# Initiation of Pulse Detonation in Sprays by Means of Successively Triggered Electric Discharges

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Experimental studies of multipulse detonations of *n*-hexane spray in air initiated by successively triggered electric discharges are presented. Similar to a single-shot mode reported previously, the multipulse operation mode shows the same resonant dependence of the detonation initiation energy on the time delay between the discharges. There is a potential of a considerable decrease in the detonation initiation energy per operational pulse. The issue of operational control aimed at avoiding misfires appeared to be important.

## Introduction

The objective of the study reported herein is to evaluate and experimentally realize a shock-booster concept of the pulse detonation engine (PDE). The idea of the concept suggested in [1, 2] is to repeatedly initiate a weak shock wave and to accelerate it by in-phase triggering of distributed electric discharges in the course of shock wave propagation along the smooth-walled detonation chamber. To substantiate this concept, several experimental facilities were designed, fabricated, and used during the previous research [1–4].

In [3, 4], experimental results on the effect of various means on the critical initiation energy of spray (*n*-hexane and *n*-heptane) detonation are presented. Spray detonation is initiated by a single electric discharge or by successively triggered two or three discharges in a tube with the flow of air and fine fuel drops produced by the air-assist atomizer. The effect of discharge time, shape, and location, insulating properties of the tube, tube shape and diameter, atomizer performance, distance between discharges and time delay between their triggering is studied.

Particular findings of [3, 4] are as follows. For direct initiation of spray detonation with a single discharge and minimal energy requirements, (1) it is worth to use the discharge located at the closed end of the test tube; (2) the discharge area should be properly insulated to avoid electric loss to the metal walls of the discharge chamber; (3) discharge duration should be minimized to at least 50–60 $\mu$s; (4) the detonation tube should be preferably of diameter close to the limiting tube diameter (in this case, detonation initiation by a single discharge shows relatively low energy requirements, e.g., 700–800 J for detonating *n*-hexane spray in air); (5) gradual transition between the discharge chamber and the detonation tube should be used (this allows to cumulate the arising shock wave into the detonation tube).

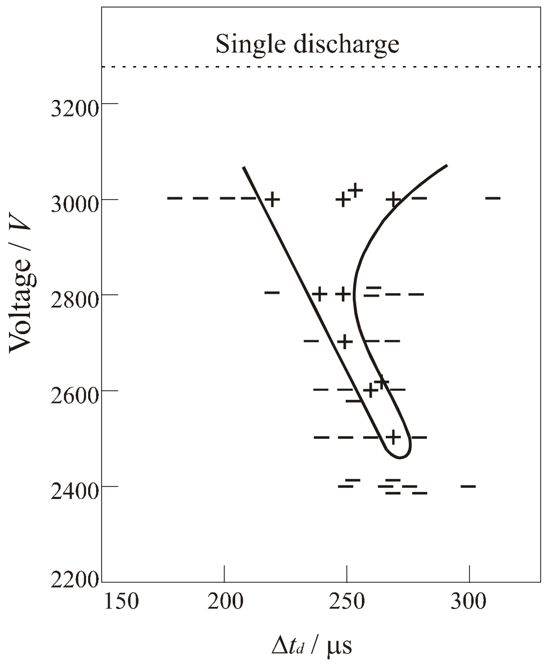


**Figure 1:** Measured detonation initiation energy (in terms of discharge voltage) as a function of delay time $\Delta t_d$ between two discharges positioned at a distance of 200 mm from each other [3, 4]. Plus sign = go, minus sign = no go condition for detonation

Further decrease in the total detonation initiation energy can be achieved by using several successively triggered discharges rather than a single discharge [1–4]. The tests with two successively triggered discharges [3, 4] resulted in the following main findings (see Fig. 1): (1) there exist resonant conditions for successive triggering of two discharges that have to be met in order to initiate detonation; (2) the minimal total detonation initiation energy is lower than that required for direct detonation initiation by a single discharge; and (3) the detonation peninsula at the "initiation energy vs.

triggering time delay" plane is very narrow and indicates the necessity of careful synchronization of successive discharge triggering.

