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ANALYSIS OF CONVERGENCE OF DETONATION WAVE IN MAGNETIC FIELD

Influence of magnetic field on parameters of normal detonation wave and cumulation process of cylindrical detonation wave in gaseous explosive mixture was examined. A review of applications of generalised Chester-Chisnell-Whitham (CCW) method used for analysis of implosion processes of detonation waves is presented.

1. Introduction

Self-similar solution [1] describes cumulation processes of shock waves and detonation waves in the regions in which boundary conditions do not influence wave propagation (in the case of shock waves) or heat of chemical reaction (released at the front of detonation waves). This theory is similar for shock and detonation waves because, with the increase in intensity of waves that are close to the centre of their focusing, the heat of chemical reaction can be neglected in comparison with the work of pressure forces [2]. In theoretical investigations of detonation waves implosion, self-similar solutions and numerical methods are mainly used. They have limited range of applications. The Guderley's solution [1] is of asymptotic nature. It describes the process of wave implosion in an ideal gas near the focusing centre. Numerical methods are used for detailed analysis of detonation wave cumulation, but these are not a good tool for determination of general processes.

The paper presents an analysis of implosion of cylindrical detonation wave (DW) in gaseous explosive mixture subjected to magnetic field. The parameters of wave and magnetic field are influenced by electromagnetic forces and energy exchange between moving medium and magnetic field [3], [4], [5], [6]. Calculation analyses were performed on the basis of the theoretical model

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presented in [3] constructed by means of the CCW method [7], [8], [9], [10], [11], [12].

Information on CCW method [7], [8], [9], [10] and its generalised form [11], [12] is given in Section 2. Section 3 presents analyses of detonation waves performed with CCW method. In Section 4, the author presents the method of determination of normal detonation wave in gaseous explosive mixture being in magnetic field. Calculation results are given in Section 5, and in Section 6 all considerations are summarised.

2. Chester-Chisnell-Whitham method

The analyses are made with CCW method, the bases of which are formulated in [7]. One-dimensional approximation is used for the analysis of shock wave passing through a channel of variable cross-section $A(x)$. Analyses were aimed at determination of influence of the change of channel cross-section on shock wave (SW) parameters. It was assumed that initially the wave moves in a channel of the constant cross-section ($A(x) = A_0 = const, x < 0$). It has the constant velocity D_0 characterised by the Mach number $M_0 = |D_0|/c_0$. Dependence of the Mach number M on the variable cross-section $A(x)$ for $x > 0$ was searched for.

If the channel cross-section varies insignificantly at its length, the equations of motion obtained by averaging gasdynamic parameters in elements of channel cross-section give good approximations. These equations have the following form [10]:

$$\frac{d\rho}{dt} + \rho\left(\frac{\partial u}{\partial x} + \frac{u}{A}\frac{dA}{dx}\right) = 0,$$

$$\rho\frac{du}{dt} + \frac{\partial p}{\partial x} = 0, \tag{1}$$

$$\frac{dp}{dt} - c^2\frac{d\rho}{dt} = 0,$$

where t is the time, x is the spatial coordinate, ρ is the density, p is the pressure, u is the mass velocity, c is the speed of sound.

Assuming that changes of both cross-section and shock wave (SW) parameters are small, one formulated the formula expressing the changes of Mach number and channel cross-section [7], [10]:

$$\frac{dA}{A} = \frac{-2MdM}{(M^2 - 1)K(M)}, \tag{2}$$

where $$K(M) = 2\left[\left(1 + \frac{2}{\gamma+1}\frac{1-\eta^2}{\eta}\right)\cdot\left(1 + 2\eta + \frac{1}{M^2}\right)\right]^{-1}, \tag{3}$$

$$\eta^2 = \frac{(\gamma-1)M^2 + 2}{2\gamma M^2 - (\gamma-1)}, \qquad \gamma \text{ - polytropic exponent.} \tag{4}$$

