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Research Article

INVESTIGATION OF THE OUTFLOW OF DETONATION PRODUCTS DURING THE EXPLOSION OF ELONGATED CHARGES OF EXPLOSIVES IN BOREHOLES AND WELLS IN UNDERGROUND CONDITIONS

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ABSTRACT
The article proposes a numerical technique for solving the problem of the theory of a strong point explosion and for calculating the excess pressure arising in a cylindrical cavity during an explosion. At the same time, the proposed sequence of numerical modeling provides a relative error of no more than 15% compared to analytical and experimental data and will make it possible to apply this model to study the outflow of detonation products in the explosion of an elongated explosive charge.

***Keywords**: Downhole, Detonation, Borehole, Initiation, Dynamics, Rarefaction Wave, Shock Wave, Camouflage, Rock, Elongated Charge*

INTRODUCTION
Increasing the efficiency of driving underground mine workings by drilling and blasting is one of the priority directions for the development of mining production.
When using stemming in drilling and blasting operations, the most important thing is to ensure a sufficiently long delay in reducing the pressure of detonation products (PD) in boreholes (wells), at which the formation of quasi-static stress fields and the corresponding destruction of rocks would occur reliably (Baranov, 1991).
Despite the available theoretical and empirical relationships, a number of factors are not always taken into account to determine the rational types of stemming:
- properties of the stemming material, its spacing, the influence of the direction of initiation on the stemming movement, the change in pressure in the borehole as the PD expires, etc.

At the same time, generalized relations based on multivariate experiments are cumbersome and inconvenient for practical calculations, and the influence of individual factors is unjustifiably underestimated or not taken into account at all. In addition, until now there is no generalized theory of the influence of stemming types, its movement and the outflow of PD on the effectiveness of the explosion of an elongated charge in boreholes. Theoretical estimates of the impact of stemming on the efficiency of rock destruction by an explosion are in no way connected with the formation of stress fields and the processes of rock destruction by explosive charges. There is no clear understanding of the methods for determining the parameters of the PD outflow, the kinematics of stemming movement and their relationship with the formation of quasi-static stress fields in the rock destroyed by the explosion.

MATERIALS AND METHODS
To determine the parameters of the PD outflow, it is necessary to integrate the system of one-dimensional unsteady equations of gas dynamics taking into account the boundary conditions. The corresponding equations of gas dynamics in the Lagrangian coordinate system in the presence of losses of kinetic and potential energy take the form:
- preservation of the moment of momentum

$$\frac{du}{dt} = -\frac{d(p+q)}{dh} - \frac{du\,|u\,|}{2d};\qquad (1)$$

- conservation of mass

$$v = \frac{1}{p} = \frac{dr}{dh}\qquad (2)$$

- energy saving

$$\frac{de}{dt} = -(p+q)\frac{du}{dh} - \frac{du\,|u\,|}{2d}\ \frac{\gamma}{\gamma-1}\ \frac{P}{T}\frac{T-T_o}{P_\Gamma}\qquad (3)$$

where:

e= C_vT; $\frac{dr}{dt} = u$;

e - internal energy, Dj/mole;

C_v - specific heat at constant volume, Dj/(K*mole)

r- Euler radius, m;

t- time, s;

p,u,v.T- pressure, speed, specific volume and temperature PD, Pa, m/s, m^3/kg, K;

q- artificial viscosity, Pa;

γ- the ratio of the specific heat capacities, in the general case depending on the current value of the density of the gas mixture;

h- lagrangian coordinate;

λ- coefficient of friction on the inner surface of the borehole;

d- borehole diameter, m

The left boundary condition corresponds to the case of a gas-tight wall, i.e. the value of the mass velocity and on the left border always with the passage of time takes on a value equal to O. The boundary condition at the borehole cut is written in the form of an additional term in equation 1, which characterizes the resistance of the PD at the cut-off at their super-sonic outflow:

$$\frac{du}{dt} = k_0(p - p_0)\qquad (4)$$

where: k_0- proportionality coefficient, determined by the amount of gas involved in the movement inside the borehole by the rarefaction wave (the value k_0 is assumed to be unchanged);

p_0- atmospheric pressure, Pa.

To approximate the equations of gas dynamics, a finite-difference, conditionally stable "cross" type scheme was used with artificial viscosity (Kryukov, 1993).

The proposed numerical technique is proposed for solving the problem of the theory of a strong point explosion and for calculating the excess pressure arising in a cylindrical cavity during the explosion of gas mixtures. At the same time, the proposed sequence of numerical modeling provides a relative error of no more than 15% compared to analytical and experimental data table 1, which will make it possible to apply this model to study the outflow of PD in the explosion of an elongated explosive charge.