In general, it has been shown that various means can be used to considerably decrease the initiation energy of spray detonation while keeping the predetonation distance and time both feasible for PDE applications. Contrary to DDT involving partial blockage of tube cross-section with turbulence-generating elements, the means studied herein do not produce much additional drag and the detonation tube is essentially smooth-walled.

Reported herein are further accomplishments dealing with repeated detonations initiated by several successively triggered discharges.

## Experimental Setup and Data Acquisition System

The schematic of the experimental setup is shown in Fig. 2. The detonation tube 51 mm in diameter comprises the air-assist atomizer and two sections: booster section and measuring section. Air receiver of 40-liter volume is supplied with a compressed air by a compressor. The nominal air pressure in the receiver is 6 atm. Air is fed to the atomizer via the air valve (valve 1 in Fig. 2). Liquid fuel is fed to the atomizer via fuel valve (valve 2 in Fig. 2) from pressurized fuel unit. The booster section currently consists of two (2) electric discharges ($D_1$ and $D_2$) mounted between the atomizer and the measuring section. The distance between $D_1$ and $D_2$ is 200 mm, the same as in Fig. 1. The measuring section is a steel tube 1 m long. It is equipped with three piezoelectric pressure transducers (PT1, PT2, and PT3) that form two measuring bases (base 2 and base 3 in Fig. 2) 400 and 200 mm long, respectively. Measuring base 1 is set from the center of first discharge $D_1$ to the axis of pressure transducer PT1. The measuring section is connected to atmosphere through a detonation arrester.

A high-voltage rectifier with a nominal voltage of 3.5 kV and remote control is used to feed discharge circuits. The rectifier provides operation voltage to charge capacitors $C_1$ and $C_2$ (300 $\mu$F each) via a distributor and a digital controller. The controller, based on the preset program, activates triggering units $I_1$ and $I_2$ which, in their turn, activate discharges $D_1$ and $D_2$, respectively. Energy deposition by electrical discharges results in violent ignition of fuel spray and generation of shock and detonation waves in the facility.

The data acquisition system is composed of two subsystems allowing for registration of processes in two essentially different time scales. A two-channel subsystem (L-154) with an access time interval of 5 ms registers the voltage at the high-voltage blocks and air pressure in the air-assist atomizer (with pressure transducer PT4). A four-channel subsystem (L-783) registers up to 3000 pixels per channel with the interval of 300 ns. First three channels register the signals of pressure transducers PT1, PT2, and PT3. The fourth channel is used for supplementary diagnostics.

A special digital controller has been designed and fabricated. The controller consists of several units that implement the preset algorithm of facility operation and provide operational safety.

