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Initiation of PETN Detonation by an Impactor and a High-Enthalpy Gas Flow

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Abstract: This paper compares two methods of near-threshold initiation of a loose-packed PETN charge: by impact of a plate and by injection of an intense flow of hot gases into the powder. Synchrotron diagnostics of material density was used. Both methods lead to the development of detonation in about 10 μs, but the nature of initiation differs sharply. Initiation by an impermeable piston involves the formation of a dense plug of compressed material. After some delay, a wave is formed at the front of this plug which initiates chemical reaction and accelerates to normal detonation. For high-enthalpy initiation by a hot gas flow, the compression of the powder is low and the process develops in the gas-permeable material, starting from the stage of rapid convective combustion followed by transition to detonation.

Keywords: initiation, detonation, combustion, deflagration-to-detonation transition.

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INTRODUCTION

The classical scenario of deflagration-to-detonation transition (DDT) for powdered explosives described in, e.g., [1] consists of the following basic stages. Initially, slow layer-by-layer combustion occurs in the vicinity of the igniter. As the pressure increases, combustion propagates into the pores, resulting in much more rapid convective combustion, whose propagation velocity reaches hundreds of meters per second. Acceleration of the wave creates conditions under which compression of the material causes significant chemical reaction and the formation of a low-velocity detonation wave, which in turn develops into a normal detonation wave. Since the initial stage of layer-by-layer combustion is slow, this process takes a significant (compared with typical detonation) time—about hundreds of microseconds—and, therefore, occurs upon ignition of explosives enclosed in strong confinement.

In a number of studies [2–6], we investigated the initiation of porous explosives by a high-enthalpy gas flow. The flow was produced by electrical explosion of a wire or by breakthrough of combustion products from a separate chamber after diaphragm rupture or by gas-detonation product flow. In all these situations, the scenario of detonation was the same: explosive particles were ignited by a hot gas flow, resulting in rapid convective combustion with an initial velocity of about 1 km/s, which developed to normal detonation in about 10 μs. This acceleration of DDT is explained by elimination of the slow stage of layer-by-layer combustion. Since this time is much smaller than the time of typical classical DDT, a strong casing is not required. Detonation can be achieved for a charge diameter starting from several millimeters. In particular, initiation is possible within the scale of a standard detonator.

Recently new results obtained using synchrotron radiography [7, 8] have confirmed these concepts. To synchronize the process with the operation of the accelerator generating synchrotron radiation (SR), the initiating gas flow was generated by explosion of a small active explosive charge. The flow parameters behind the air shock wave incident on the investigated charge were similar to those achieved with the above-described methods of initiation, resulting in the same dynamics of the process. Thus, the shock wave in air generated a

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gas state with high enthalpy sufficient for ignition of the powder after penetration of the flow into the pores. The mechanical impact of the air wave was of secondary importance. Note that similar conclusions were expressed by Belyaev et al. [9] in a study of the detonation transmission through an air gap. According to [9], the gas penetrating into the pores ignites explosive particles. If the injection is sufficiently vigorous, combustion does not die out and is then accelerated by the gas released in the reaction, producing detonation also in about 10 μs. An initial stagnation pressure of the initiating flow of several hundred atmospheres is sufficient for successful initiation.

This pressure is much lower than is required for shock-wave initiation (see, e.g., [10, 11]). The smooth front of the propagating wave and the weak compression of the material in it [2, 4] are also distinguishing features of high-enthalpy initiation as compared to shock-wave initiation. However, during initiation by a weak shock wave, the time of detonation development can also be about several microseconds, which suggests that these processes are similar in nature.

An approach close to shock-wave initiation (see a review [12]) is the one in which deflagration-to-detonation transition occurs in the absence of an igniter—an explosive charge is impacted by a piston moving with a velocity of about 100 m/s. The motivation for this approach was the desire to obtain a more controllable one-dimensional process. The authors identify a scenario different from the classical one [1] and called it DDT of type 1: the impactor first compresses the powder, resulting in the formation of a dense region, which is then relatively slowly expanding. Ignition starts at the interface between the explosive and impactor, after which the compression is accelerated and an almost impermeable plug occurs within the compressed region. Acceleration of this plug by combustion products leads to the formation of a shock wave in the compressed powder, which then produces into a detonation wave. Certain skepticism has been expressed regarding the classical scenario, especially the convective stage, although convective transport in the longitudinal channels formed in the powder by the gas pressure is assumed to be possible, especially at low charge density.