Table 1: Velocity and density distribution behind the shock front in a strong point explosion in air at E_{exp}=5*10^3DK

r/r_{shw}		0.9	0.8	0.5	0.3
$\frac{v}{v_{shw}}$	t.r.	0.86	0.63	0.42	0.24
	h.r.	0.95	0.55	0.48	0.27
	d,%	+10.5	-12.7	+14.3	+12.5
$\frac{p}{p_{shw}}$	t.r.	0.52	0.18	0.06	0.015
	h.r.	0.55	0.2	0.07	0.013
	d,%	+58	+11,1	+16.6	-13.3

However, the process of destruction of rock by explosion is significantly influenced by the physical and technical parameters of stemming (length, density, material, coefficient of friction, etc.) and the theoretical assessment of these factors requires significant labor and material costs (Mislibaev, 2015).
It is theoretically possible to establish that the time τ_1, during which the stemming takes place from a stationary state, is determined by the fact that the beginning of the movement of various parts of the stemming occurs gradually as they become involved in movement and, therefore, the stemming as a whole begins to move only after the longitudinal the compression wave will run along its length at least 3-4 times (Mislibaev *et al.*, 2017).
As the basic parameters for the process under consideration, 1, ρ_3, C_p are taken so that following the - theorem of the theory of similarity and dimensionality, the time τ_1 can be represented in the form of a certain dependence:

$$\tau_1 = \frac{1}{C_p} F\left(1,1,1,\frac{P}{\rho_3 C_p^2},\frac{\rho}{\rho_3},\frac{d}{1},\frac{C}{\rho_3 C_p^2},\frac{h}{1}\right), \text{c.} \qquad (5)$$

where, taking into account the nature of this process, the value of hw was introduced - the thickness of the boundary layer. The maximum value of h does not exceed 5dh, which was taken as the basis. Under the assumptions made and the physical nature of the phenomenon under consideration, the ratios d/1 and h/1 are constant during the entire time τ_1 and therefore the dependence 5 on them was not further determined.
After mathematical processing of the experimental data, dependence 5 looks as follows:

$$\tau_1 = 3{,}76 \frac{1\rho_3 C_p}{P}\left(1 + 9{,}48\frac{\rho}{\rho_3}\right)\left(1 + 8{,}44 * 10^{-5}\frac{\rho_3 C_p^2}{C}\right) \qquad (6)$$

The process of stemming along the borehole is determined by the laws of conservation of energy and momentum, taking into account friction losses:
for continuous stemming

$$m_3 \frac{dx^2}{dt^2} = SP(1-\delta), \qquad (7)$$

where S is the cross-sectional area of the borehole, m^2;
P- pressure in the PD;
δ - sliding friction coefficient (for wood and lead δ equals · 0.45 and 0.1, respectively).
For bulk stemming

$$\frac{dx^2}{dt^2} = \frac{[1-k*(1-x)]P}{\theta l}, \qquad (8)$$

where k* is the specific value of the coefficient of friction (for sand-0.86 m-1);
l- stemming length, m;
θ - specific gravity of damming material (for sand θ = 1600 kg / m^3).
The solution to the differential equation 8 is an integral curve, the equation of which with the initial conditions x (0) = O looks like this:

$$x = \frac{S(1-\theta)P\tau^2}{m_3}, \text{ m}, \qquad (9)$$

In addition, the solution of equation 9, satisfying the same initial conditions is the dependence t(x):

$$\tau_2 = \sqrt{\frac{\theta 1}{\kappa^*}} \ln\left|\varphi(x) + \sqrt{\varphi^2(x) + \varphi(x)} + 1\right|, \text{c}; \qquad (10)$$

$\varphi(x) = \frac{\kappa^* x}{1-\kappa^* l}; 0 \le x \le 1.$

In this case, the change in pressure P in the hole, due to the expansion of the PD, is calculated according to the following formula:

$$P = P_1 \left\{\frac{L-1}{L-1+x}\right\}^{\gamma} \qquad (11)$$

where: P_1- the pressure established after the start of the stemming movement;
γ - isoanthrope indicator of PD.

