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NUMERICAL MODELING OF INTERIOR BALLISTICS PROCESSES IN LIGHT GAS GUNS

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An improved procedure for modeling the operation of a light-gas gun is proposed. The motion of working bodies in both the firing chamber and the light-gas chamber is studied within the framework of the mechanics of heterogeneous media. The problem of barrel heating taking into account its melting and removal of thermal ablation products into the medium inside the bore is solved in a coupled formulation. Heat and mass transfer and friction on the barrel surface are calculated using empirical dependences. The deformable piston is considered compressible and elastoviscoplastic. Allowance is made for the presence of a clearance between the lateral surface of the piston and the barrel bore walls and the associated gas flow between the firing and the light-gas chamber. Calculation results are given.

Key words: *high-velocity acceleration, light-gas gun, multiple-velocity polydisperse mixture, deformable piston, ablation, erosion.*

Light-gas guns (LGGs) have been used in studies of a high-velocity impact and aerodynamic and aerophysical phenomena in a high-velocity flight. Modern LGGs consist of a firing chamber and piston and ballistic barrels joined by a tapered adapter. The piston barrel length is about 150 diameters long, and the ballistic barrel length is up to 300 diameters. The ratio of the diameters of the piston and ballistic barrels is in the range of 3–6, and the cone angle of the tapered adapter between them is the about 10° [1]. Numerical modeling of the operation of LGGs has been performed in many studies [2–7]). In the present paper, we describe an improved mathematical model of interior ballistics processes that takes into account the main real processes.

The operation of the first stage is modeled taking into account the possibility of using a multicomponent powder shell. It is assumed that the gas–powder mixture is a multiple-velocity polydisperse mixture of a gas and powder species. Some species can burn with the formation of a gas phase, and others, for example, the barrel ablation products are inert. The mixture of the working light gas and ablation products is also polydisperse; therefore, the motion of these two media can be calculated within the framework of the same model. In the one-dimensional approximation of the mechanics of heterogeneous media [8], the motion of a medium in the LGG barrel bore is described by the following system of differential equations [7]:

$$\frac{\partial(\rho_j S)}{\partial t} + \frac{\partial(\rho_j u S)}{\partial x} = m_j S, \qquad j = 0, \ldots, J; \tag{1}$$

$$\frac{\partial(\rho S)}{\partial t} + \frac{\partial(\rho u S)}{\partial x} = \sum_{j=1}^{J} m_j S; \tag{2}$$

$$\frac{\partial(\beta_j \delta_j S)}{\partial t} + \frac{\partial(\beta_j \delta_j u_j S)}{\partial x} = (M_j - m_j) S, \qquad j = 1, \ldots, J; \tag{3}$$

$$\frac{\partial(\rho u S)}{\partial t} + \frac{\partial(\rho u^2 S)}{\partial x} = -\alpha S \, \frac{\partial p}{\partial x} + \sum_{j=1}^{J} (m_j u_j - f_j) S + 2\pi R \sigma_w^{n\tau}; \tag{4}$$

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$$\frac{\partial(\beta_j\delta_j u_j S)}{\partial t} + \frac{\partial(\beta_j\delta_j u_j^2 S)}{\partial x} = -\beta_j S\,\frac{\partial p}{\partial x} + (f_j - m_j u_j)S, \qquad j = 1,\ldots,J; \tag{5}$$

$$\frac{\partial(\rho e S)}{\partial t} + \frac{\partial(\rho e u S)}{\partial x} = -p\,\frac{\partial(\alpha u S)}{\partial x} - p\sum_{j=1}^{J}\frac{\partial(\beta_j u_j S)}{\partial x}$$

$$+ S\Big\{\sum_{j=1}^{J}\Big[m_j\Big(Q_j + \frac{(u-u_j)^2}{2}\Big) + f_j(u-u_j)\Big] + Q_r - \sum_{j=1}^{J} q_j\Big\}; \tag{6}$$

$$\frac{\partial(\beta_j\delta_j e_j S)}{\partial t} + \frac{\partial(\beta_j\delta_j e_j u_j S)}{\partial x} = S\Big[M_j\Big(H_j + \frac{u_j^2}{2}\Big) + q_j\Big], \qquad j = 1,\ldots,J; \tag{7}$$

$$\frac{\partial(\beta_j\delta_j\psi_j S)}{\partial t} + \frac{\partial(\beta_j\delta_j\psi_j u_j S)}{\partial x} = m_j S(1-2\psi_j), \qquad j = 1,\ldots,J. \tag{8}$$

