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ON THE DETONATION FAILURE DIAMETER OF THE DINA/ACETONITRIL SOLUTION

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The 68,5/31,5 wt % transparent solution of solid DINA in liquid acetonitril has been under investigation. The minimum shock pressure (7,4 GPa) to initiate the solution's detonation, the detonation velocity (from 5,78 till 6,10 km/s in the range of charge diameters from 52 till 150 mm), CJ pressure (8,7 GPa for 52 mm charge diameter), chemical spike pressure (10,7 GPa for 52 mm charge diameter) and width (0,45 mks) as well as the value of failure wave velocities have been measured experimentally. The failure waves originating under the effect of rarefaction waves at the detonation's transition from cylindrical charges of copper confinement through a sudden enlargement of the confinement's diameter have been observed from the butt-end of charges with a high-speed optical camera. It has been found that at small change of the detonation velocity for all charges used the value of failure wave velocities decreases with diameter considerably. Interpretation of all data obtained leads to the conclusion that the solution's detonation front is kinetically stable and that the detonation failure diameter is presumably about 200 mm.

INDRODUCTION

It is well know that the value of failure diameter of any condensed explosive charge along which the explosive's detonation can still propagate steadily d_{fc} depends on the charge confinement's properties and thickness. In regard to liquid explosives it was found out in the late sixties[1] that the failure diameter tube from which liquid explosive's both stable and unstable detonation could transfer into a larger volume of the same explosive depended neither on the material, nor the thickness of the tube's wall. In this case the tube's failure diameter coincided with a good degree of accuracy with the detonation failure diameter d_f of the same explosive charge of a thin cellophane confinement. The intent of the study performed was to measure d_f of a solid explosive solution. No investigations of the kind are known; this is undertaken for the first time.

EXPERIMENTAL

The 68,5/31,5 wt % transparent solution of solid DINA[2] (diethanolnitramindinitrat, $C_4H_8N_3O_6$, monocrystal density ρ_0 = 1,67 g/cm^3, heat of explosion 1250 kcal/kg) in liquid acetonitril (D/A) has been under investigation, DINA's content in the solution

being close to its maximum at room temperature. Acetonitril (C_2H_3N) was used with initial density ρ_0 = 0,783 g/cm^3 and refraction index 1,3442 which did not different from the data available in literature.[3] All experiments were performed not later than twenty-four hours after the preparation of the solution's batch. The solution's density (ρ_0 = 1,198 g/cm^3) and refraction index (1,4325 – 1,4335 for different batches) measured at room temperature beforehand did not changed during some days. The data testified that the solution was chemically stable. The solution's stability was additionally monitored by acetonitril's distillation off the solution at 40^{0}C temperature. After the distillation DINA reminded intact; it did not differ by weight and melting temperature from the starting substance.

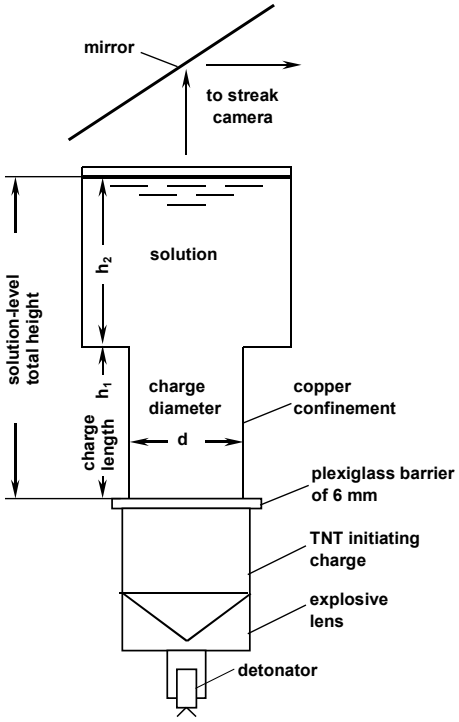


FIGURE 1. SHEMATIC VIEW OF THE EXPERIMENTAL SET-UP TO OBSERVE THE LUMINESCENCE OF ON-COMING DETONATION FRONTS.

