DETONATION INITIATION BY CONTROLLED TRIGGERING OF MULTIPLE ELECTRIC DISCHARGES

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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 a premixed propane-air mixture at distances as short as 0.6-0.7 m in a 51-millimeter diameter tube at normal initial conditions. Such a technique of detonation initiation presents a promising approach for PDE applications.

Introduction

One of the most challenging problems encountered in the development of pulsed detonation engines (PDE) 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 project suggests a promising technique for detonation initiation that is based on the necessity of the strong coupling between a shock wave and energy deposition. Fundamentally, no matter how the energy is deposited into the post-shock 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 a highly activated nature 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 of 20-30 g. The latter approach implies the use of an external energy source to artificially induce exothermic reactions behind a relatively weak shock wave in order 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. The idea of the proposed technique is to initiate a weak shock wave and to accelerate it by in-phase triggering of distributed external energy sources (spark igniters) in the course of shock wave propagation along the tube.

Experimental Setup and Procedure

Figure 1 shows the experimental setup. A detonation tube is 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 sits for igniters and 1 sit for the aft igniter, 10 pressure transducers, and the opening for feeding a test mixture. The lateral sits for igniters are flash mounted to the tube at an angle of 45° as shown in Fig. 1. In the cross-section 1 (CS1), there are two sits 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 sits for pressure transducers and ionization probes, and the opening for evacuating the tube. The distance between successive sits for the pressure transducers is 100 mm.

Three types of igniters were applied allowing one to produce electrical discharges of various duration and intensity. Igniters of type I are the prechamber-type igniters with replaceable nozzles of different diameter connecting a prechamber with the booster section. Type II igniters comprise the copper central electrode and the isolated coaxial copper cylinder with the discharge gap of 1.5 mm. The igniters of type III were also made of copper and encountered thicker discharge gaps (2.5 mm). Each igniter is fed independently from an individual high-voltage capacitor. The characteristic rated capacity was 100 μF. The discharge triggering time is
controlled with a controller. The controller provides time-delayed impulses to successively trigger, 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 50 to 500 $\mu$s. The discharge intensity of each igniter is controlled by the capacitor voltage. The following values of capacitor voltage were used: 1500 V, 2100 V, 2300 V, and 2500 V. The duration of energy deposition of type-I 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 type-II and III igniters was estimated as less than 80–100 $\mu$s. The high-voltage wires were properly grounded to avoid the interference with the measurement signals. The data acquisition system comprised oscilloscopes, frequency meters and a PC.

All experiments were performed at atmospheric pressure 0.1 MPa and ambient temperature 292–297 K. As test mixtures, three compositions were used: (i) pure air, (ii) stoichiometric propane – oxygen enriched air $C_3H_8+(O_2+3N_2)$, and (iii) stoichiometric propane–ir $C_3H_8+(O_2+3.76N_2)$.

The experimental procedure encountered a number of steps dealing with ‘tuning’ the controller in terms of the preset delay times for triggering the successive igniters. 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, other conditions being constant.

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 igniter 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. By using the pressure transducers in CS3 and CS5, the shock wave velocity at this new section of the tube was then measured. In the subsequent runs, by varying the time delay of ignition 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.
Table 1: Measured shock wave velocities in pure air at two measuring stations indicated by cross-section (CS) numbers. Characteristic capacitor voltage is 2500 V. The results are relevant to best trigger timing of successive igniters

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

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 has been found that the results were satisfactorily reproducible both in air and in the reactive mixtures.

Results

Experiments on Shock Wave Propagation in Pure Air

Table 1 presents some results on shock wave propagation in a pure air at characteristic capacitor voltage 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.

Experiments on Shock Wave Amplification in C₃H₆–(O₂+3N₂) Mixture

Figure 2 shows the distance–time diagram that summarizes the results of experiments relevant to shock wave amplification in the stoichiometric C₃H₆–(O₂+3N₂) 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 cross-section. These lines show the experimental distance–time diagrams of shock waves.
Table 2: The effect of capacitor voltage on accelerating a shock wave in the stoichiometric propane—oxygen enriched air mixture. Base 1 is between CS8 and CS10. Base 2 is between CS11 and CS14. Copper igniters of type III.

