реакцию в детонационном фронте уже не может считаться константой. Ее значение может быть равным 1 лишь в случае «сильно неидеальных ВВ».

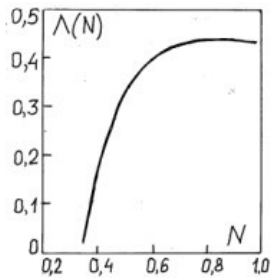

Рисунок 4. Соотношение между комплексами $\overline{\theta_\tau}$ и $\overline{\theta_\tau^*}$ в моделях [2] и настоящей работы

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NON-IDEAL DETONATION MODEL FOR EVALUATING A CRITICAL DIAMETER ACCORDING TO AVERAGE REACTION RATE IN A DETONATION FRONT

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The paper aims to provide a simple model of non-ideal detonation that would allow determining factors, mechanisms and their degree of influence on detonation ability of open cylindrical charges of condensed explosives by usage of analytical methods.

V. O. Rosing and Yu. B. Khariton [1] formulated a necessary condition of stable detonation propagation in their pioneering work devoted to detonation ability of condensed explosive charges: scattering time θ of reacting explosive should exceed its main decomposition time τ. In other words, the condition of stable detonation propagation was taken as $\theta/\tau = \overline{\theta_\tau} \geq 1$. Afterwards Yu. B. Khariton [2] determined scattering time as a charge diameter d divided by sound velocity c, $\theta = d/c$, and equated the critical value of the resultant dimensionless complex $\overline{\theta_\tau}$ to one. Khariton wrote the critical condition of the stable and non-decelerating detonation propagation in the form:

$$\frac{d}{c \cdot \tau} = 1, \quad (1)$$

that they named «Khariton's principle». In the paper, he considered various mechanisms of converting condensed explosives into gaseous detonation products in the detonation front and obtained expressions for estimating the response time τ therein. At the same time "nonplanar symmetry" of reacting substance flow in the detonation front was not taken into consideration, and an upper estimate of the sound speed c in the reacting explosive was equated to the sound speed in the «pure explosion products» (detonation products).

Physically clear explanation of shock front shape influence on peculiarities of a reactive medium flow in the detonation wave propagating stably along a cylindrical charge with an open lateral surface was obtained with V. S. Trofimov and A. N. Dremin [3] (Figure 1).

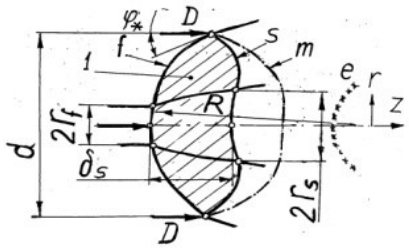

Figure 1. Flow diagram upon detonation of the explosive charge having limited diameter d:
1- detonation front; f-shock front; s-sonic surface; m- lateral release wave front;
e-surface of explosive decomposition completion

The role of the lateral release wave propagating from a free surface of the charge at the stage of detonation setting adds up to such distortion of the shock front under which the shock front surface becomes inclined to the generatrices of the cylindrical surface of the charge at "sonic angle φ_**. The rate of flow behind the front of the shock wave in relation to its points of intersection with the surface of the charge and the sound speed behind the said front become equal and the lateral release wave is able no longer to penetrate into the detonation front. Upon steady-state mode of the non-ideal detonation the lateral release wave from the free surface of the charge does not may affect the reaction in the detonation front, it only affects its completion within supersonic flow and does not affect the velocity of the non-ideal detonation.

In terms of new notions about the mechanism of influencing lateral release waves on the behavior of the reaction within a steady-state detonation front and within an area of completing the explosive decomposition behind the said front V. T. Trofimov together with K. M. Mikhayluk [4] and then I. F. Kobylkin [5] created a basis of the critical detonation diameter theory which is alternative to the notions of V. O. Rosing and Yu. B. Khariton. The estimation of critical detonation diameters requires knowledge of a relationship between the detonation velocity and the charge diameter, which is problematic.

The present paper provides a method of estimating critical detonation propagation conditions, the method being alternative to the theories of the authors [4] and [5]. It consists in deriving an equation for the relationship between a detonation velocity and a charge diameter by usage of first principles, and finding the critical diameter as a boundary of an area of values thereof for which a solution to this equation exists.

