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INTERIOR BALLISTICS OF A POWDER-DRIVEN PULSED WATER CANNON

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Results of theoretical and experimental studies of the interior ballistics of a powder-driven pulsed cannon are presented. The liquid flow in the facility is considered in quasistationary and nonstationary formulations. Conditions for the applicability of the quasistationary approximation are determined. The effect of the compressibility of the liquid on the performance of the pulsed cannon is evaluated. Calculation results are compared with experimental data obtained on a particular installation.

Pulsed water cannons (PWC) and hydroguns (HG) — devices for producing high-velocity pulsed liquid jets — were first designed at the Institute of Hydrodynamics of the Siberian Division of the Russian Academy of Sciences [1]. At that Institute, experimental and theoretical studies of the first hydropulsed facilities were performed under the direction of B. V. Voitsekhovskii. An analytic solution of the problem of inflow of an incompressible liquid into the HG nozzle was obtained in [2]. Further experimental and theoretical studies of hydropulsed installations [3] showed that neglect of the compressibility of the liquid not only leads to considerable quantitative errors but also changes the process qualitatively. It is known that the hitting range of the jets from an HG is several decimeters and the hitting range of the jets from a PWC can reach several meters, which is a significant advantage of PWC [4, 5]. Among the shortcomings of a PWC is that the dynamic pressure of the jet from a PWC is lower than the static pressure inside the facility, whereas the dynamic pressure of the jet from an HG can be several times higher than the static pressure in the facility [2, 3]. Usually, the maximum velocity of the jet from a PWC does not exceed 1500 m/sec, and for HG, it can reach 3000 m/sec. For the attainment of high velocities, the HG nozzle should have a special shape and sufficient length, which imposes limitations on the dimensions and weight of the facility [2–4]. A small-sized portable facility for producing pulsed liquid jets of 10–20 mm diameter with a velocity of up to 1000 m/sec can be designed by the diagram of a powder-driven PWC.

For a powder-driven PWC, the variational problem of the optimal control of powder combustion for producing a pressure pulse of specified shape was solved in a quasistationary formulation by Atanov [6]. The interior ballistics of a powder HG has been studied theoretically and experimentally [7, 8]. In the present paper, the interior ballistics of a powder-driven PWC is examined in various hydrodynamic formulations.

A powder PWC consists of a combustion chamber 1, barrel 3, and nozzle 5 (Fig. 1). The barrel and the nozzle are filled with water 4 and separated from the combustion chamber by wad 2. The pressure was measured by gauge 6 located at the nozzle entry. At the initial time, the powder is ignited, and the powder gases compress the water and push it through the convergent nozzle exit. A pulsed high-pressure liquid jet discharges from the nozzle with a velocity as high as 1500 m/sec. For jet stabilization, the nozzle terminates with a collimator.

To construct a mathematical model for the powder PWC shot, we adopt the following assumptions. The liquid is considered ideal and compressible, and viscosity, heat conductivity, and the effect of the wad

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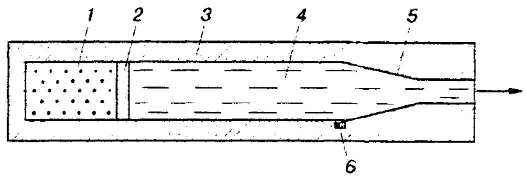

Fig. 1. Diagram of a powder pulsed water cannon: combustion chamber (1), wad (2), barrel (3), water (4), nozzle (5), and pressure gauge (6).

are neglected. The nozzle profile is assumed to be smooth, and the radial flow components are ignored. The moment of powder ignition is taken as the beginning of the process. The coordinate origin coincides with the nozzle entry.

In the adopted formulation, the quasi-one-dimensional flow of an ideal compressible liquid in the water cannon is described by the following system of nonstationary gas-dynamic equations:

$$\frac{\partial \rho F}{\partial t} + \frac{\partial \rho u F}{\partial x} = 0, \quad \frac{\partial u}{\partial t} + \frac{\partial}{\partial x}\Big(\frac{u^2}{2} + \frac{n}{n-1}\,\frac{p+B}{\rho}\Big) = 0, \quad p = B\Big[\Big(\frac{\rho}{\rho_0}\Big)^n - 1\Big].$$

Here t is time, x is a coordinate, u is the velocity, $F(x)$ is the cross-sectional area of the piping (barrel and nozzle), p and ρ are the pressure and density, and $B = 304.5$ MPa, $n = 7.15$, $\rho_0 = 10^3$ kg/m^3 are constants in the Tait equation of state for water.

