# Experimental and numerical investigation on interaction between gaseous detonation and solid explosive

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## *Introduction*

Ignition of solid explosive in typical conditions is well studied. There is a lot of data for deflagration and detonation of the solid explosive in literature. The kinetic properties of the materials were measured for relatively slow heating rates at low pressure or for extremely high temperatures and pressures behind detonation front in solid explosives. Unfortunately there is lack of data concerning the combustion of such materials under conditions which exist behind a gaseous detonation wave. In this conditions the explosive is very fast heated to temperature up to 3000 K, when pressure (in our experiments) is only in range of 3÷10 bar. These parameters places the process of ignition between conditions typical for deflagration and detonation of such explosive.

The interest in ignition of explosive behind the detonation wave comes from new idea of boosting a ram-accelerator by layer of solid explosive. Main advantage of this idea is utilizing energy stored in the explosive. The solid explosive has much higher chemical energy density than combustible gaseous mixtures. Combustion of explosive inside ramac tube should result in increase of pressure and thus producing the higher trust. The concept is more detailed described in [4, 5, 6]. The crucial parameters for such application is ignition delay and increase of pressure. They are the main subject of the research.

## *Experimental research*

The experiments were carried out by use of shock tube equipped with visualization section. The tube length is 3.5 m, and cross-section 35x35 mm. Driven section was filled with stoichiometric mixtures of oxygen and hydrogen with addition of helium. Explosion in driving section easily caused detonation in driven section, which was filled with oxygen-hydrogen mixtures at low pressures (0.2 bar). The compositions of mixtures were changed to obtain different detonation velocity and temperatures behind the wave front. The visualization section is shown in Fig.1. The layer of the solid explosive was placed on bottom wall of the section. Pressure was measured in front of layer (P1), over the

layer (P2) and under the layer (P3). Ignition delay was measured by means of streak photo. As a solid explosive were used PETN and HNM mixed with methyl methacrylate (plexi). Weight ratio of methyl methacrylate was 10%.

Measured ignition delays are shown as a function of reciprocal temperature (Fig. 2). For PETN there is good correlation and points can be well approximated by Arrhenius equation. Much more complicated situation there is for HNM. This material has minimum ignition delay for temperatures about 3000 K. Ignition delay for higher temperatures is longer what can be caused by changes in chemical composition of gases behind detonation front.

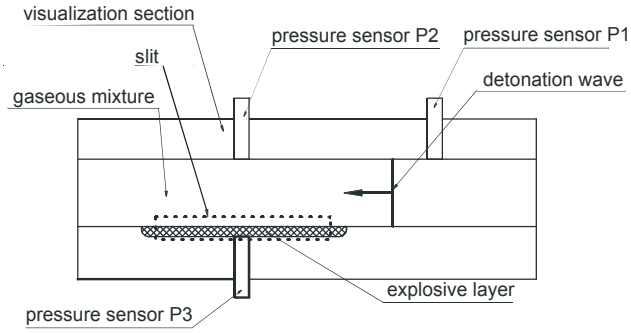



**Fig. 1. Scheme of visualization section.**

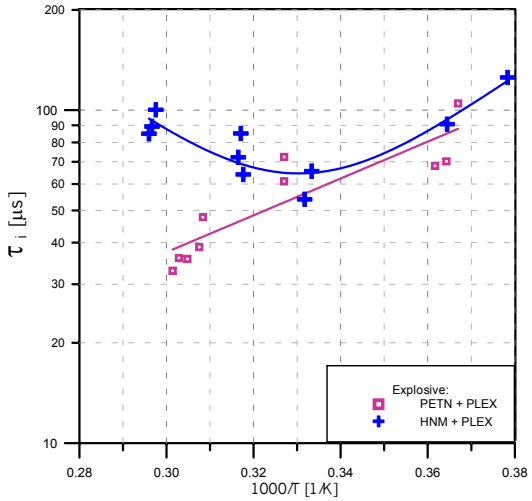
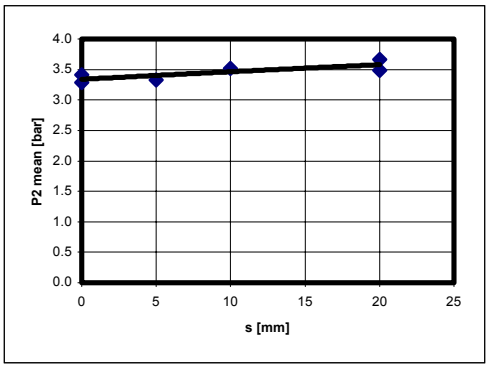



