# Spark Discharge Detonation Initiation

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## 1 Introduction

The initiation of energy-efficient periodic detonation is the most daunting problem to be solved while creating a pulse detonation engine. Therefore, the studies of spark discharge as a source of direct initiation of the detonation are targeted at the search of the ways to reduce total consumption of electric energy required for the detonation initiation.

V.V. Golub, et al. have experimentally shown [1] that the exposure of spark discharge channel to a strong magnetic field results in increased intensity of the shock wave generated by a spark. Such an exposure provides the shortening of deflagration-to-detonation length. The main drawback of such a method of initiation is that it requires the generation of strong magnetic fields, which results in huge additional energy consumption. For example, the magnetic field generated to carry out the above experiment required the energy input of more than 3 kJ.

The distribution of spark discharge energy during the detonation initiation has been analyzed and the mechanisms of influence on the high-current spark discharge that allow for the reduction of the total consumption of electric energy required for the detonation initiation have been proposed in this paper.

## 2 Spark Discharge Energy Distribution

The detonation is initiated by the shock wave that results from the rapid local gas heating. Therefore, if the detonation is initiated by the high-current spark discharge it requires fast conversion of the stored electric energy with a high efficiency factor into the heat energy of gas. It is known that a decrease in the discharge energy consumed to heat gas is caused by a considerable energy consumption required for dissociation, ionization and radiation processes. Spark discharge energy losses occur in the external circuit and in electrode-adjacent areas. A low efficiency of spark discharge is also related to a technical complexity of fast interruption of energy input into a discharge channel following the detonation initiation moment with the recuperation of discharge energy.

A mathematical modeling of transient processes that arise in the electric circuit, which serves as an equivalent circuit for spark discharge of electric capacitor, and a mathematical modeling of the detonation initiation by the capacitor in the hydrogen and oxygen mixture at atmospheric pressure have been performed for the quantitative estimation of energy distribution of a spark discharge. The description of mathematical models is given in the scientific papers [2, 3]. In contrast to the model of VA. Levin, et al [1], in which the amount of energy input into a discharge channel varied only in time, the developed model allowed for the additional change in radius used for the energy input. This is caused by the fact that a radius of conducting spark channel is increased during the real process of spark channel development.

The above mathematical modeling was performed with regard to the capacitor discharge at a rating of $C$ = 0.25 μF, capacitor charge voltage of $U_{c0}$ = 15 kV, circuit inductance of $L$ = 2 μH, discharge gap length of 5 mm and an active resistance of circuit R = 20 mohm. In this case the damped oscillatory discharge takes place at the stage of spark development corresponding to the pulsed arc. According to the scientific paper of R. Knistautas and J. Lee [4] the detonation is initiated at the exposure to a discharge energy released during ¼ of discharge period. Therefore, the energy distribution has been meant for the given time point (Fig. 1).

