EXTERNALLY ENHANCED DETONATION

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Detonation wave affected by the external energy source is studied numerically. Side expansion sharply reduces the effect of external power. The results can be understood considering the effective heat (reaction heat minus expansion losses) released before the Chapman-Jouguet point.

INTRODUCTION

In the detonation zone of high explosives (HEs) a substantial electrical conductivity arises (1–10 Ohm^{-1} cm^{-1}). The conducting zone width varies from $\sim$1 mm to several cm, depending on the HE sort and charge configuration[1–3]. The conducting zone and detonation products in the adjacent low-conducting region have rather good breakdown strength up to 100 kV/cm[4]. These features naturally lead to idea of electrical enhancement of the detonation wave.

In our experimental paper[4] the high electric voltage was applied to the charge of 3 × 5 mm cross-section which was placed between copper electrodes 2 mm thick and 10 cm long. The electrodes were properly isolated by mylar and PMMA to prevent a breakdown ahead of the detonation front. The results of one shot are shown in Fig. 1. After turning on, current and voltage across the charge increased gradually due to the circuit inductance. Maximal current was $\approx$ 15 kA. From the current onset (label 1 in the figure) till the final breakdown at 27 kV (label 2) the electric energy was released in the detonation zone. The streak record clearly demonstrates the luminous zone which appeared during the heating time behind the detonation front. The synchronous graph of the electric power is shown in the inset. The power developed by the explosive chemical reaction is $\approx$ 1000 MWt. So, an external source added about 40% of power in this experiment.

As a result, the detonation velocity D in the heated part was $\approx$ 7.3 km/s (normal velocity is 7.0 km/s), i.e., the relative increment of D was 3–4%. So, the electric effect is rather weak and barely detectable.

In the simplest case (an ideal one-dimensional wave, ideal-gas EOS) the detonation velocity $D \sim \sqrt{Q + \Delta Q}$, which is much stronger dependence (18% increase of velocity for $\Delta Q/Q = 0.4$). The detonation enhancement was treated by Tarzhanov[5] and Cowperthwaite[6] using various EOS. It was shown[5] that for realistic EOS the external effect on D becomes notably weaker, which can partly explain the experimental result.

Actually the electrical enhancement of detonation is not one-dimensional process. For the charges of modest cross-section, which can be affected in practice, the side expansion is clearly important. In the present paper the role of this expansion is studied numerically.

MATHEMATICAL MODEL

We assume that the side expansion is rather weak, and the transverse flow velocity can be neglected. So, quasi-one-dimensional approximation can be used in this case. The expansion is described by a single parameter—a relative cross-section of the flow tube A, which is initially unity. So, the Eulerian gas-dynamic equations take the form:

$$
\begin{aligned}
&\frac{\partial \rho A}{\partial t}+\frac{\partial \rho A u}{\partial x}=0,\\
&\frac{\partial \rho A u}{\partial t}+\frac{\partial \rho A u^2}{\partial x}+A\frac{\partial p}{\partial x}=0,\\
&\frac{\partial \rho A\left(\varepsilon+\frac{u^2}{2}\right)}{\partial t}+\frac{\partial \rho A u\left(\varepsilon+\frac{u^2}{2}\right)}{\partial x}+\frac{\partial p A u}{\partial x}\\
&\qquad +p\frac{\partial A}{\partial t}=\sigma E^2.
\end{aligned}
\tag{1}
$$

Here ρ is the density, u is the flow velocity, p is the pressure, ε is the internal energy, σ is the electrical conductivity of detonation products, E is the electric field strength and σE^2 is the external power per unit volume.

An additional equation for the side expansion is needed:

$$
\frac{\partial^2 A}{\partial t^2}=\beta(p-p_0),
$$

where β is the governing expansion parameter (the reciprocal effective mass of charge envelope) and p_0 is the external “atmospheric” pressure.

NUMERICAL PROCEDURE

Non-stationary, quasi-one-dimensional code was developed using Lagrangian variables. The front-tracking procedure was used evaluating the wave velocity at each time step. The code is similar to that described earlier[7].