**Fig. 2. Ignition delay for solid PETN and HNM.**

Temperatures higher than 3000K are obtained in mixtures which have lower concentration of oxygen, what can also influence on ignition process. But weak point of this explanation is that HNM has excess oxygen in opposite to PETN which has small deficit of oxygen. Therefore the behaviour of HNM must be carefully studied in further experiments where composition of gaseous mixtures will have the same amount of excess oxygen at different temperatures.

The influence of combustion of explosive on pressure behind detonation front was also analyzed. Experiments showed that amount of released energy depends rather on surface (wideness) of layer than on thickness. Next graphs indicate these relation for mean pressures measured over the layer as the functions of layers parameters.

a) b)



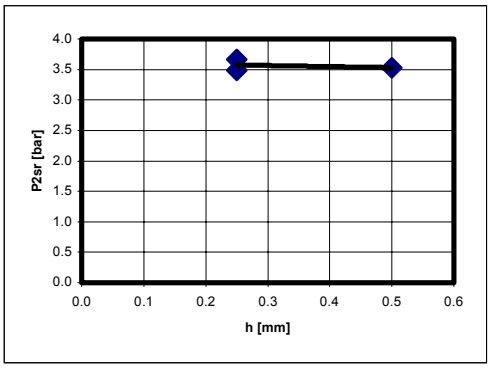




**Fig. 3. Mean pressures over the layer as a function of a) wideness, b) thickness**

## *Numerical simulations*

Heating of layer is the basic process for the ignition of explosive. Thus firstly simply model of heat transfer between detonation products and explosive layer was studied. In this work was used analytical approach proposed by Sichel et. al [2, 3]. The heat flux to the layer is calculated by using equation 1.

$$\frac{q_w}{\rho_1 u_s (h_r - h_w)}\left(\frac{\rho_1 u_s x}{\mu_e}\right)^{1/5} = -0.0366\left(\frac{\mu_m}{\mu_e}\right)^{1/5}\left(\frac{\rho_m}{\rho_e}\right)^{3/5}\left(\frac{u_s}{u_e}\right)^{3/5} Pr^{-2/3} \qquad (1)$$

The temperature profile inside the layer is described by heat equation, initial and boundary conditions (eq.2).

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial y^2} + \frac{Q}{\rho c_p}, \quad T(y=0) = T_{ambient}, \quad \lambda\frac{\partial T}{\partial y}\bigg|_{y=h} = q_w, \; T(t=0) = T_{ambient} \qquad (2)$$

Decomposition of the explosive and heat release is calculated from Arrhenius law (eq. 3)

$$\frac{dm}{dt} = -mke^{-E_a/RT} \qquad (3)$$

These relation and measured ignition delays were used in one dimensional model to determine activation energy and preexponential constant of PETN (PETN shows good correlations with Arrhenius law). The estimated parameters are: $E_a$=110.5 kJ/mol, k=12.761110E+19 $s^{-1}$.

Next the obtained kinetic properties of PETN was used to carried out two-dimensional simulation of propagation of a detonation over the explosive layer. The interaction between the layer and detonation was introduced as complicated boundary condition with heat and mass transfer. To calculated the gaseous detonation a TDV scheme developed by T. Fujiwara, M.H. Lefebvre and J. Leblanc was used [1]. Heating and decomposition of explosive was described by heat equation and Arrhenius low. First result are shown in the next figures (Fig. 4, Fig. 5). Most important information from numerical simulation is that only very small part of layer is heated and is decomposed. It is in good qualitative agreement with experiment where thickness of layer (0.25 or 0.5 mm) do not play important role in pressure increase much more important is wideness (surface) of the layer.

## *Conclusions*

Experiments proved that solid explosives can be applied in high velocity propulsion like ram-accelerators. Ignition delays are relatively short. Pressure increase is significant (as compare to the gaseous mixture only) and can be higher if surface of explosive will be increased. Numerical simulations gave deeper look inside the process. Comparison between simulation and experiment allowed creating first simple model of ignition, and can be very useful in future application.