The initial and the boundary conditions are given by

$$u(0,x) = 0, \qquad p(0,x) = 0, \qquad \rho(0,x) = \rho_0, \qquad -L \leqslant x \leqslant L_s;$$

$$p(t,L) = 0, \qquad p(t,x_g) = p_g, \qquad u(t,x_g) = u_g,$$

where L and L_s are the lengths of the barrel and the nozzle with the collimator, respectively, x_g is the coordinate of the contact surface, and p_g and u_g are the pressure and velocity of the powder gases on the contact surface.

The powder combustion is calculated by a procedure described in [8], using the standard assumptions of problems of interior ballistics in artillery [9]. In the quasistationary approximation, the equations of powder combustion and the initial conditions have the form

$$\frac{dz}{dt} = \frac{u_1 p_g}{h_1}, \quad Q_g = \frac{dm_g}{dt} = m_{p0}\sigma(z)\,\frac{dz}{dt}, \quad \frac{1}{k-1}\,\frac{d(p_g V_g)}{dt} + p_g F u_g = qQ_g,$$

$$\frac{dV_g}{dt} = Q_g\Big(\frac{1}{\rho_p} - \alpha\Big) + u_g F, \qquad u_g = \frac{dx_g}{dt}; \tag{1}$$

$$z = 0, \quad V_g = V_{g0}, \quad m_g = m_{g0}, \quad p_g = p_{g0}, \quad x_g = -L.$$

Here h_1 is half the thickness of a powder grain, z is the thickness of the burnt layer referred to h_1, u_1 is the burning-rate constant, p_g is powder-gas pressure, Q_g is the supply velocity of the powder gases, $\sigma(z) = 3(1-2z+z^2)$ is the relative combustion area for a powder grain of spherical shape, α is the correction to the natural volume of molecules, m_g and m_{p0} are the mass of gas and the initial mass of the powder, respectively, k is the adiabatic exponent, q and ρ_p is the specific heat of combustion and density of the powder, V_g is the volume of the powder gases, and V_{g0} m_{g0}, and p_{g0} are the gas parameters after operation of the igniter.

As shown in [10, 11], under certain conditions, the PWC parameters can be calculated with adequate accuracy in the quasistationary approximation. In this case, the water pressure is equal to the gas pressure and the interior ballistics of the PWC is described by the equations

$$\frac{dm_b}{dt} = -\rho_0 u_s F_s, \qquad u_s = a_0\sqrt{\frac{2}{n-1}\Big[\Big(\frac{p+B}{B}\Big)^{(n-1)/n} - 1\Big]},$$

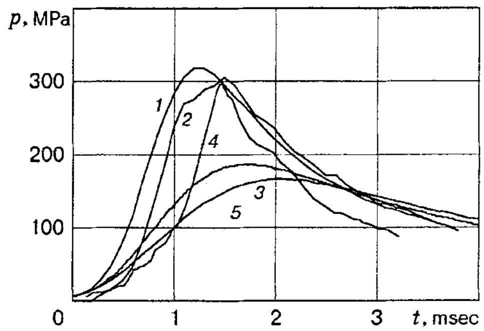

Fig. 2

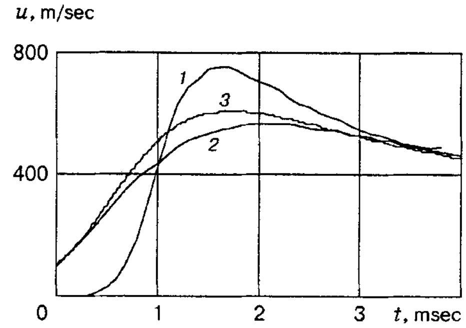

Fig. 3

Fig. 2. Pressure versus time in the combustion chamber (nonstationary formulation) (curve 1) and at the nozzle entry (nonstationary formulation) (curve 2): curve 3 refers to the quasistationary approximation, curve 4 to the experiment, and 5 to an incompressible liquid.

Fig. 3. Jet velocity versus time for the nonstationary formulation (curve 1), the quasistationary formulation (curve 2), and an incompressible liquid (curve 3).

$$p = B\left[\left(\frac{m_b}{V_b\rho_0}\right)^n - 1\right], \qquad V_b = V_{b0} - \int_{-L}^{x_g} F\,dx, \qquad m_b = m_{b0},$$

where m_{b0} and m_b are the initial and current masses of water, u_s is the velocity of jet discharge from the nozzle, F_s is the nozzle exit area, a_0 is the speed of sound in water at atmospheric pressure, and V_b and V_{b0} are the current and initial volumes of water.

