Experimental investigation of detonation waves instabilities in liquid high explosives

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Abstract. Experimental investigation of unstable detonation front structure in mixtures of liquid high explosives (nitromethane and FEFO—bis-(2-fluor-2,2-dinitroethyl)-formal) with inert diluents (acetone, methanol, DETA—diethylene triamine) has been carried out. Inhomogeneities have been registered by electro-optical camera NANOGATE 4BP allowing to make 4 frames with the exposure time 10 ns. According to experimental results the detonation front in nitromethane–acetone mixture is unstable. It is evident that pulsations on detonation front do not form spatial periodic structure and their dimensions differ several times. But mean longitudinal size of pulsation is about 500 $\mu$m at 20 wt% of acetone concentration. This means that the typical size of cell equals to reaction zone width. The same structure of cellular front have been registered in 70/30 FEFO–methanol mixture. Second kind of instability, failure waves, was observed in neat nitromethane at the free surface. In this case the stability loss result in turbulent flow which is clearly detected in the shots obtained. Adding small amount of DETA (0.5 wt%) results in disappearance of the failure waves and flow stabilization. The effect is caused by the fact that DETA sharply accelerates initial rate of chemical reaction because it is sensitizer for nitromethane.

1. Introduction
Detonation waves are propagating both in the stationary and the unstable (pulse) mode in homogeneous high explosives [1–5]. The two types of the instabilities can be distinguished: the instability of one-dimension flow (cellular structure of the detonation front) and the instabilities of the flow at the edge of the charge (the failure waves) [6]. Many laws of the appearance and development of instabilities of detonation waves in liquid HE has not yet been studied. In work [6] triple wave configuration formed as the result of instability development is suggested for the description of the flow.

The most striking feature of this configuration is that the main part of HE reacts in the transverse detonation waves which are propagates in shock-compressed unreacted matter. But the question of universality of this configuration in any unstable detonation front is still open. Currently the use of the methods with high spatial and time resolution allows us to expect the possibility of obtaining experimental results which may concretize conception of the structure of unstable detonation waves in liquid HE. To this end in this work experimental investigation of the structure of instability of detonation front in HE mixtures (nitromethane and FEFO—bis-(2-fluor-2,2-dinitroethyl)-formal) with inert diluent (acetone, methanol, diethylenetriamine).
Figure 1. The experimental setup.

Figure 2. Photograph of nonstable detonation front in mixture nitromethane–acetone 80/20.

Registration of the instabilities was carried out with the high-speed camera Nanogate 4BP which had let us to get 4 frames with exposure time 10 ns.

2. Cellular structure of the detonation front

Luminescence of instable detonation front is nonuniform, thus registration of self-luminescence allows us to get information about cellular structure of the detonation front, average size of cells, character of its evolution during propagation of the wave. Corresponding experiments were carried out high-speed camera Nanogate 4BP with following characteristics: minimal exposure time—10 ns, matrix resolution—1389:1024 px, spatial resolution—no less than 100 µm.

Figure 1 schematizes the experimental setup. Investigated HE 1 was placed into the shell 2. Initiation of detonation was produced by the charge of phlegmatized RDX 3. Luminescence of the detonation was sent to the camera by the use of the turning mirror 4. The figure 2 shows the results for the mixture HE (nitrometane–acetone) 80/20. Diluent content is expressed in weight percent. In this case the still shell with the internal diameter 36 mm and wall thickness 2 mm was used. Registration was started in the moment when the detonation wave was at 87 mm from the initiation charge. One can see that luminescence is consisting from light and dark spots, i.e. instability of detonation front leads to formation of cell structure. The spots are arranged randomly; any periodic structure is absent. Its character size is about 400 µm.

With the rise of acetone concentration character size of impurities is increasing. Figure 3 shows the luminescence of the detonation front at 30 wt% of diluent, that is the limiting concentration for this mixture [6]. The fist snapshot, figure 3(a), was made at 89 mm from the initiation charge, the second, figure 3(b), at 1 mks after the first. Stationary regime is not establishing in this case, the detonation wave is attenuating and this is followed by the growth of impurities to the size more than 5 mm. Its form is also changing. If in figure 3(a) impurities
Figure 3. Evolution of impurities during the propagation of attenuated detonation in mixture nitromethane–acetone 70/30. Picture (b) was made in 1 µs after picture (a).

has developed corrugated border, then after a microsecond edges are smoothed and impurities take shape close to an oval.

Instability of detonation front occurs not only in mixtures of liquid HE with inert diluent but in individual HE too. The example is FEFO, instability in which was found during the registration of mass velocity profiles by interferometer VISAR [7]. Estimation is showing that the longitudinal dimension of the impurities is less than 100 µm, which is close to the limit of spatial resolution of the optical scheme used in this work. That is why the luminescence of the detonation front in FEFO is homogeneous with such spatial resolution. A feature of this powerful explosive is not non-increasing size of instabilities and, moreover, stabilization of detonation front upon dilution with methanol in the concentration range from 10 wt% to 15 wt%. Only with a further increase in the methanol concentration the front losing the stability again and the size of instabilities starting to grow. Figure 4 shows the picture of luminescence of detonation front in mixture FEFO–methanol 70/30. Impurities are clearly visible. It should be noted that the character of impurities it shapes noticeably different from registered in mixture nitromethane–acetone (figure 2).