A simple approximated form of dependence $M=M(A)$ can be obtained considering that the function $K(M)$ varies in a narrow interval of values [10]:

$$A^K\left(M^2 - 1\right) = const. \tag{5}$$

For a very strong SW ($M \to \infty$) we have:

$$K \to K_\infty = 2\left[\left(1 + \left\{\frac{2}{\gamma(\gamma-1)}\right\}^{1/2}\right)\cdot\left(1 + \left\{\frac{2(\gamma-1)}{\gamma}\right\}^{1/2}\right)\right]^{-1}, \tag{6}$$

$$M \sim A^{-K_\infty/2}. \tag{7}$$

In [8], dependence (7) was used for description of concentrically convergent shock waves. Using the symbol r to denote the distances between shock wave fronts and the axis of symmetry centre, close to the focusing place of waves, we have:

$$M \sim r^{-K_\infty/2} \tag{8}$$

for cylindrical SW and

$$M \sim r^{-K_\infty} \tag{9}$$

for spherical SW.

The values of the exponents $K_\infty/2$ and K_∞ can be compared with the values of Guderley solution [1]; convergence for various values of polytropic exponent γ is very good [8], [9], [10], [11], [12].

The Chester-Chisnell-Whitham method has numerous applications as a simple and efficient tool for the analysis of cumulation processes. A review of solutions converging detonation waves [3], [13], [14], [15], [16] based on a generalised form of CCW method [12] will be presented in Section 3.

In a general case, theoretical analysis of detonation waves needs finding a solution of partial differential equations completed with initial and boundary conditions (for $r = r_1$). Description of implosion of detonation waves by means of CCW method simplifies the analysis of the problem, reducing it to the initial problem. One solves ordinary differential equation [12]:

$$\frac{dq}{dr} = f_a(q,r) \tag{10}$$

with the initial condition $q(r = r_1) = q_J$.

The parameter q, characterising detonation wave front, is chosen in such a way that a simple form of the equation can be obtained. We assume that at the initial moment DW is a normal wave - its parameters are characterised, by the so-called, Chapman-Jouguet's point at the detonation adiabate (J point).

According to the generalised CCW method [12], at the front of converging detonation wave, the following laws are fulfilled: the law of conservation of mass, momentum conservation law, law of conservation of energy, equation of state detonation products and differential relation for the negative characteristics (propagating in the direction of wave front). If the physical properties of detonation products are described by the equation of state of an ideal gas, the equations of the problem are of the form:

$$\rho_0 D = \rho(D - u), \tag{11}$$

$$p = p_0 + \rho_0 D u, \tag{12}$$

$$E = E_0 + \frac{1}{2}(p + p_0) \cdot \left(\frac{1}{\rho_0} - \frac{1}{\rho} \right) + Q, \tag{13}$$

$$p = (\gamma - 1)\rho E, \tag{14}$$

$$\frac{dp}{\rho c} - du + \frac{cu}{u - c}\frac{\nu dr}{r} = 0, \tag{15}$$

where E and Q are the energy and heat of chemical reactions, respectively, referred to the unit of mass, ν is the coefficient of system symmetry ($\nu = 1$ – cylindrical symmetry, $\nu = 2$ – spherical symmetry). The index 0 denotes parameters of non-disturbed medium that is before DW front.

In [12], [13], [14], and [17], the authors was assumed that Q was constant parameter characterising gaseous explosive mixture or explosives. However, it was shown in [18] that during detonation wave convergence the heat of chemical reactions Q decreases (this fact was considered in [15], [16]).

In theoretical analysis of gasdynamic problems, the important completion of the equations determining the conservation laws is the equation describing thermodynamic properties of the medium. The simplest state equation is the equation of an ideal gas (14). Detonation products (DP) can be taken as an ideal gas when average potential energy of molecules interaction is significantly lower than their kinetic energy [12], [13], [16], and [17]. Description of condensed explosives is more complex, the properties of the explosives are similar to the properties of solids. Discussion on equations of state of detonation products of condensed explosives is given in [12], [19].

