Initiation of Strong Reactive Shocks and Detonation by Traveling Ignition Pulses

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Introduction

Detonation initiation in a reactive medium implies the necessity of strong coupling between a shock wave (SW) and energy deposition. Fundamentally, it does not matter how the energy is deposited into the post-shock flow: spontaneously, due to shock-induced chemical reactions, or by means of inducing chemical activity with an external energy source. In the former approach, due to the high activation energy of exothermic chemical reactions in fuel–air mixtures, shock waves of high amplitudes and proper durations are required to ensure the coupling. Such shock waves can be obtained by means of exploding high-explosive charges with a mass exceeding 20–30 g. The latter approach implies the use of an external energy source to artificially induce exothermic reactions closely behind a relatively weak SW in order to stimulate the strong coupling. The external energy source can be either distributed or concentrated and should provide continuous or pulse coupling of energy deposition with a propagating SW.

Originally, the idea of using external sources to drive a detonation belongs to Zel'dovich and Kompaneetz [1]. They have shown theoretically that motion of an ignition source in a compressible reactive mixture at the characteristic detonation velocity would result in formation of a self-sustaining detonation in a long run. To model the moving ignition source, Zel'dovich and coworkers [2, 3] considered the nonuniformly preconditioned reactive mixture, implying that the initial gradient of auto-ignition delay time will produce a similar effect. As a matter of fact, it has been proved computationally that temperature and composition nonuniformities in the reactive mixture preconditioned to auto-ignition may result in the spontaneous onset of detonation. Thibault *et al.* [4] reported their one-dimensional numerical study of the situation when the external energy source traveled at a constant velocity in an inert compressible medium. It has been shown that the strength of the SW arising in the medium depends on the energy source velocity and attains a maximum value when this velocity approaches the characteristic detonation velocity based on the specific energy (per unit mass of gas) deposited by the source, i.e., substantiated the original idea of Zel'dovich and Kompaneetz computationally. Later, Yoshikawa *et al.* [5] extended the analysis to take into account coupling between the moving energy source and the SW. Lee *et al.* [6] have suggested the concept of SWACER (abbreviation for Shock Wave Amplification by Coherent Energy Release) and applied it to qualitatively explain the experimental findings in photochemical initiation of detonation [7], detonation initiation by injecting hot turbulent jets into explosive mixture [8] and 'explosion in the explosion' phenomenon during deflagration-to-detonation transition (DDT) [9]. Among recent publications further generalizing the issue are those by Shepherd and Lee [10] and Khokhlov *et al.* [11]. Direct experimental substantiation of the ideas and mechanisms discussed herein was reported recently by Frolov *et al.* for gaseous [12, 13] and heterogeneous [14–17] mixtures.

The objective of this paper is to describe the experimental studies of the possibility to efficiently accelerate a weak SW by in-phase triggering of distributed external energy sources (electric discharges) in the course of SW propagation along the tube filled with reactive mixture.

Experiments with Gaseous Mixtures

In the experiments with gaseous mixtures, a sealed smooth-walled tube 51 mm in diameter and 1.5 m in length was used (Fig. 1).

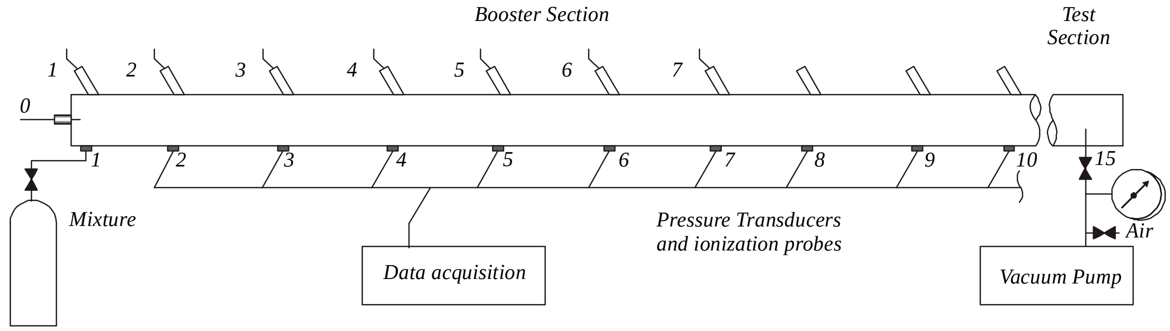

Figure 1: Experimental setup for detonation initiation in gaseous fuel–air mixtures [12, 13]. A relatively weak primary shock wave generated by electric dischargers 0 and 1 is amplified to detonation intensities by triggering dischargers 2, 3, 4, *etc.* in phase with SW arrival at their position