<table>
<thead>
<tr>
<th>Capacitor voltage, V</th>
<th>Velocity, m/s</th>
<th>No. of capacitors (100 µF)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base 1</td>
<td>Base 2</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>1767</td>
<td>1805</td>
<td>9</td>
</tr>
<tr>
<td>2300</td>
<td>1606</td>
<td>1748</td>
<td>9</td>
</tr>
<tr>
<td>2100</td>
<td>565</td>
<td>648</td>
<td>9</td>
</tr>
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that are generated by all igniters located prior to the points denoted by crosses. Thus, these lines are plotted for different experiments. Clearly, beginning from CS8, at a distance of 0.6–0.7 m from the aft igniter, the detonation-like 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 detonation wave propagates at this velocity towards the closed end of the test section that is indicated by pressure transducers in the test section.

Decrease in the characteristic capacitor voltage to 2100 V (see Table 2) resulted in a failure of detonation initiation with properly tuned igniters, with other conditions kept similar to those relevant to Fig. 2.

**Experiments on Shock Wave Amplification in C₂H₆–Air Mixture**

Figure 3 shows the distance–time diagram that summarizes the results of experiments relevant to shock wave amplification in the stoichiometric C₂H₆–air mixture. The characteristic capacitor voltage in this series was 2500 V. To generate a stronger initial shock wave, the rated capacity 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 on the curve correspond to the optimized preset times of igniter triggering and open circles approximately correspond to shock wave arrival times to corresponding booster cross-sections. Clearly, in CS8, at a distance of about 0.7 m from the aft igniter, the detonation-like process is achieved in the booster when all available igniters are triggered in one run. This wave propagates at the velocity of about 1800 m/s in a test section as indicated by the corresponding pressure transducers.

**Discussion**

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. The initial (registered) shock wave Mach number in these cases was as low as 2.0–2.5. It has been found that for attaining the highest rates of shock wave amplification, the igniters should be triggered prior to the arrival of a shock wave to the igniter location. For the conditions of Figs. 2 and 3, the average advance time in triggering the igniters attains 80 to 100 μs, i.e., the value correlating with the estimated discharge duration. In the C₂H₆–(O₂+3N₂) mixture, triggering of each consecutive igniter located in CS1 to CS5 resulted in increasing

![Figure 3: Experimental distance–time diagram of shock wave amplification in the stoichiometric C₂H₆–air mixture. Detonation occurs after CS7](image-url)
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 C₂H₆–air mixture, the shock wave velocity was gradually increasing from 850 ± 12 to 1767 ± 25 m/s by successive triggering of igniters in CS1 to CS7. Between CS11 and CS14, the shock wave propagated at the velocity of 1770 ± 25 m/s. In all series of experiments with successful detonation initiation, the igniters of type II and III were used. In all tests with prechamber igniters of type I, detonation initiation was failed, apparently due to relatively long duration of energy deposition.

The physical mechanism of shock wave acceleration in these experiments is very similar to that characteristic for deflagration-to-detonation transition phenomena. However, instead of spontaneous coupling of the reaction front with the shock wave, as is the case in the deflagration-to-detonation transition, an external energy source is used to produce a reaction front closely coupled with 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 detonation intensities will be less than obtained here. In addition, the energy requirements are also expected to be less 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.

Conclusion

A promising technique for detonation initiation has been suggested and validated experimentally. It implies the use of distributed external energy sources to artificially induce exothermic reactions behind a relatively weak shock wave in order 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. Detonation-like regimes have been obtained at a distance of 0.6–0.7 m in stoichiometric C₂H₆–(O₂+3N₂) and C₂H₆–air mixtures under normal conditions. The technique is considered as promising for pulsed detonation engines applications.

References