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Detonation Initiation by Controlled Triggering of Electric Discharges

S. M. Frolov* and V. Y. Basevich†
N. N. Semenov Institute of Chemical Physics, 119991, Moscow, Russia
and
V. S. Aksenov‡ and S. A. Polikhov§
Moscow Physical Engineering Institute, 115522, Moscow, Russia

It has been proved experimentally that the use of a sequence of relatively weak igniters with properly tuned triggering times allows one to initiate detonation in premixed propane–oxygen-enriched air and propane–air mixtures at distances as short as 0.6–0.7 m in a 2-in.- (51-mm-) diam tube at normal initial conditions. Simple one-dimensional calculations have been used to get better insight into the mechanism of detonation onset. The proposed technique of detonation initiation presents a promising approach for pulse detonation engine applications.

Introduction

ONE of the most challenging problems encountered in the development of pulse detonation engines (PDEs) is detonation initiation in fuel–air mixtures at distances that are feasible for propulsion applications. As is well known, detonation occurs via a transient stage of strong coupling between the shock wave and the shock-induced reaction in the explosive medium.

This paper deals with a promising technique for detonation initiation that is based on the necessity of the strong coupling between a shock wave and energy deposition. Fundamentally, it does not matter how the energy is deposited into the postshock flow: spontaneously, due to shock-induced chemical reactions, or by means of inducing chemical reactions 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 induce artificially exothermic reactions closely behind a relatively weak shock wave to stimulate the strong coupling. Clearly, in this case the external energy source should be distributed rather than concentrated and should provide pulse or continuous coupling of energy deposition with a propagating shock wave.

Originally, the idea of using external sources to drive a detonation came from 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 et al.[2,3] considered the nonuniformly preconditioned reactive mixture, implying that the initial gradient of autoignition 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 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 proved that the strength of the shock wave 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, that is, 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 shock wave. Lee and Moen[6] have suggested the concept of shock wave amplification by coherent energy release and applied it to explain qualitatively the experimental findings in photochemical initiation of detonation (Lee et al.[7]), detonation initiation by injecting hot turbulent jets into explosive mixture (Knystautas et al.[8]), and explosion in the explosion phenomenon during deflagration-to-detonation transition (DDT) (Oppenheim[9]). Shepherd and Lee[10] and Khokhlov et al.,[11] among others, further generaled the issue. So far, there has been no direct experimental substantiation of the ideas and mechanisms discussed.

The objective of this paper is to describe experimental studies of the possibility to accelerate a weak shock wave efficiently by in-phase triggering of distributed external energy sources (electric discharges) in the course of shock wave propagation along the tube filled with a nonreactive or reactive mixture. The research discussed herein has been partly summarized in Ref. 12. The results of simple one-dimensional simulations are included to better understand the accompanying phenomena.

Experimental Setup and Procedure

Figure 1 shows the experimental setup. A detonation tube (Fig. 2) is 2 in. (51 mm) in inner diameter and 1.5 m long with closed ends. The tube comprises a booster section 1.0 m long and a test section 0.5 m long connected by means of a flange. The booster section is equipped with 11 lateral ports for electrical igniters and 1 port for the aft igniter, 10 pressure transducers, and the opening for feeding a test mixture. The lateral ports for igniters are flush mounted to the tube at an angle of 45 deg as shown in Figs. 1 and 2. In cross section 1 (CS1), there are two ports for lateral igniters positioned opposite to each other. The axial distance between successive lateral igniters is 100 mm. The axial distance between the aft igniter and the igniters in CS1 is 26 mm. The test section is equipped with ports for pressure transducers and ionization probes and the opening for evacuating the tube. The distance between successive ports for the pressure transducers is 100 mm.

Three types of igniters were applied allowing one to produce electric discharges of various duration and intensity (Fig. 3). Igniters of

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*Director of Laboratory, Department of Combustion and Explosion, 4, Kosigin Street; smfrol@center.chph.ras.ru.
†Chief Scientist, Department of Kinetics and Catalysis, 4, Kosigin Str.
‡Engineer, Department of Technical Physics, 31, Kashirskoe Shosse.
§Postgraduate Student, Department of Technical Physics, 31, Kashirskoe Shosse.

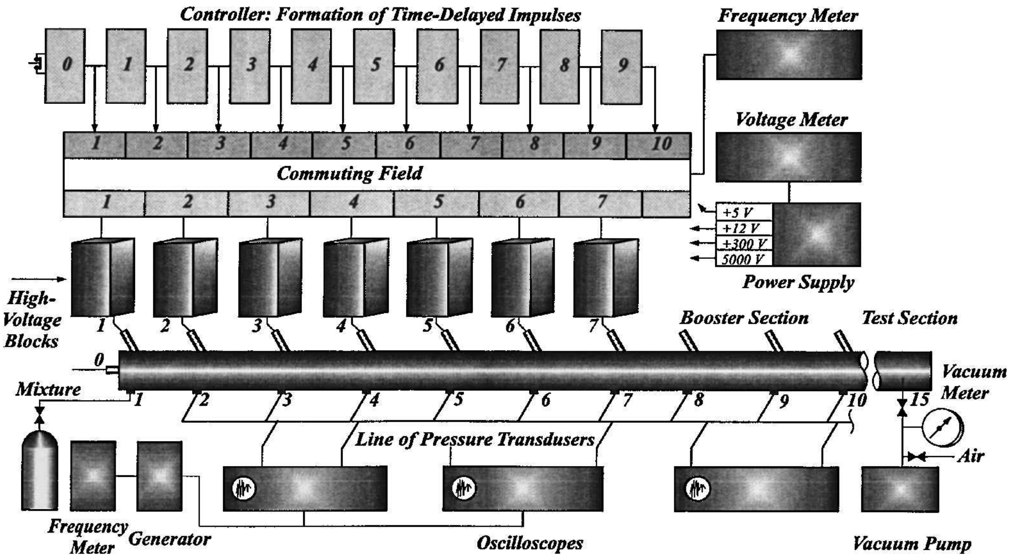


Fig. 1 Experimental setup.