The tube consisted of a booster section 1 m long and a measuring section 0.5 m long. A triggering electric discharger "0" was placed at the end plane of the booster section. Beginning with cross section 1, CS1 (see numbers in Fig. 1) at a distance of 26 mm from the end plane, additional electric dischargers were mounted along the booster section at intervals of 100 mm (CS2, CS3, etc.). The electric power supply of each discharger comprised a high-voltage capacitor. The discharge-triggering signal came to the dischargers from a multichannel controller. This controller made it possible to preset the triggering delay time for each of the dischargers. The discharge current duration was 100 μs. The tube was filled with a stoichiometric propane–air mixture up to a pressure of 1 atm. To measure wave dynamics, piezoelectric pressure transducers and ionization probes were used. For these transducers and probes, ports were made in the tube along its full length at 100 mm intervals, the ports in the booster section being located in the same cross sections as the dischargers. The data acquisition system included oscilloscopes, frequency meters, and a PC. The experiments were run with the aim to select the triggering times of successive discharges in such a way as to provide a maximum amplification of a weak primary SW while it propagates along the tube and to initiate a detonation wave (DW). The primary SW arose on triggering the end-plane discharger "0" and the discharger in CS1.

Figure 2 shows the space–time diagram of experimental results [12, 13]. The voltage on the battery of capacitors was 2500 V. The capacitance of the end-plane discharger was 200 μF; the capacitance of the discharger in CS1 was 400 μF, and the capacitance of each of the remaining dischargers was 100 μF. The dashed lines *1* and *2* correspond to the slopes of the characteristic sound velocity and Chapman–Jouguet detonation velocity in the reactive mixture. The black circles correspond to the experimental optimal triggering times for the dischargers, and the white circles correspond to the time of the arrival of the SW at the corresponding CS. When two, three, etc., up to seven, dischargers were switched on in the same experiment, detonation in the tube was not observed. Only when eight dischargers were successively triggered in the same experiment, the primary SW velocity gradually increased from 850 $\pm$ 12 to 1770 $\pm$ 25 m/s; i.e., beginning with CS7 or CS8 (at a distance of 0.6–0.7 m from CS1), a DW arose in the booster section. In the measuring section, the DW propagated with a constant velocity of 1750 ± 50 m/s (average in 10 runs). To produce a DW, the dischargers should be switched on ahead of the arrival of a SW at the corresponding CS of the tube. The required ignition advance was 80 – 100 μs, which correlated with the discharge current duration.

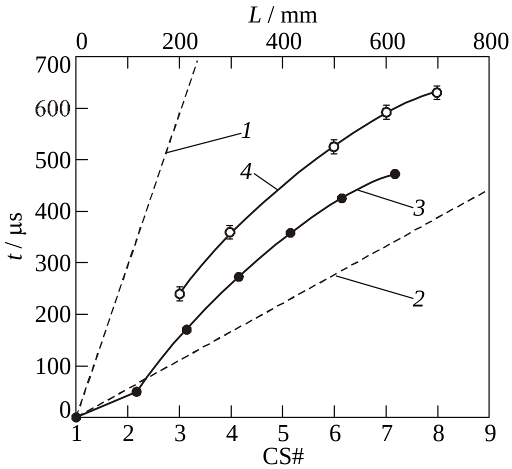

Figure 2: Experimental distance–time diagram of shock wave amplification in the stoichiometric C_3H_8–air mixture. Detonation occurs after cross-section CS7 [12, 13]. *1* – slope of sound velocity, 342 m/s, *2* – slope of detonation velocity, 1800 m/s, *3* – triggering timing of dischargers in various cross-sections, and *4* – shock wave arrival timing

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In addition, the sensitivity of the process to small deviations of the discharger triggering delay time was studied. The startup of the discharger in CS4 with a delay of 320 μs instead of the optimal value 270 μs (Fig. 2) resulted in the initiation failure, other conditions being equal. The same result was obtained when the triggering time of the dischargers in CS5, CS6, and CS7 deviated from the corresponding optimal value by 50 μs. These facts point to the resonance character of the process.