For description of physical properties of DP of condensed explosives, the Jones-Wilkins-Lee (JWL) equation is often used [20]:

$$p = A_1 \cdot \left(1 - \frac{\omega}{R_1 \cdot V}\right) \cdot \exp(-R_1 \cdot V) + A_2 \cdot \left(1 - \frac{\omega}{R_2 \cdot V}\right) \cdot \exp(-R_2 \cdot V) + \omega \rho E , \quad (16)$$

where the symbols $V = \rho_0 / \rho; A_1, A_2, R_1, R_2, \omega$ are constant coefficients.

Analyses of DW convergence in condensed explosives, where the properties of DP are approximated in equation (16), are shown in [12], [14]. Description of DP properties is sometimes presented in the form of system of many equations, e.g., equation of state DP of octogen [21]. A generalised CCW method allows for an efficient analysis of DW implosion also in such cases.

When we analyse a convergence of detonation waves in magnetic field, and magnetic induction has only the axis component $B = B_z$, the dependence along characteristics propagating in the direction of the front is of the form [3], [4], [5], [6]:

$$dp + \frac{1}{\mu} BdB - \rho a du + \frac{\rho a^2 u}{u - a} \frac{dr}{r} = 0 , \quad (17)$$

where $a^2 = c^2 + \dfrac{B^2}{\mu \rho}$; μ is the coefficient of magnetic permeability.

For some problems, the system of equations that must be fulfilled in the analysis of DW in CCW approximation is completed with additional equations. For example, if during a cylindrical implosion of DW a non-conducting medium becomes an ideal conductor, that is the result of interaction between magnetic field and the conducting detonation products moving towards the system axis, then the compression of magnetic flux takes place [3], [4], and [6]. Equations of CCW method should be completed with the law of a magnetic flux conservation of the form [22]:

$$\frac{dB}{B} = -\frac{2u}{D} \frac{dr}{r} . \quad (18)$$

3. Implosion of detonation wave in CCW approximation

Scheme of implosion of detonation wave is presented in Fig. 1. The characteristics initiated at the DW front are not shown. According to CCW method, disturbances propagating along them do not affect the motion of the wave front [7], [8], [9], [10]. Exhaustive discussion on theoretical and experimental investigations of imploding detonation waves is given in [12], [23]. In [13], [14], propagation of converging DW in gaseous explosive mixtures and condensed explosives was analysed. The results confirmed the fact, mentioned in [12], [23] i.e., that in one of the fundamental work [2] the one made a calculation error that distorted the final results.

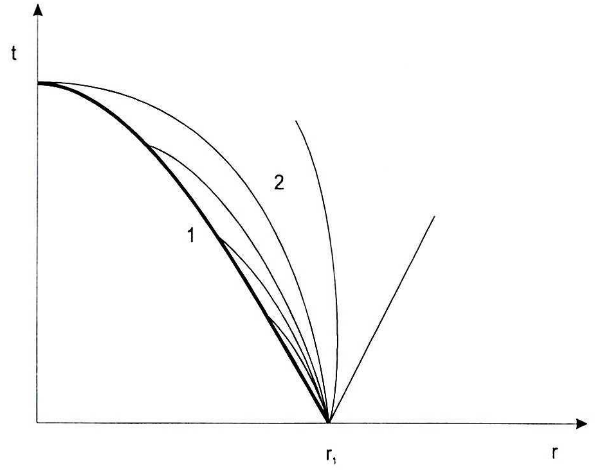

Fig. 1 Scheme of propagation of concentrically converging detonation wave; 1 - trajectory of detonation wave front, 2 - trajectories of negative characteristics

Basing on equations (11)-(15), in the work [13] one analysed propagation of converging detonation waves in gaseous mixtures. As a result, an analytic solution describing relation between the wave parameters and the front position was given. The obtained results were in good agreement with the experimental results and the asymptotic solution. It was shown that, for the initial stage of DW, convergence the following dependence could be assumed:

$$|D| = D_J = const, \qquad \frac{p}{p_J} = \left|\frac{u}{u_J}\right| = \left(\frac{r_1}{r}\right)^{\frac{\nu\gamma}{2(\gamma+1)}}. \tag{19}$$

Theoretical image of trajectories of transverse waves at the front of imploding detonation was determined. For cylindrical detonation wave in acetylene-oxygen mixture, theoretical image was the same as that obtained from experiments (see [12]).