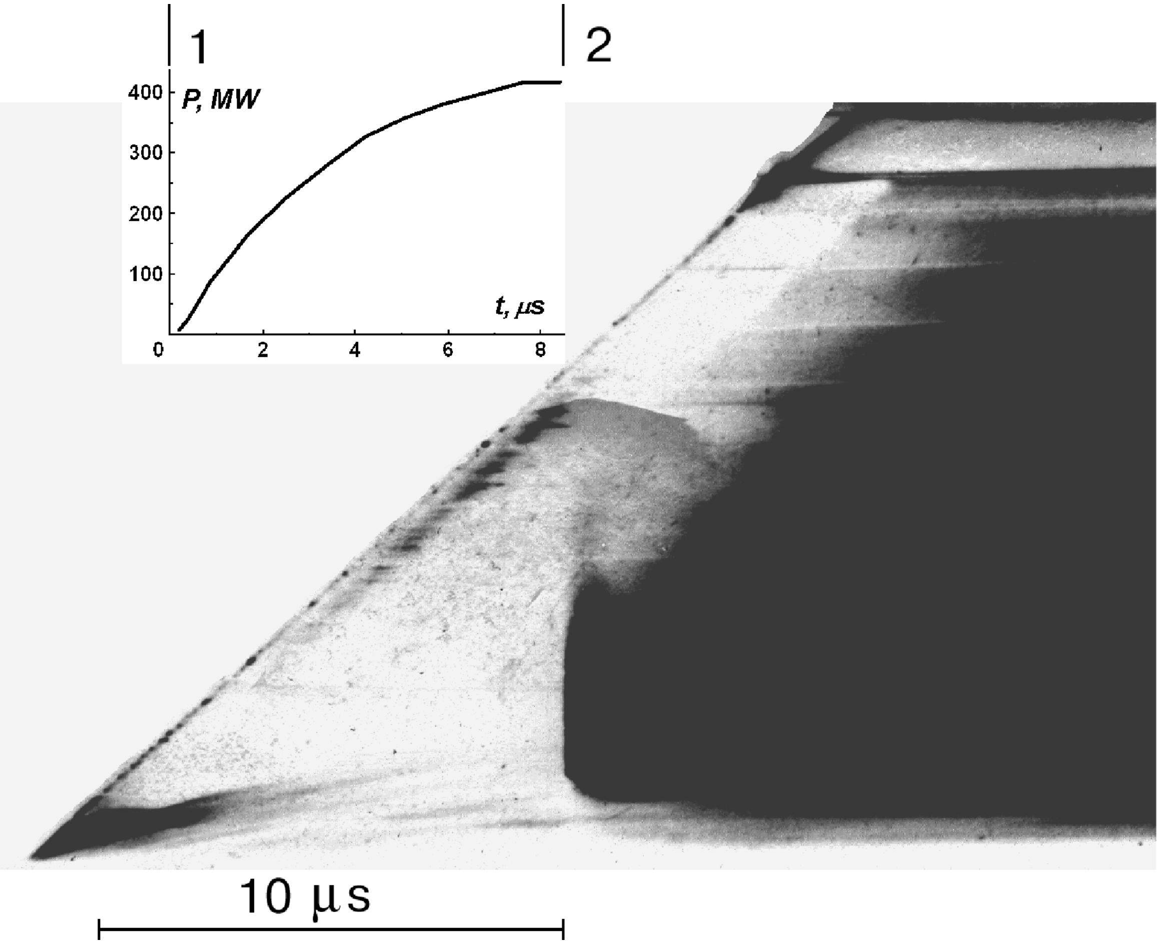

FIGURE 1. DETONATION OF THE SEMTEX PLASTIC AFFECTED BY THE EXTERNAL ELECTRIC POWER. THE SPACE BETWEEN VERTICAL MARKS IS 1 CM.

To isolate the expansion effect we used the simplest model assuming an ideal-gas EOS:

$$\varepsilon = \frac{p}{(\gamma - 1)\rho} + Q(1 - w)$$

with an adiabatic index $\gamma = 1.4$. The part of the chemical energy Q released within the reaction zone is described by the parameter w, which is equal to 0 at the detonation front and $w = 1$ after the completion of the reaction. The initial parameters were $\rho_0 = 1$ g/cm^3 and $P_0 = 1$ kbar. The latter figure, somewhat unusual, results from the EOS to provide reasonable initial temperature and sound velocity.

The chemical reaction started at the shock front. A model function of the energy release rate was used. The reaction rate in the Lagrangian point was set to be constant over the fixed time interval T_q (more exactly, near the end of this interval the rate smoothly fell down to zero):

if $t_r < 0.8T_q$ then $\dfrac{dw}{dt} = \dfrac{1}{T_q}$

else if $t_r < 1.2T_q$ then $\dfrac{dw}{dt} = \dfrac{1}{T_q}\cos^2\left(\dfrac{5\pi t_r}{4T_q}\right)$

else $\dfrac{dw}{dt} = 0$.

Here t_r is the time elapsed in the Lagrangian point after the detonation front ignited the reaction there. The reaction rate graph is shown in Fig. 2.

Initially a small part of the charge was shocked, and the reaction, once ignited, accelerated the wave further. The wave reached the stationary state after 10–20 T_q. The charge was 9 cm long and T_q was 0.6 μs. These parameters are close to the experimental ones[4].

