Mechanism of Deflagration-to-Detonation Transition in High-Porosity Explosives

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Abstract

This work represents the key results of a complex investigation of deflagration-to-low-velocity detonation transition, carried out for granular nitrocellulose propellants confined in steel tubes. The transition occurs according to the mechanism in which the detonation wave rises upstream of the convective flame front in the unburnt explosive column. Experiments were performed employing a combined technique that comprises simultaneous optical and piezometric monitoring of the process. The details of the flame trajectory and the space pressure profile are discussed. Precompaction of the explosive material ahead of the flame front leads to stabilization of the flame propagation, explosive particle movement, and a decrease in the pressure rise rate. Before the onset of detonation, the explosive density ahead of the flame front approaches the theoretical maximum value, and the particle velocity increases up to 200 m/s. The distance to low-velocity-detonation onset is proportional to the initial particle diameter. Experimental results are compared with the numerical modeling. Fairly good agreement is obtained for explosive performance. Limits of applicability of modern theory of convective burning are determined. Essential deviations of the theory from the experimental data are found to exist for fine explosives [i.e., in the case of picric acid and pentaerythritol tetranitrate (PETN)]. Deflagration-to-detonation transition (DDT) in the explosives occurs via formation of a strong secondary compresssion wave in the combustion zone downstream of the flame front. The detonation occurs when this secondary wave overtakes the leading flame front. Criteria are derived to distinguish between the two mechanisms of DDT considered.

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Introduction

The results of the recent investigation by the authors on the deflagration-to-detonation transition (DDT) in porous explosives are systematized. Particular attention is given to the mechanism and regularities of the propagation of an unsteady-state convective burning and its transition to a low-velocity detonation (LVD) [Sulimov and Ermolaev (1986); Sulimov et al. (1987); Belyaev et al. (1973)].

The experimental data on convective burning development are compared with the results of the numerical modeling. The quantitative criteria are established, making it possible to distinguish between the conditions under which two types of DDT are realized.

Experiments were made with nitrocellulose grain charges contained in strong confinements. The initial grain size varied from 0.6-3.3 mm. Porosity of charges was near 0.45. The complex experimental technique enabled the simultaneous optical and piezometric recording of the process up to the initiation of a low-velocity detonation (Fig. 1). Nitrocellulose grains were placed into the cylindrical channel of a thick-wall confinement of 15 mm i.d. and 200-800 mm long. On one end the confinement was closed with a plug in which an igniter was mounted; the other end carried a plug with a membrane. Pressure measurements (up to 1 GPa) were provided by high-frequency piezoelectric pressure gages described elsewhere (Belyaev et al. 1973). Such pressure gages (up to 8 pieces) were located along the confinement, one of them being near the igniter. The process was optically recorded either

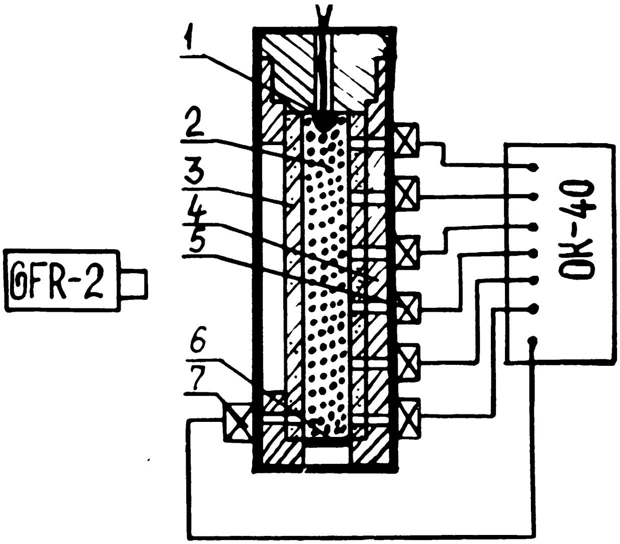

Fig. 1 DDT transparent pipe test configuration. 1: Igniter; 2: explosive; 3: Plexiglas pipe; 4: steel tube with slit; 5: pressure gage; 6: membrane; 7: photodiode.

through a transparent unit consisting of a Plexiglas cylindrical tube inserted into the ground channel of the steel confinement with a longitudinal slit or through a number of small-diameter radial holes drilled in the encasement. Synchronization of piezometric and optical measurements was provided by a photodiode positioned in the same section as a piezoelectric pressure gage. Signals from pressure gages were displayed on the screen of an eight-ray oscilloscope (OK-40); the process was photographed with a streak camera (GFR-2).