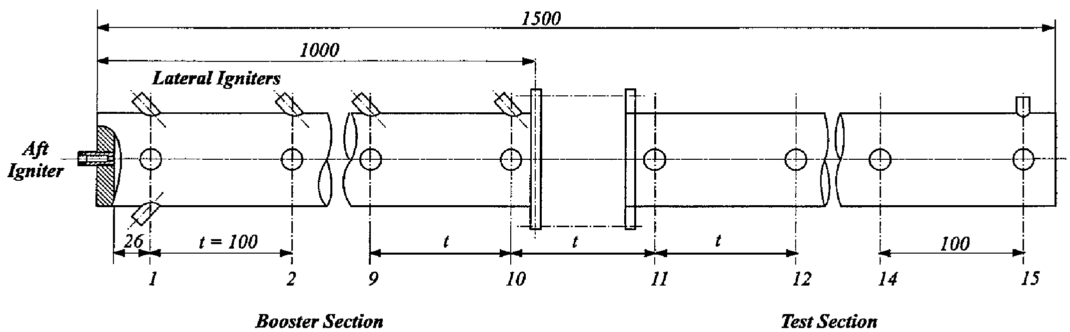


Fig. 2 Schematic of detonation tube.

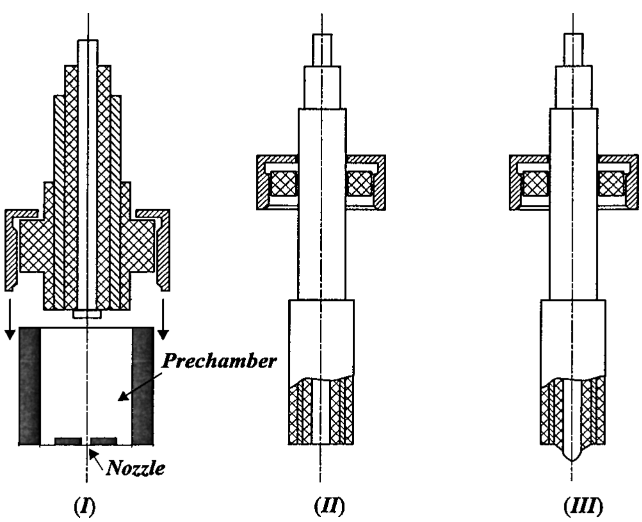


Fig. 3 Three types of igniters used in experiments.

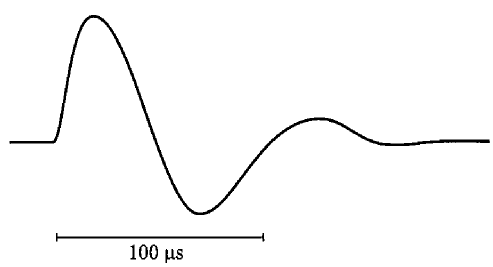


Fig. 4 Discharge current measured by Rogovsky coil mounted on the high-voltage cable; signal was obtained at a voltage of 2500 V and rated capacitance of 300 μF. Shape of current is close to sine wave with the oscillation period of 100 $\pm$ 10 μs

type 1 are the prechamber-type igniters with replaceable nozzles of different diameter connecting a prechamber with the booster section. The volume of the prechamber was varied from 5 to 15 cm^3. Type 2 igniters comprise the copper central electrode and the isolated coaxial copper cylinder with the discharge gap of 1.5 mm. The igniters of type 3 were also made of copper and encountered thicker discharge gaps (up to 2.5 mm). Contrary to igniters of type 1, igniters of types 2 and 3 were inserted into the tube to position a tip of the electrode 15 mm from the nearest tube wall. Each igniter is fed independently with an individual high-voltage capacitor. The characteristic rated capacitance is divisible to 100 μF. The discharge triggering time is controlled with a controller. The controller provides time-delayed pulses to trigger successively, via the commuting field, the individual high-voltage blocks of the igniters with a preset time delay. The time delay could be varied within a wide range (from 10 to 500 μs). The energy of discharges is controlled by the voltage, which is the same for all high-voltage blocks. The following values of voltage were used: 1500, 2100, 2300, and 2500 V. The duration of energy deposition of type-1 igniters was determined by the prechamber nozzle diameter (2, 4, and 8 mm) and attained a value of several milliseconds for the smallest nozzle. The duration of energy deposition of types-2 and 3 igniters was estimated as 80–100 μs (Fig. 4). The high-voltage lines were properly grounded

Table 1 Measured shock wave velocities in pure air at two measuring stations indicated by CS numbers[a]

Number of capacitors (100 μF)	Velocity, m/s	Velocity, m/s, between CS11 and CS14 (300 mm)
3 (aft igniter plus 2 lateral igniters in CS1)	609 ± 9 (between CS2 and CS4)	468 ± 7
4 (aft igniter plus 2 lateral igniters in CS1 and igniter in CS2)	560 ± 8 (between CS3 and CS5)	460 ± 7
5 (aft igniter plus 2 lateral igniters in CS1 and igniters in CS2 and CS3)	579 ± 9 (between CS4 and CS6)	489 ± 7
6 (aft igniter plus 2 lateral igniters in CS1 and igniters in CS2, CS3, and CS4)	569 ± 8 (between CS5 and CS7)	494 ± 7
7 (aft igniter plus 2 lateral igniters in CS1 and igniters in CS2, CS3, CS4, and CS5)	540 ± 8 (between CS6 and CS8)	490 ± 7

[a]Characteristic capacitor voltage is 2500 V. Results are relevant to best trigger timing of successive igniters.

to avoid the interference with the measurement signals. The data acquisition system comprised oscilloscopes, frequency meters, and a personal computer.

All experiments were performed at atmospheric pressure of 0.1 MPa and ambient temperature of 292–297 K. As test mixtures, three compositions were used: 1) pure air, 2) stoichiometric propane–oxygen-enriched air [C_3H_8–(O_2+3N_2)], and 3) stoichiometric propane–air [C_3H_8–(O_2+3.76N_2)]. The mixtures were prepared in the mixing bottles and were kept for more than 24 h before the experiments.

The experimental procedure encountered a number of steps dealing with "tuning" the controller in terms of the preset delay times for triggering the successive electric discharges. The aim of the tuning was to obtain a blast wave of the highest possible velocity in the nearest downstream measuring base in the booster, with other conditions being fixed.