RESULTS

As a test case we computed the detonation wave without expansion, i.e., for $\beta = 0$. Our results exactly reproduced the well-known "ideal" dependencies of detonation parameters on Q. Theoretical expression for D is

$$D = \sqrt{(\gamma^2 - 1)Q/2 + c_0^2} + \sqrt{(\gamma^2 - 1)Q/2},$$

where c_0 is the sound velocity of an unshocked gas. The results of computation are shown in Fig. 3 where Q varies from 0.5 to 8 kJ/g. The corresponding interval of D was 1.1–3.7 km/s, being below the range typical for real explosives because of EOS used. The theoretical line is also shown; one can see good agreement. Since $c_0 \approx 0.37$ km/s is small the $D\left(\sqrt{Q}\right)$ dependence is almost straight line.

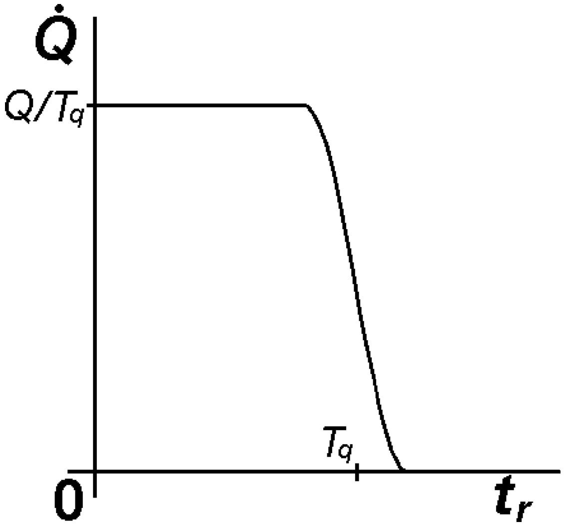

FIGURE 2. THE QUASI-CONSTANT KINETICS.

In simulations with expansion the wall inertia was adjusted to get $A = 1.2$, i.e., 20% side expansion in the Chapman-Jouguet (CJ) point for $Q = 5$ kJ/g. With expanding walls, the wave becomes generally weaker: see Fig. 4, line 1. The "ideal" dependence is represented by line 4. Also the slope of $D(Q)$ is less (about 0.59 times).

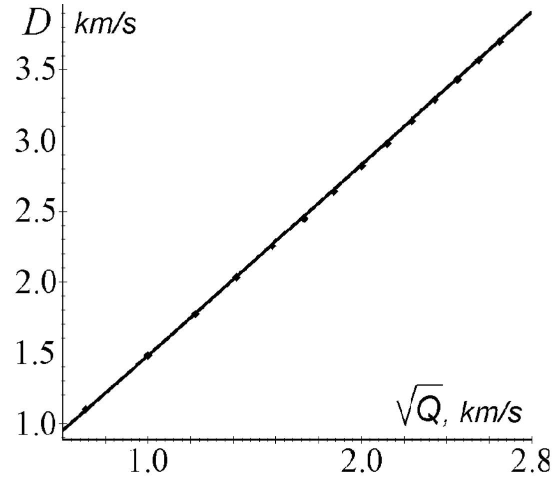

FIGURE 3. THE IDEAL DETONATION VELOCITY.

The increase of Q in the above calculations can be understood as an addition of electric ΔQ given that the electrically conducting zone and the chemical reaction zone are identical. The kinetics for this case is shown in Fig. 5 (the left graph).

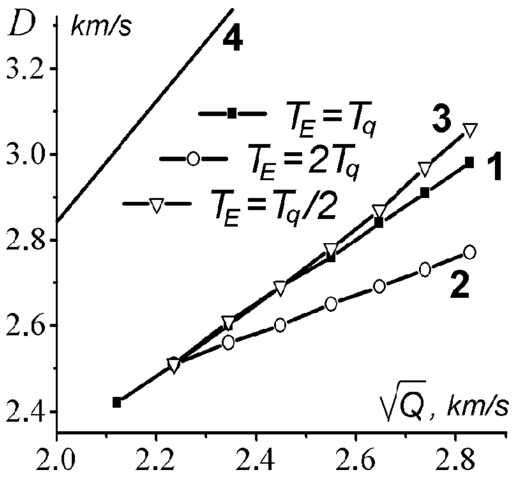

FIGURE 4. DETONATION VELOCITY VS. TOTAL HEAT RELEASE FOR DIFFERENT RELEASE TIMES.

Also the different zone widths were simulated, i.e., the ΔQ release period T_E was either two times longer or two times shorter than the main reaction time T_q; see the schematic kinetic graphs in Fig. 5 (center and right, respectively). The form of the additional "electric" term was the same as for standard kinetics. Starting from the standard $Q = 5$ kJ/g, we added ΔQ up to 3 kJ/g, i.e., 60%, in both cases. It turned out that for the fast electrical heating the wave acceleration is closer to the theoretical one, producing the D increment about 0.64 of the ideal value (Fig. 4, line 3). Prolonged heating is half as effective (Fig. 4, line 2).