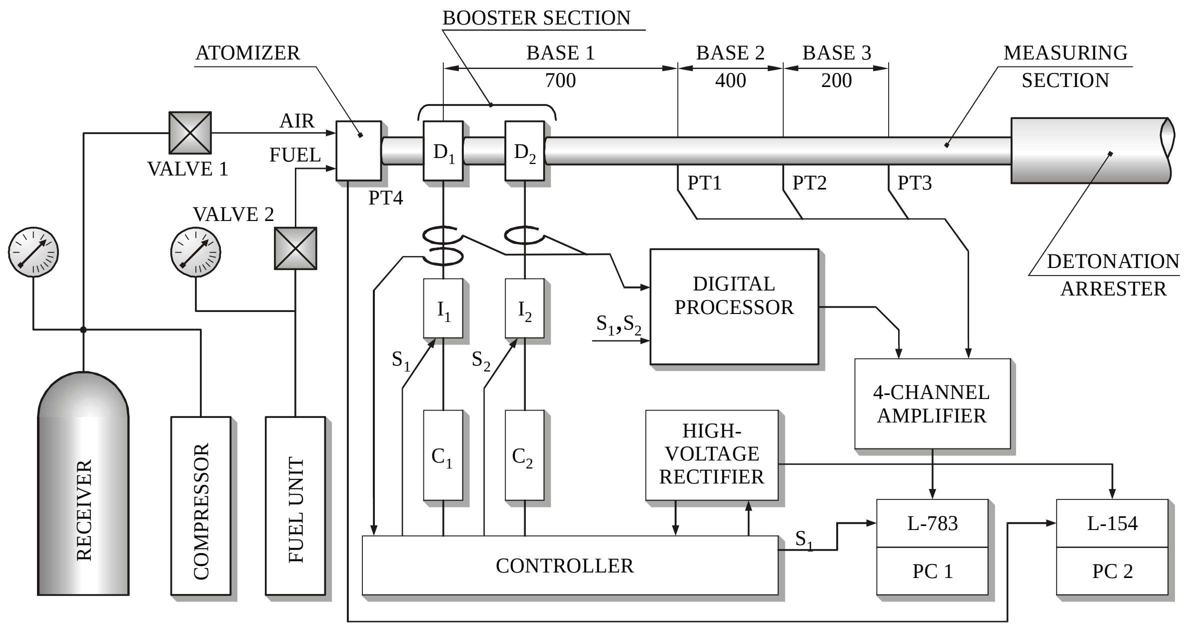


**Figure 2:** Schematic of experimental facility

## Results of Experiments

Figure 3 shows the registered time histories of the capacitor voltage, $U$, and air pressure in the air-assist atomizer for the series of 3 pulses. Fuel supply is activated when the capacitor voltage attains the preset threshold value, $U_f$, usually corresponding to the level of $0.95U_d$, where $U_d$ = 2700 V is the discharge voltage in this experimental series. Note that according to Fig. 1, to initiate detonation by a single discharge, the minimal voltage of 3300 V is required. At time when capacitor voltage attains the preset value $U_d$, the controller generates a synchronizing pulse $S_1$ (see Fig. 2) that activates triggering of the first discharge $D_1$ and fuel supply cut off. In a similar way, triggering of the second discharge $D_2$ occurs. The voltage curves are reproduced well from pulse to pulse. The air pressure at the atomizer is set within 0.1 s. During one pulse, the air pressure drops by 4%–5%. Fuel pressure in the tank is fixed at 5.3 atm.

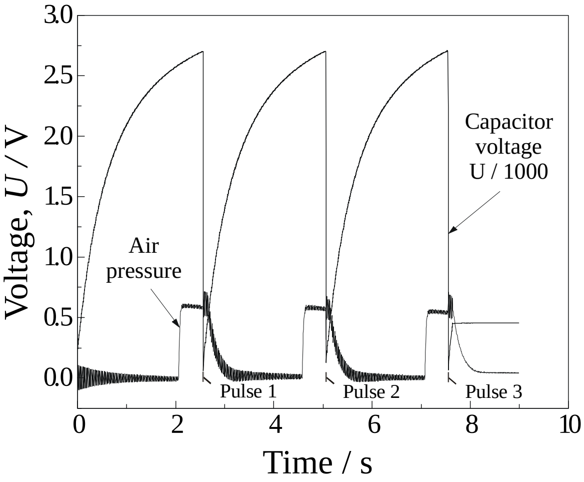


**Figure 3:** Typical registered time histories of the capacitor voltage, $U$, and air pressure in the air-assist atomizer for the series of 3 pulses.

Figure 4 shows the typical set of pressure records corresponding to 3 pulses of Fig. 3 and the record of the control channel for nearly optimal detonation initiation conditions. The control channel clearly shows the distortion of the ground signal by two successive discharges. Signals of pressure transducers PT1, PT2, and PT3 are also distorted by these discharges nearly simultaneously. In the single shot, the optimal (required for detonation initiation) time delay between the discharges is $\Delta t_d = 250 \pm 15$ $\mu$s.

