# Optimization Study of Spray Detonation Initiation by Electric Discharge

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## Introduction

One of challenging problems encountered in the development of air-breathing pulse detonation engines (PDE) is detonation initiation in fuel sprays at distances feasible for propulsion applications. For developing a PDE there is a need in experimental data on detonation initiation and propagation in heterogeneous fuel–air mixtures under well-defined conditions. The latter applies to the initiation means, initiator location, energy deposition history, geometry and physical properties of the confinement, homogeneity and properties of the fuel–air mixture, etc. This paper addresses some of these issues and shows possibilities to minimize the energy requirements for direct initiation of spray detonation.

## Basic Setup

The test facility is a steel tube 51 mm ID and 1.5 m long. To create a two-phase flow, an air-assist atomizer is mounted at one end of the tube. The atomizer is attached to the tube via the expanding cone nozzle. The other end of the tube is connected to atmosphere via the detonation arrester. The air supply system comprises a compressor, bottle, and the air solenoid valve. The liquid supply system consists of the pressurized fuel tank and the fuel solenoid valve. The air bottle and fuel tank are pressurized to preset pressures before each run. When the solenoid valves are activated, air and fuel are directed to the atomizer that provides the entire mixture flow rate through the tube. Pulse flow duration in reported experiments is about 1 s. Ignition of two-phase flow is facilitated by a powerful electrical igniter fed with a high-voltage unit via pulse generator. The igniter consists of the primary and the secondary discharges (3-electrode scheme). The primary discharge is of fixed (57 J) energy. (The energy, $E$, is calculated based on the rated capacity, $C$, and voltage, $U$, i.e., $E=CU^2/2$.) It produces plasma to trigger the secondary discharge of a considerably higher energy. The igniter is located inside the cone nozzle at a distance of 60 mm downstream from the atomizer. The capacitance of the secondary discharge is 600 $m\mathrm{F}$. The characteristic time of discharge is 100 $ms$. Three measuring stations are located 500, 900, and 1300 mm downstream from the igniter and comprise a piezoelectric pressure transducer and ionization gauge mounted at opposite walls. Measuring base 1 includes the igniter and the first measuring station with the characteristic distance of 500 mm. Measuring bases 2 and 3 are 400 mm long each. A digital controller controls opening and closing of air and fuel solenoid valves and igniter triggering. Several air-assist atomizers were designed, fabricated, and tested. The mean diameter of drops produced by atomizer A2-1 is close to 5 $m$m. The airflow rate provided by this atomizer is about 20 l/s.

## Spray Detonation Initiation

The aim of the tests was to determine the critical energy of direct detonation initiation by a single discharge. At ignition energy below 3.13 kJ no detonation was observed in the basic setup. Increase in the ignition energy from 3.13 to 3.32 kJ (which corresponds to the voltage of 3300 V at the secondary electrodes) resulted in detonation initiation in *n*-hexane–air mixture. Further increase of the ignition energy from 3.32 to 3.73 kJ exerted no effect on the detonation parameters. The detonation wave propagated at constant mean velocity of (1780 ± 100) m/s at bases 2 and 3. Figure 1 summarizes the results of experiments for *n*-hexane with different voltage at the secondary electrodes. Dashed and solid curves correspond to measured flame and shock wave velocities, respectively, at corresponding measuring bases (denoted as *1*, *2*, and *3*). At the voltage exceeding 3300 V, a detonation wave arises at all measuring bases, i.e., at $E$ > 3.2 kJ, direct initiation of detonation in *n*-hexane spray is obtained. This value can be referred to as the critical energy of direct detonation initiation in the basic setup. A similar set of experiments has been performed for *n*-heptane sprays. In runs with the secondary igniter voltage of 3300 V *n*-heptane spray did not detonate. Increase of the ignition energy from 3.32 to 3.73 kJ resulted in direct detonation initiation in *n*-heptane spray.

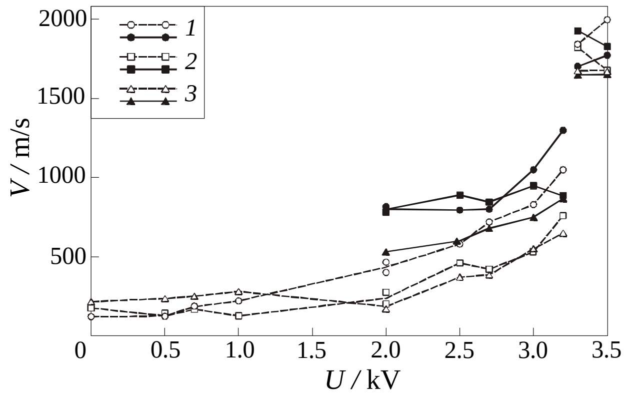


**Figure 1:** Measured shock wave (solid curves) and flame front (dashed curves) velocities vs. igniter voltage for *n*-hexane–air mixture

## Optimization Study

The aim of optimization studies is to decrease the energy required for direct detonation initiation by improving certain elements of the basic experimental setup.

***Discharge Location.*** Positioning of discharge at a distance of 100 mm downstream from its position in the basic setup results in increasing the critical voltage from 3300 V to 4100 V, i.e., increasing the critical initiation energy by more than 60%.

***Successive Triggering of Two Discharges.*** Positioning of an additional second discharge downstream from the first discharge and its triggering in phase with the arrival of a shock wave generated by the first discharge results in decreasing the critical voltage from 3300 V to 2500 V [1], i.e., decreasing the total critical initiation energy by more than 70% (each discharge having a half capacitance as compared with that of the basic setup).

