



## Initiation of strong reactive shocks and detonation by traveling ignition pulses

S.M. Frolov\*

*Department of Explosion, N. N. Semenov Institute of Chemical Physics, Russian Academy of Sciences, 4, Kosigin Str., 119991 Moscow, Russia*

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### Abstract

Experimental studies of detonation initiation by external stimulation of exothermic reactions closely behind a propagating shock wave (SW) are reported. Gaseous and heterogeneous fuel–air mixtures have been studied. Spatially distributed electric dischargers with properly tuned triggering times are shown to provide very short distances for shock-to-detonation transition in smooth-walled tubes. The energy of each individual discharger was shown to be smaller than the critical energy required for direct detonation initiation by a single discharger. The total energy of the dischargers appeared to be lower than the critical energy of direct detonation initiation. Available experiments with deflagration-to-detonation transition (DDT) in tubes with regular or irregular obstacles are also treated as detonation initiation by a traveling ignition source. In this case, instead of external stimulation of chemical activity, the localized obstacle-induced autoignition of shock-compressed gas occurs which can be closely coupled with the propagating SW. Two possible DDT scenarios are identified, namely, ‘fast’ and ‘slow’ DDT. In case the ignition timing at obstacles is closely coupled with the SW, favorable conditions for ‘fast’ DDT can occur. Otherwise, the SW decouples from the ignition pulses and ‘slow’ DDT can occur at a later stage due to cumulating of flame-induced pressure waves and ‘explosion in the explosion’ phenomenon.

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### 1. 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 Kompaneets (1955). 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 et al. (1970, 1988) considered the non-uniformly 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 non-uniformities in the reactive mixture preconditioned to auto-ignition may result in the spontaneous onset of detonation. Thibault et al. (1978) 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

\* Tel.: +7 95 9397228; fax: +7 95 6512191.

E-mail address: [smfrol@chph.ras.ru](mailto:smfrol@chph.ras.ru).

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 Kompaneets (1955) computationally. Later, Yoshikawa et al. (1979) extended the analysis to take into account coupling between the moving energy source and the SW. Lee and Moen (1980) have suggested the concept of Shock Wave Amplification by Coherent Energy Release (SWACER) and applied it to qualitatively explain the experimental findings of Lee et al. (1978) in photochemical initiation of detonation, detonation initiation by injecting hot turbulent jets into explosive mixture (Knystautas et al., 1979) and 'explosion in the explosion' phenomenon during deflagration-to-detonation transition (DDT) (Oppenheim, 1972). Among recent publications further generalizing the issue are those by Khokhlov et al. (1997); Shepherd and Lee (1992). Direct experimental substantiation of the ideas and mechanisms discussed herein was reported recently for gaseous (Frolov et al., 2001, 2003a) and heterogeneous (Frolov et al., 2002; 2003b, 2003c, 2005) 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.

## 2. 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).

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

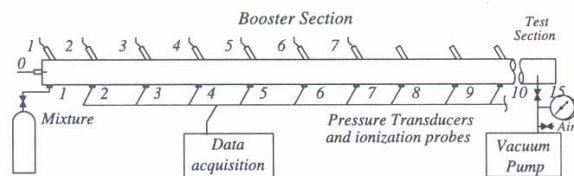


Fig. 1. Experimental setup for detonation initiation in gaseous fuel-air mixtures (Frolov et al., 2001, 2003a). A relatively weak primary shock wave generated by electric dischargers 0 and 1 is amplified to detonation intensities by triggering dischargers 2, 3, 4, etc. in phase with SW arrival at their position.

the 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  $\mu$ s. 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 were 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.

Fig. 2 shows the space-time diagram of experimental results (Frolov et al., 2001, 2003a). The voltage on the battery of capacitors was 2500 V. The capacitance of the end-plane discharger was 200  $\mu$ F; the capacitance of the discharger in CS1 was 400  $\mu$ F, and the capacitance of each of the remaining dischargers was 100  $\mu$ F. 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 2, 3, etc., up to seven, dischargers were switched on in the same