Therefore, it is of interest to make a direct comparison between initiation by a high-enthalpy flow and initiation by an impermeable impactor. For comparison, it is required to maintain, as far as possible, the same experimental conditions. This paper presents the results of such experiments using synchrotron radiography. Density diagnostics from SR absorption is a nonperturbing method for conducting observations in the test material. By comparing two approaches under, as far as possible, identical experimental conditions, one can most clearly distinguish between the processes specific to each approach.

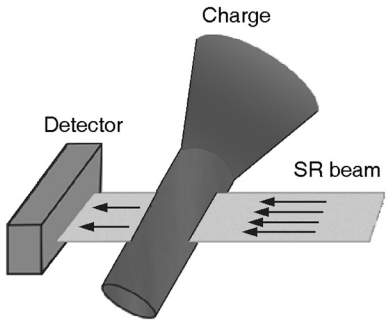

Fig. 1. Geometry of the experiment.

EXPERIMENTAL

As in [8], we investigated a loose-packed PETN charge 16 mm in diameter and 25 mm long (density 1 g/cm^3) in a thin plastic shell. The particle size of the explosive was ≈0.3 mm. In the case of high-enthalpy initiation, the open face of the charge was subjected to the hot gas flow produced by explosion of a PETN charge. In the case of initiation by an impactor, an aluminum plate accelerated by the active charge impacted the porous explosive. The initiation dynamics was examined by synchrotron diagnostics. The test charge was scanned by the SR beam from a VEPP 3 accelerator (Siberian Center of Synchrotron Radiation). The beam absorption is determined by the mass on the ray path, and in the simplest case, by the product of the density and the thickness of the sample (ρd). In a rather rough approximation (neglecting the side expansion of the sample), the ray-averaged density can be determined from the profiles of ρd. The cross-sectional area of the of SR beam was 20 × 0.1 mm. The radiation was detected by a linear gas detector with a spatial resolution of 0.1 mm. Longitudinal radiography was used (Fig. 1). In this case, the compression waves propagating in the charge were directly observed. For high-enthalpy initiation, lateral radiography data in a number of cross sections of the charge have been obtained previously [8].

The active charge was selected so as to produce near-threshold initiation. Detonation in both variants developed in approximately 10 μs after the initial impact.

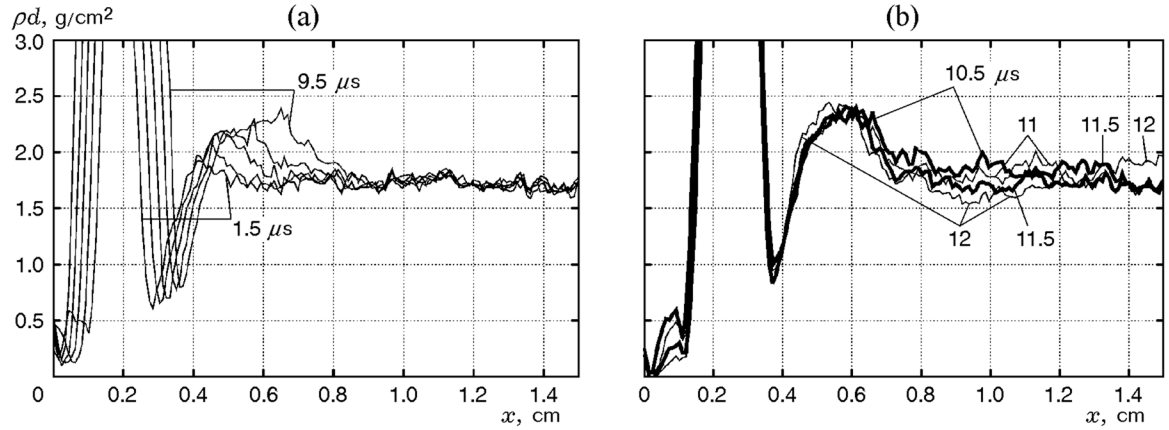

Fig. 2. Near-threshold initiation by an impactor: (a) interval 1.5–9.5 μs from the time of contact of the impactor and the charge (the gap between the profiles is 2 μs); (b) final stage of initiation (the gap between the profiles is 0.5 μs).

EXPERIMENTAL RESULTS

During initiation by the gas flow, the hot gas penetrates into the porous charge and ignites the particles near the boundary of the charge, and during initiation by the impactor, the external gas flow is eliminated and the reaction in the condensed phase is caused primarily by mechanical deformation of the powder.