In calculations using the nonstationary formulation, the equations of motion of the liquid were integrated numerically by the Godunov method and by the grid-characteristic methods of two modifications [12–14]. The calculations were performed on grids consisting of 64 to 2048 cells. During the calculations, conservation of mass and energy was verified. In calculations on fine grids, the laws of conservation of mass and energy were satisfied with errors of 0.05 and 0.2%, respectively. Results of calculations performed by different methods coincide within the error. The ordinary differential equations were integrated numerically by the Euler or Runge–Kutta methods of the fourth order.

From results of preliminary calculations, we manufactured an experimental facility (radius of the barrel 20 mm, radius of the nozzle 10 mm, length of the barrel 400 mm, length of the nozzle 86 mm, length of the collimator 70 mm, and volume of the combustion chamber 135 cm^3). The overall length of the facility is 650 mm and the diameter is 70 mm. Powder with spherical grains was used [$h_1 = 0.53$ mm, $u_1 = 0.91$ m/(sec $\cdot$ GPa), $q = 3.806$ MJ/kg, $\rho_p = 1.6$ g/cm^3, $k = 1.22$, $\alpha = 1.02$ dm^3/kg]. The initial data were $p_{g0} = 5$ MPa, $m_{p0} = 100$ g, and $m_{b0} = 600$. The initial volume and mass of the gas were determined from the volume of the combustion chamber $V_{\rm ch}$, the mass of the powder, and the gas pressure after operation of the igniter:

$$V_{g0} = V_{\rm ch} - \frac{m_{p0}}{\rho_p}, \qquad m_{g0} = \frac{p_{g0}V_{g0}}{(k-1)q}.$$

Figure 2 shows calculated (curves 1–3) and experimental (curve 4) curves of pressure versus time. Curves 1 and 2 are obtained by calculation in the nonstationary formulation and correspond to the combustion-chamber pressure and the nozzle-entry pressure, respectively. Curve 3 is obtained by calculation in the quasistationary approximation. The pressure and velocity were measured by instrumentation intended for studies of the interior ballistics of barrel guns [8]. The calculation in the nonstationary formulation agrees well with experimental data (curves 2 and 4 in Fig. 2). The difference in the maximum pressure is less than 3%. In the calculation using the quasistationary formulation, the pressure is averaged

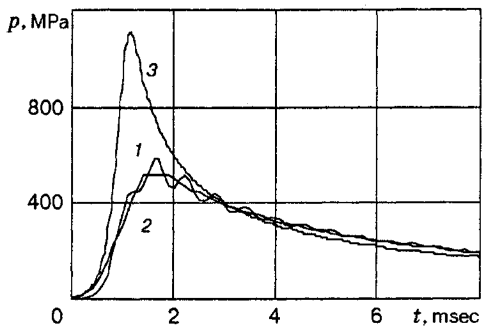

Fig. 4

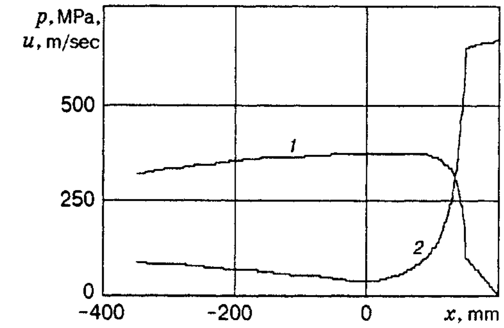

Fig. 5

Fig. 4. Pressure versus time at the nozzle entry (nonstationary formulation) (curve 1) and in the combustion chamber and at the nozzle entry (quasistationary formulation) (curve 2): curve 3 refers to an incompressible liquid.

Fig. 5. Distributions of liquid pressure (curve 1) and velocity (curve 2) along the length of the facility at $t = 1$ msec.

over the entire volume and is an integral characteristic. The difference in the maximum pressure for the approximations considered is about 46% (curves 3 and 4 in Fig. 2).

Figure 3 shows curves of the jet velocity versus time calculated in the nonstationary and quasistationary formulations (curves 1 and 2). The maximum velocities differ less than the maximum pressures (by approximately 25%). The maximum jet velocity recorded in the experiments is 730 m/sec (3.5% lower than the calculated value). For the present PWC design, the pressure rise factor k_p (the ratio of the maximum jet stagnation pressure to the maximum pressure in the facility) calculated in the more accurate nonstationary formulation is equal to 0.95. We note that the maximum value of this factor for PWC is equal to 1 if the process is quasistationary [10].

To assess the applicability of the quasistationary approximation, we studied the PWC shot for various ratios of the radii of the barrel and the nozzle and various weights of the powder. Below, we give calculation results for powder PWC with the following characteristics: radius of the barrel 20 mm, radius of the nozzle 4 mm, length of the barrel 400 mm, length of the nozzle 150 mm, length of the collimator 50 mm, volume of the combustion chamber 135 cm^3, and weight of the powder 100 g.