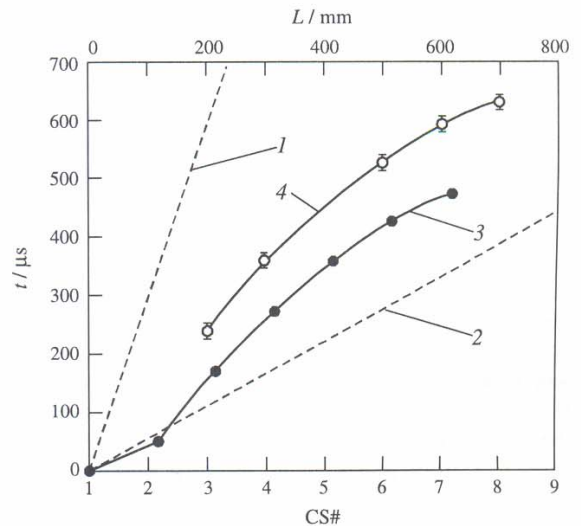


Fig. 2. Experimental distance-time diagram of shock wave amplification in the stoichiometric  $C_3H_8$ -air mixture. Detonation occurs after cross-section CS7 (Frolov et al., 2001, 2003a). 1—Slope of sound velocity, 342 m/s, 2—Slope of detonation velocity, 1800 m/s, 3—Triggering timing of dischargers in various cross-sections, and 4—Shock wave arrival timing.

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  $1750 \pm 50$  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  $\mu$ s, which correlated with the discharge current duration.

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  $\mu$ s instead of the optimal value 270  $\mu$ s (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  $\mu$ s. 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 (Borisov, 1999). 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 (Veysiere et al., 2003) or a tube with turbulizing elements in the form of regular obstacles more than 60 diameters in length (Santoro et al., 2002) is required. For 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 by Zel'dovich and Kompaneets (1955). 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  $1.68 \text{ MJ/m}^2$ , which is lower than the value  $3 \text{ MJ/m}^2$  reported by Borisov

(1999) 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% (Nettleton, 1987)), 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.

### 3. Experiments with liquid fuel sprays

In the experiments with heterogeneous mixtures (Frolov et al., 2002, 2003b, 2003c, 2005), the experimental setup shown in Fig. 3 was used.

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 5–6  $\mu$ m in diameter at a location of first discharger (60 mm from the atomizer nozzle). 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 (Frolov et al., 2003c).

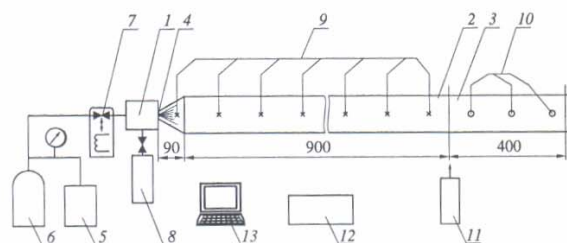


Fig. 3. Experimental setup for detonation initiation in fuel spray–air mixtures (Frolov et al., 2002, 2003b, 2003c, 2005). 1—Air-assist liquid-fuel atomizer, 2—Booster section, 3—Test section, 4—Cone, 5—Compressor, 6—Bottle, 7—Solenoid valve, 8—Fuel tank, 9—Igniters, 10—Pressure transducers and ionization probes, 11—Droplet sizing unit, 12—Controller, 13—PC. Dimensions in mm.

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  $\mu\text{s}$  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  $\tau$  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  $\Delta\tau_d = 100 \mu\text{s}$  were used. The capacitance of the capacitor of each discharger was  $C_1 = C_2 = 300 \mu\text{F}$ . The voltage  $U$ , delay time  $\tau$ , and distance  $L$  were varied in the runs. Fig. 4 is plotted for  $L = 200$  mm. The plus signs in Fig. 4 correspond to the  $U$  and  $\tau$  values at which a DW propagating over the segments 0.7–1.1 and 1.1–1.3 m at a mean velocity of  $1780 \pm 100$  m/s (average in 10 runs) was observed.

The DW velocity measured is close to the Chapman–Jouguet 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 ( $C_1 = 600 \mu\text{F}$  or  $C_2 = 600 \mu\text{F}$ ), 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. Fig. 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  $\mu\text{s}$  at  $U = 3000$  V and 10  $\mu\text{s}$  near the initiation limit ( $U = 2500$  V).

The minimal voltage  $U_{\min}$  and the optimal time delay  $\tau$ , at which  $U = U_{\min}$ , depend on the distance  $L$  between the dischargers. In particular, at  $L = 100$  mm,  $U_{\min} = 3000$  V and  $\tau = 100 \mu\text{s}$ ; at  $L = 200$  mm,  $U_{\min} = 2500$  V and  $\tau = 270 \mu\text{s}$ ; and at  $L = 300$  mm,  $U_{\min} = 3000$  V and  $\tau = 370 \mu\text{s}$ .