Figure 2 shows the mass dynamics on the ray during initiation of a PETN charge of density 1.05 g/cm^3 by an aluminum impactor—a plate 1.5 mm thick. The impactor was accelerated by the gas pressure produced by explosion of a small explosive charge located at a distance of a few centimeters. The impactor velocity was close to the critical value of 125 m/s. The high (off-scale) peak on the left corresponds to the impactor. Since the plane of the SR beam is horizontal, the axis of the charge is also horizontal in longitudinal radiography. A layer of foam of density ≈0.2 g/cm^3, which did not prevent the acceleration of the plate, was placed between the end of the charge and the impactor to fix the charge face. In the profiles of ρd, the dip on the right of the impactor corresponds to this insert; next follows the portion corresponding to the charge itself.

First (Fig. 2a), a dense plug is formed, whose dynamics if very slow (front speed of about 400 m/s). Reactions in the plug and subsequent expansion of the material do not occur—on the contrary, the density increases. Neglecting the lateral expansion, the plug density increases by a factor of approximately 1.4, i.e., at least to 0.83 of the crystal theoretical maximum density (TMD). However, by the time $t \approx 10$ μs, a wave is formed at the leading edge of the compressed region, and is rapidly accelerated to ≈3 km/s (Fig. 2b, time interval of 11.0–11.5 μs). By the time $t = 12$ μs, the wave front goes beyond the observation region. In the last two profiles, one can see a decrease in the density behind the wave front caused by gas-dynamic expansion of the material, which is a feature of chemical reaction. Within the compressed plug, there is still no noticeable reaction (the density of the material does not decrease), while the plug is slowly shifted to the left by the pressure of the reaction products.

In the experiment described above, the impactor was accelerated until interaction with the explosive sample. In a somewhat simplified formulation, the impactor was placed close to the charge and was thus itself a fixing boundary. In this case, the impact on the powder was smoother and the compression front in the powder propagated more slowly. The results of such an experiment are shown in Fig. 3a. The compressed plug can be seen at the time $t = 3$ μs (shown by an arrow). Here an initiation wave also occurs and it is much faster: in the interval of 5–7 μs, its average velocity reaches 3 km/s. At $t = 7$ μs, one can clearly see the gas-dynamic expansion due to chemical reaction, as well as the backward displacement of the impactor by the pressure of explosion products.

In some experiments, to prevent breakthrough of the gases accelerating the impactor, we used an impactor of larger diameter, which was also placed close to the charge. The results are shown in Fig. 3b. In this case, the shell of the charge is also deformed by the impactor and the increase in the mass on the ray path in the near zone ahead of the impactor is due to the accumulation of the shell material. This makes it more difficult to distinguish the compressed plug of the explosive. Nevertheless, it can be seen from Fig. 3b that in the initial stage, the compression wave front is near

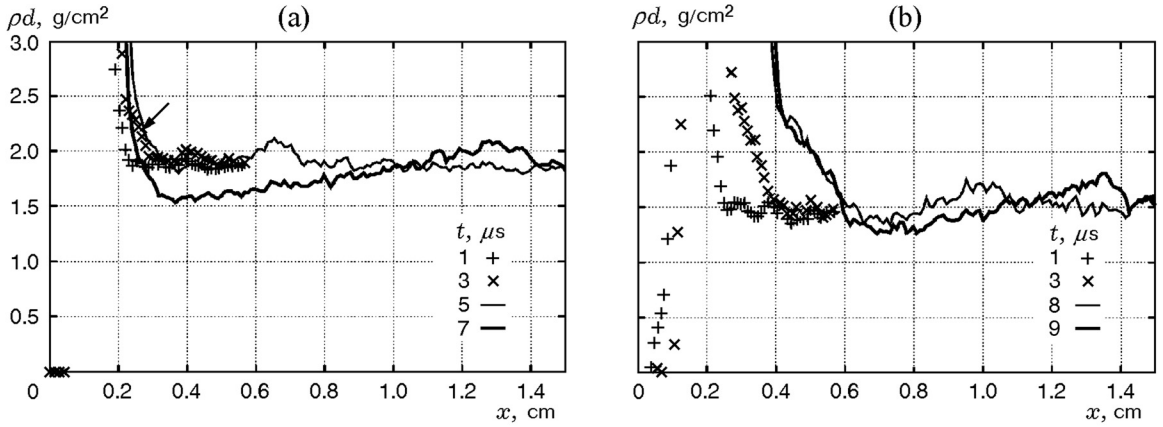

Fig. 3. Near-threshold initiation by an impactor located close to the charge: (a) the diameter of the impactor equal to the diameter of the charge; (b) the diameter of the impactor is greater than the diameter of the charge.

the impactor for 2–3 μs and its velocity is not greater than 600 m/s at an impactor velocity of ≈120 μ/s. In the interval of 3–5 μs, an individual wave front begins to separate from the general shock ahead of the impactor, followed by acceleration of the front. In both cases shown in Fig. 3, the initiation wave became separately distinguishable and began to accelerate markedly at a depth of about 4 mm.