Here t is time, R is the radius of the barrel bore, x is the dimensional coordinate, S is the variable cross sectional area of the barrel bore, J is the number of solid fractions, the subscript j denotes the fraction number, the subscript 0 corresponds to the starting gas, ρ_j is the mean density of the jth component of the gas mixture produced by combustion of the jth fraction of species; ρ is the mean density of the gas mixture, δ_j and u_j are the true density and velocity of the jth fraction, u is the gas velocity, e_j and e are the specific internal energies of the jth fraction and the gas mixture, respectively, p is the pressure, β_j is the volume portion of the jth fraction, α is the volume portion of the gas, ψ_j is the degree of conversion of the jth fraction, m_j is the mass rate of formation of the jth gas in combustion of the jth sort of species per unit volume of the mixture, M_j is the mass rate of formation of the jth sort of species per unit volume of the mixture due to ablation, f_j is the resisting force that arises because of the difference in phase velocities, $\sigma_w^{n\tau}$ is the shearing stress on the barrel bore wall, Q_j is the heat release due to combustion of the jth sort of species (calorific value), Q_r is the heat flux per unit volume due to heat exchange with the barrel walls, q_j is the heat flux from the gas to the jth sort of inert species per unit volume (for burning powder species, $q_j = 0$), and H_j is the specific enthalpy of the jth fraction (for ablated species, the specific enthalpy at the moment of melting with allowance for the heat of the phase transition).

It is assumed that combustion gases of different sorts of species do not react with one another and obey the equations of state with a covolume [2–6]. In this case, the gas mixture is also described by an equation of state with a covolume. The effective coefficients of the calorific and thermal equations of state of the mixture are expressed in terms of the effective coefficients for the components from the equality conditions for temperatures and pressures [7].

The internal energy equation (7) is used for inert species, and the equation for the degree of conversion (8) is used for powder species. All condensed components are considered incompressible. From the momentum equations (4) and (5) it follows that ablated species introduced into the mixture have zero initial velocity and are accelerated in the gas flow. We note that in the present model, the ablated species are considered spherical and their diameter is identical for all fractions; i.e., different fractions of ablated species differ only in velocities. The internal energy of inert species is considered a known function of temperature, and the heat of the phase transition is allowed for. Before melting, the known dependences for alloy steels are used; after melting, the specific heat is considered constant. The dependence of the species density on the temperature and phase transition is ignored.

The mass and force interaction of the phases is described by the following relations:

$$m_j = \frac{\beta_j\delta_j}{1-\psi_j}\,\frac{S_{0j}}{W_{0j}}\,\sigma_j(\psi_j)U_j(p),$$

$$f_j = \frac{3}{4}\,\frac{\beta_j}{d_e}\,C_{dj}\rho^0|u-u_j|(u-u_j), \qquad q_j = \beta_j s_j\,\frac{\lambda\mathrm{Nu}_j}{d_e}\,(T_\mathrm{g} - T_{wj}).$$

Here S_{0j} and W_{0j} are the initial surface area and volume of a powder species of the jth sort, σ_j and U_j are the relative burning surface area and the linear burning rate of the jth sort of species, ρ^0 is the true gas density, d_eff is the effective species diameter, C_{dj} is a resistance coefficient that depends on the parameters of the gas equation of state, the Reynolds number of the relative motion of the gas, the species shape, and the gas flow restriction (volume fraction of the gas), T_{wj} is the surface temperature of the jth sort of species, T_g is the gas temperature, s_j is the surface area of the jth sort of species per unit of their volume (for spherical species, $s_j = 6/d_e$), Nu_j is the dimensionless coefficient of heat exchange between the gas and the jth sort of species, defined by the following formula [8]:

$$\mathrm{Nu}_j = \begin{cases} 2 + 0.636\alpha\,\mathrm{Re}_j\,\mathrm{Pr}^{1/3}, & \mathrm{Re}_j \leqslant 33.3, \\ 2.274 + 1.993(\alpha\,\mathrm{Re}_j)^{0.67}\mathrm{Pr}^{1/3}, & \mathrm{Re}_j > 33.3. \end{cases}$$

Here $\mathrm{Re}_j = \rho^0|u - u_j|/(s_j\mu)$ is the Reynolds number of the relative motion of the gas, $\mathrm{Pr} = c_p\mu/\lambda$ is the Prandtl number, c_p, and μ, and λ are the specific heat, viscosity, and thermal conductivity of the gas, respectively.

The interaction of the polydisperse medium with the barrel bore walls is found by calculating the coupled problem of the wall temperature distribution in gas flow. The thermal layer on the wall is considered thin enough to be described by the one-dimensional heat-conduction equation [9]

$$\delta_b c_{pb}\,\frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\Big(\lambda_b\,\frac{\partial T}{\partial y}\Big),$$

where δ_b, c_{pb}, and λ_b are the density, specific heat at constant pressure, and thermal conductivity of the barrel material, respectively, and y is the space variable normal to the barrel surface.