The analysis of convergence of DW in the condensed explosives is given in [14]. Analytical solution for detonation products, described with the equation of state, has been obtained as

$$p = A_k \rho^k, \tag{20}$$

where A_k and k are the empirical coefficients.

One has also found a solution in a closed form, when physical properties of detonation products are expressed by JWL equation (16). Good consistence of these solutions with experimental results and numerical calculations was obtained.

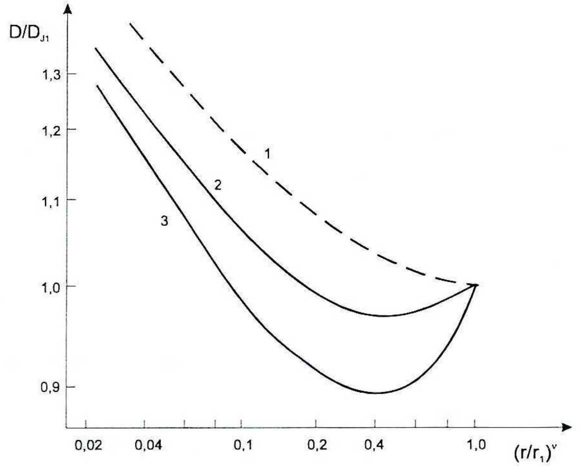

Fig. 2 Detonation wave velocity as a function of front position for Q=const (curve 1 [13]) and for $Q=Q(u)$: n_2 = 1 and 2 (curves 2 and 3 [16])

It was considered in [15], [16] that during the process of wave convergence, the heat of chemical reaction decreases. It is the result of the change of chemical balance condition at DW front due to the increase of pressure and temperature. In [16], the change of the heat Q is related to the change of parameters at the front of converging detonation wave

$$Q = Q_1 \left(\frac{u_{J1}}{|u|} \right)^{n_2}, \tag{21}$$

where Q_1, u_{J1} and n_2 are the constant coefficients.

It was shown that the changes of DW parameters depend on geometrical effects and reduction of the heat Q. It results from the analyses that the decrease in the heat of chemical reactions causes a decrease in velocity of detonation wave at the initial stage of its implosion - Fig. 2 [16].

A theoretical model that was given in [3] allows for examination of magnetic field influence on convergence of DW to the axis. This phenomenon was analysed in the following example. At the surface of a cylinder containing explosive mixture (or condensed explosives), cylindrical converging detonation wave was initiated. The system was in an external axial magnetic field. The vectors of mass velocity of detonation products and magnetic field were perpendicular - Fig. 3. It was assumed that a rapid increase in electric conduction occurs at the wave front and non-conducting medium becomes an ideal conductor. It is known that in reality detonation products have finite electric conduction (e.g., [24]). However, this simplification gives a better description of experimental reality than that given by the models presented in the earlier published works [25], [26]. It was shown that when magnetic induction is not zero, the Chapman-Jouguet condition characterises J_i ($B_0 = B_i$) point that is below $J_0(B_0 = B_i)$ point – Fig. 4.