The transition of the solution's detonation from cylindrical charges of 0,5 mm thick copper confinement (see Figure 1) of 52, 100 and 150 mm diameter into a much larger volume through a sudden enlargement of the tube diameter has been investigated with the help of a high-speed streak optical photo-camera. Figure 2 represents by way of illustration the picture obtain by computer scanning of the streak camera recording of the on-coming detonation's luminescence of 52 mm diameter charge. With the initiating charge used the solution's detonation originates immediately at the entrance of the initiating shock into the solution. With known sizes of both the solution's charge and the recording obtained (d – charge diameter, d_1 – the width of the detonation front luminescence image on the film corresponding to the detonation propagation along the solution's charge h_1, and lengths l_1, l_2) as well as the streak camera's writing speed a and angle α measured recordings of the kind enable to calculate velocities of both the detonation D and failure waves V:

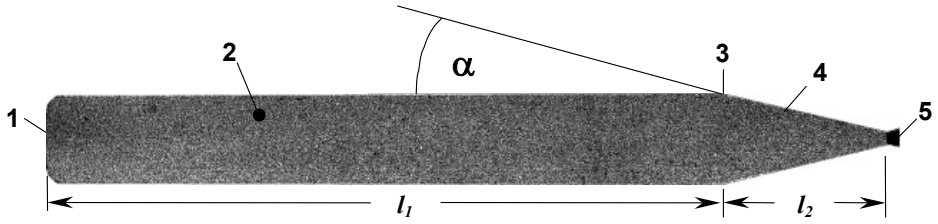
$$D = a \cdot \frac{h_1 + h_2}{l_1 + l_2} \ ,$$

$$V = \frac{D}{k} \cdot tg\alpha \ ,$$

where k- the streak camera reduction factor equals to d/d_1.

In addition to the measurement of D and V the solution's detonation wave particle velocity time profile $U(t)$ has been registered by the electromagnetic technique. The scheme of the experimental set-up is shown in Figure 3. Electromagnetic gauges of 10 mm working part have been made of a strip of duralumin foil of 10 mm width and 0,1 mm thickness, working parts locating 100 mm apart from the plexiglass barrier/solution's interface. The gauges had an additional shoulder 21 mm apart

from their working part. The shoulder being drawn into motion by the detonation front



1 – the solution's detonation origin; 2 – the solution's detonation luminescence; 3 – the moment of the detonation's transition from the copper confinement into a larger volume and the failure wave appearance; 4 – failure wave; 5 – the bright luminescence of the detonation products escaping from the charge open surface into the air; l_1 – the recording part corresponding to the detonation propagation along the first part h_1 of the solution's charge; l_2 – the recording part corresponding to the detonation propagation within the second part h_2 of the solution's charge (in this very part the detonation's front diameter is reduced under the effect of failure waves 4 originating at the detonation transition from the first part h_1 into the second one h_2).

FIGURE 2. SCHEMATIC VIEW OF EXPERIMENTAL STREAK-CAMERA RECORDING OF THE ON-COMING DETONATION FRONT LUMINESCENCE OF 52 MM DIAMETER CHARGE.

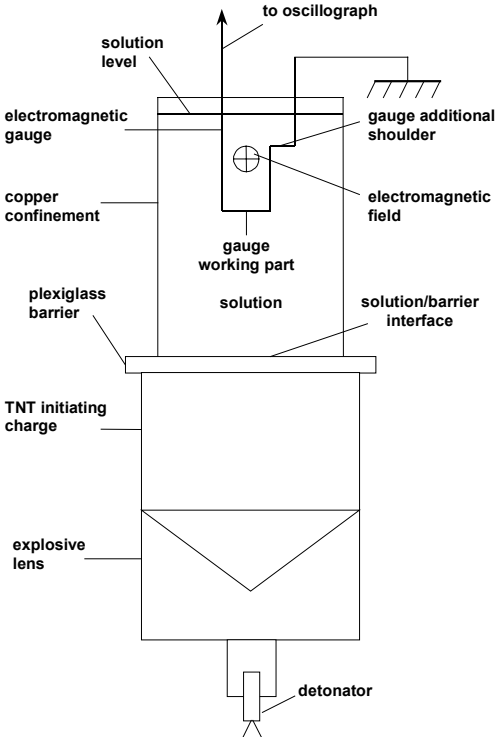


FIGURE 3. SCHEMATIC VIEW OF THE EXPERIMENTAL SET-UP TO REGISTER THE SOLUTION'S DETONATION WAVE PARTICLE VELOCITY TIME PROFILE.