At the initial time, we specify a uniform initial temperature distribution $T(x, y, t = 0) = T_0$. It is assumed that in the barrel bore, the polydisperse medium interacts with the wall only by means of the gas; i.e., the possible interaction of condensed species with the barrel surface is ignored in the present model. The problem is solved subject to the boundary conditions

$$y = 0\colon\quad -\lambda_b\Big(\frac{\partial T}{\partial y}\Big)_w = q_w, \qquad y \to \infty\colon\quad \Big(\frac{\partial T}{\partial y}\Big)_\infty = 0, \tag{9}$$

where the subscript w corresponds to the barrel bore surface and q_w is the heat flux from the medium in the bore to the barrel, determined by Newton's laws [9]:

$$q_w = \mathrm{Nu}\lambda(T_w - T_{\mathrm{g}})/D$$

[D is the bore diameter and Nu is the dimensionless heat-transfer factor (Nusselt number)].

After the beginning of melting, one should replace the first boundary condition (9) by the condition of constant surface temperature and add the equation of displacement of the melting boundary:

$$T_w = T_*, \qquad y = \int\limits_0^t u_w\,dt, \qquad \delta_b u_w \chi = q_w + \lambda_b\,\frac{\partial T}{\partial y}.$$

Here T_* is the melting point, u_w is the rate of displacement of the melting boundary along the normal to the surface, and χ is the latent heat of melting.

On the right sides of Eqs. (1)–(8), the source terms accounting for w the interaction with the barrel bore walls are defined by the formulas

$$\sigma_w^{n\tau} = -\zeta\rho^0 u|u|/8, \qquad Q_r = -2q_w/R, \qquad M_{ja} = 2\delta_b u_w/R, \qquad M_j = 0 \qquad (j \neq ja),$$

where ζ is the friction coefficient; the subscript ja corresponds to the number of the fraction that is considered ablated at the current time.

From the formula for M_{ja} it follows that the molten material of the barrel is entirely carried away by the gas flow. Obviously, the species entrained in the flow later have the lower velocity; i.e., they have a greater decelerating effect on the accelerating gas. The continuous species velocity distribution is replaced by a stepped one with the required accuracy; this is achieved by choosing the number fractions from preliminary calculations for each particular case.

Determining the dependences of the friction and heat exchange of the working gas with the barrel on the parameters of the medium in the bore under the extreme conditions taking place in LGGs is an independent problem, whose solution was beyond the scope of the present study. At the same time, the use of dependences obtained for steady-state conditions is a conventional approach. This approach was justified in [10], where flow under the conditions of the Lagrange problem was modeled using the Reynolds equations in a narrow bore approximation. From a comparison of calculation results with the empirical Gukhman–Ilyukhin dependences given in [11], it was concluded that these dependences, which take into account the temperature factor, are appropriate for calculating the friction stress and heat transfer on the wall. However, these conclusions are based on calculations of the initial stage of motion of the piston, when its velocity is well below the velocity of sound in the gas behind it. Estimates shows that for the data given in [10], the highest gas velocity is approximately 700 m/sec, which is an order of magnitude lower than that in a LGG. One should also bear in mind that the conditions of the Lagrange problem differ significantly from the LGG operation conditions, where the gas in the light-gas chamber is severely heated by incoming shock waves. In the present study, the friction and heat-transfer coefficients were determined from the relations of [12–15] with correction factors (matching parameters):

$$\zeta = C_f(\mathrm{M}, \eta)(0.0032 + 0.22\,\mathrm{Re}^{-0.237}),$$
$$\mathrm{Nu} = 0.022\mathrm{Pr}^{0.43}\,\mathrm{Re}^{0.8}(T_\mathrm{g}/\Theta)^{0.42}, \qquad \mathrm{Re} = \rho^0|u|D/\mu. \tag{10}$$

Here C_f is the correction factor for the compressibility and temperature nonequilibrium of the medium, Re and M are Reynolds and Mach numbers, respectively, $\eta = T_w/T_\mathrm{g}$ is the temperature factor, and Θ is the flow stagnation temperature.

In the literature, one can find a number of different relations, but calculations showed that formulas (10) provide for the most accurate description of a shot. In this case, correction factors are not needed or the factors introduced in some cases are much closer to unity than those in different relations.

System (1)–(8) is solved numerically subject to the following initial conditions:

$$p(x,0) = p_0, \qquad u(x,0) = 0, \qquad T(x,0) = T_0,$$

$$\rho_j(x,0) = \rho_{j0}, \qquad \beta_j(x,0) = \beta_{j0}(x), \qquad u_j(x,0) = 0, \qquad j = 1,\ldots,J,$$

Here ρ_{j0}, p_0, and T_0 are parameters that characterize the initial state of the gas phase and $\beta_{j0}(x)$ is the initial spatial distribution of the jth fraction.