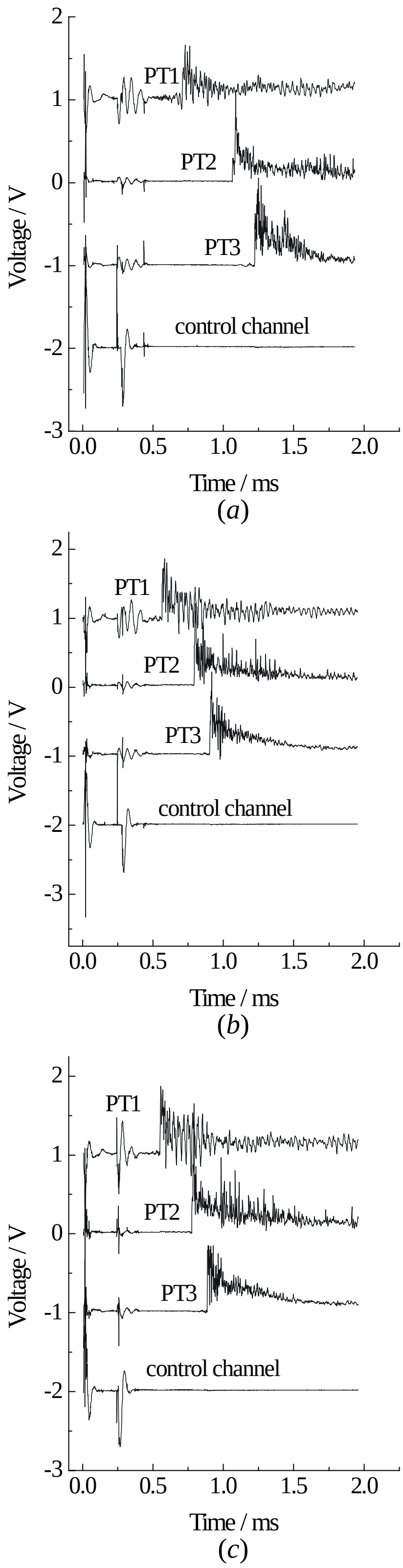


**Figure 4:** Typical set of pressure records corresponding to 3 pulses of Fig. 3 and the record of the control channel for nearly optimal detonation initiation conditions ($\Delta t_d$ =250–270 $\mu$s): (*a*) pulse 1, (*b*) 2, and (*c*) pulse 3

Table 1 shows the measured values of pressure wave arrival times at transducers PT1 ($t_1$), PT2 ($t_2$), and PT3 ($t_3$), the measured delay time between two discharges $\Delta t_d$ in each pulse, and the estimated velocities of the pressure waves at the second and third measuring bases: $V_2$ and $V_3$.

**Table 1:** Velocities at measuring Bases 2 and 3 at nearly optimal delay time between discharges

| Pulse Number | $\Delta t_d$ $\mu$s | $t_1$ $\mu$s | $t_2$ $\mu$s | $t_3$ $\mu$s | $V_2$ m/s | $V_3$ m/s |
|---|---|---|---|---|---|---|
| 1 | 260 | 709 | 1083 | 1224 | 1070 | 1420 |
| 2 | 270 | 562 | 794 | 904 | 1724 | 1818 |
| 3 | 250 | 550 | 778 | 886 | 1754 | 1851 |

Clearly, in the multipulse experiment there is a slight variation in the delay time $\Delta t_d$ caused by various unstabilizing factors. At pulse 1, the accelerating explosion process is detected with the propagation velocity increasing above 1400 m/s. At pulses 2 and 3, pressure waves with the detonation parameters (propagation velocity of about 1700–1800 m/s) are formed. The sensitivity of pressure transducers is about (0.025–0.030) V/atm, which means that the peak pressure (when disregarding noise) in the registered waves attains the values of 15–20 atm. The initiation energy of detonation in this two-discharge experiment is about 1 kJ per pulse. Note that detonation initiation in single-discharge experiments requires more than 3.3 kJ per pulse.

Similar to single shots, the pulse operation process is very sensitive to variation of the delay time $\Delta t_d$ between triggering the discharges. Figure 5 shows the set of pressure records obtained with $\Delta t_d = 230 \pm 15$ $\mu$s (checked in several single shot), which is somewhat lower than the optimized value. Other experimental parameters are taken the same as those corresponding to the run of Fig. 4.

For this run, Table 2 shows the measured values of pressure wave arrival times $t_1$, $t_2$, and $t_3$, the measured delay time $\Delta t_d$ in each pulse, and the estimated velocities of the pressure waves at the second and third measuring bases: $V_2$ and $V_3$.