The tube was evacuated and filled with the test mixture. After triggering the aft igniter and two lateral igniters in CS1, the shock wave velocity was measured between CS2 and CS4. Based on this velocity, a first approximation for the time delay of triggering the discharge in CS2 was obtained for the next run. This time delay was preset in the controller. The next run encountered time-delayed triggering of the aft igniter, two igniters in CS1, and the igniter in CS2. When the pressure transducers in CS3 and CS5 were used, the shock wave velocity at this next section of the tube was then measured. In the subsequent runs, by varying the time delay of discharge triggering in CS2, the best conditions for shock wave amplification in terms of the velocity between CS3 and CS5 were obtained.

The next step was aimed at finding the best timing for triggering the igniter in CS3 to obtain the shock wave of the highest velocity between CS4 and CS6, keeping fixed the best triggering time of igniter in CS2. This procedure was continued until all available igniters were tuned in such a way that the shock wave was amplified at a maximum rate. In some cases, information on transformation of the shock wave pressure profile was additionally taken into account in choosing the optimum timing for triggering the corresponding igniter.

At each stage of the procedure, several runs were performed to collect the statistics on the reproducibility of the results. It was found that the results were satisfactorily reproducible both in air and in the reactive mixtures.

Experimental Results

Experiments on Shock Wave Propagation in Pure Air

Table 1 presents some results on shock wave propagation in a pure air at a characteristic capacitor voltage of 2500 V. It has been shown that under the specific conditions of these experiments each igniter provided sustaining of a shock wave velocity at a level of 540–580 m/s. At the end of the test section, between CS11 and CS14, the shock wave velocity dropped to 460–490 m/s. Decrease of the characteristic capacitor voltage to 1500 V resulted in the decrease of the shock wave velocity in the booster section to the level of 400–490 m/s and to 360–440 m/s between CS11 and CS14.

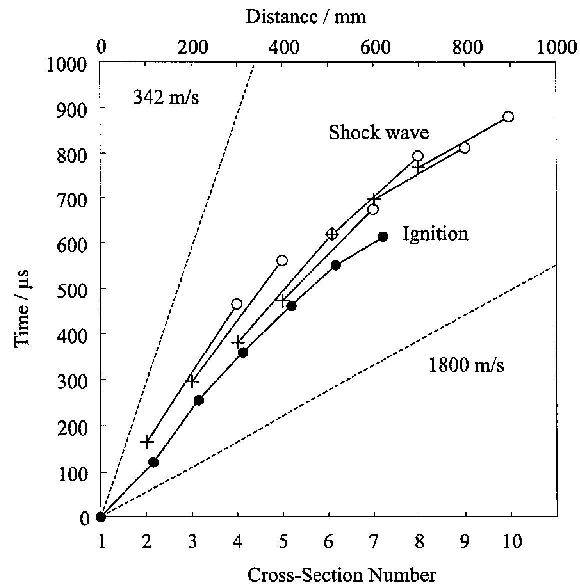


Fig. 5 Experimental distance–time diagram of shock wave amplification in the stoichiometric C_3H_8–(O_2+3N_2) mixture; detonation occurs after CS7.

Experiments on Shock Wave Amplification in C_3H_8–(O_2+3N_2) Mixture

Figure 5 shows the distance–time diagram that summarizes the results of experiments relevant to shock wave amplification in the stoichiometric C_3H_8–(O_2+3N_2) mixture. The characteristic capacitor voltage in this series was 2500 V. Dashed lines 342 m/s and 1800 m/s correspond to the characteristic values of sound and detonation velocities, respectively. Solid circles on the curve correspond to the optimized preset times of igniter triggering. Open circles on seven lines denote the measured arrival time of the shock wave to the corresponding CS. These lines show the experimental distance–time diagrams of shock waves that are generated by all igniters located before the points denoted by crosses. Thus, these lines are plotted for different experiments. Clearly, beginning from CS7 or CS8, at a distance of 0.6–0.7 m from the aft igniter, the detonationlike process with the characteristic velocity close to 1800 m/s is achieved in the booster, when all available igniters were properly triggered in one run. The detonationlike wave propagates at this (constant) velocity toward the closed end of the test section that is indicated by pressure transducers and ionization probes mounted at CS11, CS12, CS13, and CS14. Nevertheless, because the distance traveled by the wave is still short relative to that required for the establishment of self-sustained detonation after direct initiation,[13] it is preferable here to refer to the detonationlike rather than detonation phenomena.

Variation of triggering time of any lateral igniter by 40–50 μs (advance or delay) as compared to the optimized sequence of delay times resulted in detonation failure. Decrease in the characteristic capacitor voltage from 2500 to 2100 V (Table 2) also resulted in

Table 2 Effect of capacitor voltage on accelerating a shock wave in the stoichiometric propane–oxygen-enriched air mixture

Capacitor voltage, V	Velocity, m/s Base 1[a]	Velocity, m/s Base 2[b]	No. of capacitors (100 μF)	Remarks[c]
2500	1767	1805	9	Detonationlike mode
2300	1606	1748	9	Marginal detonationlike mode
2100	565	648	9	No detonationlike mode

[a]Between CS8 and CS10. [b]Between CS11 and CS14. [c]Copper igniters of type 3.

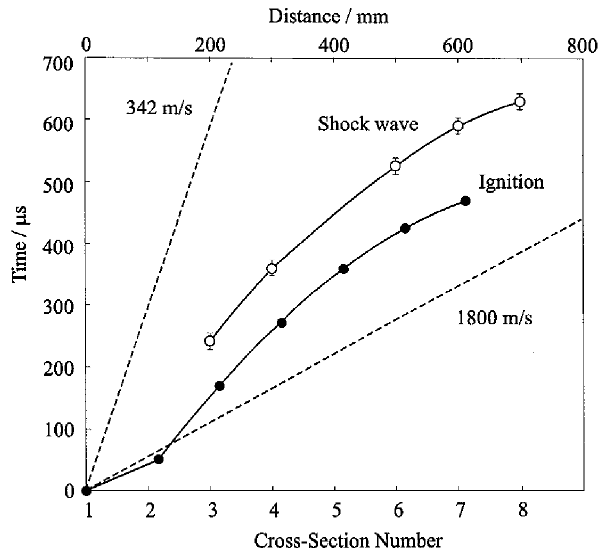


Fig. 6 Experimental distance–time diagram of shock wave amplification in the stoichiometric C_3H_8–air mixture; detonation occurs after CS7.