In specifying the boundary conditions, we consider the bottom of the firing chamber as a fixed impermeable boundary, on which the nonpenetration condition is imposed. On the boundary with the piston, the boundary conditions consist of the nonpenetration condition (if the effect of the clearance between the lateral surface of the piston and the barrel bore walls is ignored) and the continuity condition for the mass, momentum, and energy fluxes taking into account the gas flow through the clearance. On the shell, we also impose nonpenetration conditions and the velocity and position of the shell are determined by integrating the equation of motion

$$m_{pr}\,\frac{d^2x_{pr}}{dt^2} = S(p_l - p_r) - F_{fr},$$

where m_{pr} is the mass of the shell, x_{pr} is the coordinate of the shell, F_{fr} is the friction force, and p_l and p_r are the pressures on the left and right of the shell, respectively.

The deformable piston is considered as a separate calculation region. To describe its motion, we restrict ourselves to the case of axisymmetric flow. We assume that the originally plane material cross sections of the piston remain unchanged throughout the motion and the radial velocity component in the energy equation can be ignored. Then, in the one-dimensional approximation, the motion of the piston is described by the equations [16]

$$\frac{\partial(\rho_p F)}{\partial t} + \frac{\partial(\rho_p u_p F)}{\partial x} = 0,$$

$$\frac{\partial(\rho_p u_p F)}{\partial t} + \frac{\partial(\rho_p u_p^2 F)}{\partial x} = \frac{\partial(\sigma_p^{xx} F)}{\partial x} - \sigma_\mathrm{ext}^{nn}\,\frac{\partial F}{\partial x} + 2\pi R_p \sigma_\mathrm{ext}^{n\tau},$$

$$\frac{\partial(\rho_p e_p F)}{\partial t} + \frac{\partial(\rho_p u_p e_p F)}{\partial x} = \sigma_p^{xx}\,\frac{\partial(u_p F)}{\partial x} + \sigma_\mathrm{ext}^{nn}\Big(\frac{\partial F}{\partial t} + u_p\,\frac{\partial F}{\partial x}\Big) + 2\pi R_p q_{\mathrm{g}p},$$

where the subscript "ext" corresponds to the values of the parameters on the external surface of the piston, R_p is the radius of the piston, $F = \pi R_p^2$ is the cross-sectional area of the piston, and $q_{\mathrm{g}p}$ is the heat flux on the outer surface of the piston; the remaining notation is conventional.

The calorific equation of state for the material of the piston is written as

$$e_p(p_p, \rho_p) = (p_p - c_0^2(\rho_p - \rho_{p0}))/((k-1)\rho_p).$$

For high-pressure polyethylene, $\rho_{p0} = 0.91903$ g/cm^3, $c_0 = 2380$ m/sec, and $k = 1.63098$. The constants are evaluated from the experimental data of [17].

In motion, the piston is subjected to considerable deformations beyond the limits of elasticity. It is also known that polymeric materials have viscosity. Therefore, to describe the rheological behavior of the piston material, we use an elastoviscoplastic model.

It is assumed that at the initial moment, the piston is at rest and density and a stress distribution along the piston length are specified. At the butt ends of the piston, the continuity conditions for the stress vector with passage through the contact surfaces are satisfied.

In [3, 7], it was noted that after a shot, there are no traces of contact with the barrel bore surface on part of the lateral surface of the piston. One of the reasons of this phenomena is the presence of a gas layer between the lateral surface of the piston and the bore surface. Therefore, the piston motion is modeled taking into account the presence of a clearance. To determine the magnitude of the clearance $\delta(x,t) = R - R_p$, we use the continuity condition for the stress vector on the lateral surface of the piston with the gas in the clearance:

$$\sigma_p^{rr} = -p_{\rm g}$$

($p_{\rm g}$ is the gas pressure in the clearance).

The gas flow in the clearance is described by the equations obtained by integration of the equations for plane flows of a viscous heat-conducting gas over the width of the clearance [14]. It is assumed in this case that the transverse velocity component and the transverse density and pressure gradients can be ignored and the longitudinal velocity profile is specified. The equations have the following form [16]:

$$\frac{\partial}{\partial t}(\rho_{{\rm g}j}\delta) + \frac{\partial}{\partial x}(\rho_{{\rm g}j}U\delta) = 0, \quad j = 1,\ldots,J, \qquad \frac{\partial}{\partial t}(\rho_{\rm g}\delta) + \frac{\partial}{\partial x}(\rho_{\rm g}U\delta) = 0,$$

$$\frac{\partial}{\partial t}(\rho_{\rm g}U\delta) + \frac{\partial}{\partial x}[\rho_{\rm g}\delta(a_1u_p^2 + a_2U^2 + a_3Uu_p)] = -\delta\frac{\partial p_{\rm g}}{\partial x} + 4\frac{\mu_{\rm g}}{\delta}(2k+1)\Big(\frac{u_p}{2} - U\Big), \tag{11}$$