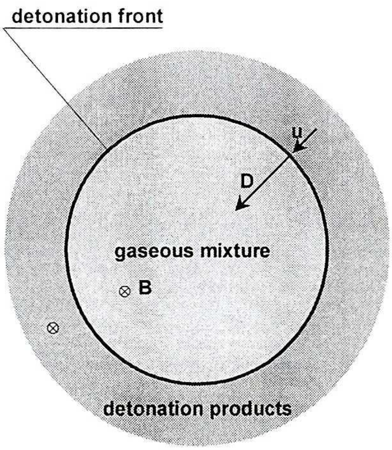

Fig. 3 Geometrical orientation of propagation of concentrically converging detonation wave in external magnetic field

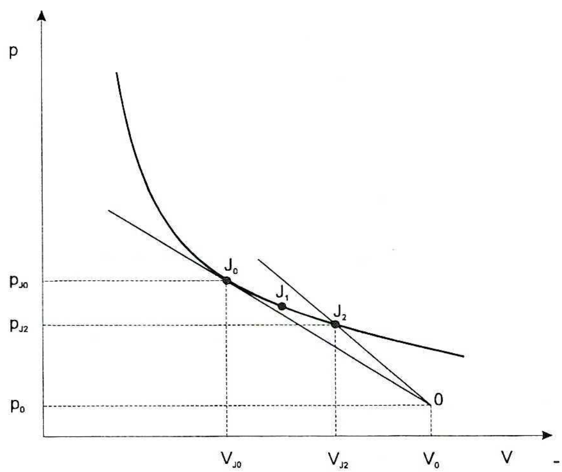

Fig. 4 Detonation adiabate and Chapman-Jouguet's (J) points for three values of magnetic induction: $B_0 = 0$, $B_0 = B_1$ and $B_0 = B_2$ ($B_2 > B_1$) [3]

Analyses presented in [3], [13], [14], [15], [16] complete the results of experiments and can be used for numerical modelling of cumulation effects at DW fronts. As an example, in [27] the approximated method for determination of values of detonation waves parameters was presented on the basis of the known parameters of waves, stationary (Chapman-Jouguet) and convergent ones. The proposed approximation makes it possible to consider easily cumulative effects at the annular front of detonation wave in numerical calculations.

4. Normal detonation wave in magnetic field

At the initial moment ($t=0$), for $r=r_1$, a convergent detonation wave is a normal one (its parameters are denoted with the index J). When detonation products are in the magnetic field ($B \neq 0$), wave velocity is determined by the following condition [3], [25]:

$$|D_J| = |u_J| + a_J, \tag{22}$$

where $a_J = \sqrt{c_J^2 + \dfrac{B_0^2}{\mu \rho_J}}$, $B_0 = B|_{t=0}$.

Taking the laws of preservation (11)-(13) and the state equations of DP (14), one can write relationship (22) as [3]:

$$p_J = \frac{p_0 + \dfrac{B_0^2}{\mu}\left(\dfrac{\rho_J}{\rho_0} - 1\right)}{1 - \gamma\left(\dfrac{\rho_J}{\rho_0} - 1\right)}. \tag{23}$$

Detonation adiabate is expressed by the equation

$$p = \frac{2p_0 + (\gamma-1)\rho Q}{\dfrac{(\gamma+1)}{2} - \dfrac{(\gamma-1)}{2}\dfrac{\rho}{\rho_0}} - p_0. \tag{24}$$

We determine the density at the front of normal DW from equations (23) and (24):

$$\rho_J = \frac{-w_b + \sqrt{w_b^2 - 4w_a w_c}}{2w_a}, \tag{25}$$

where $w_a = -\dfrac{\gamma-1}{2\rho_0^2}\dfrac{B_0^2}{\mu} + \dfrac{(\gamma-1)\gamma Q}{\rho_0} + \dfrac{\gamma(\gamma-1)}{2}\dfrac{p_0}{\rho_0^2}$,

$$w_b = \left(-\gamma^2 + \gamma + 1\right)\frac{p_0}{\rho_0} + \frac{\gamma}{\rho_0}\frac{B_0^2}{\mu} - \left(\gamma^2 - 1\right)Q,$$

$$w_c = \left(\gamma - 2\right)\left(\gamma + 1\right)\frac{p_0}{2} - \frac{\gamma + 1}{2}\frac{B_0^2}{\mu}.$$

It results from (25) that the density ρ_J takes values from ρ_0 (when $B_0 \to \infty$) to $\rho_0(\gamma+1)/\gamma$ (for $B_0 = 0 = p_0$).