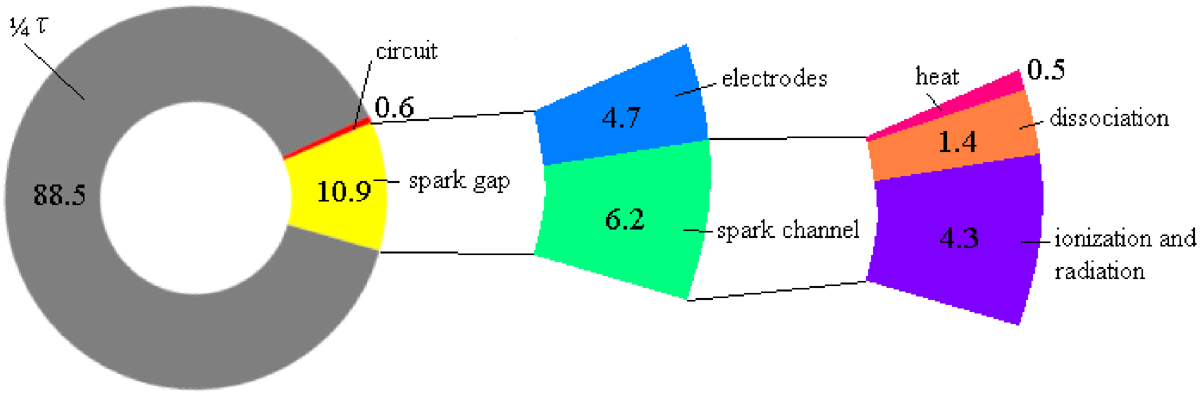
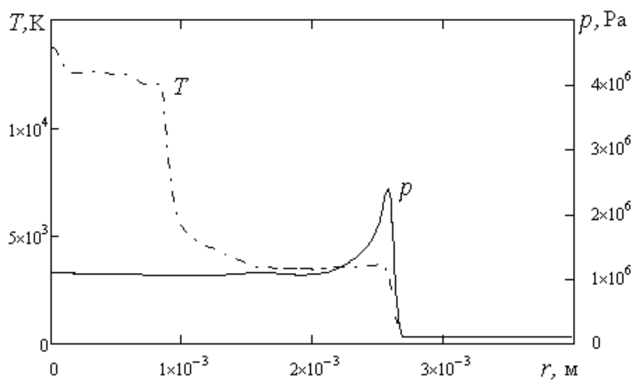



Figure 1. Energy distribution for the calculated option by the time point corresponding to ¼ of discharge period.

As for the calculated option the spark gap consumed 10,9% of total discharge energy during ¼ of discharge period. The 88,5% of discharge energy released after that time point produce no influence on the detonation initiation process and in this case these are attributed to losses. Therefore, it is very important to provide the interruption of discharge current with the discharge energy recuperation for a considerable increase in the energy efficiency of spark detonation initiation. Taking into consideration that the potential fall in the spark gap during the transition to the arc is reduced to 2000V and lower the current interruption can be achieved through the voltage drop of capacitor charge to 2000V in the electric circuit, at which high-current quick-acting electronic switches, for example of a IGBT type, operate. In the calculated option a portion of discharge energy released by the spark channel (6,2%) at the discharge gap length of 5 mm exceeded that of discharge energy released by the electrode-adjacent areas (4,7 %). The shortened length of a discharge gap will result in the reduction of the portion of discharge energy released by the spark channel with regard to the losses in electrode-adjacent regions. Therefore, the shortening of discharge gap length is unacceptable for the reduction in the breakdown voltage. To obtain the breakdown at low voltages discharge circuits with the igniting discharge should be used. In the calculated option low discharge energy losses (0,6 %) of external circuit were attained due to the low active circuit resistance.

The results of mathematical modeling of the initiation of detonation by the capacitor discharge showed that conditions for chemical reactions have not been created in the area of conducting spark channel during the initiation period. It has been established for the calculated option that the gas temperature exceeds 10000 K (Fig. 2a) in the conducting channel area, where the channel radius is equal to $r_c(t = 1\ \mu s) \approx 10^{-3}$ m,), by the time point corresponding to ¼ of discharge period. Therefore, gas is completely dissociated in this area (Fig. 2b) and it is highly ionized.



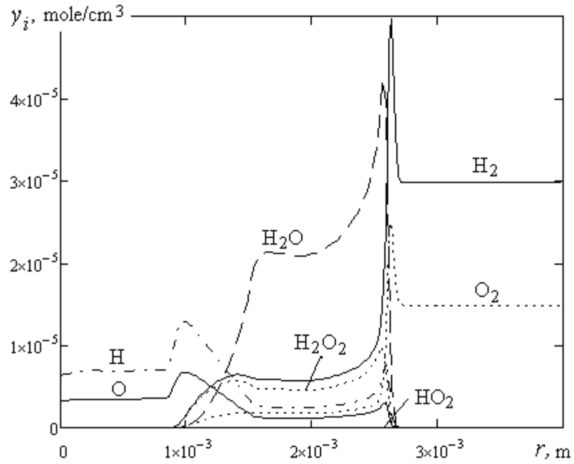




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Figure 2. Temperature, pressure and component concentration distribution for the calculated option by the time point corresponding to ¼ of discharge period.