The following characteristics were determined: the distance traveled by the flame front (glow front) and its velocity, the movement velocity of burning explosive grains near the flame front, spatial-temporal pressure profiles, and the distance in which the transition from convective burning to low-velocity detonation occurred.

The results obtained can be summarized as follows [Sulimov and Ermolaev (1986); Sulimov et al. (1987)]:

1) There are two stages of convective burning: an accelerated process and a stabilized process. In the latter stage, despite an exponential rise in pressure in the combustion zone, the flame velocity is approximately constant, being about 400-500 m/s (Fig. 2). Increasing the grain size or decreasing the conductive combustion velocity with an inhibitor leads to a decrease in the pressure gradients and an increase in the length and duration of both stages. However, the flame velocity at the stage of steady-state convective burning remains almost constant.

2) The spatial pressure profiles in the convective burning wave represent flat steps with steeply rising regions in which the flame front is localized. As time passes, the step height and the steepness of the rising

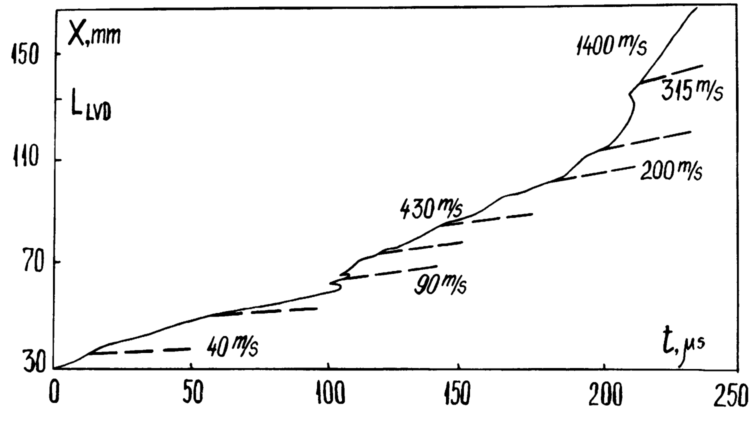

Fig. 2 Sketch of streak camera data of DDT (type 1) for nitrocellulose, grain size 0.8 mm. Solid line, luminous front, (numerical value is velocity of the front); dashed line, tracks of igniting grains near the flame front (numerical value is the grain movement velocity).

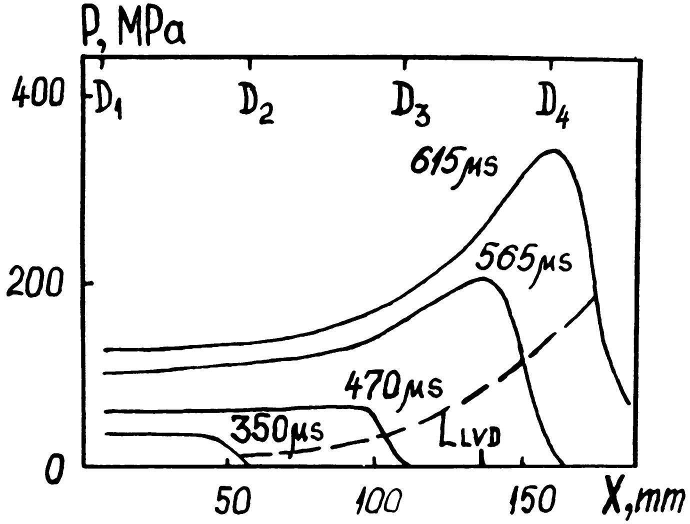

Fig. 3 Evolution of experimental spatial pressure profiles, nitrocellulose, grain size 0.8 mm. D_i, place of the pressure gage (numerical value is time of process). Dashed line, trace of luminous front.

region become large, and a "hump" appears near the flame front. This hump increases and then passes into a triangular peak when transition to a low-velocity detonation occurs (Fig. 3).

3) The pressure in the combustion zone near the igniter rises nearly exponentially, with a characteristic time proportional to the time constant calculated from the law of pyrostatics. For charges of gravimetric density, the coefficient of proportionality is equal to 1.5-2, regardless of grain size.

4) Compaction of the explosive material in the layers immediately before the flame front leads to flame velocity stabilization resulting from a decrease in the gas permeability of these layers. It also leads to a lower rate of pressure rise and to grain movement with increased velocities that amount to about 200 m/s immediately before the transition to a low-velocity detonation.

5) The distance within which the DDT occurs varies in direct proportion to the initial grain size (Fig. 4). The transition mechanism belongs to the first type in which the detonation wave is formed before the flame front in the "nonburning" explosive.