Our model is based on considering a flow in a central stream tube of the detonation front within charges whose diameter is close to critical one. Let us express the relative stream tube expansion $\omega = \left(r_s/r_f\right)^2$ approximately in terms of time t_s of overflowing a particle of reacting flow from a shock front surface f onto a sonic surface s and an average value of the gradient of the radial component of the flow velocity on the symmetry axis of the charge $\left|\partial u_r/\partial r\right|_{eff}$:

$$\omega = \left(1 + \left|\partial u_r/\partial r\right|_{eff} t_s\right)^2.$$

If we take the shock front on the charge axis as spherical one with radius R and consider flows for which detonation front width $\delta_s \ll R$, the upper estimate $\left|\partial u_r/\partial r\right|_{eff}$ will be equal to u_f/R and the lower estimation will be u_s/R, where u_f and u_s are mass velocity values relative to the initial explosive on the

shock front and the sonic surface respectively. Hereinafter we will use the expression $\left|\partial u_r/\partial r\right|_{eff} = u_{eff}/R$ for the average value of the gradient for the radial component of the flow velocity on the axis of symmetry of the charge, taking u_{eff} as equal to u_f, u_s or the average value $\left(u_f + u_s\right)/2$. Besides we will use the expression $\omega = (1 + t_s/t_R)^2,\ t_R = R/u_{eff}$. Let us call the value $t_R = R/u_{eff}$ by characteristic time of radial flow expansion.

Refining the quasi-two-dimensional model of the flow in the central stream tube of the detonation front of L. G. Bolkhovitinov we will write conservation equations for mass, pulse, energy, a selection rule for detonation velocity (in terms of reaction products characterizing by the equation of state in the form of an ideal gas) and relationships on the shock front of a detonation wave:

$$\rho_0 D = \omega_s \rho_s (D - u_s), \qquad \rho_0 D^2 = p_s + \rho_s (D - u_s)^2, \qquad Q \cdot W_s + \frac{D^2}{2} = e_s + \frac{p_s}{\rho_s} + \frac{(D-u_s)^2}{2},$$

$$e_s = \frac{p_s}{\rho_s (n_s - 1)}, \qquad c_s = D - u_s, \qquad c_s = \sqrt{n_s \frac{p_s}{\rho_s}}$$

$$\omega = (1 + t_s/t_R)^2, \qquad t_R = R/u_{eff}, \qquad D = a + b u_f, \qquad p_f = \rho_0 u_f \left(a + b u_f\right),$$

where: ρ is density; D is detonation velocity; p is pressure; Q is specific heat of explosion, e -specific internal energy; W – mass fraction of the final explosive decomposition products; c is sound velocity; n is isentropic index; 0, f and s are indices indicating the initial state of the medium (before the shock front), the state of the medium on the shock front and the state of the reactive medium on the sonic surface (Chapman- Jouguet surface) respectively.

Since we consider flows at near-critical charge diameters only, let us link up the diameter of the charge to a sphere radius with simple relationship:

$$R = K_R \cdot d\,, \qquad K_R \cong 1\,, \tag{2}$$

that is true for explosives differing in the detonation nonideality degree. Let us consider the dependence of K_R on the detonation as negligible.

Considering the approximation (2) and the expression for the ideal detonation velocity (index i) $D_i = \sqrt{2(n_i^2 - 1)Q}$ an expression for the non-ideal detonation velocity of the expression D, or the detonation nonideality degree $N = D/D_i$:

$$N^2 = \frac{n_i^2 - 1}{n_s^2 - 1} \cdot \left\{1 + n_s^2 \cdot \left[\left(1 + \frac{1}{\overline{\theta_\tau^*}}\right)^4 - 1\right]\right\}^{-1} \cdot W_s, \qquad \overline{\theta_\tau^*} = t_R/t_s = \left[\frac{d \cdot K_R}{u_{eff}}\right] \cdot \left[\frac{1}{t_s}\right], \tag{3}$$

as well as other characteristics of the detonation process:

$$u_f = \frac{N \cdot D_i - a}{b}, \qquad \omega_s = \left(1 + t_s/t_R\right)^2, \qquad t_R = R/u_{eff}, \qquad u_s = N \cdot D_i \cdot \frac{1 - n_s(\omega_s - 1)}{n_s + 1}, \qquad p_s = \frac{\rho_0 (N \cdot D_i)^2}{n_s + 1},$$

$$p_f = \rho_0 \cdot N \cdot D_i \cdot \left(N \cdot D_i - a\right)/b$$

can be obtained by solving the above system of equations.