It can be concluded that the initiation by a weak compression wave occurs as follows. The impactor produces a dense plug of compressed powder, which expands at a velocity of several hundred meters per second. In a few microseconds, a compression wave followed by a significant chemical reaction is separated from the front of the plug. A normal detonation wave develops in about 10 μs. This pattern is most pronounced in the setup corresponding to Fig. 2.

Initiation by high-enthalpy flow occurs in a completely different way. The experimental setup was, as far as possible, similar to the above, but instead of the aluminum impactor, the hot air flow produced by explosion of a small active charge of PETN was used as the initiating agent. Naturally, this charge was smaller than that required to accelerate the impactor, and was chosen so as to ensure the development of detonation within the same time—about 10 μs. This was achieved at an incident air shock wave velocity of 2.6 km/s, which corresponds to a flow velocity of 2.2 km/s. At the impact on the boundary of the test charge, the gas pressure was ≈70 MPa and the temperature was ≈5000 K.

The results of this experiment are shown in Fig. 4. Initially (Fig. 4a), the wave velocity is 500 m/s. The compression of the powder at this stage is insignificant—about 17%. However, in the interval of 7.5–8.5 μs (Fig. 4b), the average velocity of the compression front increases to ≈3.5 km/s, and these profiles show the gas-dynamic expansion due to chemical reaction. Consequently, in the interval of 5.0–7.5 μs, the wave becomes self-sustained and is accelerated by the reaction behind the front. The normal detonation velocity under our conditions (≈5 km/s) is established in another 1–2 μs. In contrast to experiments with impactors, in this setup, reaction is also observed in the compressed region adjacent to the end of the charge (local maximum ρd lowers over time). In this case, ignition is obviously caused by the action of the gases penetrating into the powder. The presence of gases (both injected from the outside and released in the combustion) reduces the compressibility of the medium, which is responsible for the slight deformation at the beginning of the process.

Note that in Fig. 4b, the profile corresponding to 5 μs is strongly smeared, which complicates the identification of the wave front. As shown by more detailed measurements, including those using cross-sectional radiography [8], the wave front in this stage is markedly curved and is therefore substantially smeared in the longitudinal projection. This is illustrated by the tomographic images extracted from the entire set of SR data shown in Fig. 5. In the intermediate time $t = 5$ μs, both the curvature of the front and the density distribution behind it contribute to the smearing of one-dimensional longitudinal profiles. At a smaller time, e.g., at $t = 3$ μs, these effects are weaker. At later times ($t = 8$ μs), the noticeable non-one-dimensionality in the outer part of the charge is compensated by the formation of a strong compression wave with a slightly curved front in the axial part.

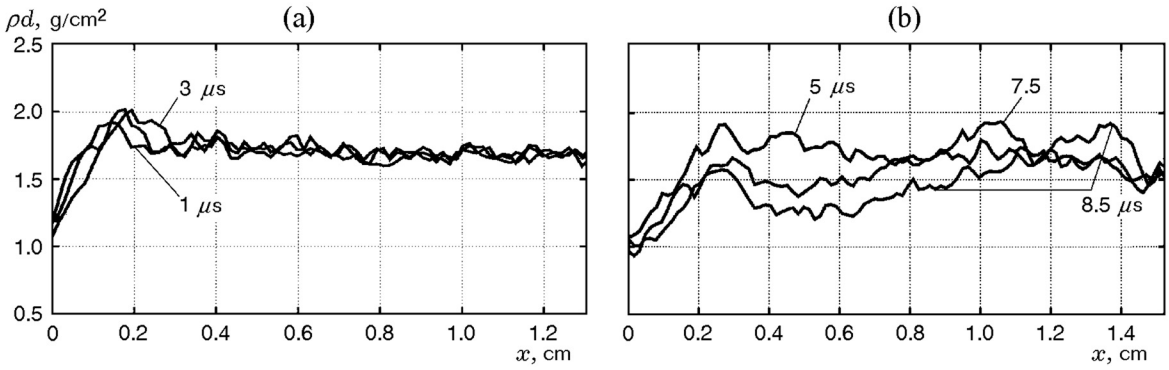

Fig. 4. Near-threshold initiation by high-enthalpy flow.