Convective burning was numerically modeled (Ermolaev et al. 1985) to better understand the mechanics of two-phase reacting media underlying the model. The following assumptions were made: 1) a detailed chemical kinetics of ignition and combustion reactions has no appreciable effect on convective burning, and the evolution of the process is mainly determined by the physiomechanical regularities of

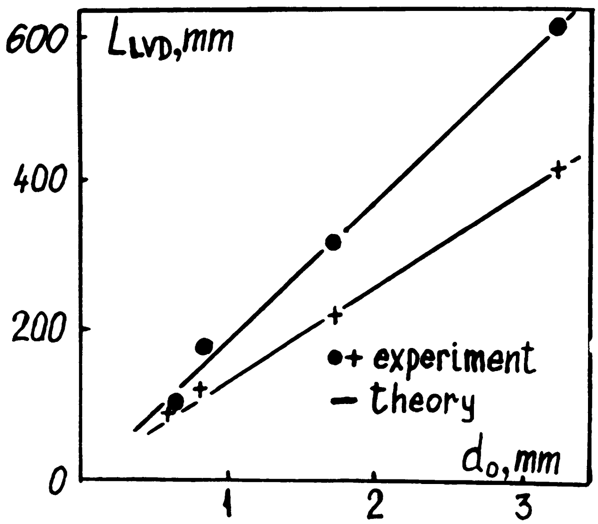

Fig. 4 Distance of the low-velocity detonation onset as a function of the initial grain size for nitrocellulose of two different levels of conductive combustion velocity. +,● Experiment; Dashed line, theory.

Table 1 Parameters used in numerical modeling of convective combustion

Properties		
Physical and geometrical for porous medium	Thermophysical and thermodynamic	Physiochemical
Effective grain size, porosity Charge length Constants in the filtration law Compressibility	Corresponding constants of explosive and combustion products Combustion heat Constants in the law of interphase heat exchange	Ignition temperature Constants in the law of conductive combustion velocity

the motion of a reacting two-phase mixture; and 2) after ignition, combustion proceeds all over the internal surface of the porous explosive (which depends on the degree of dispersion), with a regression rate equal to the velocity of steady-state conductive combustion.

The preceding assumptions enable the number of parameters used for numerical modeling to be restricted (Table 1).

The numerical modeling results were compared with the experimental data for nitrocellulose. As distinct from earlier works in which comparison was fragmentary (Devis and Kuo 1979), this comparison (Sulimov et al. 1987) was made with respect to a set of characteristics that include the x-t diagram of the flame-front travel, the velocity of travel of burning grains near the flame front, pressure change at the ignition zone, and the pre-low-velocity--detonation distance, which was determined by the instant collapse of pores in the compression zone before the flame front. Good quantitative agreement between the theory of convective burning and the experimental observations was found (see Fig. 4). The mechanism of energy transfer in the wave was refined, and the dynamics of substance compression was investigated in detail. The "traditional" mechanism of convective heating based on the transfer of the energy released in the combustion zone by the filtration stream of hot gases (the "leading" filtration mechanism in which the velocity of gases in pores is higher than the flame velocity) is found to play a decisive role, but not at very high velocities and pressures. At flame velocities above 150-200 m/s and a grain size of about 1 mm, another mechanism of the convective heating of the pore surface is realized in which the leading role belongs to gasdynamic dissipative processes that accompany a high-velocity friction of gases on the pore walls.

Earlier investigations [Belyaev et al (1973); Korotkov et al (1969)] and flash radiography [Sandusky and Bernecker (1985)] demonstrated that the explosive density in the compacting zone (ahead of the flame front) approaches a maximum (porosity tends to zero) immediately before detonation. The calculated values of the pre-low-velocity-detonation distance determined by the instant of the complete collapse of pores coincide with the experimental values for

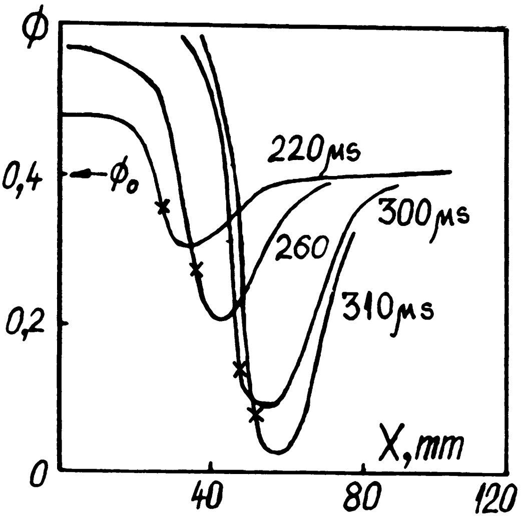

Fig. 5 Evolution of porosity profiles for nitrocellulose, grain size 0.4 mm, theory (~~Belyaev et al 1973~~). x, Flame-front location.

nitrocellulose charges with different grain sizes. Taking into account the evolution of pressure profiles (Fig. 3) and of porosity profiles (Fig. 5) and the data on shock-wave sensitivity of porous explosives (Soloviev 1977), we can conclude that it is the compression of a porous body accompanied by energy accumulation on the pore surface that is the main source of formation of hot spots during DDT. To make the DDT model closed, it is necessary for a detailed mechanism of formation of reaction sites to be involved, e.g., the mechanism of viscoplastic heating during deformation of pores (Khasainov et al. 1981).