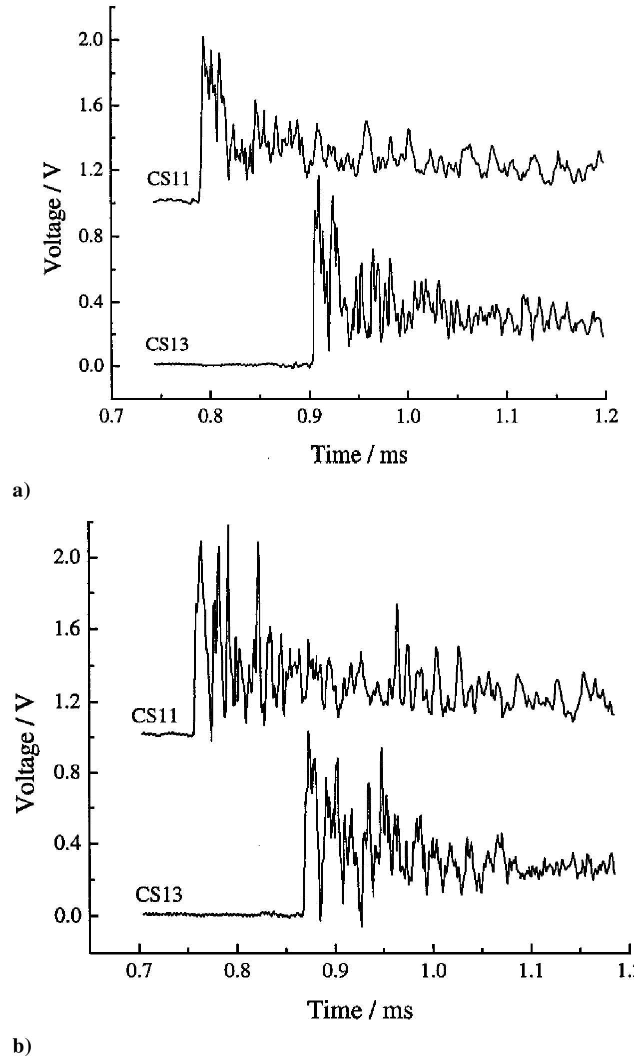


Fig. 7 Pressure records at CS11 and CS13 for case when C_3H_8–air detonation is initiated by seven successively triggered electric discharges located in CS1–CS7: two different runs under similar conditions.

a failure of detonation initiation, when other conditions were kept similar to those relevant to Fig. 5.

Experiments on Shock Wave Amplification in C_3H_8–Air Mixture

Figure 6 shows the distance–time diagram that summarizes the results of experiments relevant to shock wave amplification in the stoichiometric C_3H_8–air mixture. The characteristic capacitor voltage in this series was 2500 V. Application of conditions relevant to Fig. 5 to the fuel–air mixture did not result in detonation initiation. Therefore, to generate a stronger initial shock wave, the rated capacitance of the aft igniter capacitor was increased to 200 μF and the capacitors of the igniters in CS1 to 400 μF in total. Again, solid circles denote the optimized preset times of igniter triggering, and open circles approximately represent the shock wave arrival times to the corresponding booster CSs. Clearly, in CS8, at a distance of about 0.7 m from the aft igniter, the detonationlike process is achieved in the booster when all available igniters are triggered in one run. The detonation like wave propagates at the velocity of about 1750–1800 m/s in the test section as detected by the corresponding pressure transducers and ionization probes. For example, Fig. 7a shows pressure records obtained in the test section at CS11 and CS13. The characteristic velocity of the wave is 1745 m/s. Pressure records of Fig. 7b were obtained in another run with similar conditions. In this case, the characteristic velocity is 1785 m/s.

In a special set of runs, the optimized sequence of igniter triggering times was purposefully changed to study the sensitivity of the phenomenon to wrong timing. For example, triggering of the igniter in CS4 with the delay of 320 μs rather than with the optimized value of 270 μs in experiments of Fig. 6 resulted in failure of detonation initiation. Similar results were obtained when the triggering times of other igniters were shifted by 50 μs from their optimized values. These findings indicate that the phenomenon under study exhibits a resonant behavior.

Discussion and One-Dimensional Simulation

Thus, it has been proved that the use of a sequence of relatively weak igniters with properly tuned triggering times allows one to initiate detonation in a premixed hydrocarbon–air mixture at distances as short as 0.6–0.7 m in a smooth, 51-mm-diam tube, that is, at length-to-diameter ratio of 12–14. The initial (registered) shock wave Mach number in these cases was as low as 2.0–2.5. It has been found that to attain the highest rates of shock wave amplification, the igniters should be triggered before the arrival of a shock wave to the igniter location. For the conditions of Figs. 5 and 6, the average advance time in triggering the igniters is 80–100 μs, that is, the value correlating with the estimated discharge duration (Fig. 4). In the C_3H_8–$(O_2{+}3N_2)$ mixture, triggering of each consecutive igniters located in CS1–CS5 resulted in increasing the shock velocity by 80–140 m/s with a jump in the velocity of about 600 m/s after triggering the igniter in CS6. In the C_3H_8–air mixture, the shock wave velocity was gradually increasing from 850 ± 12 to 1767 ± 25 m/s by successive triggering of igniters in CS1–CS7. Between CS11 and CS14, the shock wave propagated at the velocity of 1770 ± 25 m/s. In the entire series of experiments with successful detonation initiation, the igniters of types 2 and 3 were used. In all tests with prechamber igniters of type 1, detonation initiation failed, apparently due to relatively long duration of energy deposition.

Two important findings of the experiments should be emphasized. First, each discharge in the sequence deposits energy that is much less than the energy required for direct detonation initiation by a single initiator. Second, the total initiation energy of detonation by means of successive triggering of electric discharges is less than the critical energy of direct detonation initiation by a single initiator. The total (theoretical) energy of discharges required for detonation initiation in propane–air mixture under conditions of Fig. 6 is estimated as $E_t = (nCU^2/2)/(\pi d^2/4) = 1.68 \mathrm{MJ/m^2}$, where n is the total number of capacitors (11), C is the rated capacitance (100 μF), U is the voltage (2500 V), and d is the tube diameter (51 mm). The value of 1.68 MJ/m^2 is close to the value of 3 MJ/m^2 reported[13] for the critical detonation initiation energy in a stoichiometric propane–air mixture. Contrary to our experiments, plane detonations[13] were initiated by three sorts of high-explosive (HE) sources: liquid nitromethane with diethylamine, plasticized HE, and a spiral of a detonating cord. Because the efficiency of conversion of electrical energy into the production of blast waves is usually low[14] (about 10%) as compared to the corresponding efficiency of HE, current results can be treated as evidence of a decrease in the total critical detonation initiation energy. As a matter of fact, successive triggering of discharges results in multiple reflections of blast waves that promote detonation initiation. Clearly, in this case there should be a difference between the flow patterns with distant and near locations of neighboring electric discharges. The effect of the distance between the discharges on the critical initiation energy of detonation was recently studied experimentally.[15,16] It was shown that there exists the optimum spacing between the igniters that allows for the largest decrease in the total initiation energy as compared to the initiation with a single electric discharge.