3. Failure waves
The difficulty of investigation of described above instability of one-dimensional detonation front is caused, first of all, by the absence of distribution periodicity of arising impurities. The instability of three-dimensional flow at the edge of charge has been studied to a lesser extent [6]. Quasi-periodic process includes reaction breakdown which caused by rarefaction waves, growth of thickness of layer of shocked HE and its subsequent explosion. The process is observed while detonation propagates in confinement having higher stiffness than one of the HE. The process is also observed while detonation wave moves from stiff confinement to a tube of larger diameter. Breakdown phenomenon at the edge of charge is named failure wave by authors [6].

In present work the registration of failure waves has been carried out according to scheme similar to one shown in figure 1. At that, the mirror 4 has absent and the steel confinement 2
Figure 4. Photograph of nonstable detonation front in mixture FEFO–methanol 70/30.

Figure 5. Exit of the detonation wave to the volume in nitromethane–diethylenetriamin mixture 99.5/0.5.

(20 mm in diameter) has been attached to a the bulk of larger diameter with transparent walls. The transition of detonation from confinement to bulk has been observed laterally using optical camera. If inner diameter of confinement is less than failure diameter of the HE under study, then the detonation wave attenuates after transition to bulk. Otherwise the detonation spreads to the entire volume. At that the dynamics of wave evolution is determined by presence or absence of failure waves. In the first case the detonation monotonically attenuates or spreads the entire volume. Whereas in the second case the flares of shocked HE at the periphery of the detonation wave is observed.

An illustration of stable spread of detonation to entire volume is shown in figure 5. In this case the nitromethane–diethylenetriamin 99.5/0.5 mixture has been investigated. Amines are sensitizers for nitromethane [8] and even its negligible adding sharply diminishes nitromethane failure diameter and stabilizes instability of flow at the edge of charge. So the detonation wave spreads to the entire volume without any oscillations. In the figure the time measured...
Quite different nature of flow is observed for nitromethane and the results of the study are shown in figure 6. After detonation wave transition into the bulk (zero nanosecond) lateral rarefaction wave diminishing the pressure behind the shock front accounting for chemical reaction breakdown. As a result the diameter of plane part of detonation wave shrinks and on the sides propagates a shock wave in HE without chemical reaction (50 ns). After a time, which is equal to induction period the thermal explosion, takes place at separate points in shocked HE. An exit of wave of reaction initiating by the thermal explosion to the border of shocked HE has been detected in the vicinity of detonation wave (figure 6, 500 ns). Subsequent emergence of new reaction centers, there development and interaction determines the dynamics of detonation wave propagation and spread (figure 6, 1000 ns and 1500 ns). As in the case the detonation wave originated in shocked HE catches the attenuating detonation front before its collapse—the detonation spreads to the entire volume [6].

The method of registration of flow instability at the border of detonation wave and shocked HE fulfilled in present work is more informative in comparison with traditional method for observation failure waves by the use of streak camera [6].

Figure 6. Exit of the detonation wave to the volume in nitromethane.
4. Concluding remarks

The obtained results not only provide a visual representation of the flow character in the unstable detonation waves, but also allow checking the accuracy of the existing ideas about the structure of cells, formed during loss of stability. As already noted, it is believed that the cells represent the triple-wave configurations in which detonation transformation occurs primarily in the transverse waves. The main part of HE in this process is shock-compressed but does not react [6]. If this model is correct, then on the pictures of the detonation front dark spots (shock-compressed matter) surrounded by bright borders (transverse detonation waves) must be seen. In fact, as may be seen at figures 2 and 3 cells are radiate with high intensity and separated with dark borders in nitromethane–acetone mixture. The character of luminescence of detonation front in FEFO–methanol (figure 4) is still less corresponds to that model.

According to the author’s investigations [6, 9] the amplitude of instabilities is ten times smaller than transverse dimension, i.e. for nitromethane–acetone 80/20 mixture is not more than 50 µm. The character width of the chemical reaction zone for this mixture is less than 400 µm [9]. Therefore, it can be argued that the observed detonation front pulsations reflect current disturbance within the reaction zone, i.e., on the surface of the detonation front the fields of shock-compressed unreacted explosive are absent. The triple waves configurations are still take place, but all three waves intersect at break point are detonation waves, shock waves without energy release directly after the jump are absent.

The information about failure waves shown on figures 5 and 6 is also of interest. In the case of study detonation process the flow has cylindrical symmetry. One would expect that thermal explosions in shock-compressed matter will also take place on a circle or at least show this trend. Nothing like that was observed in experiments. Thermal explosives take places in separate points and it leads to violation of cylindrical symmetry. Thus, applied in this paper method of recording the structure of unstable detonation waves significantly expands the possibilities of obtaining experimental data needed to test existing theoretical concepts and the development of adequate models of detonation.

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