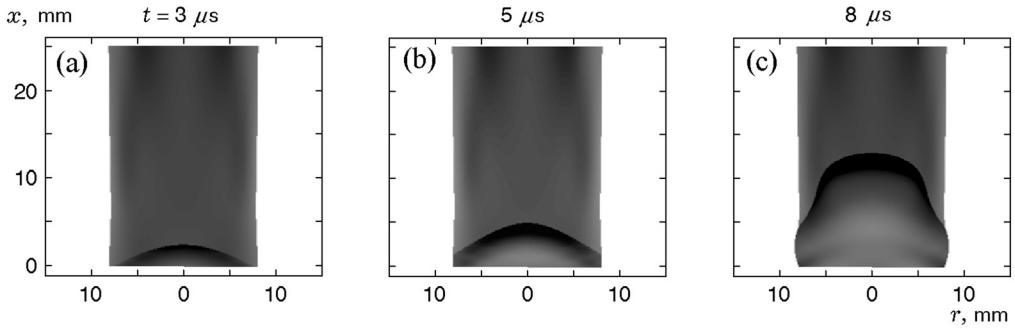

Fig. 5. Two-dimensional density distribution obtained from SR data in high-enthalpy initiation.

Despite the indicated complications of the interpretation, it can be argued that during the entire period of observation of the high-enthalpy initiation, there is no significant compression of the material, unlike in the case of initiation by the impactor (cf., for example, Figs. 2 and 4). Therefore, in the initial stage, the porous bed retains high gas permeability, which allows the development of rapid convective combustion.

DISCUSSION OF THE RESULTS

In the case of initiation by the impactor, the experimental setup is similar to that described in [12]. The sequence of events generally fits into the scenario described in [12] as DDT of type 1. Although some details of this process (such as slow combustion in the vicinity of the impactor or the occurrence of a thin monolithic plug) were not resolved in our experiments, the basic scheme looks quite acceptable. The difference is the more rapid dynamics of the process: instead of hundreds of microseconds in [12], detonation in our experiments developed in ≈10 μs. With such a small time, there is no need for a strong steel shell which is commonly used in studies of DDT, i.e., inertial confinement of the charge is quite effective.

Note that in [12] and a number of papers cited there, the use of an impactor or a piston is considered to be preferred over conventional ignition as the latter can lead to the formation of voids in the powder—channels through which gases can break. In our view, the advantages of such a choice are exaggerated. They reduce to the one-dimensional interpretability of the experiment, which is achieved at the cost of moving away from the natural DDT conditions. Non-one-dimensionality, in particular channels, obviously enhances the possibility of detonation and therefore should not be excluded only for reasons of convenience. Since the main goal of the study of DDT is to improve safety in handling explosives, the one-dimensionality of the process is not a determining factor of the study, the more so as it is attained with great effort.

Initiation by the high-enthalpy gas flow is very different from initiation by the impactor. The compression of the powder is insignificant until the last stages of the process. The process begins with rapid convective combustion, which goes over into detonation if the initial impact is intense enough. Here the slow stage

of layer-by-layer combustion characteristic of ignition starting at a pressure of the order of atmospheric pressure is eliminated. For this reason, the transition fits into 10 μs and does not require a strong shell. The rapidity of the transition also prevents any substantial three-dimensional effects such as the formation of channels.

Thus, despite the superficial similarity in kinematics, the two methods of initiation have fundamental differences that were identified using synchrotron diagnostics.

Numerical simulation of the convective process [8] gave qualitative agreement with the experiment. The effect of the injection of a hot gas flow on a porous powder charge was modeled previously in [13]. It is interesting that at a much lower rate of injection (of order of 10 m/s), that work also reproduced a process that develops according to the convective "gas-compression" scenario, although it was slower (hundreds of microseconds) and hence required a strong shell. This implies that convective initiation regimes can be implemented in a wide range of parameters.

In conclusion, it should be noted that a high-temperature initiating flow may occur, for example, during the breakthrough of a gas from a closed region into a powdered explosive. Gas parameters sufficient for rapid DDT can be obtained, in particular, dynamically inside a volume bounded by a layer of compacted powder. This indicates the possibility of unexpected explosions in the absence of any confinement and similar conditions, which are typically considered necessary for the development of detonation.

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