Gr}\left(q_w - q_l\sqrt{1-\varphi}\right), \tag{1}$$

$$q_w = \frac{(1-x)G}{\sqrt{1-\varphi}\pi d}\frac{di_l}{dz} + q_e(i_l - i_{ls}), \tag{2}$$

$$T_v = T_s(p), \tag{3}$$

$$xG = \rho_l u_l \varphi F, \tag{4}$$

$$(1-x)G = \rho\ u\ (1-\varphi)F, \tag{5}$$

$$q_{vs} = (q_l + q_l)\sqrt{1-\varphi}. \tag{6}$$

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 39, No. 3, pp. 442-448, September, 1980. Original article submitted December 26, 1979.

0022-0841/80/3903-0961$07.50

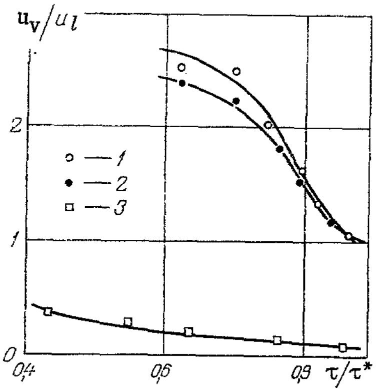

Fig. 1

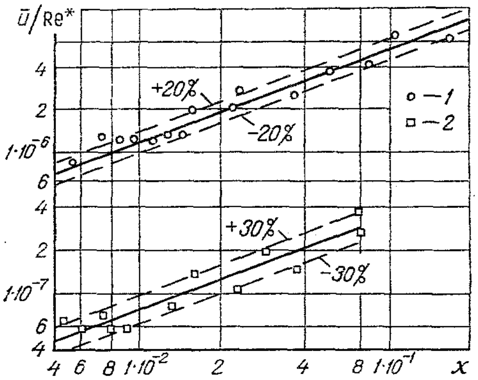

Fig. 2

Fig. 1. Variations in phase slip in nonstationary cooling of a pipeline of diameter 70 mm made of 1Kh18N9T steel at $P = 7$ bar: 1) in the section $z/d = 38$ in rising flow; 2) in the section $z/d = 24$ in rising flow; 3) in the section $z/d = 24$ in descending flow.

Fig. 2. Generalization of the phase-circulation: 1) rising flow; 2) descending flow.

The initial conditions are

$$z = z_{vs} = 0;\ x = x_0;\ \varphi = \varphi_0;\ T_l = T_{l\,0}, \tag{7}$$

and the boundary condition is

$$T_w = T_w(z). \tag{8}$$

We are justified in assuming that the mass-mean temperature is close to the saturation temperature by results [2] obtained with thermocouples on the film of vapor with nitrogen flowing in piston mode. Also, we have measured the vapor temperature for piston flow of hydrogen in large pipes, which confirm that (3) can be used. If a unique solution is to be obtained to the system defining the parameters of the two-phase flow at each point, we must have equations describing φ, q_l, q_w; in [1, 2, 4], the heat flux going to the liquid (for $T_l < T_s$) was described by an equation for the heat transfer to a single-phase flow of liquid in a circular tube:

$$Nu_l = 0.023\, Re_l^{0.8} Pr_l^{0.4} f(z/d), \tag{9}$$

as well as an equation derived from processing experimental data on the assumption that the heat flux q_e going to evaporation at high mass speeds and low liquid temperatures is small, so one can assume $q_w \approx q_l$; the equation then takes the form

$$Nu_l = 0.012\, Re_l\, Pr_l\, [1 + 1.22 \exp(-0.038\, z/d)], \tag{10}$$

and was used to calculate q_l when this is less than q_w, i.e., it was assumed that q_l is independent of the thickness of the vapor film.

The scope for using (9) and (10) has not been demonstrated in any of the direct measurements on the heating of liquid pistons.

In order to derive firmly based relationships for the slip and the heat transfer to the liquid, we performed experiments on the nonstationary cooling of a pipeline of diameter 70 mm containing hydrogen. The laboratory system provided for supplying the pipeline heated to 300-350°K with a single-phase hydrogen flow. The pipeline had vacuum insulation. We measured the following quantities: mass flow rate, pressure, wall temperature at ten points, and liquid temperature at the core at four points, as well as the volume vapor content at two points. The latter was determined by a radioisotope method. The source and detector were placed at diametrically opposite points in the cross section. The volume vapor content was determined from

$$\varphi \equiv \frac{F_v}{F} = k\,\frac{\rho_l - \rho_{mi}}{\rho_l - \rho_{vs}}, \tag{11}$$