Thus, these experiments demonstrated that detonation in a gaseous mixture can be initiated by a traveling ignition pulse, which is formed by successively triggering several dischargers with thoroughly adjusted delay times. This mode of initiation of detonation differs significantly from conventional methods, direct initiation or DDT. In direct initiation by one source, detonation arises after the stage of attenuation of a very strong primary SW; therefore, the major part of the energy of the initiator and reactive mixture is consumed away for compression, heating, and thermal dissociation of reaction products behind the SW. It takes a distance of 1.0–1.5 m for the self-supporting planar detonation front to arise [18]. For the DDT to take place, the flame should be accelerated to an apparent velocity on the order of 1000 m/s. To attain such a velocity in a propane–air mixture, a smooth-walled tube more than 260 diameters in length [19] or a tube with turbilizing elements in the form of regular obstacles more than 60 diameters in length [20] is required. In this mode of detonation initiation, some energy is also consumed away for compression and heating of a large volume of combustion products.

When a traveling ignition pulse is used, the energy of the reactive mixture is supplied to the shock front so that the SW is rapidly amplified up to the intensities sufficient for initiation of detonation. To obtain detonation at the shortest distances, the ignition pulse should move with acceleration rather than at constant (detonation) velocity as suggested in [1]. In the experiments, the DW arose at distances of 0.6–0.7 m, corresponding to 12–14 tube diameters. The primary SW was relatively weak and had the velocity (over the distance between CS2 and CS4) $M \approx 2.0$–2.5. The overall nominal energy of electric discharges for the conditions in Fig. 2 is 1.68 MJ/m^2, which is lower than the value 3 MJ/m^2 reported in [18] for the critical energy of detonation initiation by a flat charge of a high explosive. Inasmuch as the efficiency of conversion of the electric discharge energy into the SW energy is low compared to the high-explosive efficiency (as a rule, 10 % [21]), the actual total critical initiation energy appears to be much smaller.

Based on these findings, three conclusions can be drawn. First, the method under consideration provides very short distances before the appearance of a DW in a smooth-walled tube. Second, the energy of each of the individual ignition sources is much smaller than the critical energy required for direct initiation of detonation by one source. Third, the resulting total energy of ignition sources appears to be considerably lower than the critical energy of direct initiation of detonation.

Experiments with Liquid Fuel Sprays

In the experiments with heterogeneous mixtures [14–17], the experimental setup shown in Fig. 3 was used.

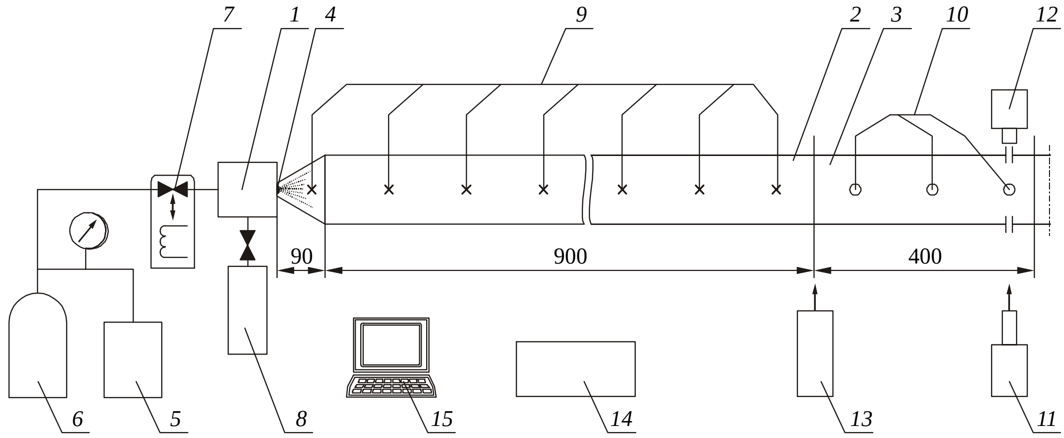


Figure 3: Experimental setup for detonation initiation in fuel spray – air mixtures [14–17]. *1* – air-assist liquid-fuel atomizer, *2* – booster section, *3* – test section, *4* – cone, *5* – compressor, *6* – bottle, *7* – solenoid valve, *8* – fuel tank, *9* – igniters, *10* – pressure transducers and ionization probes, *11* – laser, *12* – optical system, *13* – droplet sizing unit, *14* – controller, and *15* – PC. Dimensions in mm

Three sets of experiments were carried out with the objective of initiating detonation in liquid *n*-hexane and *n*-heptane sprays in air by means of several successively triggered electric dischargers. Steel tubes 51 and 28 mm in diameter were used. At one end of a tube, an air-assist atomizer was mounted; it provided the airflow at a rate from 20 to 30 l/s and finely sprayed the fuel to give drops 5 to 6 μm in diameter. The other end of the tube was connected with the atmosphere through a flame arrester, a chamber packed with a metal tape. The experiments were run under pulse supply of air and fuel. The pulse duration was 1 s. Each tube consisted of an initiating section, with electric dischargers, and a measuring section. Here, only experiments with two dischargers will be discussed. Experiments with more successively triggered dischargers have been reported elsewhere [16].