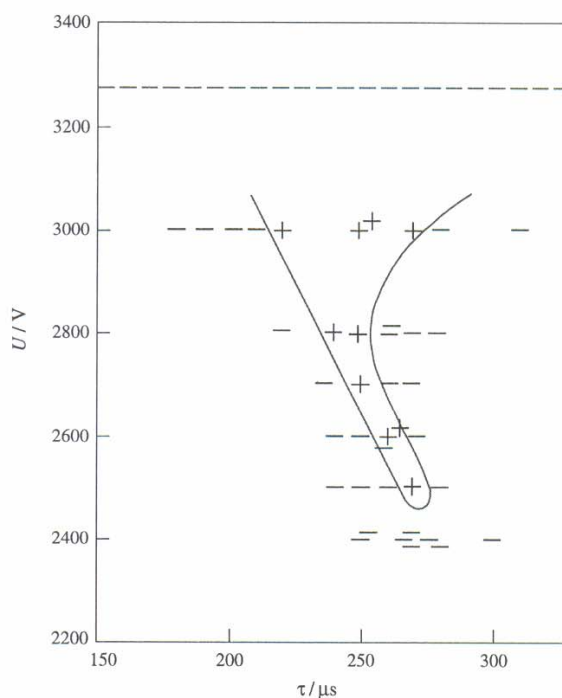


Fig. 4. Detonation initiation energy (in terms of voltage  $U$  applied to high-voltage blocks of two dischargers with similar capacitance of 300  $\mu\text{F}$ ) vs. the delay time  $\tau$  of the second discharger triggering (counted from activation of the first discharger) (Frolov et al., 2002, 2003b, 2003c, 2005). Tube diameter is 51 mm. Dashed line shows voltage required for detonation initiation by a single discharger of capacitance  $2 \times 300 \mu\text{F} = 600 \mu\text{F}$ .

At  $L = 400$  mm and  $U = 3000$  V, detonation was not initiated at any  $\tau$ . Thus, the lowest energy of detonation initiation is achieved at an optimal distance between the dischargers of  $L = 200$  mm.

In the second set of experiments, a tube 28 mm in diameter and dischargers with  $\Delta\tau_d = 50 \mu\text{s}$  were used. The capacitance was  $C_1 = C_2 = 225 \mu\text{F}$ . The delay time  $\tau$  was varied at  $U = 2000$  V and  $L = 200$  mm. The detonation onset was observed at  $211 < \tau < 221 \mu\text{s}$ ; i.e. as in the tube 51 mm in diameter, the detonation peninsula width at the initiation limit is very small (10  $\mu\text{s}$ ). The lowest overall discharge energy at which detonation was initiated was  $E = 0.9$  kJ. Fig. 5a and 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  $\tau$  of (a) 214 and (b) 211  $\mu\text{s}$ .

In Fig. 5a, a DW was observed, whereas, in Fig. 5b, an attenuating SW was observed. Note that the mean velocity of the primary SW formed by the first discharge was  $1020 \pm 12$  m/s in both cases. In Fig. 5a, the mean DW velocity over two measuring segments was, respectively,  $1700 \pm 13$  and  $1720 \pm 13$  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. 5b,

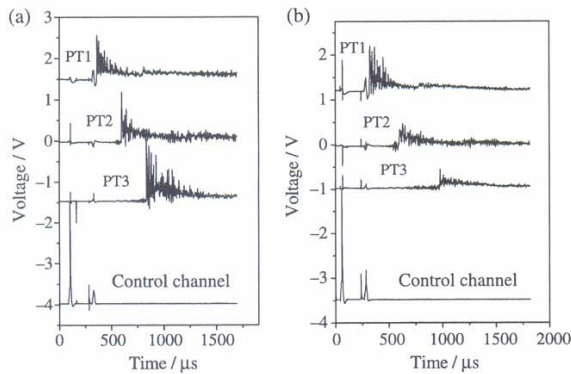


Fig. 5. Samples of pressure records with (a) successful detonation initiation (time delay between two discharges of 214  $\mu\text{s}$ ), and (b) initiation failure (time delay of 211  $\mu\text{s}$ ).

the mean velocity of the attenuating SW over the same segments was, respectively  $1440 \pm 11$  and  $1060 \pm 8$  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  $\mu\text{s}$ . 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  $\tau_0 \approx 214$   $\mu\text{s}$  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. 5a 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  $\Delta\tau_d = 50$   $\mu\text{s}$  were also used (Frolov et al., 2005). To reduce the detonation initiation energy  $E$ , a Shchelkin spiral 460 mm long coiled from a steel wire, 4 mm in diameter, with a pitch of 18 mm was placed between the dischargers (see Fig. 6).

