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Abstract

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CRITICAL DIAMETER OF DETONATION OF LIQUID EXPLOSIVES

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According to the hydrodynamic theory of detonation of Ya. B. Zel' dovich ([1]), the detonation wave is represented as a smooth shock wave with a chemical reaction behind its front. Proceeding from the finiteness of the reaction time t in the front of the detonation wave, Yu. B. Khariton ([2]) developed a theory of the detonability of explosives (E.S.), from which it follows that the value of the critical diameter d_{cr} is determined by the expression:

$$d_{cr} \approx 2tC_1, \tag{1}$$

where C_1 is the speed of sound in the detonation products.

In many works, in particular in ([2-4]), it is assumed that, in liquid explosives, the temperature reached upon compression of the explosive at the shock front of the detonation wave determines the reaction time t, and consequently also d_{cr}. As a result of a number of works ([5, 6]) carried out in recent years on the study of the detonation of nitromethane (NM) and its mixtures with acetone (A), a new conception of the mechanism of detonation of liquid explosives was advanced. The essence of this conception is as follows. Owing to the transparency of the indicated substances, it was possible to record the luminosity of the detonation front by applying photographic time scanning of the process of detonation propagation into the end face of the charge with the aid of a high-speed SFR photorecorder. It was thereby established that the luminosity of the front of the detonation wave is nonuniform. The photographs constitute a system of intersecting light and dark bands, the angle of inclination of which gives the velocity v of displacement of inhomogeneities along the shock front of the detonation wave.

Nonuniform luminosity of the front of the detonation wave means that the reaction arises not simultaneously over the entire cross section of the charge, but in separate places. The fact that the reaction arises not simultaneously over the entire cross section of the charge means that the shock front of the detonation wave is not smooth. By analogy with the concepts developed for gaseous detonation in works ([7-12]), it may be assumed that, as a consequence of instability of the plane of ignition ([7]) (in the model of a detonation wave with a smooth

shock front, the plane of ignition lags in time behind the shock front of the detonation wave by the amount i), oblique shock waves arise at the shock front of the detonation wave in liquid explosives. In this case the initiation of the reaction is transferred from the plane of ignition to the places where the oblique shock waves collide, since the delay in initiation of the reaction in these places is much smaller than behind the smooth shock front of the detonation wave.

Thus, according to the new conception, the propagation of detonation along a charge of a liquid explosive is determined by conditions favorable or unfavorable for the collision of oblique shock waves. It is of interest to obtain an expression for d_{cr}, proceeding from the conception set forth above. For this purpose, let us consider the propagation of detonation near the surface of a cylindrical charge without a casing, or in a very weak casing when it may be neglected. A relatively dense, low-compressibility ···

the casing may be regarded as weak if its mass per unit surface area of the charge is much less than the mass of the high-explosive layer corresponding to one inhomogeneity (the dimension x in Fig. 1). Otherwise the casing may be regarded as strong.

Since in a charge without a casing the edge oblique shock waves have nothing to interact with, this leads to the extinction of the edge centers of reaction initiation. As a consequence, no new oblique shock waves are formed at the edge of the charge; this in turn leads to the extinction of neighboring, deeper centers of reaction initiation in the course of detonation. Thus a wave of absence of reaction is formed, propagating into the depth of the charge with the velocity v of displacement of the oblique shock waves along the shock front of the detonation wave. The considerations set out above are represented schematically in Fig. 1.

Fig. 1. Scheme of the formation, during detonation of a liquid high explosive, of a wave of absence of reaction at the lateral surface of a cylindrical charge without a casing.
1 —lateral surface of the charge; 2 —place of extinction of an edge center of reaction initiation; 3 —places of collision of oblique shock waves, centers of reaction initiation; 4 —positions of the shock front of the detonation wave at the moments of successive initiation of reaction; 5 —places of successive extinction of the centers of reaction initiation.

Experimentally, in work ([5]) it was established that if the regions of absence of reaction do not overlap even a small part of the charge, detonation proceeds without changing its velocity. If, however, the waves of absence of reaction overlap all cross sections of the charge, detonation, as a rule, dies out. Let us consider to what depth the region of absence of reaction can penetrate into the charge (see Fig. 2). From the reasoning given above it is evident that this depth is precisely the critical radius of detonation of a liquid high explosive, R_{cr}.

Fig. 2. Scheme explaining the nature of the critical radius of detonation of liquid high explosives.
1 —smooth shock front remaining after the extinction of oblique shock waves

on the shock front of the detonation wave 4; 2 –interface: explosion products– compressed high explosive; 3 –boundary of propagation of the front of the wave of absence of reaction; l –depth at which reaction arises behind the smooth shock wave 1 at point b;

$$t_1 = \frac{R_{\text{cr}}}{v};$$

$$t_2 = \frac{l}{v} + \tau.$$

The densely hatched region is the region of the compressed liquid high explosive by the smooth shock wave; the sparsely hatched region is the region swept by the unloading wave propagating from point a with velocity C_2.

