Investigation of the gas-dynamic processes in the operation of an explosion-reactive complex

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Abstract. To conduct drilling and blasting operations in difficult climatic and geological conditions at mining enterprises, it is promising to use explosion-reactive complexes (ERC). Having a clear advantage, these devices have a number of disadvantages, mainly due to the gas-dynamic instability of the process of their functioning. A non-stationary gas-dynamic model of the development of such processes at different stages of ERC operation was developed and analyzed. The analysis was performed by methods of numerical mathematical modelling. The simulation results allowed the authors to further justify the rational parameters of the installation and its individual components, which significantly increased its efficiency.

1. Introduction
Structurally portable ERC is a complex with a set of disposable cassettes of explosive, working on the principle of recoilless guns. The principle of operation of the ERC is based on the use of features of the flow of gas-dynamic processes in the explosion of explosive cassettes in the semi-closed volume of the well.

2. Problem statement
The aim of this work is to study the features of the development of gas-dynamic unsteady processes in the resulting space of a cylindrical cavity by mathematical modeling. The results of the study will improve the efficiency of such an explosive energy converter as ERC, by optimizing the design features of the complex and its modernization.

3. Method of research
To study the flow of gas-dynamic processes, a mathematical model was developed in which the gas-dynamic parameters of the state of the explosion products (EP) and the air medium are described by the conservation equations in the axisymmetric formulation:
\[
\begin{align*}
\frac{\partial p}{\partial t} + v \frac{\partial p}{\partial x} + u \frac{\partial p}{\partial y} + \rho \left( \frac{\partial v}{\partial y} + \frac{\partial u}{\partial x} \right) &= -\frac{\rho u N}{r} ; \\
\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} + u \frac{\partial v}{\partial y} + \frac{1}{\rho} \frac{\partial \rho}{\partial y} &= 0; \\
\frac{\partial u}{\partial t} + v \frac{\partial u}{\partial x} + u \frac{\partial u}{\partial y} + \frac{2}{\rho} \frac{\partial \rho}{\partial y} &= 0; \\
\frac{\partial k}{\partial t} + v \frac{\partial k}{\partial x} + u \frac{\partial k}{\partial y} &= 0;
\end{align*}
\]  
\( p = \rho \rho^k, \)  

(1)

where \( p, \rho, \nu \) respectively, the pressure and density, \( v \) and \( u \) components of the mass velocity (radial and axial components of the velocity), \( k \) - isentropic index, \( N \) - the number of particles of the medium per unit mass (for cylindrical symmetry \( N = 1 \)).

As boundary conditions on the rigid walls of the ERC and the cavity of the created well, it was assumed that the radial component of the EP velocity on the axis is zero (\( v = 0 \)). To set the initial conditions of the gas-dynamic parameters in the cavities of the ERC and the created well, the parameters of the undisturbed standard atmosphere at \( k = 1.4 \) were used. In model calculations for EP was used the experimental data: \( k = 3.05 \), the magnitude of the detonationvelocity \( D = 8730 \text{ m/s} \) and \( \rho_0 = 1780 \text{ kg/m}^3 \) - the value of the initial explosive density. It was assumed that the process of detonation of each explosion cartridge flows instantly and parameters on the detonation wave front are determined by the formula:

\[
P_n = \rho_0 D^2, \quad \rho = \rho_0 \frac{D^2}{\kappa + 1},
\]

(2)

where \( P_n \) is the pressure of the detonation products at the Chapman-Jouguet point.

The joint solution of the system of equations (1) and (2) was carried out by the method of finite differences of the second order of accuracy of predictor-corrector type in floating grids using the method of three-point smoothing.

4. Research results

The research considered two variants of operation installation: option A – ERC directly is to blow up the rock surface and is the operation of the first explosive cassette; option B – ERC, having formed the well is finished and triggered the last cassette (figure 1).

![Figure 1. Options for the operation of the unit.](image)

In the first variant, at the initial moment of time, the first (lower) cassette triggers with the formation of a single cavity in the rock. The nature of the rock fracture and the distribution of gas-dynamic parameters obtained by calculation for several initial moments of time (\( t_1, t_2, t_3 \)) in the form of pressure fields and Mach numbers are presented in figure 2.
Figure 2. Distribution of gas-dynamic parameters at the initial moment of time:
a) change in pressure EP on the outer wall of the WM and the wall of the well, MPa,
b) distribution of pressure P (MPa) and Mach numbers (M) in the central channel of the ERC WM.

The model calculation of stages of development of explosive influence on a bottom hole of the formed well at the initial moment of time is given on figure 2a.

With further expansion of the gas-dynamic flow, it is ejected to the surface and the central channel is filled with gas-sludge mixture. The distribution of pressure and Mach numbers in the central channel of the ERC WM for this stage are shown in figure 2b. Then there is a further expansion of the jet and a powerful emission of a mixture of rock and gases in the vertical direction. In this moment is happening "locking" central canal ERC WM products explosion and sludges under large pressure. The dynamics of the pressure distribution and Mach numbers in the central channel of the ERC WM for this stage are shown in figure 3.

Figure 3. Distribution of gas-dynamic parameters of sludge discharge and vertical surface of bottom hole:
a) change in pressure EP on the outer wall of the WM and the wall of the well, MPa,
b) distribution of pressure P (MPa) and Mach numbers (M) in the central channel ERC WO.

