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A. I. Gol' binder, V. F. Tyshevich

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Abstract

Full Text

PHYSICAL CHEMISTRY

A. I. Gol' binder, V. F. Tyshevich

ON THE CHANNEL EFFECT IN THE DETONATION OF EXPLOSIVES

(Presented by Academician Ya. B. Zel' dovich on 17 II 1964)

The detonation of an explosive (e.v.) is facilitated if it is enclosed in a casing that hinders lateral scattering. However, under the usual conditions of use of explosive cartridges, whose diameter is smaller than the diameter of the borehole, there is a free channel between its walls and the charge, and for this reason detonation may be interrupted. This phenomenon, which has been given the name channel effect, was first described by Urbanskii ⁽¹⁾ and later studied by many investigators ^(2-4,6,8). It was established that the cessation of detonation is associated with a phenomenon accompanied by luminescence and propagating along the channel with a velocity exceeding the detonation velocity. The question of the nature of this phenomenon and the mechanism of the channel effect has not yet been clarified. Usually the cessation of detonation was associated with compaction of the charge ahead of the detonation front, which for industrial mixed explosives leads to an increase in the critical diameter. A number of facts established recently do not permit this simple explanation to be accepted. Thus, the channel effect was observed ⁽²⁾ for individual explosives of normal strength, whose critical diameter decreases with increasing density.

In the present work the channel effect was studied by methods of high-speed motion-picture photography* (500-1000 thousand frames per sec) and pulsed radiography. In the latter case charges made of a finely ground mixture of TNT and lead azide (10-20%) with a density of 0.6-0.7 g/ml were used. In the remaining experiments, charges of finely dispersed TNT and hexogen of low density (0.5 g/ml) were used. In both methods, charges of rectangular cross section in rectangular casings made of organic glass were employed. With such a charge arrangement, the phenomena propagating along the charge and along the channel are clearly separated in space, which simplifies and makes more reliable their recording and the interpretation of its results.

Study of frames of high-speed filming and, especially, of X-ray photographs, both those obtained by us and those published earlier for other explosives by Dubnov and Khotina ⁽³⁾, showed that the boundary of the expanding explosion products for all the explosives studied is quite sharp and never outstrips the detonation front. The luminescence propagating in the channel, contrary to

Fig. 1

Figure 1: Fig. 1

an opinion that has been expressed ⁽⁴⁾, is not connected with the motion of explosion products in it, but is a shock wave. The explosion products, the oblique expansion front of which moves in the direction of detonation with its velocity, are as it were a moving piston creating a shock wave in the channel. This conclusion is confirmed by the results of our experiments, which revealed a strong dependence of the intensity of luminescence on the nature of the gas. If the channel is filled with argon, this intensity is maximal; it is smaller in the case of air and still smaller in the case of carbon dioxide.

Let us now consider the action of the wave on the charge. As the photographs show, detonation ceases when the front of the wave in the channel, moving faster than the detonation front, outstrips the latter by a distance exceeding some limiting value; in other words, when the duration of the action of the shock wave on some section of the charge becomes sufficiently large. Before the attenuation of detonation, there is observed, on the one hand, a decrease in the cross section of the charge, and on the other hand, a reduction in the height of the detonation luminescence, which covers only the lower part of the compressed charge. At the same time

* High-speed motion-picture photography was carried out on an SFR-2 camera in the time-loupe mode.

simultaneously the detonation velocity decreases. Fig. 1 shows two frames from a series obtained for the explosion of a TNT charge.*

As confirmed by X-ray photographs, one of which is shown in Fig. 2, the dynamic compression of the charge caused by the shock wave is not uniform over its cross section. In the upper part of the charge a compacted layer is formed, whose thickness increases as it propagates.