After the extinction of the oblique shock waves at the edges of the front of the detonation wave, a smooth shock wave remains (see Fig. 2, 1), which is supported by the detonation products as by a piston. The smooth shock wave compresses the high explosive and initiates reaction in it after a time τ, the ignition delay corresponding to the temperature and pressure behind this wave.

Since a rarefaction wave travels from the charge edges through the compressed substance, reaction arises at that point b which this wave has not yet reached and in which the compressed substance had remained for a time τ. The resulting re-

reaction propagates to the lateral surface of the charge through the rarefied substance. Into the depth of the charge the reaction propagates through the shock-compressed substance with velocity D_2. This wave catches up with the front of the wave of absence of reaction at the depth R_{cr} and terminates the decay of the oblique shock waves (point e in Fig. 2).

From the considerations given, it is not difficult to obtain a formula for $d_{\text{cr}} = 2R_{\text{cr}}$:

$$d_{\text{cr}} = 2K\tau,$$

$$K = \frac{1}{1 - \dfrac{v}{D_2 \sin\alpha}} + \frac{1}{\dfrac{v}{C_2 \sin\alpha} - 1}. \tag{2}$$

In deriving formula 2 we assume that the reaction propagates into the depth of the charge as if from the point b', since the compressed explosive is displaced in the course of detonation with velocity U. The angle α is determined from the expression $\operatorname{tg}\alpha = \dfrac{v}{D-U}$, where D is the detonation velocity of the explosive, and U is the mass velocity of the substance behind the smooth shock wave 1. To calculate U, we assume that after the disappearance of the reaction at the shock front of the detonation wave, the elevated pressures corresponding to the

reaction zone disappear in a time much smaller than τ, so that their influence may be neglected. In this case, the detonation products in the Chapman-Jouguet state impinge with velocity U_{ev} on the fresh explosive, producing in it a shock wave with velocity D_{sh}. Using the acoustic approximation ([13]), we obtain:

$$U = \frac{2U_{\text{ev}}}{\frac{D_{\text{sh}}}{D} + 1}.$$

Solving this equation together with the known shock adiabat, we find U. To calculate C_2 it is necessary to know the equation of state of the explosive. Roughly, C_2 may be calculated under the assumption that the shock adiabat coincides with the isentrope of expansion, but this gives an overestimated value of C_2 and d_{cr}.

It has been shown that d_{cr}, determined from the study of the propagation of detonation in cylinders with a weak casing, coincides with d_{cr} determined from the transition of detonation from a tube with a strong wall (steel several mm thick) into a volume. This coincidence is understandable, since during the transition from the tube into the volume a wave of absence of reaction is likewise formed, a smooth shock wave arises, and a rarefaction wave arises, just as during the propagation of detonation through a charge without a casing; i.e., the phenomena near d_{cr} are analogous in both cases. The only difference is that, during the transition of detonation from a tube into a volume, the rarefaction wave lowers the parameters of the shock wave less than during expansion of the explosive with a free surface of the charge, since the expansion of the compressed substance then occurs at the expense of compression of the surrounding explosive in the volume. However, since the onset of reaction takes place in the unloaded region behind the smooth shock wave, this does not influence the magnitude of d_{cr}.

Expression (2), in contrast to (1), relates d_{cr} not only to kinetic parameters but also to the mechanical properties of the substance. Moreover, it follows from (2) that a situation is quite possible in which a kinetically more active substance, because of its mechanical properties (for example, compressibility), will have a larger d_{cr}.

According to formula (2), d_{cr} is a function of seven parameters, and not all of them are known with sufficient accuracy. A separate communication will be devoted to the calculation of d_{cr} by this formula. We shall only point out that a rough estimate gives, for NM, a value $d_{\text{cr}} \sim 50$ mm, in contrast to ~ 20 mm in the experiment.

It should be noted that in a strong casing detonation can propagate at diameters much smaller than d_{cr}. However, even in this case, as experiment shows, there exists a diameter below which detonation cannot propagate. This diameter is apparently associated with losses into the wall, the mechanism of whose

influence is not yet understood. The present communication is devoted to d_{cr} of a liquid explosive charge without a casing, and therefore, with regard to the second critical diameter, we shall confine ourselves to the following remark. Undoubtedly directly related to this phenomenon is the increase in the size of the inhomogeneities (x, see Fig. 1) observed by us as the diameter is decreased. It is possible that, as x increases, the pressure and temperature at the site of collision of oblique shock waves fall so much that the delay in the initiation of reactions then proves to be longer than the time during which this focus of elevated pressure and temperature has time to disappear under the action of rarefaction waves from neighboring weaker regions.

In conclusion, the author considers it a pleasant duty to express gratitude to Corresponding Member of the Academy of Sciences of the USSR K. I. Shchelkin and Ya. K. Troshin for their interest in the work and valuable comments, and also to V. S. Trofimov and O. K. Rozanov for discussion of certain points of the work during its preparation.

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Note: Figure translations are in progress. See original paper for figures.