To gain better insight into the mechanism of detonation initiation by successive triggering of electric discharges, a series of simple one-dimensional calculations has been conducted. Consider a straight tube of length L closed at both ends and put the origin of the longitudinal coordinate X at one of the closed ends. The tube is filled with the premixed reactive mixture at initial pressure $P = P_0$. Assume that chemical activity in the mixture is governed by single-step Arrhenius-type kinetics with fuel mass fraction a as the chemical variable. Thus, the energy release function is taken in the form $H = Qk\rho a \exp(-E/RT)$, where Q is the reaction heat, k is the preexponential factor, ρ is the density, E is the activation energy, R is the gas constant, and T is the temperature.

The initial shock wave is generated by placing a hot spot at the closed end of the tube. The initial temperature distribution in the mixture is taken as[3]

$$T(0, X) = T_m - \kappa X \quad \text{at} \quad 0 \le X \le X_{hs}$$
$$T(0, X) = T_0 \quad \text{at} \quad X_{hs} < X \le L$$

where T_m is the maximum temperature in the hot spot, T_0 is the temperature outside the hot spot, κ is the temperature gradient (assumed constant) in the hot spot, and $X_{hs} = (T_m - T_0)/\kappa$ is the size of the hot spot.

At fixed location $X_1 \le X \le X_1 + \Delta X$ along the tube, a provision is made for the external energy source that conditionally models a single electric discharge. The source is assumed to occupy a finite length ΔX. The source is triggered at time $t = t_1$ and is active during time t_0. External energy deposition function is taken in the form $H_{ex} = (\pi/2) Q_{ex} \sin[\pi(t - t_1)/t_0]/t_0$, where Q_{ex} is the specific energy of the source. It is implied that external energy deposition will stimulate chemical activity in gas particles located at or traversing the position of the energy source at $t_1 \le t \le t_1 + t_0$.

The mathematical formulation of the problem is very similar to that reported elsewhere,[3] except for the provision of the external energy source. A set of governing equations for the ideal-gas reactive medium is written in the dimensionless Lagrangian form:

$$\gamma \frac{\partial u}{\partial \tau} + \frac{\partial p}{\partial x} = 0, \qquad \frac{\partial \xi}{\partial \tau} = u, \qquad \frac{\partial \xi}{\partial x} = v$$

$$\frac{(\gamma - 1)^{-1} \partial \theta}{\partial \tau} + \frac{p \partial u}{\partial x} = \alpha a \exp[\beta(1 - \theta^{-1})] + \psi q v$$

$$\frac{\partial a}{\partial \tau} + a \exp[\beta(1 - \theta^{-1})] = 0, \qquad pv = \theta \tag{1}$$

where

$$p = \frac{P}{P_0}, \qquad \theta = \frac{T}{T_m}, \qquad u = \frac{U}{\sqrt{\gamma R T_m}}, \qquad v = \frac{P_0 V}{R T_m}$$

$$\alpha = \frac{Q}{RT_m}, \qquad \beta = \frac{E}{RT_m}, \qquad \tau = tk \exp(-\beta)$$

$$x = \left(\frac{kRT_m}{P_0 \sqrt{\gamma R T_m}}\right) \exp(-\beta) \int_0^X \frac{\mathrm{d}X}{V(t, X)}$$

$$\xi = \left(\frac{Xk}{\sqrt{\gamma R T_m}}\right) \exp(-\beta), \qquad q = \frac{Q_{ex}}{P_0}$$

$$\psi = \left(\frac{\pi}{2\tau_0}\right) \sin\left[\frac{\pi(\tau - \tau_1)}{\tau_0}\right], \qquad \tau_1 = t_1 k \exp(-\beta)$$

$$\tau_0 = t_0 k \exp(-\beta) \tag{2}$$

In Eqs. (1) and (2), γ is the specific heat ratio (assumed constant), U is the velocity, V is the specific volume, x is the dimensionless Lagrangian coordinate, and ξ is the dimensionless Eulerian coordinate. Source term ψq is nonzero only for gas particles with $\xi_1 \le \xi \le \xi_1 + \Delta\xi$ at time $\tau_1 \le \tau \le \tau_1 + \tau_0$.

Initial and boundary conditions are specified as follows:

$$p(0, x) = 1, \qquad u(0, x) = 0, \qquad a(0, x) = 1$$

$$\theta(0, x) = \begin{cases} \exp(-\lambda x) & \text{at} \quad 0 \le x \le x_{hs} \\ \theta_0 & \text{at} \quad x_{hs} < x \le x_0 \end{cases}$$

$$\xi(0, x) = \begin{cases} \lambda^{-1}[1 - \exp(-\lambda x)] & \text{at} \quad 0 \le x \le x_{hs} \\ x - x_{hs} + \lambda^{-1}[1 - \exp(-\lambda x_{hs})] & \text{at} \quad x_{hs} < x \le x_0 \end{cases}$$

$$u(\tau, 0) = 0, \qquad u(\tau, x_0) = 0$$

$$\xi(\tau, 0) = 0, \qquad \xi(\tau, x_0) = \xi_0 \tag{3}$$

where $\theta_0 = T_0/T_m$, x_0 and ξ_0 are the dimensionless Lagrangian and Eulerian tube lengths, respectively, x_{hs} is the dimensionless size of the hot spot, and $\lambda = (\kappa\sqrt{(\gamma R T_m)}/kT_m)\exp(\beta)$ is the dimensionless temperature gradient in the hot spot.