Let us present the value W_s in (3) as the product of t_s and the average rate of explosive decomposition in the detonation front η_{fs}:

$$\eta_{fs} = \frac{\int_0^{t_s} \eta dt}{t_s}, \tag{4}$$

where η is the decomposition rate depending on the pressure, the degree of explosive decomposition W and explosive compression intensity on the shock front.

Let us assume that the time t_s for non-ideal detonation is linked up to chemical peak duration for ideal detonation t_{si} by the relationship

$$t_s = t_{si}/T(N), \tag{5}$$

where $T(N)$ is a function whose type depends on the formal kinetic equation (FKE) of explosive decomposition (its type will be given hereinafter).

Let us consider the detonation front in the case of simple FKE corresponding to representation of the explosive decomposition behind the shock front as combustion around the initial centers of effective hot spots;

$$\eta = k(p_f) \cdot \psi(W) \cdot p^{\nu}, \tag{6}$$

$$\psi(W) = (W_0 + W)^x \cdot H(W_m - W) + \left[\frac{(W_0+W_m)^x}{(1-W_m)^y}(1-W)^y\right] \cdot H(W - W_m) \cdot H(1-W).$$

The first factor in (6) proportional to the concentration of initial centers of focal combustion and constant B ($u_B = Bp^\nu$ in the combustion law) depends on intensive compression of the explosive in the shock front p_f. This relationship may be expressed as a function of N: $K = A^*(p_{fi})/\varphi(N)$.

The relationship $\psi(W)$ represents two stages of changing a specific burning surface: a progressive stage (when $0 \le W \le W_m$) and a regressive stage ($W_m < W \le 1$). H is the Heaviside function which is equal to 1 for positive argument values and to 0 for the rest values). We will take the pressure p equal to average value for the chemical peak: $p = (p_f + p_s)/2$.

FKE parameters are such that when the detonation nonideality degree $N = 1$, i. e. when $D = D_i$ the average reaction rate in the detonation front η_{fs}becomes equal to η_{fsi}. The rate η_{fsi} in turn is the inverse of the chemical peak duration for the ideal detonation t_{si}:

$$\eta_{fsi} = \frac{1}{t_{si}} \tag{7}$$

In this form of assigning FKE we will obtain finally:

$$\eta_{fs}(N) = W_s/t_s \tag{8}$$

$$W_s = \left[A(1-x)t_s - {W_0}^{1-x}\right]^{\frac{1}{1-x}} \text{ при } 0 \le t_s \le t_m, \quad t_m = \left[\frac{1}{(1-x)A}\right] \cdot \left[(W_0 + W_m)^{1-x} + {W_0}^{1-x}\right], \tag{9}$$

$$W_s = 1 - \left[(1-W_m)^{1-y} - (1-y)\frac{(W_0+W_m)^x(t_s-t_m)A}{(1-W_m)^y}\right]^{\frac{1}{1-y}} \text{ при } t_m < \mathrm{t_s} \tag{10}$$

$$\mathrm{A}=t_{si}^{-1}\left(\frac{p_{fs}}{p_{fsi}}\right)^\nu \frac{(1-y)[W_0+W_m-{W_0}^{1-x}(W_0+W_m)^x]+(1-x)(1-W_m)}{\varphi(N)\cdot(1-x)(1-y)(W_0+W_m)^x}, \qquad p_{fsi} = \frac{p_{fs}+p_{fsi}}{2}. \tag{11}$$