Conditions for the chemical reaction behavior are created in the section between the conducting channel and the leading edge of shock wave. A quantitative estimate of the distribution of discharge energy in the spark channel showed large ionization and radiation losses (4,3%). In the case of the problem of detonation initiation it is impossible to reduce dissociation losses of discharge energy (1,4 %), because it is impossible to attain high plasma conductivity at a high pressure gas discharge and a temperature below 5000 K. Therefore, the technique of influence on discharge parameters to restrict the gas temperature increase in the conducting channel for the purpose of reduction of ionization and radiation losses of discharge energy should be developed.

## 3 Mechanisms of Influence on Spark Plasma Parameters

A question is raised of the possibility of producing influence on plasma parameters in the spark discharge to increase the discharge efficiency required by the detonation initiation problem. As a rule the spark channel impedance at the stage of transition to the pulse arc is considerably lower than the external discharge circuit reactance. Therefore, the discharge current curve is actually prescribed by parameters of discharge circuit *LC*, i.e. the curve of discharge current *i* can be manipulated by selecting discharge circuit parameters (inductance *L*, capacitance *C*, etc.) Due to the fact that the conducting channel is expanded during the spark advance the slope of a curve of discharge current produces influence on the current density *j*. The current density curve predetermines the amount of discharge energy *Q*, released by a volume unit of conducting channel of a unit length and a current radius $r_c$. The amount of energy released by the plasma volume unit defines specific plasma temperature *T*. The discharge energy consumption for ionization $Q_i$ and radiation $Q_{em}$ processes is reduced with a drop in the plasma temperature. This phenomenon can be realized through the control of discharge current *i* using the electric circuit in the following sequence

$$LC \rightarrow i \rightarrow j \rightarrow Q/r_c^2 \rightarrow T \rightarrow (Q_i + Q_{em}). \qquad (1)$$

It is known that during the initiation processes of the detonation by a capacitor discharge maximum densities of discharge current are attained at the initial stage of spark channel progress. High plasma temperature and pressure are achieved in the channel. As a result, the shock wave of high intensity is initially formed with further decay of it at a rapid decrease in the discharge current density. Naturally, the above losses are abruptly increased due to high temperature values attained in the discharge channel.

It is assumed that during the detonation initiation period the input of energy into a spark channel should be performed in the way that provides constant pressure for the shock wave front $P_{fr}$ = const. The substantiation of the curve of discharge current at which this condition is met has been derived from the following assumption. The wave front pressure $P_{fr}$ is in direct proportion to the amount of energy $Q$ input into the discharge channel volume, which is represented for cylindrical symmetry by the proportionality [5]

$$P_{fr} \sim \frac{Q}{r_{fr}^2}, \tag{2}$$

where $r_{fr}$ is a radius of shock wave front.
The proportionality (2) can be represented as

$$\int \frac{i^2 \cdot l}{\sigma_{ch}\pi(D_{ch}t)^2} dt \sim P_{fr}(D_{fr}t)^2, \tag{3}$$

where $l$ is a length of discharge gap; $\sigma_{ch}$ is an electrical conductance of conducting channel; $D_{ch}$, $D_{fr}$ are expansion velocities of conducting channel and shock wave front, respectively; $t$ is a time.
Assuming that $P_{fr}$ = const, $D_{fr}$ = const, $D_{ch}$ = const, $\sigma_{ch}$ = const, we will obtain

$$i \sim t^{\frac{3}{2}}. \tag{4}$$

A different mechanism of influence on spark plasma parameters is based on the introduction of easy – to-ionize dopants into a discharge medium. It is sufficient to introduce for this purpose about 1% of a dopant. A decrease in the ionization threshold results in the rapid increase in plasma conductivity at lower temperatures; with regard to the spark channel this may speed-up the expansion of current conduction area (radius $r_c$) with the appropriate decrease in the discharge current density and the drop in plasma temperature in the discharge channel.