For the known density ρ_J, using Eq. (3.3), we determine the pressure at the wave front p_J. The velocity of wave front D_J and the velocity of DP motion u_J at the wave front can be calculated from the relationship:

$$\left|D_J\right| = \sqrt{\frac{p_J - p_0}{\rho_0\left(1 - \dfrac{\rho_0}{\rho_J}\right)}}, \qquad \left|u_J\right| = \left|D_J\right|\left(1 - \frac{\rho_0}{\rho_J}\right). \tag{26}$$

The parameters of normal detonation waves are shown in Table 1. For calculations, one takes the following values of parameters of explosive gaseous mixture and DP: $p_0 = 0{,}1\ \mathrm{MPa}$, $\rho_0 = 0{,}5\ \mathrm{kg/m^3}$, $\gamma = 1{,}15$ and $D_{J0} = 2800\ \mathrm{m/s}$ (D_{J0} denotes normal velocity of DW for $B_0 = 0$).

The stronger magnetic field - the lower the points at the detonation adiabate that characterise the states at the front of normal DW [3]. It is illustrated by Table 1 - with the increase in the magnetic induction B_0, the following parameters decrease: density ρ_J, the velocity of DP motion u_J and the pressure p_J but the wave velocity D_{J0} increases.

Table 1.

Parameters of normal detonation waves

B_0 [T]	0	0,2	0,5	1	2	5
ρ_J [kg/m^3]	0,935	0,929	0,890	0,798	0,630	0,523
p_J [MPa]	1,823	1,816	1,730	1,529	1,176	0,960
D_J [m/s]	2800	2805	2810	2862	3376	6608
u_J [m/s]	1302	1295	1231	1069	697	291

5. Analysis of implosion of detonation wave in magnetic field

The equations describing the considered problem, according to CCW method, presents the system of equations; (11)-(14), (17), and (18). The parameters of detonation wave front can be easly expressed, similarly as the pressure in formula (24), as density functions at DW front:

$$|D(\rho)| = \sqrt{\frac{p(\rho) - p_0}{\rho_0\left(1 - \frac{\rho_0}{\rho}\right)}}, \qquad c(\rho) = \sqrt{\frac{\gamma p(\rho)}{\rho}},$$

$$|u(\rho)| = \sqrt{[p(\rho) - p_0]\left(\frac{1}{\rho_0} - \frac{1}{\rho}\right)}. \tag{27}$$

Taking formulae (27), one can write the law of conservation of the magnetic flux (18) as

$$\frac{dB}{B} = -2\left(1 - \frac{\rho_0}{\rho}\right)\frac{dr}{r}, \tag{28}$$

and the relation for negative characteristics (17) is:

$$dp + \rho a d|u| = dB\left[\frac{\rho a^2 |u|}{2(|u| + a)B\left(1 - \frac{\rho_0}{\rho}\right)} - \frac{B}{\mu}\right]. \tag{29}$$

Equation (29) is reduced to the following form:

$$\frac{d\rho}{dB} = F(\rho, B), \tag{30}$$

where

$$F(\rho, B) = \left[\frac{\rho a^2 |u|}{2(|u| + a)B\left(1 - \frac{\rho_0}{\rho}\right)} - \frac{B}{\mu}\right] \cdot \left\{G \cdot \left[1 + \frac{a}{2|u|}\left(\frac{\rho}{\rho_0} - 1\right)\right] + \frac{(p - p_0)a}{2|u|\rho}\right\}^{-1},$$

$$G(\rho) = \frac{\frac{2(\gamma + 1)Q}{\gamma - 1} + \frac{4p_0}{(\gamma - 1)\rho_0}}{\left(\frac{\gamma + 1}{\gamma - 1} - \frac{\rho}{\rho_0}\right)^2}.$$

The analysis of propagation of cylindrically convergent detonation wave in gaseous explosive mixture was carried out on the basis of Eqs. (27)-(30) (Fig. 3). Solving equation (30), completed with the condition $\rho(B = B_0) = \rho_J$, we have $\rho = \rho(B)$. Next, using relation (28), we have $\rho = \rho(r)$ and $B = B(r)$ and from formulae (24) and (27), dependencies of other DW parameters on the front position.