In this run, detonation arises only at pulse 1, when the delay time $\Delta t_d$ is occasionally optimal (apparently, due to accidental distortions). When the delay time is 20 $\mu$s less than the optimal value, detonation initiation by two successively triggered discharges fails as was observed in single-shot runs too

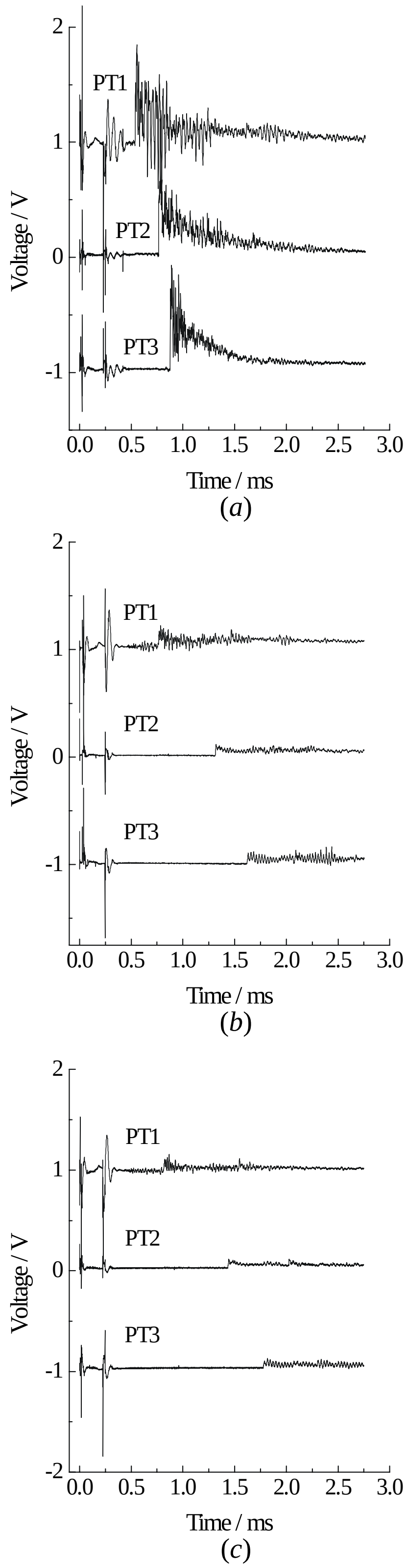


**Figure 5:** A set of pressure records corresponding to 3 pulses of Fig. 3 at wrong discharge timing ($\Delta t_d$ = 220–240 $\mu$s): (*a*) pulse 1, (*b*) 2, and (*c*) pulse 3

**Table 2:** Velocities at measuring Bases 2 and 3 at nonoptimal delay time between discharges

| Pulse Number | $\Delta t_d$ $\mu$s | $t_1$ $\mu$s | $t_2$ $\mu$s | $t_3$ $\mu$s | $V_2$ m/s | $V_3$ m/s |
|---|---|---|---|---|---|---|
| 1 | 243 | 540 | 766 | 878 | 1770 | 1785 |
| 2 | 225 | 765 | 1315 | 1617 | 727 | 662 |
| 3 | 225 | 822 | 1438 | 1778 | 650 | 588 |

(see [3, 4]). At pulses 2 and 3, the decaying shock waves (propagation velocity of 600–700 m/s) are registered.

The pulse operation process is also sensitive to mixture composition in the detonation tube. Figure 6 shows the set of pressure records obtained with fuel pressure of 5.0 atm, which is lower than the optimized value of 5.3 atm. Other experimental parameters are taken the same as those corresponding to the run of Fig. 4. Table 3 shows the measured values of $\Delta t_d$, $t_1$, $t_2$, and $t_3$, as well as the estimated velocities of the pressure waves: $V_2$ and $V_3$.