gives an additional jump of electromagnetic signal and so provides possibility to perform an additional measurement of the solution's detonation velocity. TNT charges of 1,59 g/cm^3 density and 60 mm height, have been used to initiate the solution's detonation, the charges' diameter slightly exceeding the diameter of solution's charges. Figure 4 is an

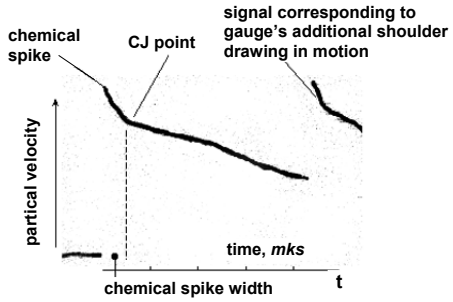


FIGURE 4. EXPERIMENTAL OSCILLOGRAM OF THE SOLUTION'S DETONATION WAVE PARTICLE VELOCITY TIME PROFILE.

oscillogram of the solution's detonation wave particle velocity time profile. It should be mentioned that the oscillogram enables to

calculate particle velocity with the precision ~ 3 %, and to evaluate time width of chemical spikes with the precision ~ 20 %.

The particle velocity time profile registered enables to calculate the solution's detonation wave pressure of both the wave's chemical spike $P_{CS} = \rho_0 D U_{CS}$ and the wave's *CJ* point $P_{CJ} = \rho_0 D U_{CJ}$, as well as the *CJ* sound velocity $C_{CJ} = D - U_{CJ}$.

The minimum shock intensity to initiate the solution's detonation has been found with the help of an experimental set-up analogous to that represented in Figure 1. In this case only initial part of the charge (75 mm diameter) was used, its height being equal to some sm. The solution's selfignition under the effect of shocks has been observed with the streak camera. The shock intensity was varied by changing of TNT initiating charge density and the plexiglass barrier thickness. For the minimum shock intensity still capable to initiate the solution's detonation the electromagnetic gauge with an additional shoulder 10 mm apart from its working part was located by its working part at the plexiglass/solution's interface (see Figure 3). It enables to determine the shock pressure through simultaneously measured both the shock's front and particle velocities.

RESULTS AND DISCUSSIONS

The solution's detonation velocity measured for charges of 52 mm diameter is equal to 5,78 ± 0,05, for 75 mm – to 6,00 ± 0,02, for 100 mm – to 6,12 ± 0,05, and for 150 mm – to 6,07 ± 0,05 km/s. The data testify that for charges of smaller than a 100 mm diameter the velocity shows evidence of a slight dependence on the diameter's value.

The solution's detonation wave particle velocity time profile *U(t)* has been measured with charges of 52 mm diameter (see Figure 3). Two experiments have been performed. It has been found that the wave's chemical spike particle velocities are equal to 1,53 and 1,54 km/s, the wave's *CJ* particle velocity U_{CJ} – to 1,24 and 1,28 km/s, and the wave's chemical spike time t_{CS} for both experiments – to ~ 0,45 mks. The data enable to calculate the following values of P_{CS} = 10,7 GPa, P_{CJ} = 8,7 GPa, C_{CJ} = 4,52 km/s.

It turned out that the maximum value of time delay (> 4 mks) of the shock compressed solution's selfignition at the plexiglass/solution's interface has been observed with the shock ~ 7,40 GPa pressure. The pressure has been calculated through the shock's front (4,48 km/s) and particle (1,38 km/s) velocities measured. The shock intensity (7,40 GPa) should be considered as the minimum one necessary to initiate the solution's detonation in these conditions.