The calculation results are presented in Figs. 5-8. The results for the values 0,5T, 1T and 2T of the magnetic induction B_0 are denoted by 1, 2, and 3, respectively. Dashed line corresponds to the relationships for $B_0 = 0$ [13].

It results from Fig. 5 that during DW implosion process a magnetic induction increases in the area enclosed by the wave front. It should be noticed that in reality the magnetic field compression is lower than this shown in Fig. 5 as a result of finite electric conduction of DP.

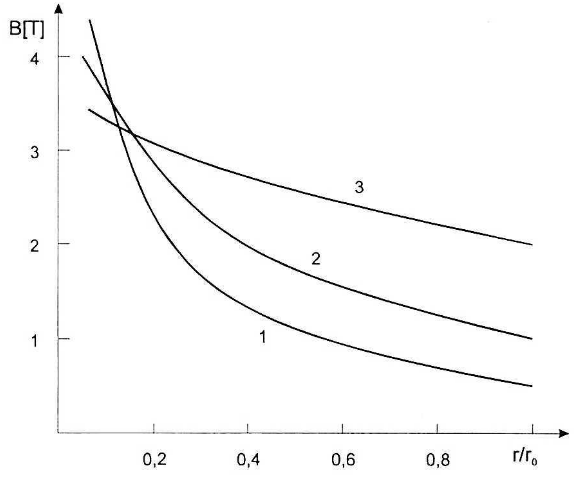

Fig. 5 Magnetic induction at detonation wave front as a function of front position

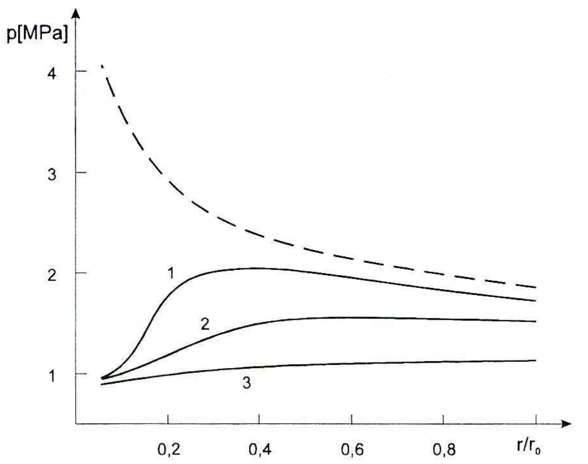

Fig. 6. Pressure at detonation wave front as a function of front position

Curves 1 and 2 in Fig. 6 show that intensity of detonation wave decreases after reaching its maximal value. For converging shock waves, this effect was discussed in detail in [4], [6]. It turned out that for high magnetic induction B_0, the pressure at the front of converging detonation wave decreases during the whole process (curve 3).