To establish the generalizing regularities of the PD outflow, a dimensionless similarity criterion χ was considered in the region of a supersonic gas flow in accordance with the law of conservation of momentum with the use of the results of a numerical calculation of free outflow:

$$\chi = \frac{\Delta P \Delta t}{\rho_1 (r_1 + \Delta r_1)|\Delta U|}, \qquad (12)$$

where:

$$\Delta U = \frac{1}{M} \sum_{j-1}^{n} \rho_1 (U_1 - U_{l-1}) \Delta r_1; M = \sum_{j-1}^{n} \rho_1 \Delta r_1;$$

r_1- the current value of the Euler coordinate corresponding to J- 1 layers of time, m;
Δr_1- coordinate increment per interval$\Delta t = t^j - t^{j-1}$, m;
ρ_1- the average value of the density of the gas mixture enclosed between the bottom of the hole and the section with the coordinate r_1, kg / m^3;
the average value of the density of the gas mixture enclosed between the bottom of the hole and the section with the coordinate r_1, kg / m^3;

As a result of the analysis (12), the general dependence of the time of the expiration of the PD in an arbitrary cross-section of the borehole during the explosion of an elongated explosive charge in it on the dimensionless parameters ae, n and the detonation time t was determined, which takes the following form : æ

$$\tau_3 = t_0 \left\{1.17\vartheta \left[1 + \frac{0.2}{æ-1}\right] + 33.36æ^2 - 60.08æ + 26.72\right\} + \frac{L-\check{x}}{c}, \qquad (13)$$

where $\check{x}$ - - distance from the mouth of the borehole to the investigated section, m; distance from the borehole mouth to the investigated section, m;
N - number of repair points;
L - borehole length, m;
s - speed of sound in PD, m / s;
n = 1+N; n= n/N;1 $<$ æ $\le$ 2.
$P = \frac{P}{æ^n}$, Pa.

The obtained dependences (6) + (14) with sufficient for practice accuracy within 15% of the value of the relative error allow to determine the dynamics of stemming movement and the outflow of PD from boreholes (Djuraev *et al.*, 2020).

With a rational stemming material, capable of delaying the outflow of the PD from the borehole, at least in the area adjacent to its mouth, by the value τ_1 (the time of quasi-static loading of the HZ explosion), as a result of which the potential for the explosion of an elongated charge will be practically fully realized to maximize the formation zones of fine fragmentation to a value that allows the formation of a quasi-static stress field near the charge. The value ofτ_1: is determined by the deformation of the HZ in the zone closest to the borehole during a camouflage explosion of an elongated explosive charge, according to the theory of Rodionov (Fig. 1).

The considered numerical method for calculating the change in pressure in cylindrical cavities of finite length due to the outflow of the PD from the cavity provides a relative error of no more than 15%, which makes it possible to apply this model for investigating the outflow of PD during the explosion of elongated explosive charges in boreholes and wells (Merkulov *et al.*, 2020).

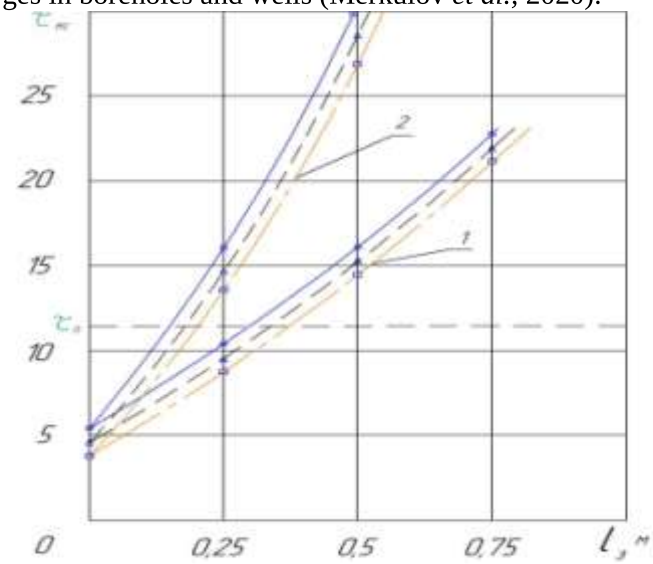

Figure 1: Dependence of the pressure drop time in different sections of the borehole on the stemming material during the explosion of AM №6 JV in sandstone.

1- sand stemming; 2 - explosive pressing of the borehole mouth.

Based on the above, it can be concluded that with the use of stemming, the process of PD outflow from the model occurs in three stages:

- at the first stage with duration τ_1, the stemming is removed from the stationary state under the action of elastic waves generated in it by the PD;
- at the second stage with duration τ_2, stemming moves from the borehole;
- at the third stage, a quasi-stationary outflow of AP with duration τ_3 occurs, which, in turn, is subdivided into two stages.

During the first stage with duration τ_1, the propagation of a special resolution wave along the PD from the borehole mouth with a sharp abrupt decrease in pressure is observed; during the second stage of duration τ_2, a quasi-stationary discharge of the PD from the hole with a gradual decrease in pressure in it is observed.

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