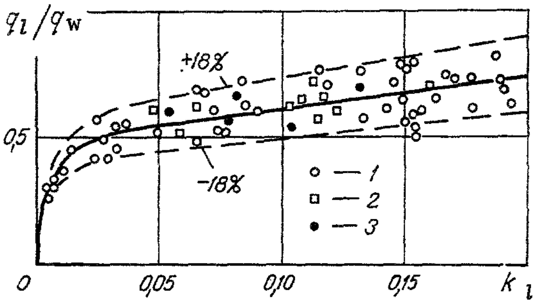

Fig. 3. Ratio of the specific heat fluxes q_l/q_w as a function of k_l: 1) rising flow; 2) descending flow of hydrogen; 3) descending flow of nitrogen.

in which the reduced density of the vapor—liquid mixture was calculated from the output signal of the radiation detector at the instant of measurement U together with the value at the reference point U_o, when the pipe contained vapor of density ρ_{vo}, and also at the reference point U_m, when the pipeline was filled only with liquid of density ρ_m:

$$\rho_{mi} = \rho_m - \frac{\rho_m - \rho_{vo}}{U_m - U_o} (U_m - U). \tag{12}$$

The densities of the vapor and liquid at the reference points corresponding to the start and end of cooling were determined from the measured temperature and pressure, while the absence of boiling at the end of cooling was monitored by measuring the wall temperature with platinum resistance thermometers (condition $T_w \leq T_s$ was met). The coefficient k in (11) relates the vapor content averaged over the volume to the local value in the region of the radioactive source, and this was determined by calibrating the system with foam-plastic fillers, which constituted rods of various diameters. A rod imitated the liquid phase, while air simulated the vapor. The data were processed to give the true phase parameters in the sections where φ was measured by means of (1)-(6) and (7). The heat flux q_w at the inner wall was calculated from the change in enthalpy of a wall element during cooling [7]. The mass vapor content was determined by integration over the length of the pipe by means of a formula for the gradient:

$$\frac{dx}{dz} = \frac{\pi d q_w}{G(r + i_l - i_{ls})} - \frac{1 - x}{r + i_l - i_{ls}} \cdot \frac{di_l}{dz}, \tag{13}$$

which was obtained by solving (1), (2), and (6) together with the equation of mass conservation of the vapor phase:

$$\frac{dx}{dz} = \frac{\pi a \sqrt{1 - \varphi}\, q_e}{Gr}. \tag{14}$$

The enthalpy change in the liquid was deduced from the temperatures measured at the core; the temperature measurement at three points over the cross section showed that a power law was followed closely, with power of 1/7. The Prandtl number is close to 1 for liquid hydrogen, and therefore there is similarity in the velocity and temperature patterns, so the mass-mean temperature of the liquid was determined from

$$T_l = 0{,}817\, T_c + 0{,}183 T_s. \tag{15}$$

The volume vapor content was measured and the mass vapor content was calculated, so (4) and (5) gave the slip:

$$\bar{u} \equiv \frac{u_v}{u_l} = \frac{x(1 - \varphi)\rho_l}{(1 - x)\varphi\rho_{vl}}. \tag{16}$$

Figure 1 shows the results for this case of nonstationary cooling for rising and descending flows. The slope was close to 1 only for cooling of the wall to temperatures close to the crisis point for film boiling $\tau/\tau^* \approx 0.9$ in rising flow.

In the case of descending flow, this quantity was considerably less than 1 throughout the cooling, i.e., the vapor speed was less than the speed of the liquid. The low vapor speed in descending motion was due to the reduction in pressure difference in the direction of the motion on account of gravitational forces. Therefore, the experiments showed that the assumption [1, 2, 5] that the phase slip is constant is unrealistic.

This analogy showed that the slip is dependent on the flow parameters at the inlet and on the mass vapor content; the criterion for the parameters of the two-phase flow at the inlet is the Reynolds number $\mathrm{Re}^* = G\, l_{\mathrm{cr.v}}/F\mu_{\mathrm{v}}$, in which the characteristic dimension is taken as the critical capillary-wave length $l_{\mathrm{cr.s}}$ at the interphase surface, while the inertial forces are characterized by the mass velocity G/F, and the frictional force is characterized by the vapor viscosity $\mu_{\mathrm{v.s}}$.