## 4. Experimental Validation of Engineering Solutions of Spark Control During the Detonation Initiation

The efficiency of proposed engineering solutions of spark control during the detonation initiation was experimentally validated using the tube-like test bench with the internal diameter of 73 mm and a length of 405 mm (Fig. 3).

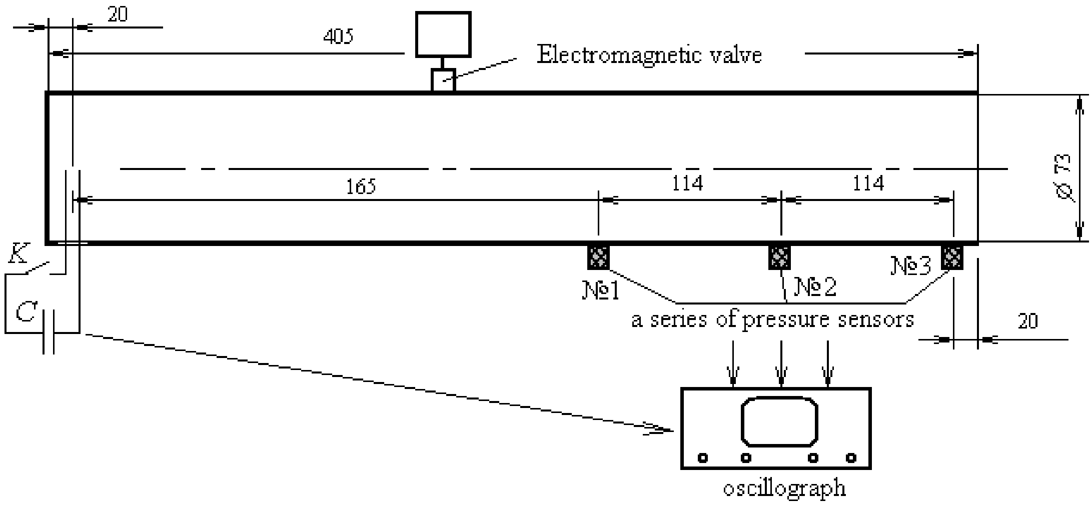


Figure 3. Experimental test bench structure. Dimensions in [mm].

A conclusion on availability of detonation was made up proceeding from the traveling time of shock wave between the pressure sensors and a shape of the pressure wave front (the used pressure sensors make noise). We checked the pressure sensors are insensitive to electric noise generated by discharge system. To provide reliable synchronization of sweep and spark discharge origination the voltage divider TEKTRONIX 6015A (1:1000) was connected to the discharge capacitor. Signals were recorded by the TEKTRONIX 2024B oscillograph. The sweeping was performed from the voltage divider in the waiting mode across the incident signal front (4-th channel).

The tube was filled with the stoichiometric hydrogen and oxygen mixture of atmospheric pressure. The results of research showed that the deflagration-to-detonation transition (DDT) took place in the vicinity of the third sensor at the spark discharge initiation in the interelectrode space of 7 mm long and full discharge energy of 52 J. In this case the capacitor with the rating of 2,9 μF was used. The obtained oscillogram (Fig. 4a) allows us to make an assumption that most probably the detonation resulted due to reflection of the generated shock wave from the membrane located at the detonation tube exit. The DDT time was equal to 520 μs and the DDT length was equal to 0.4 m.

Using the same plant, the same mixture and the same capacitor with the realization of spark control technology we managed to reduce the DDT length and time while the full discharge energy was reduced to 42 J (Fig. 4b). According to the oscillogram the detonation occurred in the vicinity of the second sensor. The DDT time was approximately equal to 360 μs at the DDT length of 0.3 m.

