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Detonation Initiation in Liquid Fuel Sprays by Successive Electric Discharges

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In promising air-jet engines, hydrocarbon fuel combustion in a periodically generated traveling detonation wave (DW) is suggested to produce thrust [1]. It is expedient to feed these engines with a common liquid fuel of the type of aviation kerosene without active additions, directly injecting it into a combustion chamber without preliminary mixing with air. The low detonation capacity of fuel sprays and high energies required for detonation initiation [2] lead to the emergence of a number of fundamental problems. These problems may be solved by use of a predetonator [3], an intermediate device in which a DW is relatively readily initiated in a fuel–oxygen mixture. The resulting DW is then passed into a combustion chamber with a fuel–air mixture. In this work, we put forward and studied a new method for initiating detonation in liquid fuel sprays, which opens the way to the development of a predetonator working on a fuel–air mixture, without use of oxygen. The method is based on the idea of Zel'dovich and Kompaneets [4] that gaseous detonation can be initiated by means of forced ignition by distributed external sources mounted along a channel with a fuel gas. This idea was experimentally proven in [5] for a gas propane–air mixture.

Three sets of experiments were carried out with the objective of initiating detonation in a liquid *n*-hexane spray in air by means of two successively triggering electric dischargers. Steel tubes 51 and 28 mm in diameter were used. At one end of a tube, an air-assisted atomizer was mounted; it provided an airflow at a rate of 20–30 L/s and finely sprayed the fuel to give drops 5–6 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 two electric dischargers, and a measuring section. The first discharger was placed at a distance of 60 mm from the sprayer nozzle, and the second discharger was mounted at a 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 τ 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 diagnostic system included an analog-to-digital converter and a PC. The experiments were run with the aim of selecting the triggering delay time Δt_d 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, a tube 51 mm in diameter and dischargers with $\tau = 100$ μs were used. The capacitance of the capacitor of each discharger was $C_1 = C_2 = 300$ μF. The voltage U, delay time Δt_d, and distance L were measured in the runs. Figure 1 was plotted for $L = 200$ mm. The plus signs in Fig. 1 correspond to the U and Δt_d 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 was observed. 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), a voltage of 3300 V (for the first discharger) or

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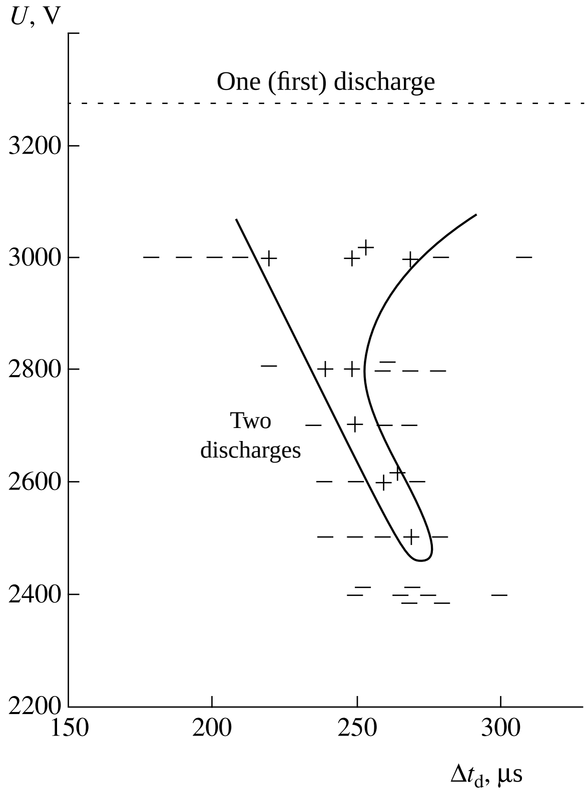

Fig. 1. Detonation peninsula for an *n*-hexane spray in air in a tube of 51 mm in diameter when detonation is initiated by two successive electric discharges.