The comparison of the theoretical conclusions with the experimental findings made it possible to determine the applicability limits of the convective burning model. Essential deviations from theoretical predictions were found in the case of explosives whose grains were less than 50-100 μm in size because of the incompleteness of ignition of the grain surface in the flame front. In this case DDT proceeds by the second mechanism: an intense secondary pressure wave (Ermolaev et al. 1985) is formed in the combustion zone, and when it overtakes the flame front (Sulimov and Ermolaev 1986), a detonation wave (Belyaev et al. 1973) arises (Fig. 6).

The concept of two types of DDT was first advanced in works devoted to a study of DDT in fine-grained PETN [Belyaev et al. (1973); Korotkov et al. (1969)] and was then considered by Bernecker and Price (1974). Using the literature data [Sokolov and Aksenov (1963); Bernecker et al. (1976)] and findings from our laboratory for fine-grained PETN, tetryl, and picric acid [Sulimov and Ermolaev (1986); Belyaev et al. (1973); Korotkov et al. 1969)], we have found the quantitative regularities that permit us to distinguish between the two types of DDT.

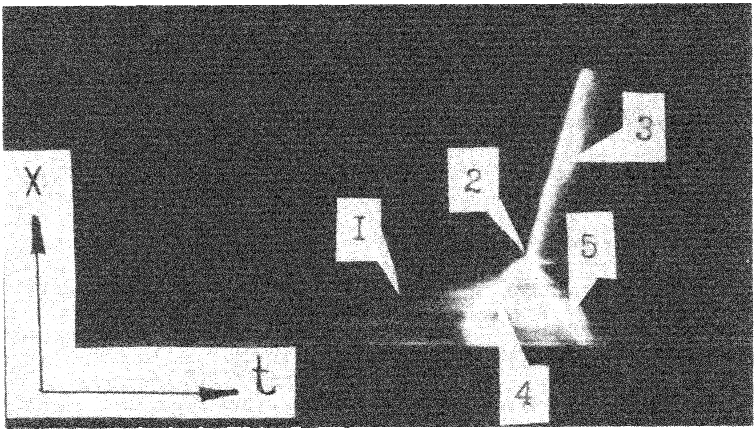

Fig. 6 Streak camera data of DDT (type 2) in fine PETN (Korotkov et al. 1969). 1: Convective burning front; 2: detonation onset; 3: detonation wave; 4: secondary wave; 5: detonation wave.

The first type of DDT studied in detail in the previously mentioned experiments on coarse-grain nitrocellulose (grain size at least 0.6 mm) is characterized by the following features: 1) a pronounced and regularly reproducible flame front corresponding to the convective burning can be observed on the photographs obtained with the streak camera; 2) the pressure in the combustion zone rises at a rate close to that predicted by the mathematical modeling, assuming the complete surface combustion of the explosive grains behind the flame front; and 3) the pre-low-velocity-detonation distance varies approximately in proportion to the grain size. The characteristic features of the second tytpe of DDT are as follows: 1) no pronounced regular flame front can be observed in the photographs obtained during convective burning, and the glow represents a set of separate nearly horizontal bright streaks; 2) the rate of pressure rise, up to the moment of the appearance of the secondary wave, is considerably lower (1-2 orders) than the calculated one that corresponds to the ignition of the complete grain surface; and 3) the fineness of the explosive makes the explosion development difficult and leads to an increase in the predetonation distance.

These features make it possible to explain the difference in the character of explosion development by the fact that during convective burning under certain conditions the flame does not penetrate into the small pores, and most of the explosive surface is not ignited. As a result, the flame propagates only through large pores (Belyaev et al. 1973). As the pressure in the combustion zone rises, the favorable conditions are created for convective ignition of small pores when the critical pressure is reached, the combustion surface increases sharply, and the secondary wave with a high pressure rise rate appears. Thus, the type of DDT is determined by the physical state of an explosive rather than by its nature. Depending on the grain size and charge density, both types of transition can be realized with the same explosive (Korotkov et al. 1969). This concept differs from that of American investigators (Bernecker et al. 1982), who connect the difference in the DDT mechanism only with the nature of explosives.

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