$$\frac{\partial}{\partial t}(\rho_{\rm g}e_{\rm g}\delta) + \frac{\partial}{\partial x}(\rho_{\rm g}e_{\rm g}U\delta) = -p_{\rm g}\Big(\frac{\partial}{\partial x}(U\delta) + \frac{\partial\delta}{\partial t}\Big) + \frac{2\mu_{\rm g}}{\delta}\Big[\frac{u_p^2}{4} + \frac{(2k+1)^2}{4k-1}\Big(\frac{u_p}{2} - U\Big)^2\Big] - q_{{\rm g}b} - q_{{\rm g}p};$$

$$a_1 = \frac{k+1}{3(4k+1)}, \qquad a_2 = \frac{4k+2}{4k+1}, \qquad a_3 = -\frac{1}{4k+1}.$$

Here $q_{{\rm g}b}$ is the heat flux on the barrel bore surface (like $q_{{\rm g}p}$, it was determined using the empirical formulas of [12, 13]), U is the velocity averaged over the volume flow rate, and $u_{\rm g}$ is the longitudinal velocity whose distribution is given by

$$u_{\rm g}(x,y,t) = u_p\frac{y}{\delta} + \frac{2k+1}{2k}\Big(\frac{u_p}{2} - U\Big)\Big[\Big(\frac{2y}{\delta} - 1\Big)^{2k} - 1\Big]$$

(k is a positive integer). For $k = 1$, this function coincides with the known exact solutions of the equations of a Couette viscous incompressible fluid [14]. It is assumed that for laminar flow $k = 1$ and for turbulent flow k increases with increase in Reynolds number:

$$k = \begin{cases} 1, & \mathrm{Re}_c < 2000, \\ E((3/128)\,\mathrm{Re}_c\exp[-(2.809 + 7272\,\mathrm{Re}_c^{-1.23})] - 1/2), & \mathrm{Re}_c > 2000. \end{cases}$$

Here $E(z)$ is the integer part of z (special function), $\mathrm{Re}_c = \rho_{\rm g}UD_{\rm h}/\mu_{\rm g}$ is the Reynolds number, and $D_{\rm h}$ is the hydraulic diameter. The dependences written above approximate empirical data on the hydraulic flow resistance [18]. Equations (11) are supplemented by the gas equations of state. To distinguish a corresponding solution of the system, natural initial and boundary conditions are specified.

The equations describing the gas flow in the barrel bore and in the clearance were calculated using improved Godunov's method [3, 7], which has second-order approximation in time and third-order approximation in the space coordinate.

To estimate the effect of the clearance, we calculated a number of versions of motion of the deformable piston in the LGG barrel with initial clearances of 1 μm (which corresponds to surface roughness) to 0.2 mm. The calculation results show that the clearances available at the initial moment decrease. However, even if the clearance in a calculation is retained intentionally, the gas flow through it does not have a significant effect on the interior ballistics parameters of the shot. In this connection, the presence of a clearance was ignored in the calculations given below.

TABLE 1

Experiment	ω, g	m_p, g	m_{pr}, g	$p_0 \cdot 10^{-4}$, Pa	Calculation		Experiment	
					u_p, m/sec	u_d, m/sec	u_p, m/sec	u_d, m/sec
20/80	200	888	0.9407	6.90	848.8	9555	826.6	9418
21/81	225	888	0.9475	15.52	879/3	7480	872.0	7864