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 1 shows that, energetically, detonation initiation by two dischargers is more efficient: as compared to initiation by single discharges, 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. 1 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 Δt_{d0}, at which $U = U_{min}$, depend on the distance L between the dischargers. In particular, at L = 100 mm, U_{min} = 3000 V and Δt_{d0} = 100 μs; at L = 200 mm, U_{min} = 2500 V and Δt_{d0} = 270 μs; and, at L = 300 mm, U_{min} = 3000 V and Δt_{d0} = 370 μs. At L = 400 mm and U = 3000 V, detonation was not initiated at any Δt_{d0} values. 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 τ = 50 μs were used. The capacitance was $C_1 = C_2$ = 225 μF. The delay time Δt_d was variable at U = 2000 V and L = 200 mm. The detonation onset was observed at $211 < \Delta t_d < 221$ 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 2a and 2b show the oscillograms of the pressure at transducers T1, T2, and T3 located in the cross sections at distances of 0.265, 0.665, and 1.065 m at Δt_d of (a) 214 and (b) 211 μs. In Fig. 2a, a DW was observed, whereas, in Fig. 2b, an attenuating shock wave (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. 2a, the mean DW velocity over the 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. 2b, 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. 2 shows the records of the diagnostic channel, with the signals of the controller and discharge currents. These records allow us 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 oscillograms as perturbations of the zero line. It is worth noting that the optimal triggering time $\Delta t_d \approx 214$ 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 T1 in Fig. 2a 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 τ = 50 μs were also used. To diminish the detonation initiation energy E, a Shchelkin spiral 460 mm long and with a pitch of 18 mm, coiled from a tungsten wire 4 mm in diameter, was placed between the dischargers. The capacitance C_1 was decreased to 25 μF, and the capacitance C_2 was left unaltered at 225 μF. The variables in these runs were the voltage U and the triggering delay time Δt_d of the second discharger with respect to the time of arrival of the primary SW at a special probe 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 = 0.66 kJ, which is 80 and 87% lower than the minimal energy of detonation initiation by single dischargers in a tube 51 mm

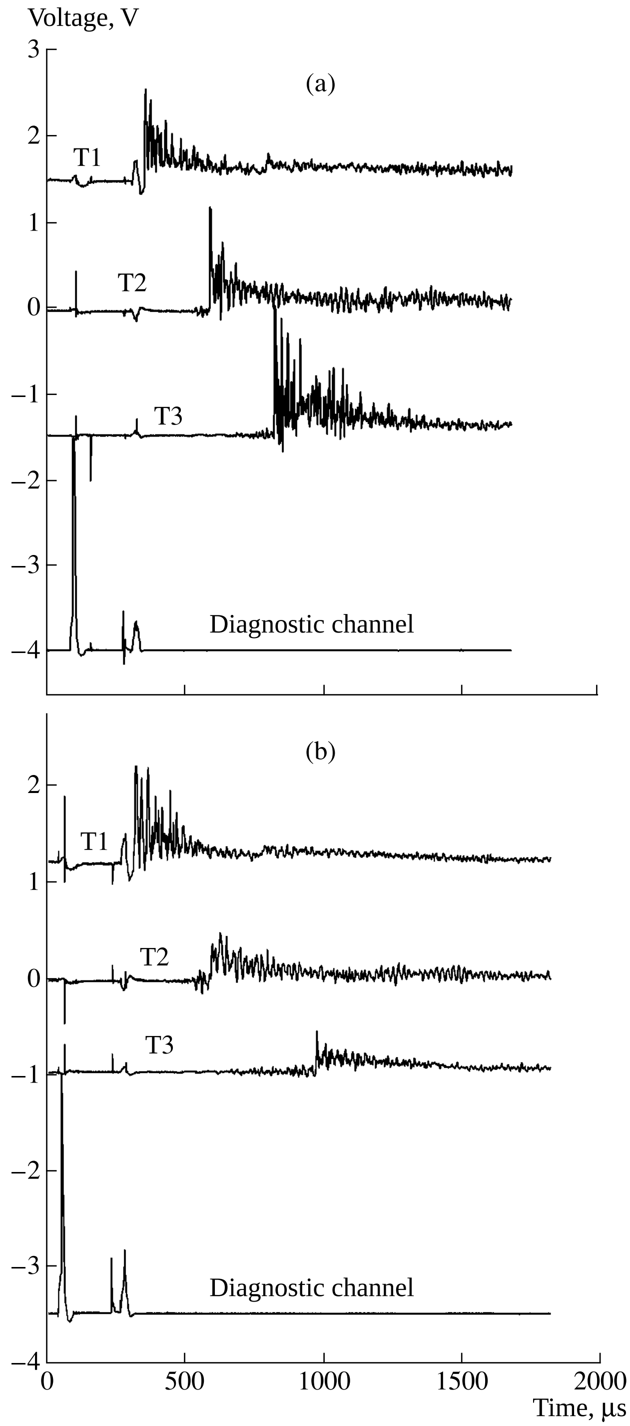

Fig. 2. Pressure oscillograms upon (a) detonation and (b) lack of detonation in the spray of *n*-hexane in air. The tube diameter was 28 mm. Detonation was initiated by two successive electric discharges.

in diameter. In the runs with the spiral, detonation was initiated at $60 < \Delta t_d < 120$ 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 discharge and the arrival of the primary SW.

Thus, a new method for detonation initiation in sprays of liquid fuel in air was experimentally demonstrated. The method complements the known methods—direct DW initiation and deflagration-to-detonation transition—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 a Shchelkin spiral enhances the efficiency of the method by decreasing the energies required and extending the detonation initiation limits.

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