The capacitance  $C_1$  was decreased to 25  $\mu\text{F}$ , and the capacitance  $C_2$  was left unaltered, 225  $\mu\text{F}$ . The variables in these runs were the voltage  $U$  and the triggering delay time  $\tau$  of the second discharger with respect to the time of arrival of the primary SW at a special sensor 6 (Fig. 6) mounted in

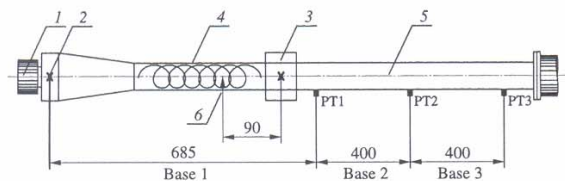


Fig. 6. Experimental setup with 28-millimeter tube and Shchelkin spiral between two dischargers (Frolov et al., 2005): 1—Air-assist liquid-fuel atomizer, 2—First discharger, 3—Second discharger, 4—Shchelkin spiral, 5—Tube, and 6—Sensor; PT1, PT2, and PT3 stand for pressure transducers. Dimensions in mm.

the 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  $60 < \tau < 120$   $\mu\text{s}$ ; 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. In the course of further experiments with combination of various other means the minimal detonation initiation energy in the 28-millimeter tube was lowered to  $E = 30$  J. In the experiments with *n*-heptane sprays similar trends were observed, however the energy requirements for detonation initiation were somewhat higher (Frolov et al., 2002, 2003b, 2003c, 2005).

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  $\mu\text{s}$  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.

#### 4. 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 (Shchelkin, 1949), 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 (Shchelkin, 1949; Zel'dovich and Kompaneets, 1955). 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

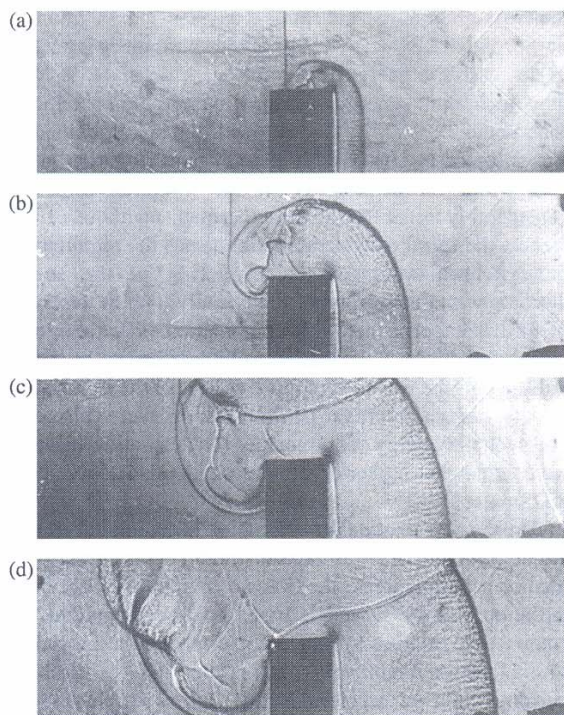


Fig. 7. Spark Schlieren photographs for obstacle-induced detonation initiation in  $C_2H_4 + 3O_2 + 12Ar$  mixture (initial SW Mach number  $M = 3.2$ , initial pressure 0.053 atm, 20  $\mu s$  frame interval) (Brown and Thomas, 2000). The primary SW propagates from right to left.

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, Fig. 7 shows detonation initiation due to propagating SW reflection from an obstacle (Brown and Thomas, 2000). If temperature behind the reflected shock is high enough, explosion-like autoignition ('strong explosion,' Oppenheim, 1972) occurs.

## 5. 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. The latter DDT scenario can be referred to as 'slow' DDT. With this understanding, new approaches to safety precautions against 'fast' accidental DDT should be developed.

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