The list of dimensionless parameters to be specified includes α, β, γ, θ_0, λ, ξ_0, q, τ_1, τ_0, ξ_1, and $\Delta\xi$. The set of Eqs. (1) with initial and boundary conditions (3) was solved numerically through the use of the artificial viscosity technique.[2,3,17] The code used for calculations has been verified in previous work.[3]

Figure 8 presents the test cases studied herein. The objective of the test case shown in Fig. 8a is to find out what kind of pressure

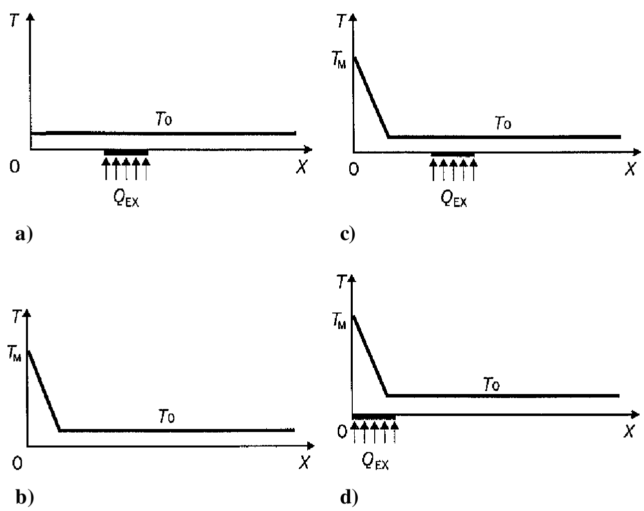


Fig. 8 Test cases studied computationally.

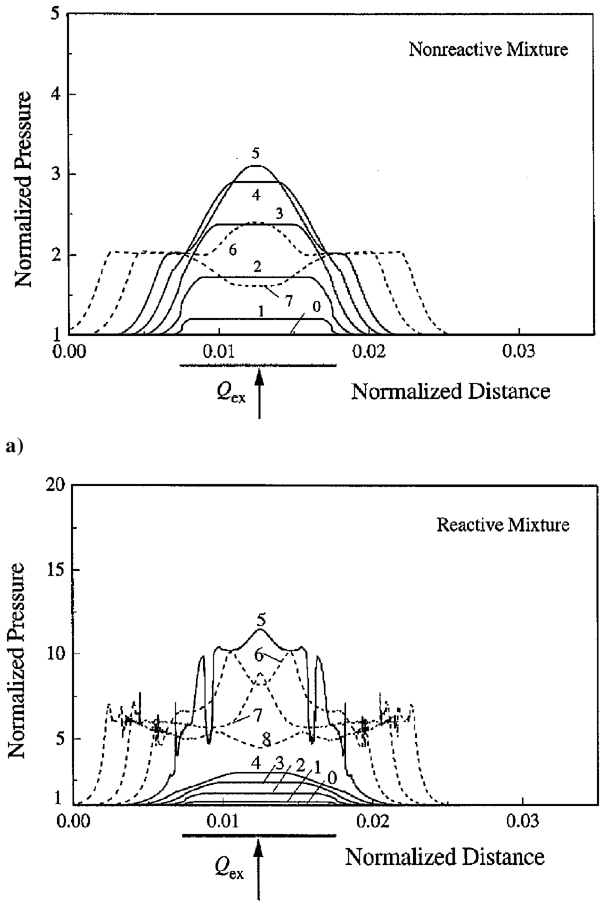


Fig. 9 Calculated temporal evolution of pressure disturbances produced by the external energy source in a) nonreacting gas where 0) τ = 0, 1) τ = 0.908, 2) τ = 1.816, 3) τ = 2.724, 4) τ = 3.632, 5) τ = 4.54, 6) τ = 7.264, and 7) τ = 9.08 and b) in a reacting gas where 0) τ = 0, 1) τ = 0.908, 2) τ = 1.816, 3) τ = 2.724, 4) τ = 3.632, 5) τ = 4.54, 6) τ = 5.448, 7) τ = 6.356, and 8) τ = 7.264.

disturbance is produced by an external energy source in a thermally uniform mixture. Test case of Fig. 8b is aimed at studying the pressure disturbance produced by the hot spot itself. The aim of test case of Fig. 8c is to find the conditions of detonation initiation by proper triggering of the external energy source. Finally, test case of Fig. 8d is aimed at studying the energy requirements for detonation initiation by the external energy source placed at the closed end of the tube.

Figures 9–12 show the results of calculations for the system with the following dimensionless parameters: $\alpha = q = 7$, $\beta = 10$, $\gamma = 1.3$, $\theta_0 = 0.25$, $\lambda = 0.123$, $\xi_0 = 680$, $\tau_0 = 4.54$, $\xi_1/\xi_0 = 0$ and 0.0075, and $\Delta\xi/\xi_0 = 0.01$. Note that these parameters were chosen for purposes of illustration and do not necessarily correspond to a particular reactive mixture. The triggering time τ_1 of the external energy source is the parameter of primary interest. Figures 9–12 are the plots of the normalized pressure p vs normalized distance ξ/ξ_0.

Figures 9a and 9b show the calculated temporal evolution of pressure disturbances produced by the external energy source in a nonreactive [$a(0, x) = 0$, Fig. 9a)] and a reactive (Fig. 9b) mixture, respectively, and correspond to the test case of Fig. 8a. Clearly, external energy deposition with given q, $\Delta\xi$, and τ_0 can result in a localized overpressure $\Delta p = p - 1$ of approximately 2.1 in the nonreactive mixture and is capable of igniting the reactive mixture with the ignition delay time close to τ_0.

Figure 10 presents the results of calculations for the test case of Fig. 8b in terms of the temporal evolution of the pressure wave generated by a hot spot. Autoignition of the mixture in the core of the hot spot followed by coupling between the reaction front and