The first discharger was placed at a distance of 60 mm from the atomizer nozzle, and the second discharger was mounted at distance *L*, a multiple of 100 mm, from the first one. The electric power supply of the dischargers included high-voltage capacitors with the capacitances C_1 and C_2. The discharge energies E_1 and E_2 were varied by changing the voltage *U* on the capacitors, which was the same for both dischargers. The energy was calculated from the capacitance of the capacitors and the voltage. The discharge-triggering signal came to the dischargers from a digital controller. This controller made it possible to specify the triggering delay time for the second discharger with respect to the first discharger. The discharge current duration $\Delta\tau_d$ was varied from 50 to 100 μs by using dischargers of different design. To measure wave dynamics, piezoelectric pressure transducers were used. Three transducers were mounted in the measuring section. The distances to the transducers were measured from the first discharger. The data acquisition system included an analogue-to-digital converter and a PC. The experiments were run with the aim to select the triggering delay time τ for the second discharge in such a way as to provide detonation initiation at the lowest overall discharge energy $E = E_1 + E_2$.

In the first set of experiments with *n*-hexane sprays, a tube 51 mm in diameter and dischargers with $\Delta\tau_d$ = 100 μs were used. The capacitance of the capacitor of each discharger was $C_1 = C_2 = 300\ \mu\text{F}$. The voltage *U*, delay time τ, and distance *L* were varied in the runs. Figure 4 is plotted for *L* = 200 mm. The plus signs in Fig. 4 correspond to the *U* and τ values at which a DW propagating over the segments 0.7–1.1 and 1.1–1.3 m at a mean velocity of 1780 ± 100 m/s (average in 10 runs) was observed.

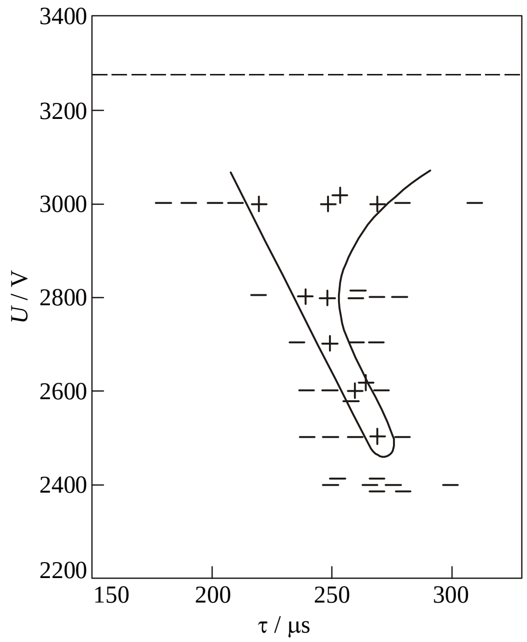
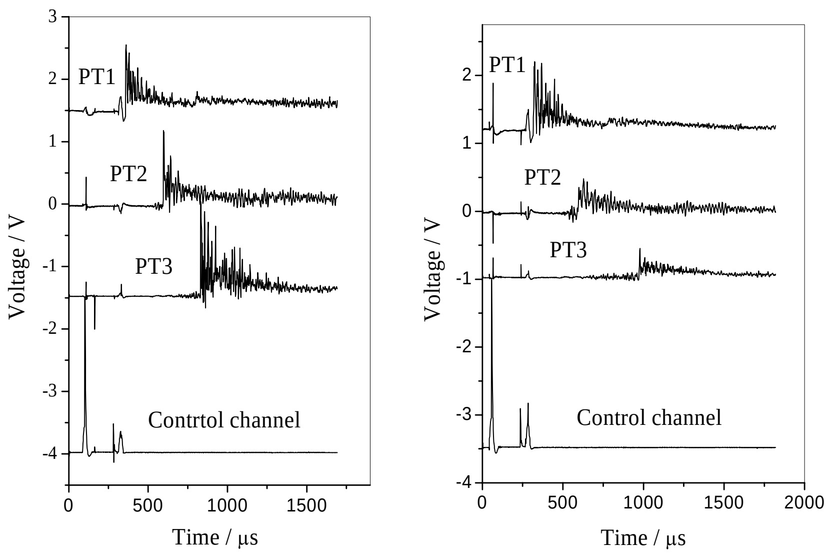


Figure 4: Measured dependency of detonation initiation energy (in terms of voltage *U* applied to high-voltage blocks of two dischargers with similar capacitance of 300 μF) *vs.* the delay time τ of the second discharger triggering (counted from activation of first discharger) [14–17]. Tube diameter 51 mm. Dashed line shows voltage required for detonation initiation by a single discharger of capacitance $2\times300\ \mu\text{F} = 600\ \mu\text{F}$.

