THE EQUATION OF STATE FOR EXPLOSIVE DETONATION PRODUCTS

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ABSTRACT

Current paper contains the equation of state for detonation products. The author discusses why the detonation process deviates from the ideal and analyzes the main conditions of using equations of state for commercial explosives from the position of ideal detonation. An analysis also covers the mechanisms of hotspot generation and shockwave decomposition. A method to calculate colume has been proposed.

Keywords: Explosives, Pressure, Detonation Products, Detonation Parameters, Colume.


1. INTRODUCTION

Russian mining companies use a wide variety of explosives. They can be divided into two groups: emulsion explosives containing water and prilled explosives with zero water content. The most commonly used prilled explosives are granulites and ANFO (ammonium nitrate/fuel oil) [3]; being relatively cheap they have low water resistance, which causes the detonation wave to fade inside the blasthole. Emulsion explosives have higher water resistance and better detonation properties, which contributes to the safety of transportation and blasthole charging.

2. RATIONALE

Detonation parameters of explosives in quarries and open coal mines differ from the ones in laboratory conditions. This happens due to a great number of factors affecting the detonation process – critical diameter, explosive composition, quality of its ingredients, geological conditions of charging, presence of mud in the blasthole etc. Another critical parameter of real-life detonation is the composition of released gaseous products. As a general rule, an
orange-yellow colour of released gases indicates the presence of nitrogen oxides and the prevalence of oxidation phase in the explosive composition. On the contrary, dark-coloured gaseous products contain carbon oxides and have a prevailing combustion phase. Such indications mean that the explosives were either manufactured from low-quality ingredients or mixed in a wrong way, which resulted in a positive or negative oxygen balance and consequently interfered with the detonation process.

3. PROBLEM STATEMENT

The aim of current research was to justify the equation of state for detonation products in order to determine detonation parameters of commercial explosives.

The first step was to identify the pattern of chemical reaction in the explosives. If the charging density is below 800 kg/m$^3$, chemical decomposition is initiated by a convective mechanism – a hotspot-based reaction, prevailing over the shockwave mechanism [8,11]. For densities between 800 and 1100 kg/m$^3$ both mechanisms of detonation decomposition are possible. For densities between 1100 and 1300 kg/m$^3$ shockwave detonation decomposition can be considered a dominant pattern. The upper boundary of the interval is a generally accepted value, and higher charging densities lead to a fading detonation of emulsion explosives [7].

Other important factors analyzed in paper [6] are minimal diameter and cap rock hardness. Blastholes usually have a diameter of 130-250 mm. For most explosives the minimal diameter should be no less than 100 mm. The majority of mining operations is performed in the rocks with a Protodyakonov strength index of 4 or higher. Hence the cap rock, serving as a "cover" for the explosive charge, should be hard enough for the detonation process and be a source of reflected detonation waves [5].

4. THEORY AND CALCULATIONS

The main thermodynamic characteristics of the explosive are its specific volume, temperature and pressure of detonation products. They are all included in the general equation of detonation products:

\[ PV = nRT \]  

For actual gases equation (1) is only applicable under pressures not exceeding $10^6$ Pa. To calculate parameters of detonation products for condensed explosives under greater pressures it is important to take into account physical volume of the molecules, or covolume [2].

To estimate the latter one should express results of comparison between equations of mass and impulse conservation in terms of Michelson line [1]:

\[ D = v_0 \left( \frac{P_d - P_0}{v_0 - v_d} \right)^{0.5} \]  

where \( v_0 = \frac{1}{\rho_e} \) – specific volume of the explosive, m$^3$/kg; \( v_d = \frac{1}{\rho_d} \) – specific volume of detonation products outside the zone of chemical reaction, m$^3$/kg; \( P_0 \) – initial pressure, Pa; \( P_d \) – pressure of detonation products, Pa; \( D \) – minimal steady velocity, also referred to as normal detonation velocity, m/s.

Analytically the curve \( \alpha(v_d) \) can be defined using Johansen-Pearson equation [4]:

\[ \alpha_{\text{cov}}(v_d) = 10^{-3} e^{-0.410^3 \rho_e} \]  

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Polytropic equation adjusted for covolume will be the following:

\[ P_d \left( v_d - \alpha_{cov} \right)^\gamma = \text{const} \]  

(4)

where \( P \) – polytropic coefficient.