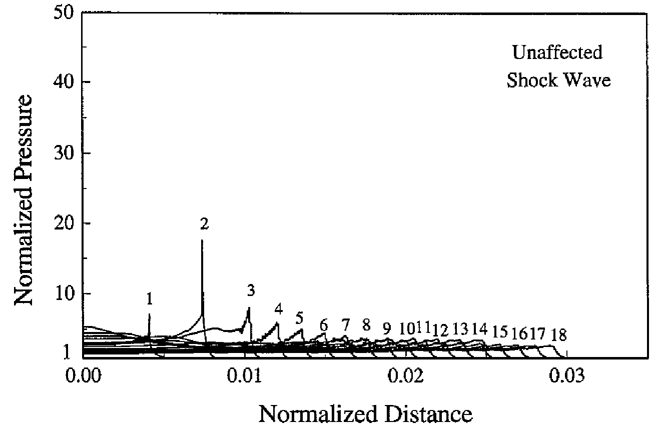


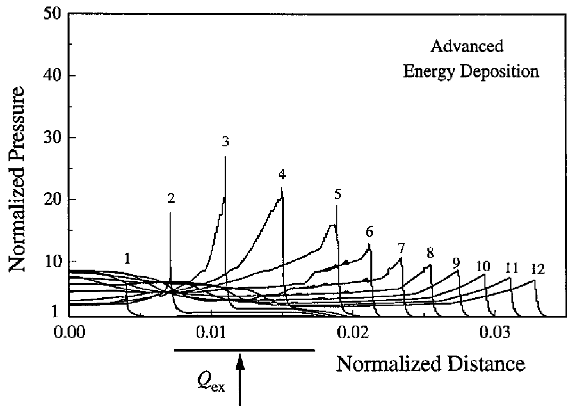
Fig. 10 Calculated temporal evolution of pressure waves generated by a hot spot in a reacting gas: 0) τ = 0, 1) τ = 0.908, 2) τ = 1.816, 3) τ = 2.724, 4) τ = 3.632, 5) τ = 4.54, 6) τ = 5.448, 7) τ = 6.356, 8) τ = 7.264, 9) τ = 8.172, 10) τ = 9.08, 11) τ = 9.988, 12) τ = 10.896, 13) τ = 11.804, 14) τ = 12.712, 15) τ = 13.62, 16) τ = 14.528, 17) τ = 15.436, and 18) τ = 16.344.

the pressure wave[2,3] leads to formation of an intense shock wave with $\Delta p \approx 17$ at the periphery of the hot spot. This shock wave is unable to initiate detonation in the test mixture and gradually attenuates.

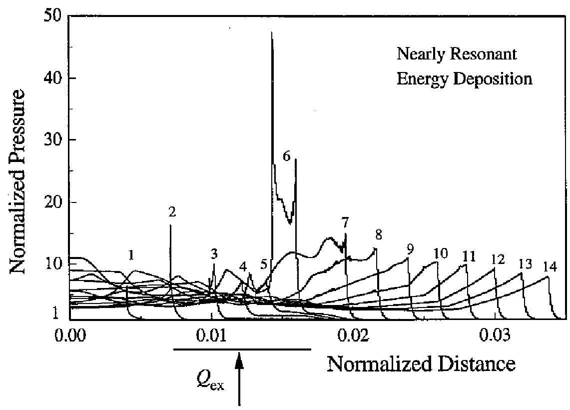
Consider now the results of calculations corresponding to the test case of Fig. 8c. Early activation of the external energy source (with $\tau_1 = 0$) results in some amplification of the shock wave generated by the hot spot (Fig. 11a) as compared to Fig. 10. The maximum shock overpressure $\Delta p \approx 26$ is attained shortly after the penetration of the initial shock wave into the zone of external energy deposition. Further shock acceleration is terminated by ignition of the mixture immediately in front of the shock wave. As a result, the shock wave enters the pockets of burned material and decays. Activation of the external energy source at $\tau_1 = 1.87$ (Fig. 11b) rather than at $\tau_1 = 0$ (Fig. 11a) leads to a more vigorous explosion in the energy deposition zone and temporary formation of a reactive retonation wave propagating upstream. The shock wave propagating downstream is still too weak to initiate detonation. Finally, activation of the external energy source at $\tau_1 = 2.91$ (Fig. 11c) results in detonation initiation. The detonation wave propagates in a self-sustained mode to the end of the tube ($\xi \to \xi_0$) with the oscillatory overpressure of $\Delta p \approx 33 - 35$ that roughly corresponds to the thermodynamic value of $\Delta p \approx 34.7$. Further increase in τ_1 leads to failure of detonation initiation because the decaying shock wave fails to ignite the test mixture with appropriate ignition delays.

Thus, it follows from Figs. 11a–11c that external energy deposition timing exerts a dramatic effect on the initial shock wave dynamics. If energy deposition is properly tuned with respect to the shock arrival time, the shock wave is capable of initiating detonation.

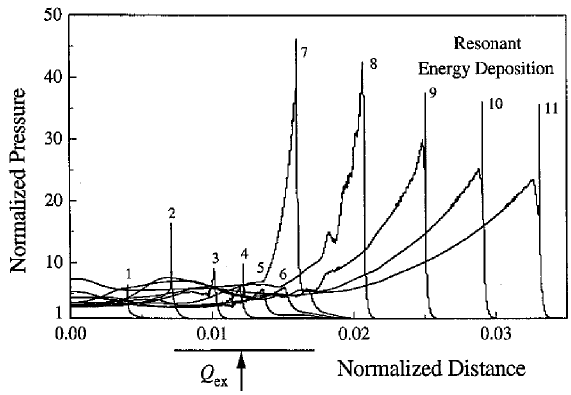
In view of this, it is important to find what the minimum energy and power requirements are for detonation initiation. In this particular study, we restrict ourselves by considering the test case of Fig. 8d. In the configuration of Fig. 8d, the energy of the external source is supplementary to the energy concentrated in the hot spot. Nevertheless, when triggering the external energy source at $\tau_1 = 0$, one obtains the flow pattern very similar to that shown in Fig. 10, that is, no significant evidence of shock wave amplification exists in this case. Increasing external energy deposition by a factor of five ($q = 5\alpha$), with other conditions unchanged, also does not result in detonation initiation as seen from Fig. 12a. Only when q is increased by a factor of 10, that is, with $q = 10\alpha$, is detonation successfully initiated (Fig. 12b). The comparison of total energy requirements for "resonant" detonation initiation in Figs. 11c and for "direct" detonation initiation in Fig. 12b indicates that the former is by the order of magnitude less than the latter. Because this implication is based on simple one-dimensional calculations, its validity remains questionable, and more sophisticated studies are required to substantiate it.



a)

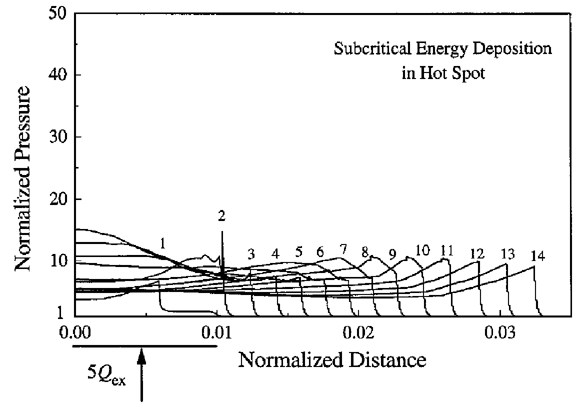


b)