The DW velocity measured is close to the thermodynamic detonation velocity in a homogeneous stoichiometric *n*-hexane–air mixture (1840 m/s). The minus signs denote the conditions under which detonation was not initiated. To initiate detonation by one discharger with a capacitor of doubled capacitance (C_1 = 600 μF or C_2 = 600 μF), the voltage 3300 V (for the first discharger) or 4100 V (for the second discharger located at a distance of 260 mm from the nozzle) was required. These voltages correspond to the discharge energy $E = E_1$ = 3.3 kJ and $E = E_2$ = 5.1 kJ. Figure 4 shows that, energetically, detonation initiation by two dischargers is more efficient: as compared to initiation by single dischargers, the minimal voltage required U_{min} decreases by 25% (from 3300 to 2500 V) and 39% (from 4100 to 2500 V), while the initiation energy decreases by 43% (from 3.3 to 1.9 kJ) and 62% (from 5.1 to 1.9 kJ). The detonation "peninsula" width in Fig. 4 is very small: 50 μs at U = 3000 V and 10 μs near the initiation limit (U = 2500 V).

The minimal voltage U_{min} and the optimal time delay τ, at which $U = U_{min}$, depend on the distance L between the dischargers. In particular, at L = 100 mm, U_{min} = 3000 V and τ = 100 μs; at L = 200 mm, U_{min} = 2500 V and τ = 270 μs; and at L = 300 mm, U_{min} = 3000 V and τ = 370 μs. At L = 400 mm and U = 3000 V, detonation was not initiated at any τ. Thus, the lowest energy of detonation initiation is achieved at an optimal distance between the dischargers (L = 200 mm).

In the second set of experiments, a tube 28 mm in diameter and dischargers with $\Delta\tau_d$ = 50 μs were used. The capacitance was $C_1 = C_2$ = 225 μF. The delay time τ was varied at U = 2000 V and L = 200 mm. The detonation onset was observed at 211 < τ < 221 μs; i.e., as in the tube 51 mm in diameter, the detonation peninsula width at the initiation limit is very small (10 μs). The lowest overall discharge energy at which detonation was initiated was E = 0.9 kJ. Figures 5*a* and 5*b* show the pressure records at transducers PT1, PT2, and PT3 located in the cross sections at distances of 265, 665, and 1065 mm at τ of (*a*) 214 and (*b*) 211 μs.



(*a*) (*b*)

Figure 5: Samples of pressure records with (*a*) successful detonation initiation (time delay between two discharges of 214 μs), and (*b*) initiation failure (time delay of 211 μs)

In Fig. 5*a*, a DW was observed, whereas, in Fig. 5*b*, an attenuating SW was observed. Note that the mean velocity of the primary SW formed by the first discharge was 1020 ± 12 m/s in both cases. In Fig. 5*a*, the mean DW velocity over two measuring segments was, respectively, 1700 ± 13 and 1720 ± 13 m/s, which is lower than the thermodynamic detonation velocity since the tube diameter is close to the limiting diameter. The sensitivity of the pressure transducers was 0.025–0.030 V/atm; thus, the pressure in the DW front was 15–20 atm (without regard for "noise"). In Fig. 5*b*, the mean velocity of the attenuating SW over the same segments was, respectively 1440 ± 11 and 1060 ± 8 m/s. In addition to the pressure transducer signals, Fig. 5 shows the records of the control channel, with the signals of the controller and discharge currents (measured by the Rogovsky coil). These records allow one to determine the true triggering delay time for the second discharger with an error of 0.3 μs. The signals of discharge currents are seen in the pressure records as perturbations of the zero line. It is worth noting that the optimal triggering time $\tau_0 \approx 214$ μs for the second discharge is consistent with the arrival of the primary SW at the cross section of the second discharger: the signal of transducer PT1 in Fig. 5*a* coincides with the termination of the discharge current at the second discharger.

In the third set of experiments, a tube 28 mm in diameter and dischargers with $\Delta\tau_d$ = 50 μs were also used [17]. To diminish the detonation initiation energy *E*, a Shchelkin spiral 460 mm long coiled from a tungsten wire, 4 mm in diameter, with a pitch of 18 mm was placed between the dischargers (see Fig. 6).