A correlation analysis was performed with an M-222 computer and showed that $\bar{u}$ is proportional to Re* to the first power. The measurements for rising and descending flows of hydrogen gave the empirical equations

$$\frac{\bar{u}}{\mathrm{Re}^*} = \begin{cases} 0{,}355\cdot 10^{-4} x^{0{,}75} & \text{for} \quad \gamma = \pi, \\ 0.245\cdot 10^{-5} x^{0{,}75} & \text{for} \quad \gamma = 0, \end{cases} \tag{17}$$

which are shown in Fig. 2 and which relate to the following ranges in the parameters $p/p_{\mathrm{cr}} = 0.23\text{–}0.65$; $k_l = 0\text{–}0.20$; $k_{\mathrm{v}} = 1.2\text{–}6.2$; $\mathrm{Re}^* = 3.5\cdot 10^5\text{–}3.1\cdot 10^6$; $x = 0.0051\text{–}0.129$. These empirical relationships can be used with (4) and (5) to calculate the volume vapor content from the following formula if the parameters of the two-phase flow at the input are known along with the distribution of the mass vapor content:

$$\varphi = \left[1 + A\mathrm{Re}^* \frac{\rho_{\mathrm{vs}}(1-x)}{\rho_l\, x^{0,25}}\right]^{-1}, \tag{18}$$

in which $A = 0.355\cdot 10^{-4}$ for a rising flow of hydrogen and $A = 0.245\cdot 10^{-5}$ for a descending one.

Solution of (2) and (4) allows one to process the experimental data, i.e., to calculate the heat flux to the liquid for known distributions of x and φ from measurements of T_c via (15), which gives T_l. The working formula is

$$q_l = \frac{G}{\pi d\sqrt{1-\varphi}}\left[(1-x)\frac{di_l}{dz} + (i_l - i_{ls})\frac{dx}{dz}\right]. \tag{19}$$

Calculations from (9) and (10) together with (19) showed that (9) and (10) do not give satisfactory accuracy.

The main factors that influence the heat transfer to the liquid are the temperature of the liquid and the heat flux at the pipe wall. The data were worked up in terms of the ratio of the heat flux to the liquid to the heat flux at the wall, with dimensionless underheating of the liquid as independent variable. Figure 3 shows results for nitrogen and hydrogen, where the curves are described to ±18% by

$$\frac{q_l}{q_{\mathrm{w}}} = 0.49\,[1 + 2.45k_l - \exp(-80k_l^{0.8})], \tag{20}$$

which covers the heat-transfer data for rising and descending flows in pipes of diameters 70 and 40 mm for the following ranges in the dimensionless parameters:

$$p/p_{\mathrm{cr}} = 0.19 - 0.65, \quad k_l = 0.005 - 0.21,$$

$$k_{\mathrm{v}} = 1{,}2 - 7.2, \quad z/d = 1.1 - 50,$$

$$\mathrm{Re}_{l.\mathrm{cr}} = 1.5\cdot 10^4 - 1{,}5\cdot 10^6.$$

The ratio of the heat fluxes is substantially dependent on the X parameter when the latter is less than 0.005; then the heat transfer to the liquid can be described by

$$\frac{q_l}{q_{\mathrm{w}}} = 0.49\,(1.7 - 140\,X)\,[1 + 2.45k_l - \exp(-80k_l^{0.8})], \tag{21}$$

which applies for the ranges in p/p_{cr}, k_l, k_{v}, Re_l, for which (20) applies, and which fits the experimental points for nitrogen and hydrogen in descending and rising flows in pipes of diameter 70 and 40 mm. There is a rapid rise in q_l/q_{w} as the underheating increases at low values because of the increased heat transfer to the liquid as the temperature difference $T_s - T_l$ increases. For $k_l < 0.025$, the increase in the ratio of the heat fluxes is less rapid, because the thickness of the vapor film decreases, and there are fluctuations in the interphase surface, which causes increased heat transfer at the wall. This results in a slower rise in q_l/q_w, although the absolute values of the heat fluxes to the liquid increase.

The rapid increase in q_l/q_w at low relative evaporation rates, which is characterized by X, is due to the reduction in q_w while q_l is constant or increases slightly.

These general relationships for the phase slip and heat transfer to the liquid allow one to use the one-dimensional system (1)-(6) with the initial and boundary conditions to process the data and derive equations for the heat transfer to the inner wall of a pipeline, which fits the experimental points with a maximum error of ±22%.

NOTATION

k_l, dimensionless liquid subcooling; k_v, dimensionless temperature difference; l_{cr}, critical length of capillary wave at interface; Nu, Nusselt number; Pr, Prandtl number; $Re_{l.cr}$, Reynolds number; X, relative evaporation rate; c, specific heat for $p = \mathrm{const}$; d, diameter; F, area; G, mass flow rate; g, gravitational acceleration; i, enthalpy; ρ, density; γ, angle between gravity and direction of motion; φ, volume vapor content; x, mass vapor content; r, latent heat of vaporization; σ, surface tension; T, temperature; u, velocity; V, voltage; z, motion coordinate; τ, time; τ^*, time of film boiling crisis for unsteady-state cooling. Subscripts: l, liquid; e, evaporation; cr, critical; s, parameter on the saturation line; v, vapor; w, wall; mi, mixture; c, flow core.

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