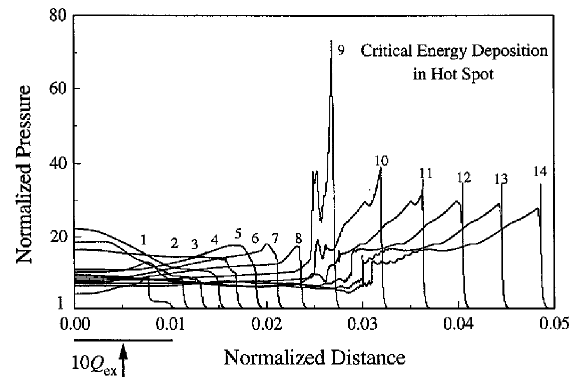


c)

Fig. 11 Calculated temporal evolution of pressure waves generated by a hot spot and external energy deposition in a reacting gas: a) poorly synchronized (advanced) triggering of energy source at $\tau_1 = 0$ where 0) $\tau = 0$, 1) $\tau = 0.908$, 2) $\tau = 1.816$, 3) $\tau = 2.724$, 4) $\tau = 3.632$, 5) $\tau = 4.54$, 6) $\tau = 5.448$, 7) $\tau = 6.356$, 8) $\tau = 7.264$, 9) $\tau = 8.172$, 10) $\tau = 9.08$, 11) $\tau = 9.988$, and 12) $\tau = 10.896$; b) nearly resonant triggering of energy source at $\tau_1 = 1.87$ where 0) $\tau = 0$, 1) $\tau = 0.908$, 2) $\tau = 1.816$, 3) $\tau = 2.724$, 4) $\tau = 3.632$, 5) $\tau = 4.54$, 6) $\tau = 5.448$, 7) $\tau = 6.356$, 8) $\tau = 7.264$, 9) $\tau = 8.172$, 10) $\tau = 9.08$, 11) $\tau = 9.988$, 12) $\tau = 10.896$, 13) $\tau = 11.804$, and 14) $\tau = 12.712$; and c) resonant triggering of energy source at $\tau_1 = 2.910$ where 0) $\tau = 0$, 1) $\tau = 0.908$, 2) $\tau = 1.816$, 3) $\tau = 2.724$, 4) $\tau = 3.632$, 5) $\tau = 4.540$, 6) $\tau = 5.448$, 7) $\tau = 6.356$, 8) $\tau = 7.264$, 9) $\tau = 8.172$, 10) $\tau = 9.080$, and 11) $\tau = 9.988$.



a)



b)

Fig. 12 Calculated temporal evolution of pressure waves generated by a combination of hot spot and external energy deposition at the tube closed end: a) $q = 5\alpha$, $\tau_1 = 0$ and b) $q = 10\alpha$, $\tau_1 = 0$ where 0) $\tau = 0$, 1) $\tau = 0.908$, 2) $\tau = 1.816$, 3) $\tau = 2.724$, 4) $\tau = 3.632$, 5) $\tau = 4.54$, 6) $\tau = 5.448$, 7) $\tau = 6.356$, 8) $\tau = 7.264$, 9) $\tau = 8.172$, 10) $\tau = 9.08$, 11) $\tau = 9.988$, 12) $\tau = 10.896$, 13) $\tau = 11.804$, and 14) $\tau = 12.712$.

Based on the preceding computational findings, one can speculate on the mechanism of shock wave amplification and transition to detonation in our experiments. Triggering of the first igniter results in a weak attenuating shock wave. This shock wave fails to ignite the fresh mixture, thus leaving it unburned. Shock-synchronized triggering of the second igniter results in a sharp localized pressure rise followed by the formation of two secondary shock waves propagating in opposite directions. These shock waves are also too weak to ignite the mixture, even though the shock propagating upstream meets the precompressed material. The shock wave propagating downstream attenuates and, when arriving at the location of the third igniter, appears to be more intense as compared to the shock wave arriving at the location of the second igniter before its triggering. Shock-synchronized triggering of the third igniter results in complex interaction of secondary shocks, sharp pressure rise, etc. Finally, step-by-step acceleration (in average) of the lead shock wave promotes the localized onset of the self-sustained detonation propagating in the downstream direction. The regions between the igniters still contain pockets of unburned material that burn in relatively slow flames. Of course, multidimensional effects (such as shock collisions and reflections from the wall and from contact discontinuities) are of primary importance for the origin of detonation.[18]

The physical mechanism of shock wave acceleration in our experiments seems very similar to that characteristic for DDT phenomena. However, instead of spontaneous acceleration of the lead shock due to interaction with the flame-induced pressure waves, as is the case in the DDT, an external energy source is used to stimulate a stronger interaction between the reaction front and the propagating shock wave. Ideally, the reaction front can be triggered continuously in phase with shock wave propagation, rather than in separate locations, as it was done in the reported experiments. In this case, it is expected that the distance required for shock wave acceleration to the intensities required for detonation onset will be less than obtained here. In addition, the energy requirements are also expected to be lower if the energy deposition to the accelerating shock wave is continuous rather than discrete. These implications will be checked in future experiments. The outlined principles of controlled detonation initiation can be useful for PDE applications.

Conclusions

A promising technique for detonation initiation has been suggested and validated experimentally. It implies the use of distributed external energy sources to induce artificially exothermic reactions behind a relatively weak shock wave to stimulate strong coupling between the shock wave and energy deposition. In the experiments, a weak shock wave was accelerated in the reactive mixture by means of in-phase triggering of spark igniters in the course of shock wave propagation along the tube. Detonationlike regimes have been obtained at a distance of 0.6–0.7 m in stoichiometric C_3H_8–(O_2+$3N_2$) and C_3H_8–air mixtures under normal conditions. High sensitivity of detonation initiation to distortions in igniter triggering times and igniter energy indicates that the phenomenon under study exhibits a resonant behavior. Simple one-dimensional calculations have been used to gain better insight into the mechanism of detonation onset. The technique is considered as promising for PDE applications.

Acknowledgments

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