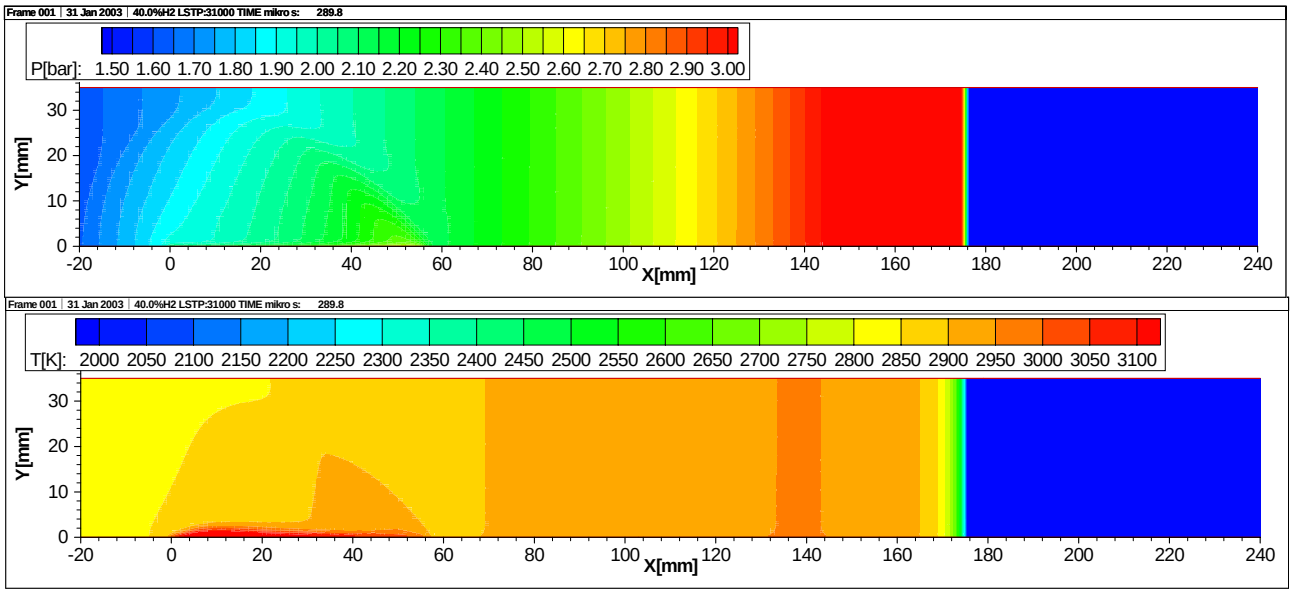



**Fig. 4. Numerical simulation of detonation propagating over explosive layer: pressure and temperature.**

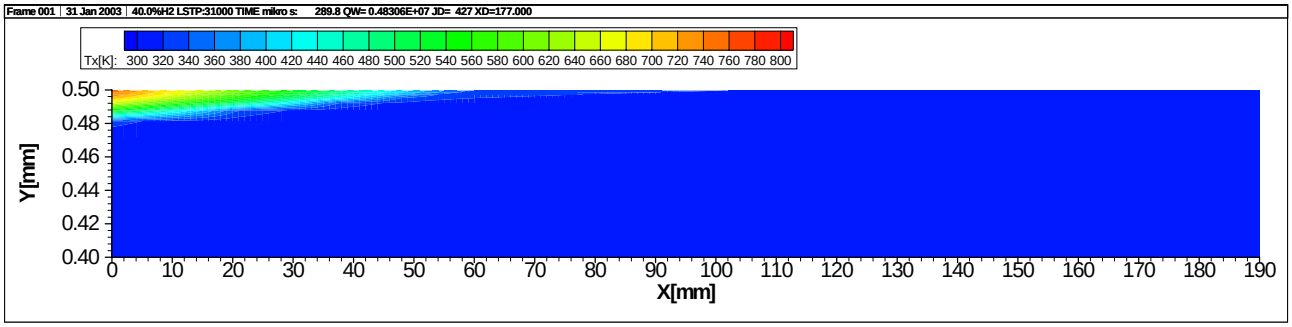



**Fig. 5. Numerical simulation of heating of PETN layer (there is only upper part of the layer 0.1 mm)**

## *References*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