As for the failure wave velocity is concerned its very first value (3,37 km/s) measured for 52 mm diameter charge turned out to be greatly unexpected. The matter is that a certain confidence there was that the solution's detonation was kinetically unstable. Really, it is well known that usually the weaker liquid explosive in power, the more kinetically unstable its detonation front.[4] And the D/A's solution in its heat of explosion (~ 856 kcal/kg), detonation velocity (5,78 km/s) and pressure (P_{CJ} = 8,7 GPa) is rather weak liquid explosive. It is substantially weaker than, for example, nitromethane (NM) which heat of explosion is equal to ~ 1080 kkal/kg,[5] detonation velocity – to 6,3 km/s and pressure P_{CJ} – to ~ 13 GPa.[4] The solution is comparable in its power with NM/acetone 75/25 Vol % mixture which heat of explosion is equal to ~ 810 kcal/kg, detonation velocity – to 5,75 km/s and pressure P_{CJ} – to ~ 9,1 GPa.[6] However, the detonation front of both pure NM and its mixtures with acetone is kinetically unstable.[4] The explosive's transformation into detonation products is carried out within the front of

unstable detonations by the mechanism of local adiabatic thermal explosions (ATE) of the shock-compressed explosive (SCE) of approximately P_{CJ} pressure.[4] In this case the explosive's energy release inside each ATE proceeds according to the so-called slow kinetics. The kinetics is characterized by an induction time followed by the explosive selfignition. For a strong exponential dependence of the ATE's induction time on the explosive's state the effect of rarefaction waves can cause its so sharp dramatic increase that under these conditions they will not appear at all. It follows that the effect of rarefaction waves is able to quench the explosive's transformation and so to discontinue the detonation. The finding of quenching of reactions proceeding according to slow kinetics' regularities by rarefaction waves was made in the late sixties and was named at the same time as the breakdown (BD) phenomenon.[4]

At the moment of any unstable detonation transition from a metal confinement charge into a larger volume (see Figure 1) lateral rarefaction waves and successive failure waves appear. In the range of the confinement's diameter from the explosive detonation failure diameter of the confined charge d_{fc} till d_f failure waves propagate over the unstable (pulsating) detonation front to the charge axis with constant velocity comparable to the detonation *CJ* sound velocity C_{CJ} in value (and even slightly in excess to all appearance for its propagation through the pulsating (turbulent) zone of the detonation front). For example, C_{CJ} of pure NM's unstable detonation wave equals to 4,42 km/s and the failure wave velocity V for its failure diameter charge d_f – to 4,75 km/s.[4]

It should be mentioned that experimental data for any unstable detonation testify that in the ($d_{fc} \div d_f$) range failure waves shut down a whole cross-section of the charge and so discontinue the detonation.[4] At the tube diameter larger than d_f failure waves have no time to overlap a whole cross-section of the charge. It was found out in the early sixties that in this case the following sequence of events took place. An adjoined shock wave there remains after the BD of ATEs in the detonation wave front. The detonation products support the wave as by a piston. It compresses the liquid explosive and initiates an ATE at some point of the detonation products/SCE's interface in the induction time corresponding to the temperature and pressure of the SCE's. The explosion leads to the origin of the SCE detonation. For the larger density of the SCE its detonation propagates with larger velocity in comparison with that of the initial explosive detonation. The SCE detonation originated overtakes the front of the adjoined shock wave and initiates detonation of the initial explosive. At the same time it propagates behind the adjoined shock wave front along the SCE in both directions: to and from the charge axis. In its propagation to the axis it catches the failure wave front at the $d_f/2$ depth and puts an end to the BD process.

For the relatively low power of the D/A's solution and in connection with the confidence that its detonation is kinetically unstable it has been expected that the velocity of failure waves should be comparable to the detonation C_{CJ} (4,52 km/s) in value. However, the velocity (3,37 km/s) measured at the detonation transition from the copper confinement charge of 52 mm diameter turned out to be substantially smaller than C_{CJ}. The finding have clearly demonstrated that the D/A solution's detonation is kinetically stable. The explosive transformation into detonation products is carried out within the front of stable detonations not by the mechanism of ATEs characteristic of unstable detonations but by a homogeneous mechanism. In this case the explosive's transformation proceeds according to the so-called fast kinetics. The kinetics is characterized by the lack of any induction time, the transformation proceeding with a

maximum rate at the very top of the stable detonation wave's chemical spike. In other words, the explosive selfignition occurs just on the chemical spike's top without any induction time. To break down the reaction proceeding according to the fast kinetics' regularities by the effect of some rarefaction wave the wave must first change the reaction's fast kinetics for a slow one. To do this the rarefaction wave has to attenuate the detonation wave front intensity to the point where an induction time of the explosive's selfignition arises. Thereafter the selfignition is broken down immediately by the rarefaction wave's continuing influence.