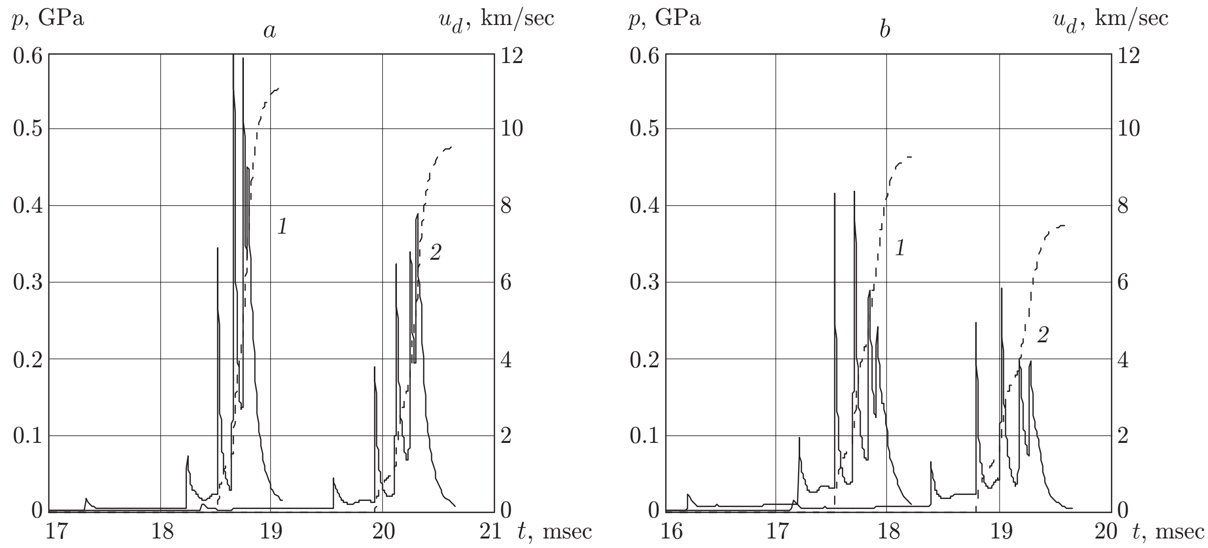

Fig. 1. Pressure on the shell (solid curves) and shell velocity (dashed curves) versus time: (a) shot 20/80, (b) shot 21/81; curve 1 refers to calculations ignoring heat release and ablation and curve 2 refers to calculations taking into account heat losses.

Calculations of a series of shots from a half-inch NASA LGG were carried out. The calculations were performed both taking into account and ignoring thermal losses and barrel ablation. Figures 1–3 give calculation results for two experiments (shots 20/80 and 21/81) [4] with close loading parameters (see Table 1); in this case, the experimentally measured muzzle velocities differ significantly.

The calculations were conducted on {10,10,20}, {10,10,50}, {20,20,50}, {20,20,100}, and {20,20,200} moving grids (the first, second, and third numbers are the numbers of calculation meshes in the gas–powder mixture, in the piston, and in the region of the mixture of the light gas with barrel ablation products, respectively). An analysis of the calculation results for the LGG shows that the most adequate is the {20,20,100} grid because the difference of muzzle velocities in calculation on this grid and the finer {20,20,200} grid is 0.3% and the maximum pressure difference is about 2%. Therefore, below we give the calculation results obtained on the indicated grid.

Some loading parameters and measured and calculated piston velocities u_p and muzzle velocity of projectiles u_d are listed in Table 1. In both experiments, identical diaphragms were used and the experimental diaphragm rupture pressure was 138 MPa. From Table 1 it follows that an insignificant increase in the mass of the powder charge ω and a simultaneous increase in the initial hydrogen pressure p_0 in experiment 21/81 in comparison with experiment 20/80 led to a sharp decrease in the muzzle velocity.

Figure 1 gives calculated curves of the shell velocity u_d and the pressure on the shell p versus time with and without allowance for heat and mass transfer of the light and powder gases with the barrel bore walls. It is evident that the motion of the light gas has a substantially wave nature; irrespective of the formulation of the problem, five shock waves arrives at the projectile in both experiments, which correspond to surges on the pressure versus time curves. Time is reckoned from the moment of speadup of the piston. It should be noted that allowance for heat and mass transfer of light and powder gases with the barrel bore walls leads to an increase in the shot duration by approximately 1.5 msec, which can be used in comparing calculated and experimental data. At the same time, neglect of heat and of mass transfer in calculations results in considerably overestimated muzzle velocity of the shell (by approximately 2 km/sec). The calculated piston and shell velocities obtained in the complete formulation are compared with experimental values. An analysis of calculated data shows that the losses due to heat release by the