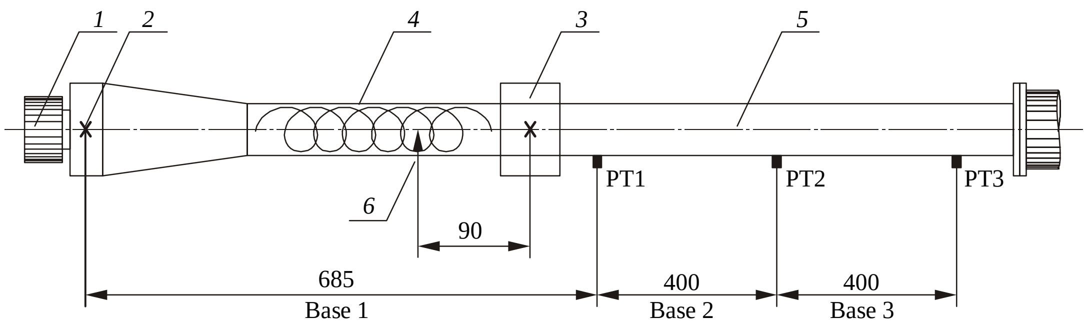


Figure 6: Experimental setup with 28-millimeter tube and Shchelkin spiral between two dischargers [17]: *1* — air-assist liquid-fuel atomizer, *2* — first discharger, *3* — second discharger, *4* — Shchelkin spiral, *5* — tube, and *6* — sensor; PT1, PT2, and PT3 stand for pressure transducers. Dimensions in mm

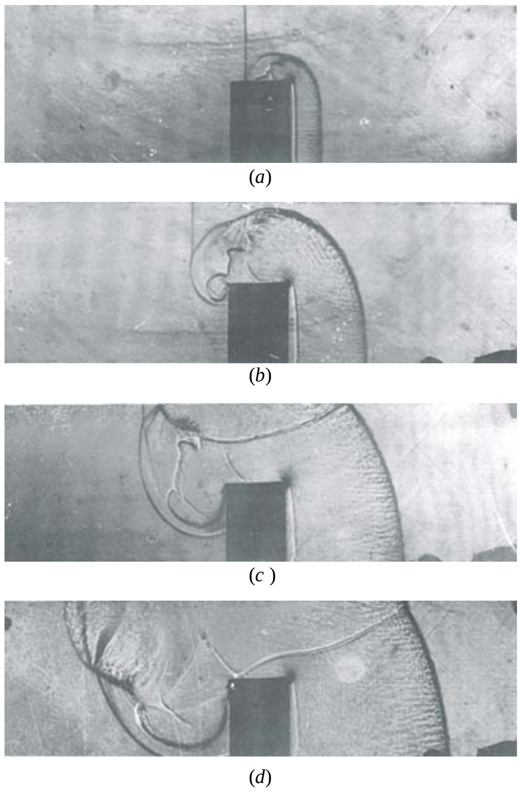
The capacitance C_1 was decreased to 25 μF, and the capacitance C_2 was left unaltered, 225 μF. The variables in these runs were the voltage *U* and the triggering delay time τ of the second discharger with respect to the time of arrival of the primary SW at a special sensor *6* (Fig. 6) mounted in the cross section with the spiral at a distance of 90 mm from the second discharger. The use of the spiral made it possible to decrease the energy to *E* = 0.5 kJ, which is 45% lower than the minimal energy of detonation initiation obtained in runs without spiral. In the runs with the spiral, detonation was initiated at $60 < \tau < 120$ μs; i.e., the detonation peninsula width in the vicinity of the initiation limit was considerably larger than in the experiments without a spiral. Hence, the spiral considerably diminishes the requirements on synchronization of the triggering of the second discharger and the arrival of the primary SW. Note that in the course of further experiments with combination of various means the minimal detonation initiation energy in the 28-millimeter tube was lowered to *E* = 0.1 kJ. In the experiments with *n*-heptane sprays similar trends were observed, however the energy requirements for detonation initiation were somewhat higher [14–17].

Thus, a new method for detonation initiation in sprays of the liquid fuel in air was experimentally demonstrated. The method complements the known methods (direct DW initiation and DDT) and is based on forced ignition of a combustible mixture by an electric discharge in the vicinity of the front of a relatively weak primary SW. A discharge current duration of less than 100 μs provides rapid combustion of the mixture and transformation of the primary SW into a DW. Detonation arises at short distances, the initiation energy being considerably lower than in the case of direct initiation by a single discharge. The use of a tube with a nearly limiting diameter and the Shchelkin spiral enhances the efficiency of the method by decreasing the energies required and extending the detonation initiation limits.