Further substitutions bring the following results:

\[ P_d = \frac{V_0 - V_d}{V_0^2} D^2 = \left( 1 - \alpha_{cov} \rho_e \right) \rho_e D^2 \left( \gamma + 1 \right) \]  

(5)

Condensed explosives are characterized by high values of initial density \((800 \leq \rho_e \leq 1500 \text{ kg/m}^3)\), significant amounts of energy released after the blast and dramatically rising pressure. The polytropic coefficient for such cases can be calculated using Landau-Stanyukovich rule [10]:

\[ D^2 = \left[ 2(\gamma^2 - 1) - 4A(\gamma + 1)b(\rho_0) \right] \rho_e \]  

(6)

where

\[ b(\rho_0) = \left( \frac{\partial D^2}{\partial Q} \right)_{\rho_e} = b10^{10} \rho_e^{r-1} \]

The density of gaseous explosion products equals:

\[ \rho_g = \frac{\gamma + 1}{(\gamma + \alpha_{cov} \rho_e)} \rho_e \]  

(7)

Substituting equation (3) into the formula (7), one can estimate the density of gaseous explosion products. Next steps include calculating covolume and detonation pressure using equations (3) and (5) respectively.

When estimating polytropic coefficient, one should use actual detonation velocity and take into account generated gaseous explosion products to determine explosion heat.

Results of calculations for different types of explosives are presented in Table 1.

**Table 1. Parameters of condensed explosives according to the proposed method**

<table>
<thead>
<tr>
<th>Type of explosive</th>
<th>Main characteristics</th>
<th>( \alpha_{cov} ), ( 10^{-4} \text{ m}^3/\text{kg} )</th>
<th>( \gamma )</th>
<th>( u_d ), m/s</th>
<th>( P_d ), Gpa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fortis 70</td>
<td>1150</td>
<td>3300</td>
<td>5300</td>
<td>6.09</td>
<td>3.10</td>
</tr>
<tr>
<td>Nitronit E70</td>
<td>1150</td>
<td>3200</td>
<td>5000</td>
<td>6.08</td>
<td>3.01</td>
</tr>
<tr>
<td>VET 700</td>
<td>1150</td>
<td>2700</td>
<td>5400</td>
<td>6.10</td>
<td>3.23</td>
</tr>
<tr>
<td>Sybarite 1000</td>
<td>1150</td>
<td>3050</td>
<td>5000</td>
<td>6.08</td>
<td>3.03</td>
</tr>
</tbody>
</table>

**5. RESULTS AND DISCUSSION**

It is suggested to analyze the proposed equation of state using the version currently applied in practice:

\[ P_d^* = \frac{1}{2} \frac{\rho_e D^2}{(\gamma + 1)} \]  

(8)
Table 2. Comparison of detonation pressure results obtained with two described methods

<table>
<thead>
<tr>
<th>Type of explosive</th>
<th>$P_d$, GPa</th>
<th>$P^*_d$, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fortis 70</td>
<td>2.37</td>
<td>3.94</td>
</tr>
<tr>
<td>Nitronit E70</td>
<td>2.15</td>
<td>3.59</td>
</tr>
<tr>
<td>VET 700</td>
<td>2.30</td>
<td>3.96</td>
</tr>
<tr>
<td>Sybarite 1000</td>
<td>2.14</td>
<td>3.57</td>
</tr>
</tbody>
</table>

Table 2 contains values of detonation pressure calculated using the proposed equation as well as the one currently applied in practice. It should be noted that detonation pressure in the formula (8) is divided by two. It is considered that $P^*_d$ value is related to detonation pressure after completion of the reaction in the blasthole charge [9]. In the proposed equation of state (5) there is no need to divide the pressure by an empirical coefficient of 2, as the proposed method takes into account the contact of Michelson line with "substantially" formed gaseous detonation products that have their own volume and non-deformed molecules. Hence the values of proposed detonation pressure are lower than the ones in Chapman-Jouguet plane by factor of 3.3 due to covolume, and lower than the pressure calculated with formula (8) by factor of 1.65. Therefore, in the "classical" equation of the state there is no need to use an empirical coefficient.

REFERENCES