In accordance with the notion Haskins P. J. let us use the approximate relationship (5) when

$$T(N) = N^{2\nu-1}[a + D_i(b-1)N]/[a + D_i(b-1)]. \tag{12}$$

After substituting the expression for $W_s = \eta_{fs} \cdot t_s$ being written by usage of FKE (6), relationships (7) and (8)- (12) into (3) and subsequent simple transformations we will obtain an equation relative to the detonation nonideality degree N:

$$\frac{n_s^2-1}{n_i^2-1}N^2 \cdot T(N)\left\{1 + n_s\left[\left(1 + \frac{t_{si}}{K_R \cdot d} \cdot \frac{u_{eff}(N)}{T(N)}\right)^4 - 1\right]\right\} = \eta_{fs}(N) \cdot t_{si} \tag{13}$$

The left part of equation (13) designated hereinafter as H_- is the ratio of the explosive decomposition rate which is necessary to maintain the detonation at the nonideality level N, to the average rate of the reaction in the chemical peak of the ideal detonation ($1/t_{si}$). The right part of the equation (13) designated as H_+ is the ratio of the explosive decomposition rate which can be achieved at given FKE when the nonideality degree is N, to the average rate of reaction in the chemical peak of the ideal detonation ($1/t_{si}$). Solution of the equation is defined by a parameter V (a charge diameter divided into chemical peak duration for the ideal detonation $V = \frac{d}{t_{si}}$) and corresponding dimensionless complex $\overline{\theta_\tau^*} = t_R/t_s = \left[\frac{d\cdot K_R}{u_{eff}}\right] \cdot \left[\frac{1}{t_s}\right]$ similar to the non-dimensional relationship in Khariton's principle (1) $\overline{\theta_\tau} = \theta/\tau = d/(c \cdot \tau)$.

Figure 2 shows graphs for dependencies $H_- = H_-(N)$ and $H_+ = H_+(N)$ made for a model explosive with characteristics: $\rho_0 = 1{,}61\ \mathrm{g/sm^3}$, $\mathrm{D_i} = 7{,}0\ \mathrm{km/s}$, $\mathrm{n_i} = 2{,}73$, $\mathrm{a} = 2{,}39\ \mathrm{km/s}$, $\mathrm{b} = 2{,}05$, $\mathrm{W_0} = 0$, $\mathrm{x} = 0{,}67$, $\mathrm{y} = 0.67$, $B = 1\ m/(s \cdot \mathrm{GPa})$, $\nu = 1$. There are taken $\varphi = N^{-3}$ and $\mathrm{n_s} = \mathrm{n_i}$. Values of the parameter V for the curves V_1, V_2, V_3 are respectively equal to: 5000 mm/μs, 225 mm/μs, 115 mm/μs. Curve W_{m1} (fig. 2) has been obtained when $W_m = 0{,}5$ and curve W_{m2} has been obtained when$W_m = 0{,}2$.

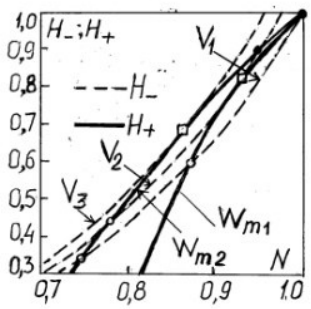

Figure 2. Solution to the equation of the non-ideal detonation velocity

In given example an intersection of the curves H_- and H_+ occurs at two points (black and white circles) representing solutions of the equation of the non-ideal detonation velocity. A condition $dH_+/dN < dH_-/dN$ which is a stable "equilibrium" condition of the necessary and provided rates of explosive decomposition is satisfied in points designated with the black circles. This inequality is the condition of the stable propagation of detonation. As the charge diameter reduces (reduction of the parameter V) curve $H_-(N)$ approaches the position in which it touches curve $H_+(N)$ at the point depicted by a square. When further reducing the charge diameter curves $H_-(N)$ and $H_+(N)$ have no longer common points, therefore equation (13) has no longer a solution. The touch condition $H_+(N)$ and $H_-(N)$defines the critical value of parameter $V-V_{cr}$ and the critical value of the detonation nonideality degree N_{cr}. The critical values of the charge diameter and detonation velocity are evaluated as: $d_{cr} = V_{cr} \cdot t_{si}$, $D_{cr} = N_{cr} \cdot D_i$. As well as t_{si} value V_{cr} depends on FKE parameters, and therefore on an explosive charge microstructure. However FKE parameters change affects V_{cr} stronger than said change affects t_{si}.