**Table 3:** Velocities at measuring Bases 2 and 3 at nonoptimal fuel pressure in the fuel supply line

| Pulse Number | $\Delta t_d$ $\mu$s | $t_1$ $\mu$s | $t_2$ $\mu$s | $t_3$ $\mu$s | $V_2$ m/s | $V_3$ m/s |
|---|---|---|---|---|---|---|
| 1 | 260 | 752 | 1221 | 1470 | 852 | 803 |
| 2 | 265 | 577 | 812 | 921 | 1702 | 1835 |
| 3 | 258 | 762 | 1304 | 1608 | 738 | 658 |

In spite of the fact that $\Delta t_d$ = 260–265 $\mu$s is within the detonation peninsula of Fig. 1, detonation arises only at pulse 2 and fails at pulses 1 and 3, apparently due to insufficient fuel supply.

## Concluding Remarks

The experimental data indicate that the lab-scale facility based on the shock-booster concept is capable of operating in a multipulse mode. Similar to single-shot mode [1–4], the multipulse operation mode shows the same resonant dependence of the detonation initiation energy on the time delay between the discharges and is quite sensitive to mixture composition. Because of this, special means should be used for stabilizing the optimal delay time between the discharges and ensuring the optimal mixture composition. With the setup of Fig. 2 it was possible to obtain the pulse detonation frequency of 2 Hz with the maximum total number of pulses of 6. The main constraint in increasing the operational time is the air supply system used. In the course of operation, the air pressure was decreasing, resulting in the deterioration of the fuel atomizer performance, fuel–air mixing, etc. A

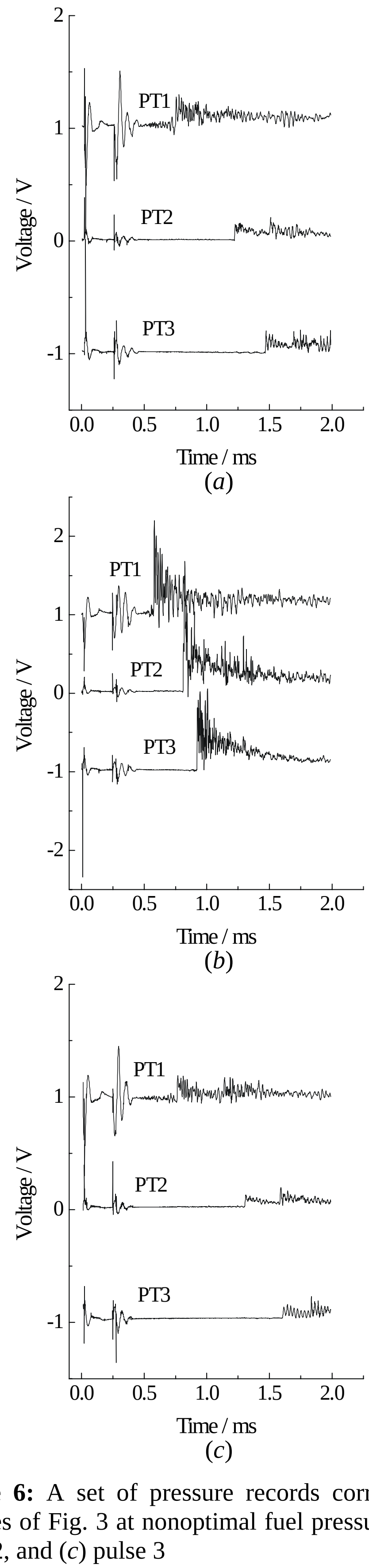


**Figure 6:** A set of pressure records corresponding to 3 pulses of Fig. 3 at nonoptimal fuel pressure : (*a*) pulse 1, (*b*) 2, and (*c*) pulse 3

new air supply system is currently developed. There is a potential of a considerable decrease in the detonation initiation energy per operational pulse. Special studies are currently under way implying the use of combinations of various initiation means. The issue of operational control appeared to be important. In the experiments with multipulse detonations of *n*-hexane spray in air it was noticed that misfires with detonation failure occurred more often at the beginning of the run (like in Fig.4). Misfires were also more frequent at lower ambient temperatures. To avoid misfires, special starting procedures are under consideration aimed at heating up the detonation tube to the nominal operation temperature by pulse deflagrations.

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