Experiments with Ignition Pulses Driven by a Traveling Shock Wave

Experiments with DDT in reactive gases using tubes with regular or irregular obstacles can also be treated as detonation initiation by a traveling ignition source. As is known [22], placing the obstacles in the tube causes a dramatic decrease in the DDT length and time as compared to the smooth-walled tubes. In this case instead of external traveling ignition sources, the phenomenon of localized obstacle-induced autoignition of gas is used. This autoignition is driven by reflections of the lead SW from the upstream surfaces of the obstacles [22, 1]. Clearly, if autoignition occurs with a long delay after SW passage, no immediate amplification of the lead SW can be expected. However, if the autoignition delay is relatively short and a volume ignited is sufficiently large, one could expect a close coupling between the propagating SW and shock-reflection induced energy deposition, and faster acceleration of the SW. In terms of the ignition delay, the conditions for coupling seem to be equivalent to those found in the experiments with external energy deposition described above. However, contrary to smooth tubes with external ignition sources, a considerable hydrodynamic drag affects the flow in tubes with obstacles, which deteriorates the conditions for shock amplification.

Obstacles can be distributed along the tube wall (Schelkin spiral, orifice plates) or fill the whole tube cross-section. As an example, Figure 7 shows detonation initiation due to propagating SW reflection from an obstacle [23]. If temperature behind the reflected shock is high enough, explosion-like autoignition ("strong explosion" [9]) occurs.



(*a*) (*b*) (*c*) (*d*)

Figure 7: Spark Schlieren photographs for obstacle-induced detonation initiation in C_2H_4 + $3O_2$ + 12Ar mixture (initial SW Mach number M = 3.2, initial pressure 0.053 atm, 20 μs frame interval) [23]. The primary SW propagates from right to left.

Concluding Remarks

Experimental studies on detonation initiation by externally stimulating exothermic reactions closely behind a propagating SW have been performed for gaseous and heterogeneous fuel–air mixtures. It is shown that spatially distributed electric dischargers with properly tuned triggering times provide very short distances for shock-to-detonation transition in a smooth-walled tube. The energy of each of the individual dischargers is much smaller than the critical energy required for direct initiation of detonation by one discharger. The resulting total energy of dischargers appears to be considerably lower than the critical energy of direct initiation of detonation. High sensitivity of the detonation initiation process to each discharger triggering time was revealed, which is indicative of resonance-like phenomena. Available experiments with DDT in reactive gases using tubes with regular or irregular obstacles can also be treated as detonation initiation by a traveling ignition source. However, in this case instead of external stimulation of chemical activity behind a propagating SW, a localized obstacle-induced autoignition of shock-compressed gas occurs which is closely coupled to the SW strength. In terms of the ignition delay, the conditions for the coupling between mixture autoignition and the propagating SW seem to be equivalent to those found in the experiments with external energy deposition. In case the ignition timing at obstacles is closely coupled with the propagating SW, favorable conditions for fast DDT can occur. Otherwise, the propagating SW decouples from the ignition pulses and DDT fails or occurs at a later stage due to cumulating of flame-induced pressure waves and "explosion in the explosion" phenomenon. With this understanding new approaches to safety precautions against accidental DDT could be developed.

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References

1. Zel'dovich Ya.B. and Kompaneets A.S. *Theory of Detonation*, Moscow, Gostekhteorizdat, 1955.
2. Zel'dovich Ya. B., Librovich V. B., Makhviladze G. M., and Sivashinski G. I. On the development of detonation in a nonuniformly preheated gas. *Acta Astronautica*, 1970, Vol. 15, pp. 313–321.
3. Zel'dovich Ya. B., Gelfand B. E., Tsyganov S. A., Frolov S. M., and Polenov A. N. Concentration and temperature nonuniformities of combustible mixtures as a reason of pressure waves generation. In: *Dynamics of Explosions*, edited by A. Kuhl, J. R. Bowen, J.-C. Leyer, and A. A. Borisov, 1988, Vol. 114, Progress in Astronautics and Aeronautics, AIAA, New York, p. 99–123.
4. Thibault P. A., Yoshikava N, and Lee J. H. S. Shock wave amplification through coherent energy release. Presented at the *1978 Fall Technical Meeting of the Eastern Section of the Combustion Institute*, Miami Beach, FL, November 30 – December 1, 1978.
5. Yoshikava N., Thibault P. A., and Lee J. H. S. Shock wave amplification in nonuniformly preconditioned gas mixtures. Presented at the *1979 Spring Technical Meeting of the Canadian Section of the Combustion Institute*, Kingston, Ontario, May 3–4, 1979.
6. Lee J. H. S. and Moen I. O. The mechanism of transition from deflagration to detonation in vapor cloud explosions. *Progress in Energy and Combustion Sciences*, 1980, Vol. 6, No. 4, p. 359–389.