In this model the expansion process of the EP in semi-enclosed volume causes a zug of unsteady shock waves, the pressure on the front of which is commensurate with the pressure in the flow EP, as well as areas pressure which is below atmospheric. These shock waves, repeatedly interacting with the walls of the well, EP and each other, cause the pulsating nature of the pressure change in the working volume. The most significant ripples occur in the zone of maximum intensity of the EP expiration. This leads to the fact that during the operation of the installation, volumetric broadband low-frequency and high-frequency oscillations are generated. These conclusions are in qualitative agreement with known experimental data.
At the second stage of operation of the ERC WM, the formation of a well in the rock occurs, the work of energy release ends and the last cassette is triggered (figure 1b). At this point, the unit is completely in the well. The nature of the rock fracture and the distribution of gas-dynamic parameters in several initial moments of time when the last cassette is triggered in the form of pressure fields are shown in figure 4.

![Figure 4](image_url)

**Figure 4.** Distribution of gas-dynamic parameters.

- a) change in pressure $EP$ on the outer wall of the PO and the wall of the well, MPa,
- b) variation of pressure and Mach numbers in the central channel of the ERC WM in the final stages of emission development.

Analysis of the simulation results showed that the unsteadiness of the gas-dynamic process and the resulting regimes of flow establishment have a significant impact on the process of rock crushing. At the first moment of time there is a gas-dynamic loading on a face and lateral walls of a well (figure 4a). During this period, the process develops mainly along the surface of the walls of the well. The body of the ERC WM at this stage is not loaded with pressure. Then there is an expansion of the gas-dynamic flow, and it begins not only to be thrown out to the surface, but also to fill the central channel of the ERC WM. At this stage, the central channel of ERC WM functions as an ejector device for removing part of the EP gases together with the sludges to the surface and thereby intensifies the process of rock destruction.

In the future, there is an expansion of the EP and a powerful release of a mixture of rock and gases from the well (figure 5). At this point, there is also a "locking" of the central channel ERC WM explosion products and rock under high pressure.

![Figure 5](image_url)

**Figure 5.** Distribution of gas-dynamic parameters.

- a) change in pressure $EP$ on the outer wall of the PO and the wall of the well, MPa,
- b), c) distribution of pressure $P$ (MPa) and Mach numbers ($M$) in the central channel of the ERC WM in the final stages of emission development.
Modelling of the processes has shown that the dynamics of the motion of expanding EP in the well
and the casing ERC WM determined by the gas-dynamic parameters of the detonation products, the
internal configuration of the cavities - their geometric dimensions and design features. It was found
that the influence of the flow establishment process on the process of formation of the EP flow and the
destroyed rock (sludge) significantly increases with a decrease in the depth and diameter of the well.
Presented results have allowed to reveal peculiarities of thermophysical loaded directly install the
ERC, and the surrounding space. This is due to the fact that structurally the installation of the ERC and
the scheme of its functioning (in particular, the presence of a gas source and its location in a semi-
closed cavity of the pit) is close to the scheme of functioning of the Hartmann resonator.

5. Summary
The numerical mathematical modelling on the developed model of the process of functioning of ERC
on the rock surface and in the well showed that at the initial stage there is the formation of a non-
stationary shock-wave process of the jet in a semi-closed volume, the pressure at the front of which is
commensurate with the pressure in the jet of detonation products, as well as pressure rarefaction zones.
These shock waves, repeatedly interacting with the walls of the well, ERC and each other, cause the
pulsating nature of the pressure change in the working volume, with the most significant pulsations
occurring in the zone of maximum flow intensity EP. This leads to the fact that during the operation of
the installation, broadband low-and high-frequency oscillations are generated, both in the surrounding
space and in the rock. This process can be compared to the work of the Hartmann resonator.
The development of such a process in the well, in which there is virtually no air ejection into the jet
of EP, leads to a violation of the Hartmann effect, based on the significant influence of air ejection into
the jet of the gas flow of EP.
The performed control of the accuracy of the energy solution showed that the error introduced into
the solution due to the finite difference approximation of the gas-dynamic energy functions does not
exceed 1%. In order to determine the reliability of the modeling process, according to the developed
program, test calculations of the interaction of the gas jet with the Hartmann resonator were
performed, the results of which were compared with known experimental data. The analysis of the
results showed that the developed mathematical model reliably describes the process of interaction of
a gas jet with a Hartmann resonator with a calculation error of no more than 10% in pressure and about
2% in frequency.
As a result of numerical mathematical modelling, the features of the development of gas-dynamic
processes in the operation of ERC were identified and studied, which allowed to further justify and
optimize the design parameters of the plant and its individual components, which increased its
efficiency.

6. References
[1] Kutuzov V N, Orlov Yu N, Solov’ev V O 2008 Creation of portable explosive complex and
field of its application Gorniy zhurnal –Mining Journal, no 5, pp 50-53.
[2] Solov’ev V O, Shvedov I M 2018 Portable complex for controlled explosive reactive drilling of
rocks IJET 7 no 2.23, pp 140-142
[3] Solov’ev V O, Shvedov I M 2019 The concept of improving the efficiency of explosive energy
converters JCP Conf. Series 1172 012007
[4] Abramovich G N 1969 Applied gas dynamics. Moscow: Science, p 824
[5] Physics of explosion 1975 ed. K P Stanyukovich-Moscow: Nauka, p 704
[6] Kestenbaum H S, Roslyakov G S and Chudov L A 1974 A point explosion. Calculation method.
Moscow: Moscow State University, p 190
[7] Physics and technology of powerful ultrasound. Book 1. Sources of powerful ultrasound 1967
ed L D Rosenberg, Moscow, Nauka, p 379