Figure 4 shows time dependences of the pressure at the nozzle entry for calculations in the nonstationary and quasistationary formulations (curves 1 and 2). In the calculation in the nonstationary formulation, pressure oscillations due to wave processes in the liquid (curve 1) are observed. The oscillation period (about 0.55 msec) corresponds to the propagation of sound waves from the contact surface to the nozzle exit and back (at a pressure of about 500 MPa, the velocity of sound in water is equal to 2240 m/sec). The maximum amplitude of the oscillations is equal to 62 MPa, which accounts for 12% of the maximum average pressure. The pressure oscillations damp with time, and the pressure tends to a quasistationary value. The calculations in the quasistationary formulation agree well with the average pressures obtained in the nonstationary formulation.

Figure 5 shows the distributions of the liquid pressure and velocities along the length of the facility at $t = 1$ msec obtained in calculations using the nonstationary formulation (curves 1 and 2, respectively). Evidently, the barrel pressure is practically identical and equal to the average value. In the nozzle, the pressure increases insignificantly and then rapidly decreases to zero in the collimator. The variation in the velocity agrees with the dependence of $p(x)$. In the barrel, the velocity is practically constant, and in the nozzle, it rapidly reaches a maximum value. From the velocity distribution, one can see the stabilizing effect of the collimator at $x \geqslant 150$ mm. The liquid velocity in the collimator practically does not vary. The applicability of the quasistationary formulation is explained by the nature of the pressure variation described above. Additional studies showed that the accuracy of calculations in the quasistationary formulation depends on the ratio of the radii of the barrel and the nozzle $k_R = R_b/R_s$. At a ratio of the radii $k_R > 6$, the difference in results for different formulations does not exceed 2%.

To estimate the effect of the compressibility of water on the powder PWC performance, we carried out calculations for an incompressible liquid. The PWC shot with nearly quasistationary parameters was calculated. In the quasistationary approximation, the interior ballistics of PWC with an incompressible liquid is described by the system

$$\frac{dV_b}{dt} = -u_s F_s, \qquad u_s = \sqrt{\frac{2p}{\rho_0}}, \qquad u_s F_s = u_g F(x_g). \tag{2}$$

Equations (1) and (2) were solved numerically by the Runge–Kutta method. In Fig. 4, the calculated dependence for an incompressible liquid is shown by curve 3. It is evident that the maximum pressure for an incompressible liquid is almost two times higher than the pressure for a compressible liquid. At the end of powder combustion, the results agree better, and at the final stage, they coincide. The discharge velocities change similarly but the difference in values is smaller. The maximum discharge velocity for an incompressible liquid is about 1500 m/sec, and for a compressible liquid it is 1000 m/sec. This phenomenon can be explained by the fact that for an incompressible liquid, powder combustion takes place in a smaller volume and proceeds much more rapidly. If the radius of the nozzle exit is greater, than, e.g., 10 mm, as in the experimental facility, the ratio of the quantities is different. In Figs. 2 and 3, the pressure and velocity dependences for an incompressible liquid are shown by curves 5 and 3, respectively. For the experimental facility, calculations ignoring the compressibility of the liquid give lower parameter values than those for a compressible liquid. The maximum pressure is 40% lower and the discharge velocity is 20% lower than those for a compressible liquid. The lower pressure and velocity are due to the fact that in the case of a greater nozzle radius, more water is discharged from the nozzle, the powder gases expand more rapidly, and powder combustion occurs less intensely. The above examples show that neglect of the compressibility of the liquid can lead to both overestimated and underestimated results, depending on the dimensions of a particular facility.

The dependence of the maximum pressure $p_{\max}$ in the water cannon and the jet discharge velocity $u_{\max}$ on the mass of the powder was studied for a PWC with a ratio of the radii $k_R = 5$. It is established that $u_{\max} \sim m_{p0}$ and $p_{\max} \sim m_{p0}^{1.5}$. For example, for a powder mass of 180 g, the discharge velocity is 1580 m/sec at a maximum pressure of 1460 MPa.

In the present study, the interior ballistics of a powder PWC is calculated in nonstationary and quasistationary formulations. A comparison with experiments and calculations in the nonstationary formulation shows that the simplified quasistationary approximation is valid for $R_b/R_s > 6$. A powder PWC is fairly effective, and its pressure rise factor is close to unity. The effect of the compressibility of the liquid on the PWC performance is evaluated. It is shown that neglect of the compressibility of the liquid can lead to great errors.

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