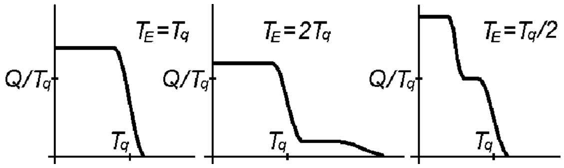

FIGURE 5. THE KINETICS FOR 40% EXTERNAL ENERGY, LEFT: $T_E = T_q$, CENTER: $T_E = 2T_q$, RIGHT: $T_E = 0.5T_q$.

The expansion influence on the detonation wave can be clarified considering two main effects: 1) the shift of the CJ point (in which $D = c+u$) into the normal reaction zone, so less chemical energy is released and 2) the energy losses accompanying the expansion. It was found that the latter effect is the most important one. The energy losses are effectively the work of expansion. From the gas-dynamic equations (1) written for a stationary wave one can obtain after some transformations an expression for the expansion losses Q_l:

$$\frac{dQ_l}{dx} = -\rho c^2 \frac{\partial \varepsilon(p,\rho)}{\partial p} \frac{1}{A} \frac{\partial A}{\partial x}.$$

So, the effective heat (chemical energy minus expansion losses) takes in the case of ideal gas the form:

$$Q_{eff} = Qw - \int \frac{\gamma p}{(\gamma - 1)\rho} \frac{1}{A} \frac{\partial A}{\partial x} dx,$$

where the integral is taken from the front backwards to the C-J point.

The recalculated dependencies $D(Q_{eff})$ are shown in Fig. 6. Here lines 1, 2 and 3 represent the same kinetics as in Fig. 4. All cases became quite close to each other. The lines for long and medium T_E almost coincide. Line 3 for the short release period is somewhat higher. Here the reaction zone (from the wave front to the Jouguet point) becomes substantially shorter which leads to comparatively smaller expansion losses.

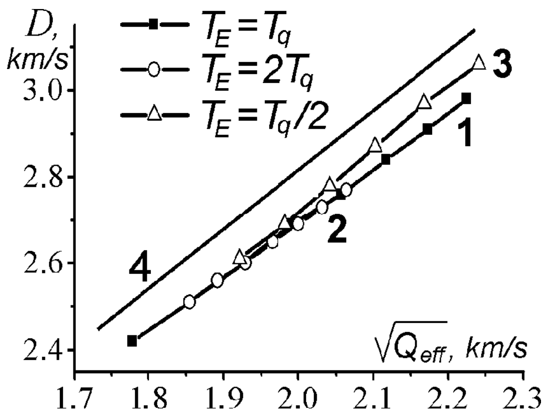

FIGURE 6. DETONATION VELOCITY VS. EFFECTIVE HEAT FOR DIFFERENT RELEASE TIMES.

All lines are almost parallel to the ideal line 4 (for which Q_{eff} coincides with Q). The difference in the D value is about 5% at $Q_{eff} = 4$ kJ/g.

So, the results can be explained considering the effective heat. Only the part released before the Jouguet point can enhance the wave. Note that we have not any theoretical proof that the effective heat should replace the regular heat. But the above results naturally lead to such suggestion, at least for small degree of expansion.

CONCLUSIONS

Even the modest side expansion seriously reduces the electric effect on the detonation wave. For the experiments[4] the conducting zone was wider than the zone of chemical reaction and the expansion alone can explain at least half of the discrepancy in the D increment. Since the real EOS works in the same direction, the small experimental value of ΔD is generally understood.

To get higher effect, the external energy should be released within the chemical reaction zone. This can be achieved by choice of explosive.

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DISCUSSION

Douglas G. Tasker
LANL

1. Other workers, e.g., Tasker and Cowperthwaite, have shown that D varies as $Q^{1/4}$, not $Q^{1/2}$. This must be because the conduction zone extends a long way behind the sonic point, e.g., for PBX-9501 100 ns vs. 1 μs.—can you comment?
2. Has Dr. Ershov tried larger sheets of explosive to reduce the effects of lateral rarefactions?

REPLY BY A. P. ERSHOV

1. I think that in a stationary one-dimensional wave being heated externally the sonic point will shift to the place where the total energy release is finished, i.e., to the end of the conduction zone. Thus for an ideal gas the final dependence should be $Q^{1/2}$. But the transformation of the near-sonic flow to this new stationary state will take a long time. So the ideal regime might not be observable practically.
2. We have reported the most interesting case in which the ratio of electric energy to the chemical one was the highest and the effect was most pronounced. You are right that for larger cross-section the rarefaction will be reduced, and such experiments are possible. Naturally, larger charge requires larger energy source. The most difficult thing is to increase the voltage (which is proportional to the charge thickness).