Fig. 1. Velocity streak record in self-luminescence. TNT charge with a cross section of 8×10 mm, density 0.5 g/ml, channel height 4 mm. 1 –channel shock wave (in its front part the width of the luminous zone in the photograph is greatly enlarged because of the high intensity of the luminescence), 2 –TNT charge, 3 –detonation front, 4 –spread of detonation products, 5 –channel above the charge, 6 –charge casing (Plexiglas), 7 –timing marks (every 50 mm)

This thickness, as well as the velocity at which the charge is compressed by the shock wave, can be estimated by calculation. Let us assume that a rectangular shock wave moves along channel *B* (Fig. 3a), i.e., over the entire distance from its front to the boundary of the spread of the detonation products the pressure is constant. Consider an element of the charge being compressed under the action

of pressure P_1 (Fig. 3b). From the known relations: $\rho_0 \cdot D = \rho_1 \cdot (D - u)$ and $P_1 - P_0 = \rho_0 \cdot D \cdot u$, it follows that

$$D^2 = \frac{P_1 - P_0}{\rho_0 \cdot \left(1 - \frac{\rho_0}{\rho_1}\right)}; \quad \text{denoting } \frac{\rho_0}{\rho_1} = K, \text{ we obtain } D = \sqrt{\frac{P_1 - P_0}{\rho_0(1 - K)}} \text{ and}$$

$$u = \frac{P_1 - P_0}{\rho_0 \cdot D},$$

where D is the velocity of propagation of the shock wave in the powder-like explosive; u is the velocity of compression of the charge by the shock wave; P_1 is the pressure in the channel shock wave; ρ_0 is the initial density of the explosive; ρ_1 is the density of the compressed layer of explosive.

Since the dependence of the compressibility of the powder on the pressing pressure is unknown to us, we used the radiograph (Fig. 2) to calculate the density of the compressed layer, which was $\rho_1 = 1.52$ g/ml. The initial density of the explosive powder was $\rho_0 = 0.7$ g/ml. From the graph of the ratio of the velocities of propagation of the shock wave and of the detonation front for a charge analogous to the charge in the radiograph, it follows that at the cross section of the charge in which the detonation front is located in Fig. 2, the shock wave, leading the detonation front by 109 mm, acted for $\tau = 33.7$ μ sec. In this case its mean propagation velocity was $U = 3230$ m/sec. A shock wave with this velocity corresponds to pressure $P_1 = 107$ atm and temperature $T = 3900^\circ\text{K}$. Substituting the values of P_1 and ρ_1 into the formulas, we obtain the velocity of propagation of the boundary ($O-3$) between the compressed and uncompressed layers of the charge

$$D = \sqrt{\frac{(107 - 1) \cdot 10^6}{0.7 \cdot (1 - 0.46)}} = 16.7 \cdot 10^3 \text{ cm/sec} = 167 \text{ m/sec}$$

and the velocity of displacement of the boundary ($O-2$) between the compressed layer of the charge and the air in the channel

$$u = \frac{106 \cdot 10^6}{0.7 \cdot 167 \cdot 10^2} = 0.91 \cdot 10^4 \text{ cm/sec} = 91 \text{ m/sec}.$$

* Schematic drawings obtained by tracing to scale from the negatives are given here, since even the positive image, and still more its typographic reproduction, is insufficiently clear.

From measurement of the radiograph it follows that the boundary ($0-3$) between the compressed and uncompressed parts of the charge, during the time $\tau = 33.7$ μ sec, moved from 0 (boundary $0-1$) to 5.4 mm, i.e., with a velocity

Fig. 2

Figure 2: Fig. 2

$$D_0 = \frac{5.4 \cdot 10^{-3}}{33.7 \cdot 10^{-6}} = 165 \text{ m/sec},$$

and the boundary (0—2) between the compressed charge and the air in the channel, over the same time, moved from 0 to 3.0 mm, i.e., with a velocity

$$u_0 = \frac{3.0 \cdot 10^{-3}}{33.7 \cdot 10^{-6}} = 89 \text{ m/sec}.$$

Fig. 2. *a*—radiograph of the detonation of a charge of TNT—lead nitrate 85/15, cross section 8×10 mm, channel height 4 mm, density 0.7 g/ml. *b*—diagram of the radiograph. 1—charge at the initial density, 2—channel above the charge, 3—compressed part of the charge, 4—position of the detonation front, 5—charge casing (Plexiglas), 6—expansion of detonation products, 7—metal witness plate deforming as the detonation passes along the charge. The dashed line shows the initial height of the charge.