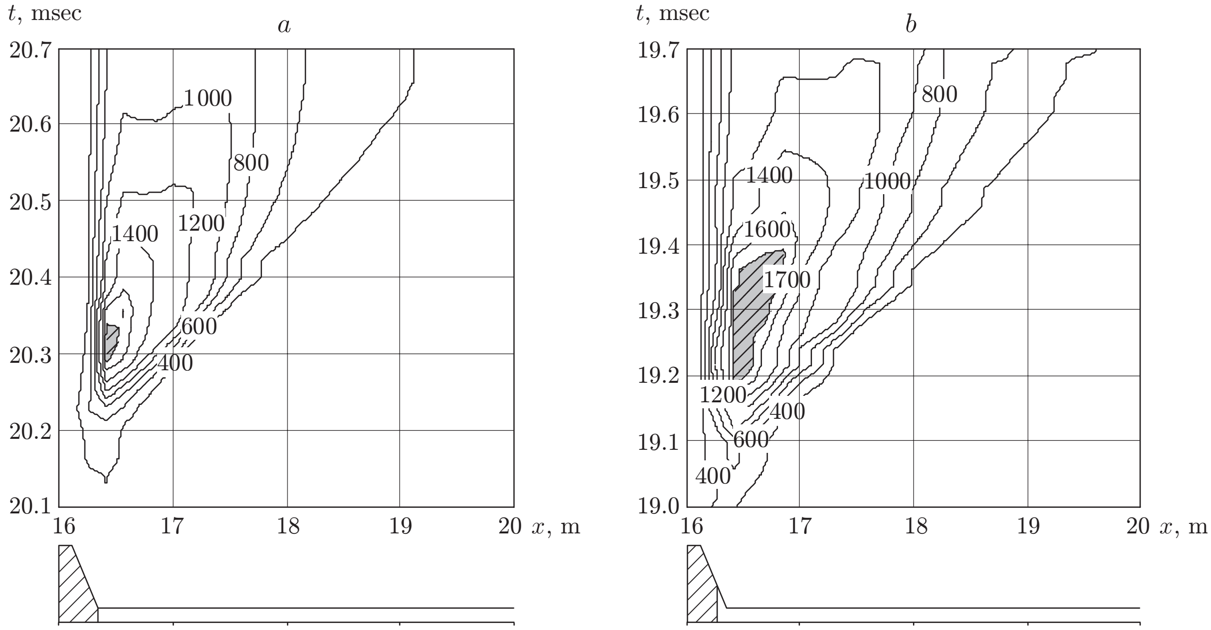

Fig. 2. Isolines of the barrel bore wall temperature in kelvins in the light-gas region (above) and the barrel bore profile with the extreme position of the piston (below): (a) shot 20/80; (b) shot 21/81.

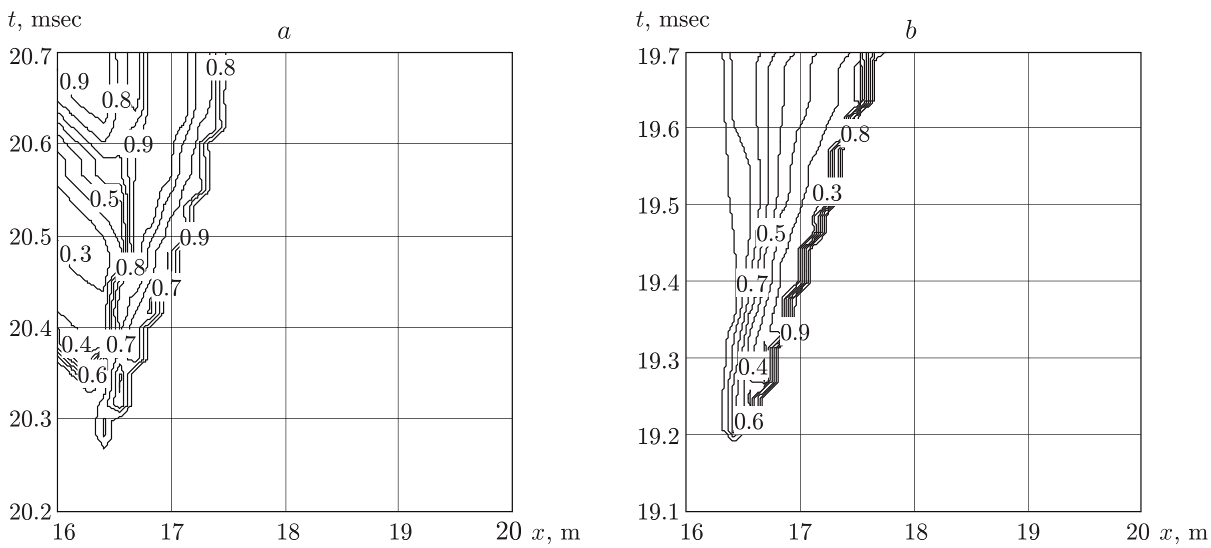

Fig. 3. Isolines of the mass fraction of the light gas: (a) shot 20/80; (b) shot 21/81.

barrel bore walls are much lower than the kinetic energy of the molten barrel material carried away by the light gas flow. This is explained by the fact that total mass of the melt is comparable with the mass of the shell. In this case, the velocity of the ablated species in the range of 4–6 km/sec; i.e., their specific kinetic energy is severalfold higher than the calorific value of known explosives.

Figure 2 shows isolines of the surface temperature in the plane (x, t) calculated in the complete formulation. In the formulation considered, the surface temperature cannot exceed the melting point of cannon steel; therefore, the boundary of the ablation zone (shaded in Fig. 2) practically coincides with the closed isoline $T = 1723$ K. The results presented here shows that a decease in the muzzle velocity in experiment 21/81 results from the faster ablation. The ablation rate can be judged from Fig. 3, which gives isolines of the mass fraction of light gas in the plane (x, t). In both experiments, the minimum mass concentration is at about 0.3, but in experiment 21/81, the low concentration region is much wider, which is explained by the larger duration and extent of the ablation process. From the configuration of the right boundary of the region occupied by a mixture of the light gas and melt species, one can determine the mean condensed-phase species velocity, which was about 5 km/sec in both experiments.