At the stable detonation transition from cylindrical charge of any confinement into a larger volume the attenuation of the detonation wave front and subsequent break down of the explosive's selfignition within the properly attenuated parts of the front (that is the subsequent origin of failure waves) is also accomplished by the effect of lateral rarefaction waves. It is well known that the intensity of lateral rarefaction waves (gradient of pressure behind their front) depends on the diameter of charges; the larger the diameter, the weaker the intensity, and vice versa, the smaller the diameter, the stronger the intensity. On the other hand, it is apparent that the stronger the rarefaction wave is, the quicker it will attenuate the detonation wave front to the proper intensity (the intensity at which an induction time of the explosive's selfignition arises and the selfignition is immediately broken down by the rarefaction wave's farther influence). In other words, the smaller the charge diameter, the smaller the time and space lags between the front of rarefaction wave and that of the failure wave. This is the reason of the dependence of the value of failure waves' velocity on the diameter of charges; the larger the diameter, the smaller the value.

Thus in the range of any confinement's diameter ($d_{fc} \div d_f$) the velocity of failure waves originating at the transition of liquid explosive detonation from charges confined into a larger volume and propagating over the detonation front to the charge axis is close in value to the detonation products sound velocity C_{CJ} and does not depend on the charge diameter in the case of unstable detonations, and it is always substantially smaller than C_{CJ} and depends on the charge diameter in the case of stable detonations. It is the only difference in the manifestation of the transition from charges confined into a larger volume between unstable detonation and stable detonation of some liquid explosives (for example, tetranitromethane type[4]). Otherwise the transition's patterns are similar. In both cases at charge diameter larger than d_f the first selfignition of SCE behind the adjoined shock wave at some point of the SCE/detonation products interface leads to the SCE's detonation appearance and its propagation in both directions to and from the charge axis. As it takes place the SCE's detonation initiates the initial explosive detonation. In total it results in the detonation spreading from the tube to a larger volume.

The foregoing pattern of stable detonations' transition from charges confined into a larger volume is not unique. For stable detonations of some explosives (for example, nitroglycerine type[4]) the transition's pattern appears complicated. In this case the first SCE's selfignition behind the adjoined shock wave leads also to the SCE detonation appearance but it propagates only to the charge axis and is unable to initiate the initial explosive detonation. The SCE's detonation in its motion to the charge axis causes a new adjoined shock wave behind which its SCE's selfignition and detonation appear again. And again the SCE's detonation propagates only to the charge axis and is unable to initiate the initial explosive's detonation. The sequence of the events can repeat more than once during the transition from charges of smaller diameter than the explosive's detonation d_f, each successive selfignition coming into view closer to the charge axis, so that finally the detonation

discontinues at all. And at charge diameter larger than the explosive's detonation d_f the sequence appears in a similar manner with one exception. In this case each successive selfignition comes into view farther from the charge axis thereby results in the detonation spreading from the tube to a larger volume.

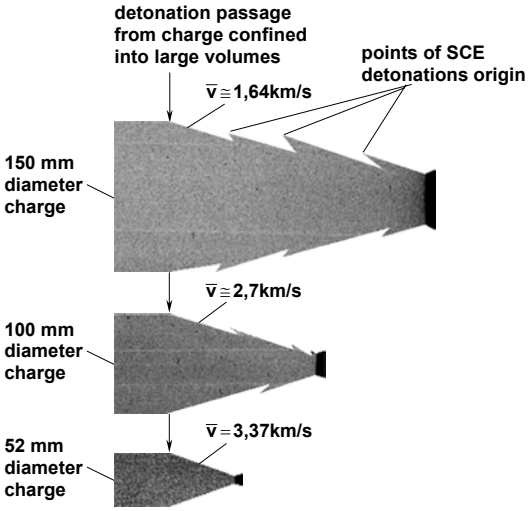


FIGURE 5. SCHEMATIC VIEW OF EXPERIMENTAL STREAK-CAMERA RECORDINGS OF THE SOLUTION'S DETONATION PROPAGATION WITHIN LARGER VOLUMES OF THE SOLUTION AFTER ITS PASSAGE FROM CHARGES CINFINED INTO THE VOLUMES.

