2. E. Dabora, Prib. Nauchn. Issled., No. 4 (1967).
3. Schneider and Hendricks, Prib. Nauchn. Issled., No. 10 (1964).
4. I. S. Grachev, D. T. Kokorev, and V. F. Yudaev, Inzh.-Fiz. Zh., 25, No. 3 (1973).
5. I. S. Grachev, D. T. Kokorev, and V. F. Yudaev, Inzh.-Fiz. Zh., 30, No. 4 (1976).
6. I. S. Grachev, Author's Abstract of Candidate's Dissertation, Moscow Institute of Chemical Engineering (1974).

FEATURES OF A CRYOGENIC FLUID FILLING VAPOR CAVITIES BEING FORMED IN FRONT OF A CUT-OFF ARMATURE

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The fundamental parameters of the unsteady processes of filling a vapor cavity in a short pipeline with water and cryogenic fluids are compared. The influence of flow interaction with the channel walls on the regularities of acceleration and deceleration is established.

An analysis of statistical data on the utilization of industrial cryogenic systems shows [1, 2] that the reason for accidental breakdowns in the equipment is most often the hydraulic shocks associated with the appearance and subsequent filling of the vapor cavities being formed in the mainlines because of the inevitable heat influxes to a cryogenic fluid. These processes possess a number of features, among which should be noted:

The vapor cavities are formed on sections with a temporary stop in the circulation (before a closed armature and in dead-end branches), a driving pulse appears because of the resumption of circulation or an abrupt rise in pressure in the system;

The governing influence on the regularities of the phenomenon is exerted by specific properties of the working fluids (nearness to the saturation curve, low heats of vapor formation and condensation);

The phenomenon is characterized by a kinematic and thermal nonstationarity as well as short duration;

The mutual influence of the hydrodynamic flow parameters and the heat and mass-transfer processes during interaction between the cryogenic fluid and the walls of the mainline and the vapor volume plays an essential role which complicates the development of a computational model considerably.

The main attention in this paper is spent on clarifying the qualitative regularities. The mechanism of the phenomenon was investigated by comparing the stream parameters with heat transfer present and absent. This was achieved because of a step-by-step execution of the experiments: initially with a high-boiling fluid (water), which afforded the possibility of the total elimination of heat transfer from the consideration and the investigation of the dependence of the nature of the process on the initial and boundary conditions (size of the gas cavity, pressurization, capacity of the terminal resistance) and also of giving a physical interpretation of the effects detected. Tests with cryogenic fluids (nitrogen and oxygen) under the same conditions permitted clarification of the influence of the thermal interaction between the stream and the channel walls on the regularities obtained earlier.

The experimental set-ups were analogous to the diagram (Fig. 1) and consisted of a 100-liter capacity pressure vessel, a working pipeline of diameter $d_y = 50$ mm and length $l = 4$ m, a fast-response valve, a set of terminal resistances, a pressurization system, and a measuring complex. The KIP system permitted writing the following quantities: the pressurization in the supply tank; the pressure in the vapor cavity in front of the diaphragm; the velocity of fluid motion; the behavior of the valve disk; and the temperature of the vapor,

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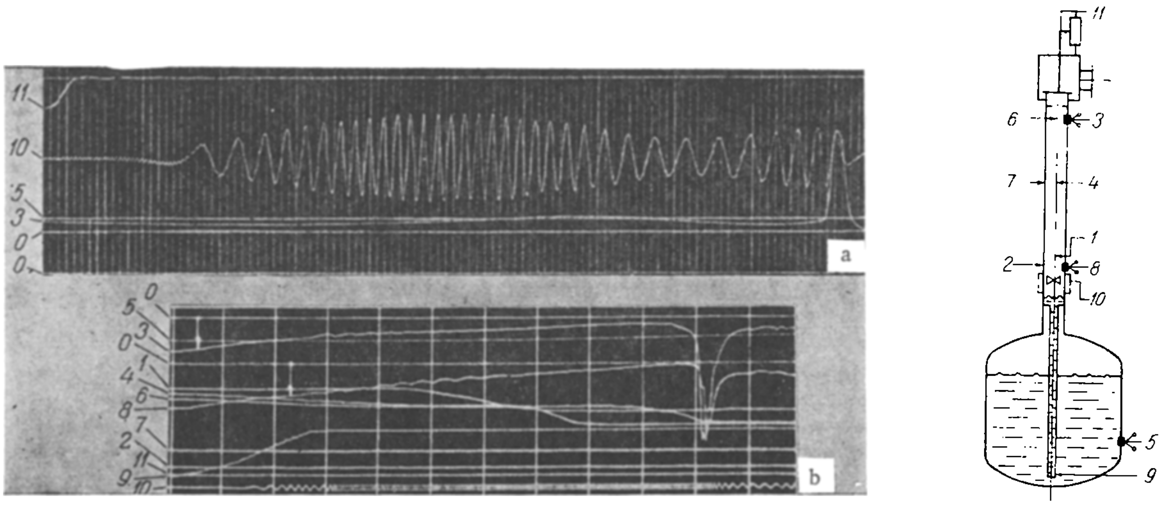