7. Lee J. H., Knystautas R., and Yoshikawa N. Photochemical initiation of gaseous detonation. *Acta Astronautica*, 1978, Vol. 5, p. 971–982.
8. Knystautas R., Lee J. H., Moen I. O., and Wagner H.-Gg. Direct initiation of spherical detonation by a hot turbulent gas jet. *Proceedings of the 17th Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1979, p. 1235–1240.
9. Oppenheim A. K. *Introduction to Gasdynamics of Explosions*, Courses and Lectures, No. 48, International Center for Mechanical Sciences, Springer-Verlag, Wien – New York, 1972.
10. Shepherd J. E. and Lee J. H. S. On the transition from deflagration to detonation. In: *Major Research Topics in Combustion*, edited by M. Y. Hussaini, A. Kumar, and R. G. Voigt, Springer-Verlag, New York, 1992, p. 439–490.
11. Khokhlov A. M., Oran E. S., and Wheeler J. C. A theory of deflagration-to-detonation transition in unconfined flames. *Combustion and Flame*, 1997, Vol. 108, p. 503–517.
12. Frolov S. M., Basevich V. Ya., and Aksenov V. S. Detonation initiation by controlled triggering of multiple electric discharges. *Proceedings of the 14th ONR Propulsion Meeting*, edited by G. D. Roy and F. Mashayek, University of Illinois at Chicago, Chicago, 2001, p. 202–206.
13. Frolov S. M., Basevich V. Ya., Aksenov V. S., Polikhov S. A. Detonation initiation by controlled triggering of electric discharges. *J. Propulsion and Power*, 2003, Vol. 19, No. 4, p. 573-580.
14. Frolov S. M., Basevich V. Ya., Aksenov V. S., and Polikhov S. A. Initiation of spray detonation by successive triggering of electric discharges. In: *Advances in Confined Detonations*, edited by G. D. Roy, S. M. Frolov, R. Santoro, and S. A. Tsyganov, Moscow, Torus Press, 2002, p. 150–157.
15. Frolov S. M., Basevich V. Ya., Aksenov V. S., and Polikhov S. A. Initiation of pulse detonation in sprays by means of successively triggered electric discharges. *Proceedings of the 16th ONR Propulsion Meeting*, edited by G. D. Roy and M. A. Gundersen, University of Southern California, Los Angeles, 2003, p. 162–167.
16. Frolov S. M., Basevich V. Ya., Aksenov V. S., and Polikhov S. A., Initiation of confined spray detonation by electric discharges. In: *Confined detonations and pulse detonation engines*, edited by G. D. Roy, S. M. Frolov, R. Santoro, and S. A. Tsyganov, Moscow, Torus Press, 2003, p. 157–174.
17. Frolov S. M., Basevich V. Ya., Aksenov V. S., Polikhov S. A. Spray detonation initiation by controlled triggering of electric discharges. *J. Propulsion and Power*, 2003 (submitted).
18. Borisov A. A. Initiation of detonation in gaseous and two-phase mixtures. In: *Gaseous and Heterogeneous Detonations: Science to Applications*, edited by G. D. Roy, S. M. Frolov, K. Kailasanath, and N. N. Smirnov, ENAS Publ., Moscow, 1999, p. 3–24.
19. Veyssiere B., Kerampran S., Proust C., Gilles S. Effect of tube length on flame acceleration and DDT in tubes of constant cross section. *Proceedings of the 19th ICDERS*, 2003, Hakone, Japan, Paper#154, ISBN 4-9901744-1-0
20. Santoro R. J., Lee S.-Y., Conrad C., *et al.* Deflagration-to-detonation transition studies for multicycle PDE applications. In: *Advances in Confined Detonations*, edited by G. D. Roy, S. M. Frolov, R. J. Santoro, S. A. Tsyganov. Moscow, Torus Press, 2002, pp. 243-254.
21. Nettleton M. A. *Gaseous Detonations.* London–New York, Chapman and Hall, 1987.
22. Shchelkin K. I. *Fast Combustion and Spinning Detonation of Gases.* Voenizdat Publ., Moscow, 1949.
23. Brown C. J. and Thomas G. O. Experimental studies of ignition and transition to detonation induced by the reflection and diffraction of shock waves. *Sock Waves*, 2000, Vol. 10, No. 1, p. 23-32.