***Discharge Parameters.*** To improve the efficiency of electric discharge in terms of transition of electric energy to the test mixture the following measures were used: (1) Interior surface of the transition cone connecting atomizer and test tube was covered with a 1-millimeter thick layer of dielectric thermo-resistant lacquer. This avoided the discharge between the igniter electrodes and the transition cone; (2) The electric connection between electrodes and high-voltage capacitors was made by using a coaxial cable rather than separate bars. These and some other measures led to modification of the discharge current shape and decrease in effective discharge duration from 100 to 50 $m$s. With the discharge of improved efficiency, the critical voltage required for direct detonation initiation in *n*-hexane by a single discharge decreased from 3300 to 2200 V, resulting in the decrease of the critical initiation energy from 3.2 to 1.5kJ.

***Optimization of Atomizer.*** Airflow rate provided by atomizer A6-2 is about 30 l/s. This atomizer produces higher level of turbulence in the flow as compared to atomizer A2-1, while providing approximately similar drop size distribution. With atomizer A6-2 and a single modified discharge, detonation was initiated at voltage of 2100-2200 V, i.e., there was no considerable difference in the performances of atomizers A2-1 and A6-2.

***Optimization of Test Tube.*** To study the effect of tube diameter on the critical detonation initiation energy, the experimental setup was modified (Fig. 2). In this setup, the atomizer assembly with the transition cone is the same as in the basic configuration. To connect the transition cone with the test tube, two possibilities are foreseen: either immediately through the converging cone 65 mm long, or through the cylindrical section of length *l*, followed by the converging cone. Figure 3 shows the results of experiments with a single discharge and $l = 0$. Contrary to Fig. 1, the dependency of the shock wave velocity on the igniter voltage is smooth and there is no evident abrupt change in the mode of combustion front propagation after attaining the value of 600–800 m/s. Starting from voltage of 1600 V, the shock wave velocity is about 1600–1700 m/s, which is at the level of detonation velocity.

Regular variation of the shock wave velocity with discharge voltage may be explained by the proximity of the tube diameter (27 mm) to the limiting tube diameter for *n*-hexane–air mixture. Voltage of 1600 V corres-

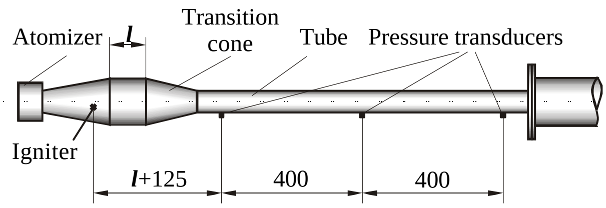


**Figure 2:** Experimental setup with the test tube of diameter 27 mm

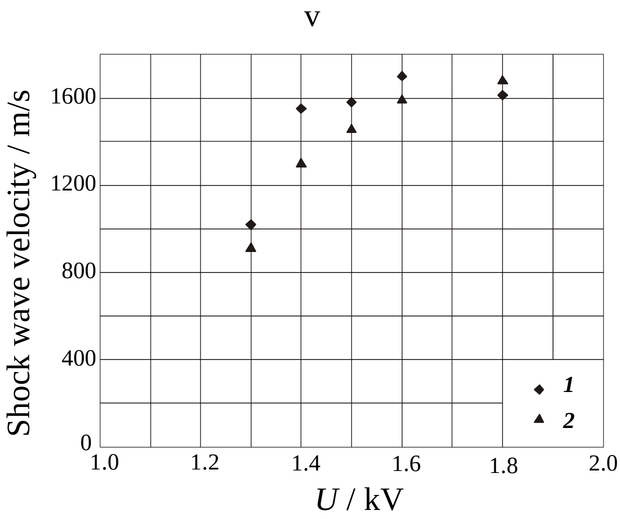


**Figure 3:** Measured shock wave velocities vs. discharge voltage (*n*-hexane spray) at two measuring bases: 2 (*1*) and 3 (*2*); test tube with no cylindrical insert; atomizer A6-2; igniter of improved efficiency

ponds to the initiation energy of about 0.8 kJ. The cylindrical transition section does not improve the overall picture of the phenomenon, as well as replacement of the converging cone with abrupt transition to the test tube. With decreasing the secondary discharge capacity (600 mF) to 400 mF, the minimal voltage of about 1900 V was required to initiate detonation of the *n*-hexane spray in the setup of Fig. 2. This voltage corresponds to the same critical initiation energy of about 0.8 kJ found in tests with higher discharge capacity.

## Concluding Remarks

For direct initiation of spray detonation with minimal energy requirements, (1) it is worth to use one igniter located at the closed end of the test tube and at least one additional igniter downstream from it to be triggered in-phase with initial shock arrival; (2) the discharge area should be properly insulated to avoid electric loss to the metal tube walls; (3) discharge duration should be minimized to at least 50 ms; (4) the test tube should be preferably of diameter close to the limiting tube diameter; (5) gradual transition between the volume with electrical discharge and the tube should be used.

## References


1. Frolov, S. M., Basevich, V. Ya., Aksenov, V. S., and Polikhov V. S., "Initiation of Confined Spray Detonation by Electric Discharges," *Confined Detonations and Pulse Detonation Engines*, edited by G. Roy, S. Frolov, R. Santoro, and S. Tsyganov, Torus Press, Moscow, 2003, p. 157–174.