Fig. 1. Diagram of the experimental test-stand and typical oscillograms of the unsteady processes in water (a) and liquid nitrogen (b): 1, 4, 6) temperature sensors within the working section (copper—constantan thermocouples); 2, 7, 9) temperature sensors on the outer wall of the working section (copper—constantan thermocouples); 3, 5, 8) pressure sensors (DDI-20); 10) flowmeter (DR-17); 11) path sensor (LKh-705); 0) reference line.

the fluid, and the pipeline walls. The numbers on the test-stand diagram denote the points at which the fundamental parameters were measured. The values to be measured were recorded in synchronization by using a loop oscilloscope. The numerical notations for the measuring points are also presented on the typical oscillograms. The method of conducting the experiment was the following: A pressurization was produced in the supply vessel with the valve closed at the end of the pipeline, a vapor bubble was formed afterwards because of underpressure or by using some pressure, the size was regulated, then the valve was opened, the

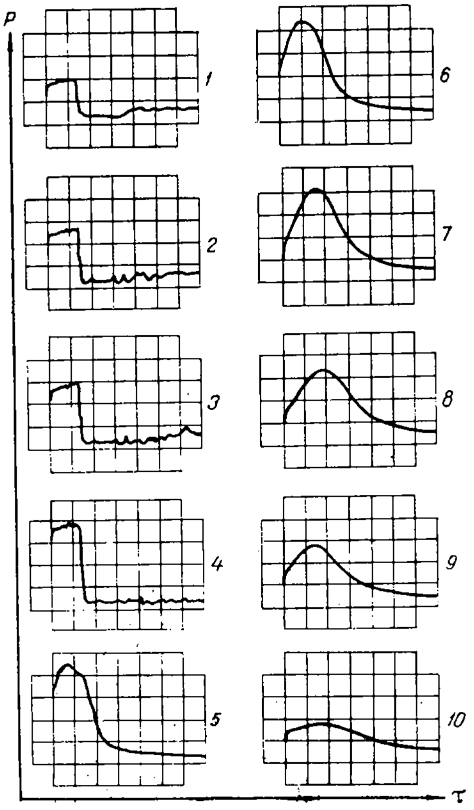

Fig. 2. Influence of the initial size of a gas cavity (l_g) on the magnitude and form of the shock pressure in water P, bar (5-bar pressure in the pressure vessel, 5-mm diameter of the terminal resistance, 12.5 bar/division ordinate, and 5 msec/division horizontal scales): 1) l_g = 0.03 m; 2) 0.06; 3) 0.10; 4) 0.15; 5) 0.25; 6) 0.50; 7) 0.70; 8) 1.00; 9) 3.00; 10) 4.00 m.

stream started to fill the working section, was accelerated, and decelerated upon meeting a terminal resistance, which caused a hydraulic shock. The pressurization, the diameter of the terminal diaphragm, the initial size of the bubble, the wall temperature, and the degree of supercooling of the fluid (for the cryogenic products) were varied in the experiments.

The whole process was divided into two stages in analyzing the phenomenon, into filling the vapor cavity, and decelerating the stream. They are characterized by a different rate of change in the parameters, which permits utilization of different assumptions in the computational model. The nature of filling the working section should depend on both the hydrodynamic factors and on the heat transfer. The heat transfer will hence influence the conditions for evacuation of the vapor volume, the mass of the vapor phase, and the dissipative losses. The degree of influence of the factors mentioned depends on the realization of some kind of boiling mode. The most probable under the test conditions is the so-called core-type self-similar mode [3]. This is associated with the fact that the characteristic parameters in experiments were within the limits inherent to this mode ($l/d < 100$, $\rho w > 3000$ kg/m^2•sec, $T_W - T_S < 230$°K). The essential nonstationarity, which hinders rapid replacement of the boiling modes, should also be taken into account.

The fundamental parameters of the acceleration stage, obtained by computations and in experiments with a cryogenic fluid, were compared.

The method presented in [1] was used for the computations. The mathematical model was based on a number of assumptions: the problem was posed in a one-dimensional formulation; thermal interaction of the stream was not taken into account, dissipative losses were found by means of stationary flow dependences. The assumptions taken for water turned out to be completely correct: two-dimensional and nonstationary effects hardly influence the flow regularities. Satisfactory agreement between the computational and experimental values of the pressure was obtained for the cryogenic fluids, while the discrepancy in the stream velocity at the end of the filling was less than 10%. These results confirm the assumption of the slight influence of heat transfer on the hydrodynamic flow characteristics in the range of modes investigated. Because of the inertia of the vapor formation and condensation processes, only a thin vapor film succeeds in being formed on the channel wall. The presence of this film reduces the friction loss somewhat, which explains the discrepancy in the velocities. In the remaining stage, filling a short pipeline with a cryogenic fluid is described completely satisfactorily by the one-dimensional equations of a single-phase flow.