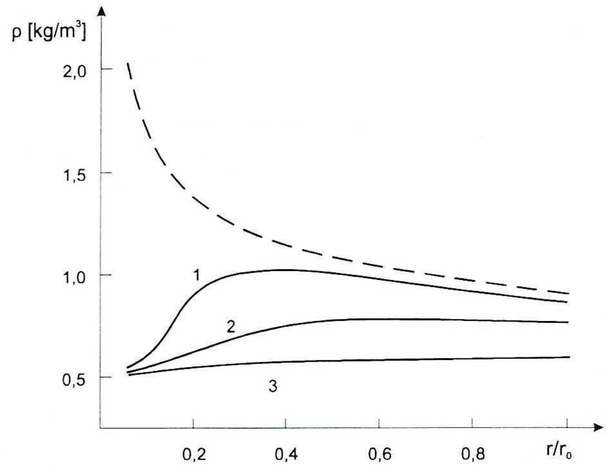

Fig. 7 Density at detonation wave front as a function of front position

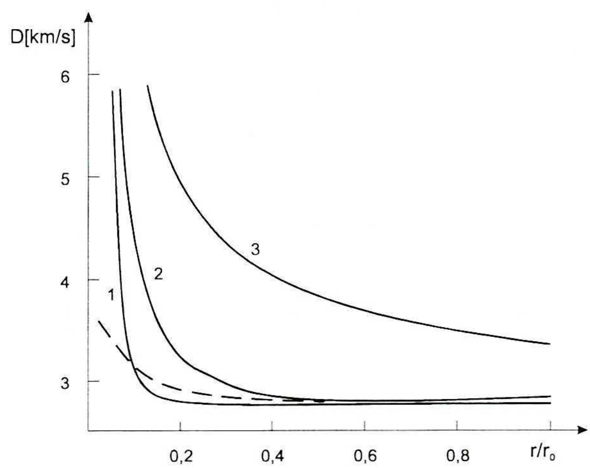

Fig. 8 Detonation wave velocity as a function of front position

Figure 7 presents the density of DP as a function of front position. Magnetic field causes reduction of compression of detonation products. With a decrease in DW intensity, density of DP at the wave front tends to the value ρ_0 [3].

Analyses described in [2], [12] showed that the assumption of constant velocity of DW at its initial stage of cumulation is a good approximation. This relation is valid for the imploding wave subjected to magnetic field, Fig. 8. The only exception is the increase in velocity D for $B_0 = 2T$ - curve 3, what does not result from geometrical effects, but is the result of magnetic field influence. Increase in the velocity D at the initial stage of DW convergence with no magnetic field results from the increase in wave intensity [12], in the analysed case it is related to weakening of DW. (The states at the front of imploding DW for $B_0 = 0$ are characterised by the higher points at the detonation adiabate, for $B_0 = 2T$ the points are at the lower part of adiabate, Fig.4).

It results from the analysis of results of the work presented in [13] that the kind of gase mixture slightly influences DW implosion process. The cumulation effects at the DW front increase with the increase in value of the polytropic exponent γ. However, considering a narrow range of changeability of γ for DP of gaseous explosive mixture, it is an insignificant influence. Increase in the initial pressure (density) of gaseous mixture does not change the character of DW convergence process. However, due to such an increase, for a fixed value of magnetic induction B_0, the intensity of imploding DW increases, and its maximal value is reached for the smallest r. (For converging shock wave this effect was analysed in detail in [6]).

6. Conclusions

Basing on the theoretical model described in [3], the author performed an analysis of propagation of cylindrically convergent detonation wave in gaseous mixtures subjected to magnetic field. It was shown that strong magnetic field significantly changes both DW parameters and the character of a convergence process. There could be cases when it is possible that intensity of detonation wave decreases during the whole implosion process. Numerical analyses were made under simplified assumption that detonation products are ideal conductors. Because they actually are characterised by a finite conductivity, thus influence of magnetic field on parameters of converging detonation waves is lower than that shown in Figs. 5-8.

A generalised CCW method is an efficient tool for analysis of implosion of detonation waves in real materials. Some paradox should be noticed. The bases of CCW method were formulated for examining propagation of a shock wave in a channel of variable cross-section, and majority of applications is connected with description of shock waves cumulation. Detailed analysis of CCW methods shows that they could be better used for description of converging detonation waves.

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Analiza zbiegania się fali detonacyjnej w polu magnetycznym

Streszczenie

Zbadano wpływ pola magnetycznego na parametry normalnej fali detonacyjnej i proces kumulacji cylindrycznej fali detonacyjnej w gazowej mieszaninie wybuchowej. Przedstawiono przegląd zastosowań uogólnionej metody Chestera-Chisnella-Withama (CCW) do analizy procesów implozji fal detonacyjnych.