Figure 2 shows the results of calculations (straight lines and points on straight lines II, III and IV, marked by crosses) and experiments (t_{si} data with pressed charges of desensitized hexogen (1) of TNT (2), of TATB with binder (3), of fine-grained cast TNT (2^*) and coarse-grained cast TNT (2^{**}). The calculated dependencies $d_{cr} = d_{cr}(t_{si})$ have been obtained for the following FKE parameters and values u_{eff}: $I-W_0 = 0;\ W_m = 0{,}3; y = 0{,}67;\ u_{eff} = (u_f + u_f)/2;$ $II-W_0 = 0.2;\ W_m = 0{,}5; y = 0{,}67;\ u_{eff} = (u_f + u_f)/2;$ $III-W_0 = 0.3;\ W_m = 0{,}05; y = 0{,}77;\ u_{eff} = (u_f + u_f)/2;$ $IV-W_0 = 0.3;\ W_m = 0{,}05; y = 0{,}77;\ u_{eff} = u_s$. The remaining parameters of the model are the same as for figure 1. At the calculation points marked by crosses, and the experimental points 2 and 2^* abscissas t_{si} are 90 and 140 nanoseconds.

It is not difficult to see that the FKE parameter change representing TNT charge microstructure change alters the chemical peak duration about 1.5 times and the calculated critical diameter 4 to 6 times.

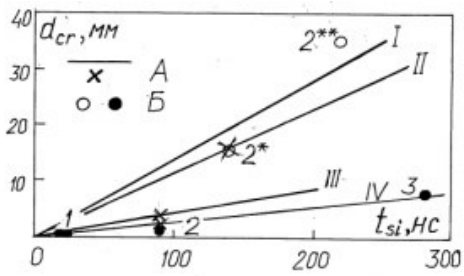

Figure 3. Calculated and experimental data on the critical detonation diameters and the duration of the chemical peak of the ideal detonation. (A - calculation, B - experiment)

Under critical conditions of detonation propagation the relationship of characteristic time of scattering reactive explosive t_R and basic reaction time $t_s - \overline{\theta_\tau^*}$ is not constant. Thus, when changing the critical value of detonation nonideality degree N_{cr} in the range of 0.5 to 0.95 by varying FKE parameter W_m

this relationship is described by the approximate ratio $lq\overline{\theta_\tau^*} = 2{,}16 \cdot N_{cr}$. Between the value $\overline{\theta_\tau^*} = t_R/t_s = \frac{d \cdot K_R}{u_{eff}} \cdot \frac{1}{t_s}$ and the nondimensional value in Khariton's principle $\overline{\theta_\tau} = \frac{d}{c \cdot \tau}$ a formal relationship can be established easily:

$$\overline{\theta_\tau} = \overline{\theta_\tau^*} \cdot \Lambda(N), \quad \Lambda(N) = \frac{D_i N - a}{bc} \cdot \frac{t_{si}}{\tau} \cdot \frac{a + D_i(b-1)}{a + D_i(b-1)N} \cdot N^{1-2\nu}$$

Approximating the equalities $t_{si} = \tau$ and $c = 3D_i/4$ we will obtain a diagram shown in figure 4 for our model explosive. Hence, it can be concluded that the nondimensional value θ_τ in the formula of Khariton's principle can be considered no longer as constant when taking into consideration the influence of the shock front curvature and flow divergence on the reaction in the detonation front. Its value may be equal to 1 only in case of "highly non-ideal explosives".

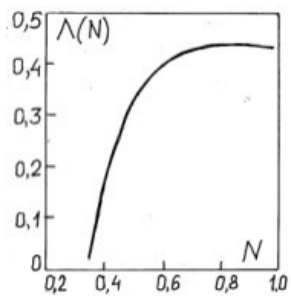

Figure 4. The relationship between complexes $\overline{\theta}_\tau$ and $\overline{\theta}_\tau^*$ in models [2] and of the present paper

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