Turning to the stream deceleration stage, it must be noted that the magnitude of the shock pressure will be defined by both the velocity of the fluid approach to the terminal resistance (diaphragm or valve) and the nature of the deceleration. In turn, the deceleration depends on such factors as the shape of the fluid front and the compressibility of the stream.

To clarify the influence of the geometry of the moving fluid front on the deceleration regularities, let us examine the oscillograms of the hydraulic shock in water represented in Fig. 2. It is seen quite well how the shape of the shock pressure pulse changes with the variation of the initial size of the vapor cavity. An increase in the time of stream contact with the channel walls would evidently strengthen the deformation of the fluid front, whereupon the nature of the deceleration at the local resistance would also change, as would therefore the shape of the pressure peak. If the deceleration time being increased were to become commensurate with the time of a double passage of the shock, the amplitude of the hydraulic shock would diminish because of the reflected wave. It is easily seen in Fig. 2 that the rectangular oscillograms are replaced by shallower ones. A comparison with a com-

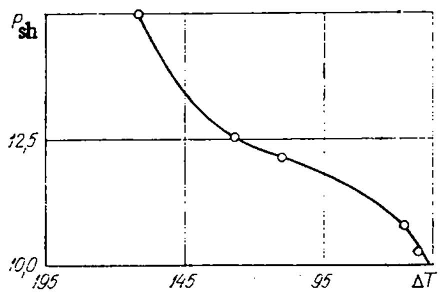

Fig. 3. Influence of wall temperature of the working section $\Delta T = (T_W - T_S)$ on the magnitude of the hydraulic shock (P_{sh}, bar).

putation shows that the test values of the pressure are 15-20% less than the computed values for a maximum bubble size greater than 3.5 m. These results qualitatively confirm the deduction about the essential influence of the shape of the fluid front on the hydraulic shock. This should be taken into account in analyzing processes of filling short pipelines since the duration of stream deceleration and the time for the reflected shock to return are commensurate in the majority of cases, which should affect the magnitude of the shock pressure strongly.

Experimental oscillograms of hydraulic shocks in cryogenic fluids, obtained in a broad range of initial pressures, channel wall, and fluid temperatures, permitted the clarification of interesting regularities. The form of the experimental oscillograms in cryogenic fluids differs substantially from those obtained in water: the appearance of sharp peaks as well as high-frequency pulsations of a cavitational nature are characteristic (Fig. 1). The test values of the hydraulic shocks differed from the computed values. The greatest agreement was observed at wall temperatures close to that of the environment. Later, the hydraulic shocks diminished substantially (Fig. 3) as the pipeline was cooled. The qualitative result was conserved for all initial fluid temperatures. With respect to the pressurization, the minimal supercooling was 8-10° while the maximal was ~40° (oxygen) and 20° (nitrogen). An estimate of the shock propagation velocity by means of the time of recording the pressure pulse at two sections, one of which was at the valve while the other was 2.5 m away, showed an abrupt diminution in the velocity in the colder mainline. The governing role in the effect detected evidently belongs to the appearance of vapor microinclusions in the single-phase liquid stream. An increase in the vapor content is related to the increase in the efficiency of heat transfer by the moving jet, which can be explained by the gradual transition from a film boiling mode to a bubble mode as the pipeline wall cools. The essential nonstationarity of the process, which contributes to the appearance and conservation of bubble boiling "spots" on the walls wetted by the fluid, plays an important part. Let us note that in the tests performed, the transition mode appeared at higher head temperatures ($T_w - T_s$) than is known from the literature [3]. It is proposed to use the effect detected as one of the methods to control hydraulic shocks in cryogenic systems [4].

NOTATION

P, pressure; w, velocity; T, temperature; l, length; τ, time; P_{sh}, hydraulic shock pressure. Subscripts: w, wall; s, saturation parameter; g, gas (vapor).

LITERATURE CITED

1. N. V. Filin, G. G. Katsnel'son, A. V. Matveev, and Ya. L. Iovnovich, "Transients in cryogenic systems," in: Questions of Modern Cryogenics [in Russian], Vneshtorgizdat, Moscow (1975).
2. N. V. Filin, A. B. Bulanov, G. G. Katsnel'son, N. A. Purtov, and A. V. Puzanov, Khim. Neft. Mashinostr., No. 9 (1975).
3. V. K. Koshkin, É. K. Kalinin, G. A. Dreitser, and S. A. Yarkho, Nonstationary Heat Transfer [in Russian], Mashinostroenie, Moscow (1973).
4. A. V. Matveev, Ya. L. Iovnovich, G. G. Katsnel'son, and N. V. Filin, Inventors' Certificate No. 542006; Byull. Otkrytii, Izobret., No. 1 (1977).