Let us determine and compare with the radiographic measurement data ΔH and Δh , on the basis of the values of the velocities D and u , if the time of action of the channel shock wave on the indicated section of the charge is $\tau = 33.7 \mu\text{sec}$.

$$\Delta H = D \cdot \tau = 167 \cdot 10^3 \cdot 33.7 \cdot 10^{-6} = 5.6 \text{ mm},$$

$$\Delta h = u \cdot \tau = 91 \cdot 10^3 \cdot 33.7 \cdot 10^{-6} = 3.0 \text{ mm}.$$

The radiographic measurement data are: $\Delta H_0 = 5.4 \pm 0.2$ mm, $\Delta h_0 = 3.0 \pm 0.2$ mm.

With progressive compression of the charge, detonation continues to propagate only in its uncompressed part and does not, at least immediately, involve the compacted layer. One of the reasons for this may be compression of gas bubbles in the explosive, caused by the shock wave; this compression is not sufficiently intense to cause rapid ignition of the particles of the explosive surrounding the bubbles, but it is sufficient for the detonability of the explosive to be greatly reduced (⁵⁻⁷). In addition, it is known that successive compression of a gas by shock waves up to a certain pressure produces a smaller rise in its temperature than a single compression to the same final pressure. Therefore, when the detonation wave approaches, the compression produced by it in the part of the charge already compressed by the channel shock wave proves insufficient to initiate an intensive reaction.

Fig. 3

Figure 3: Fig. 3

The thickness of the uncompressed part of the charge, as the lead of the shock wave over the detonation wave increases, becomes ever smaller and, since the transverse dimension of the charge is small, the detonation velocity correspondingly falls and, finally—

finally, it breaks off. The critical thickness in this case may be considerably smaller than the critical thickness in the detonation of an open charge, since the compacted part of the charge prevents scattering, playing the role of a casing.

The assumption of the essential role of compression of gaseous inclusions is also consistent with the decrease in the channel effect established in our experiments when the initial density of the explosive is increased. Naturally, the compressibility of a powder charge is the smaller the greater its density. The fact that previous investigators ^(4,8) did not detect a channel effect for individual explosives is apparently connected with this, since they worked at relatively high powder densities.

Fig. 3. *a*—diagram of the process of compression by a shock wave of a rectangular explosive charge ahead of the detonation front; *A*—powder charge of explosive; *B*—channel above the charge, along which a shock wave propagates with velocity U ; P_1 —pressure in the shock wave; 0—1—initial boundary between the channel and the explosive charge ($H_{\text{ch}} = 8$ mm); 0—2—boundary between the compressed part of the charge and the air in the channel, propagating with velocity u ; 0—3—boundary between the compressed and uncompressed parts of the charge, propagating with velocity D ; *b*—element of the charge being compressed under the action of pressure P_1 .

Extinction of detonation is not the only possible result of the action of the channel shock wave. If the shock wave changes the conditions of propagation of the explosion along the charge not so strongly as to extinguish detonation, but nevertheless reduces its velocity, then the shock wave is weakened and, as a result, a kind of “equilibrium” may be established—the propagation will occur, but with an oscillating velocity. If the explosive is highly susceptible to the action of the shock wave, it may not only hinder detonation, but also initiate it. This latter action predominated in our experiments with hexogen charges, where extinction of detonation was not observed. Upon attaining a certain lead, the shock wave initiated detonation ahead of the front of the detonation wave, whose propagation acquired a pulsating character.

The influence of partitions in the channel is of interest: if they are weak, then, in agreement with earlier results, extinction of detonation is prevented. Conversely, a strong partition, at which reflection of the shock wave occurs and consequently an enhancement of its action on the charge, leads to cessation of detonation.

It is probable that precisely such enhanced compression of the charge by the channel shock wave reflected from the bottom of the borehole is the cause of the formation of “cups” sometimes observed in blasting operations.

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Moscow Chemical-Technological Institute
named after D. I. Mendeleev

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