To estimate the effect of the clearance on the LGG operation with allowance for the deformability of the piston, we performed calculations of shot 20/80 with different initial clearances between the piston surface and the barrel bore. An analysis of the calculation results shows that the presence of a small (0.1 mm) clearance does not reduce the muzzle velocity but, on the contrary, increases it somewhat, apparently, because of a reduction in the piston friction. However, the gain in the muzzle velocity is very small (about 40 m/sec) and decreases with increase in the clearance. In conclusion, we note that the friction and heat-exchange coefficients defined by formulas (10) were multiplied by a correction factor of 0.5 to match calculated and experimental data. This indicates that the available data on friction and heat exchange under the conditions occurring in LGGs are insufficient.

Thus, the present paper gives an improved mathematical model for describing a shot from an LGG. A comparison was performed of calculated and experimental data for a series of shots; an analysis of the results gives a better understanding of the processes involved in gun firing.

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REFERENCES

1. N. A. Zlatin, A. P. Krasil'shchikov, G. I. Mishin, and N. N. Popov, *Ballistic Facilities and Their Application in Experimental Studies* [in Russian], Nauka, Moscow (1974).
2. V. V. Zharovtsev, L. V. Komarovskii, and E. I. Pogorelov, *Mathematical Modeling and Optimal Design of Ballistic Facilities* [in Russian], Izd. Tomsk. Univ., Tomsk (1989).
3. D. W. Bogdanoff and R. J. Miller, "New higher-order Godunov code for modeling performance of two-stage light gas guns," Report NASA, No. TM-110363, S. l. (1995.)
4. D. W. Bogdanoff, "CFD modeling of bore erosion in two-stage light gas guns," Report NASA, No. TM-112236, S. l. (1998).
5. N. N. Baulin, N. N. Pilyugin, and S. Yu. Chernyavskii, "Interior ballistics of a two-stage facility taking into account the friction of the piston," in: *Aerogasdynamics of Fast Processes* [in Russian], Izd. Tomsk. Univ., Tomsk (1982), pp. 3–9.
6. N. N. Pilyugin, and S. Yu. Chernyavskii, "Calculation of the gas-dynamic parameters of a two-stage light-gas ballistic facility with a deformable piston," *Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza*, No. 1, 65–73 (1976).
7. Yu. P. Khomenko, A. N. Ishchenko, and V. Z. Kasimov, *Mathematical Modeling of Interior Ballistics Processes in Barrel Systems* [in Russian], Izd. Sib. Otd., Ross. Akad. Nauk, Novosibirsk (1999).
8. R. I. Nigmatulin, *Dynamics of Multiphase Media*, Part 1, Hemisphere, New York (1991).
9. A. V. Lykov, *Heat and Mass Exchange* [in Russian], Énergiya, Mscocow (1978).
10. A. M. Bubenchikov, *Mathematical Models of Flow and Heat Exchange in Internal Problems of Dynamics of a Viscous Gas* [in Russian], Izd. Tomsk. Univ., Tomsk (1993).
11. I. P. Ginzburg, *Applied Hydrogas-Dynamics* [in Russian], Izd. Leningrad. Univ., Leningrad (1958).
12. S. S. Kutateladze, *Heat Transfer and Hydrodynamic Resistance, Handbook* [in Russian], Énergoatomizdat, Moscow (1990).
13. S. S. Kutateladze and A. I. Leont'ev, *Heat and Mass Exchange and Friction in a Turbulent Boundary Layer* [in Russian], Énergoatomizdat, Moscow (1985).
14. L. G. Loitsyanskii, *Mechanics of Liquids and Gases*, Pergamon Press, Oxford–New York (1966).
15. V. A. Mukhin, A. S. Sukomel, and V. I. Velichko, "Experimental study of heat exchange in gas flow in a round tube with a supersonic velocity at high temperature gradients," *Inzh.-Fiz. Zh.*, **5**, No. 11, 3–7 (1962).
16. O. V. Ushakova and Yu. P. Khomenko, "Calculation of the motion of a deformable piston in light-gas facilities," in: *Fundamental and Applied Problems Modern Mechanics*. Abstracts of the IInd All-Russian Scientific Conference (Tomsk, June 6–8, 2000) [in Russian], Izd. Tomsk Univ, Tomsk (2000), pp. 169–170.
17. C. E. Weir, "Temperature dependence of compression of linear high polymers of high pressures," *J. Res. Nat. Bur. Stand.*, **53**, No. 4, 245–252 (1954).
18. I. E. Idel'chik, *Handbook on Hydraulic Resistance* [in Russian], Mashinostroenie, Moscow (1975).