Figure 5 represents pictures obtained by computer scanning in the same scale of streak camera recordings of the on-coming detonation luminescence for charges of 52 mm diameter (h_2 length ~ 40 mm), 100 mm (h_2 ~ 100 mm), and 150 mm (h_2 ~ 170 mm) (see Figure 1). Most of the whole recordings corresponding to the detonation propagation along initial parts of charges h_1 are not shown in Figure 5 as they are of no interest for the investigation.

The value of failure wave velocities turned out to be substantially smaller than the explosive's detonation C_{CJ} for all charges. In addition, in accordance with the aforesaid the value decreases with the diameter of charges. If for 52 mm diameter charge it equals to ~ 3,37 km/s, then for 100 mm diameter charge the value of the initial failure wave's velocity equals to ~ 2,70 km/s, and for 150 mm diameter charge – to ~ 1,64 km/s.

It should be mentioned that for an unexpectedly small value of failure wave velocities for charges of all diameters used the h_2's lengths (see Figure 1) turned out to be insufficient for failure waves to shut down the whole cross section of the charges. However, it does not prevent to make a conclusion that even 150 mm diameter charge is still smaller than the explosive's detonation d_f.

One can see from Figure 5 that not a ATE of SCE behind the adjoined shock wave appear during the process of the detonation transition from 52 mm diameter charge into a larger volume. It testifies that 52 mm diameter is substantially smaller than the explosive's detonation d_f. At the detonation transition from confined charges of 100 and 150 mm diameters into a larger volume some ATEs and following detonations of the SCE appear, each next ATE taking place nearer to the charge axis. In addition, as in the case of liquid explosives of NG type[4] SCE's detonations turned out to be unable to initiate the initial explosive detonation and propagate out of the charge axis.

It should be mentioned that the first ATE of the SCE behind the adjoined shock wave at the detonation transition from 150 mm diameter charge takes place at the distance from the charge axis only slightly smaller than the charge's radius. It means that the explosive detonation d_f is only slightly larger than 150 mm. For too large size of charges the real value of the solution's detonation d_f has not been measured but it is reasonable to suggest that it be close to 200 mm. So large d_f testifies that even the solution of highest possible content of

DINA (~ 68,5 wt % at room temperature) is in the vicinity of its detonation capability. The suggestion is evident from the following consideration. Each liquid explosive in its sensitivity to shock initiation of its detonation is characterized by some critical value of shock impulse $P(t)_{cr}$. On the other hand, it is obvious that the explosive's dilution by some inert deluent results in the mixture's detonation parameters decrease. It is clear that the mixture's detonation would be impossible in principle if the detonation's impulse $P(t)_{det}$ turns out to be smaller than the $P(t)_{cr}$. In practice it has to be manifested just in dramatic increase of the mixtures' detonation d_f as the mixture's lower concentration is approached. In this connection the attention should be drawn to the fact that the solution's detonation *CJ* pressure (8,74 GPa) is not much larger than the minimum shock pressure (7,40 GPa) necessary to initiate the solution's detonation.

CONCLUSION

The attempt has been undertaken to measure detonation failure diameter of the 68,5/31,5 wt % solution of DINA in acetonitril. To do it the passage of the detonation from the solution charges of copper confinement into a larger volume of the solution has been observed from the butt-end of charges with the help a streak-camera. It has been disclosed that the detonation is discontinued at its transition from charges of 52, 100 and 150 mm diameters. The transition from 150 mm diameter charge in its view testifies that the diameter is only slightly smaller than the detonation failure diameter. It has been suggested that it be close to 200 mm. So large value of the failure diameter enables to speculate that the solution in DINA's content is in the vicinity of its detonation capability.

ACKNOWLEDGMENTS

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