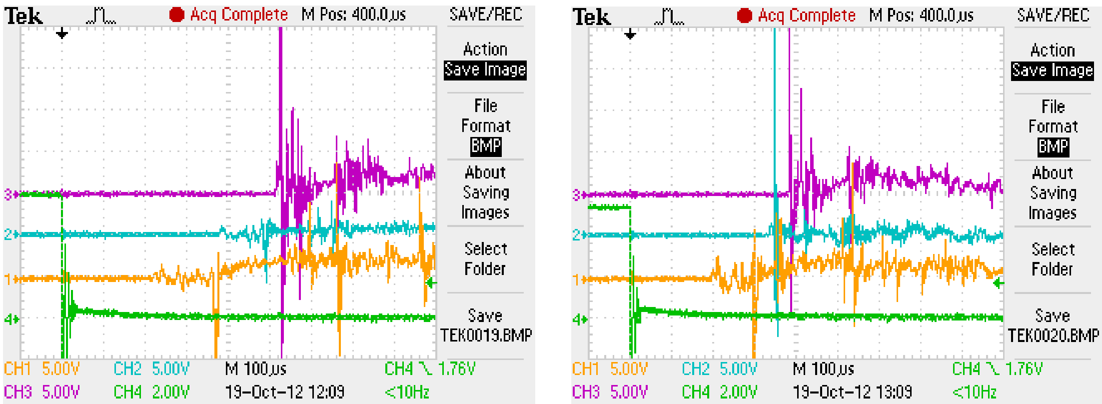


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Figure 4. Signals received from pressure (channels 1 to 3) and capacitor voltage sensors (channel 4): initiation by the capacitor discharge (a) and controlled spark-discharge initiation (b).

Further reduction of the DDT length (or shock detonation transition length) and time was achieved using the same plant, the same mixture and the same capacitor with the realization of the spark-control technology and the introduction of easy-to-ionize dopants into a hydrogen and oxygen mixture (Fig. 5). We injected cold potassium vapor into mixture of hydrogen and oxygen. The concentration of the dopant was not measured.

For the given results the full discharge energy was approximately equal to 54 J. According to the signals sent by sensors the detonation occurred between the first and the second sensor. The DDT time was approximately equal to 260 μs and the DDT length was equal up to 0.27 m. At identical energy stored by the capacitor the two-fold reduction of DDT time and 1,5-fold reduction of the DDT length was thus attained using the engineering solutions with regard to the influence produced on the spark discharge.

The special electric circuit (instead of traditional RLC-circuit) and a special electrodes system were used in the spark-control technology. The specific curve of discharge current was obtained in the circuit. Two spark discharges synchronized and near located in parallel were generated in the special electrodes system.

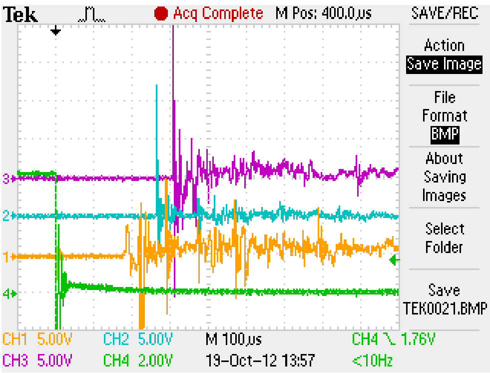


Figure 5. Signals received from pressure (channels 1-3) and capacitor voltage (channel 4) sensors in case of spark control and introduction of easy-to-ionize dopants into a hydrogen and oxygen mixture.

It has been established that the stationary detonation with Chapman-Jouguet parameters is formed at the initial velocity of shock wave generated by the detonation tube with diameter of 73 mm in the stochiometric hydrogen and oxygen mixture of atmospheric pressure under the action of spark discharge at a distance, which is equal up to 2.5 tube diameter. The initiation wave velocity exceeds (0,5…0,6)$D_{CJ}$. These results differ a little bit from those given in the scientific paper [1].

## Conclusions

On the basis of analysis of the distribution of spark discharge energy during the detonation initiation it has been established that the portion of spark discharge energy released as a heat in the calculated option was equal to 0.5 %. The energy efficiency of the spark can be increased by the interruption of discharge current, restriction of temperature rise in the discharge channel and the use of not drastically small discharge gaps.
The possibility of the DDT time and length reduction due to the increase in the energy efficiency of spark discharges has been experimentally proved using proposed mechanisms of spark control.

It needs to continue the investigation of efficiency of the spark-control technology using modern technique of detonation initiation research.

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