The Time of Effective Energy Input for Direct Detonation Initiation in Spark Discharge

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1 Introduction

Effective energy used for direct detonation initiation at high voltage spark discharge is the subject for numerous studies [1-4]. In these studies, effective energy E_{ef} is calculated by the following expression:

$$E_{ef} = \int_0^{t_{ef}} R_{sp} i^2 dt\,;$$

where R_{sp} is active resistance of spark discharge channel; i is current; t_{ef} is time of effective energy input.

The papers [5-7] show that the resistance of the spark channel during effective energy input is changed by several times. Therefore, the use of the average resistance value for the spark channel in papers [1-4] allows only approximate calculation of the effective energy value.

We have found that the time t_{ef} for effective energy input is not equal to ¼ of the period of damped oscillatory discharge, unlike some other studies [1-4]. The obtained conclusion is based on a thorough analysis of the results presented in [3], as well as on the results of our research. Since the method described in [3] is widely used for determination of the effective energy in recent studies, our results should be discussed.

2 Analysis of experimental result presented in [3]

A conclusion, that the time t_{ef} for effective energy input is equal to ¼ of the period of damped oscillatory discharge is obtained from the paper [3]. The experimental results on the basis of which this conclusion was obtained should be analyzed.

The purpose of the experiment [3] was to determine the effective energy E_{ef} by interrupting the energy input into the spark channel after a certain period of time from the start of the discharge. t_{ef} time is minimum interruption time at which detonation was initiated. We have found that interruption of the energy input into the spark channel occurred only at the half-cycles of discharge. Thus, in case of energy input interruption, the instantaneous interruption of the current should occur in the spark channel. In accordance with the presented current waveform (Fig. 1a), no instantaneous current interruption occurs at ¼ discharge period. Real discharge current after the "interruption" didn't correspond to the ideal current of clamped discharge (Fig. 1b).

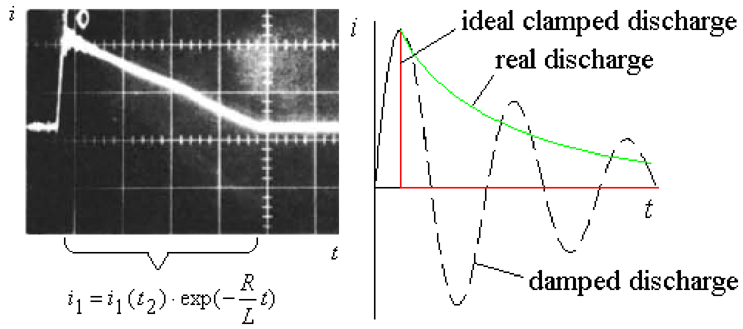

Figure1. The form of discharge current in case of real [3] (left) and ideal (right) clamping of damped discharge.

We have found, that it is impossible to obtain an ideal current of clamped discharge at ¼ of discharge period using the electrical circuit [3] consisting of a non-ideal electrical elements. Such ideal "interruption" results in violation of the law for magnetic field energy conservation.

In paper [3], electrical processes are considered in relation to the electrical circuit (Fig. 2a). The authors believed that the interruption of the energy input is provided as a result of spark gap bridging. The interruption time was regulated by changing the time period $\Delta t = t_2 - t_1$. It was considered, that after the shunt switch S_2 is connected in parallel to the spark gap, the instantaneous interruption of energy input into the spark channel occurs.

However, the fact that the real electrical circuits have inductivity is not taken into account in [3]. Therefore, the electrical transients in the real discharge circuit should be studied in accordance with the equivalent circuit (Fig. 2b).

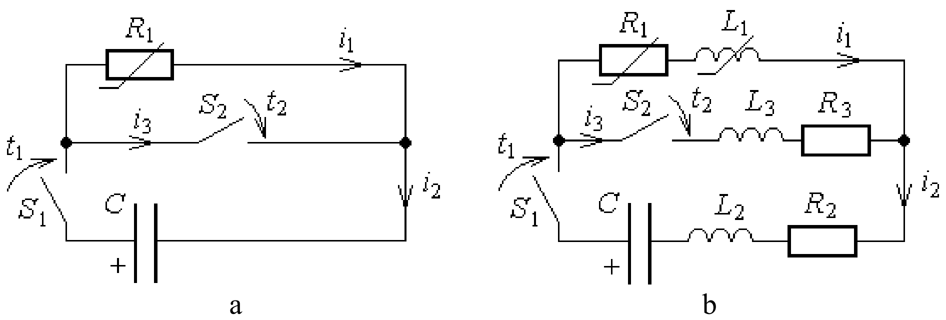

Figure 2. The circuit for bridging the spark discharge (a) and it equivalent electrical circuit (b): *R* are active resistances of the spark gap, wires and the internal capacitor resistance; *C* is capacitor; *S* are electrical switches; *L* are inductances of wires, capacitor and discharge gap.

Let us consider the operation of the circuit (Fig. 2b). In accordance with a consequence of energy conservation principle, the current in the electrical circuit with the inductance can't be changed steplike. This implies that the current i_1 in the branch R_1L_1 can't be interrupted instantaneously at switching S_2. Interruption of the current i_1 in the branch R_1L_1 due to bridging is possible when $i_1 = 0$. At ¼ of the period of the damped oscillatory discharge, the discharge current reaches the amplitude value.

The magnetic energy $L_1 i^2/2$ is stored in the inductance L_1. As a result, the intense energy input into the spark channel after ¼ of the discharge period is continued in this case. Thus, the circuit (Fig. 2a) with the real elements operates only when the switch is closed for the discharge half-cycles. It is observed in the current oscillograms [3]. This puts in question the conclusion obtained by the authors in [3], in particular, that that the time t_{ef} for effective energy input equals to ¼ of damped oscillatory discharge period.

Fast current interruption of the RLC-circuit at ¼ of the discharge period can only be achieved in case of using the high-resistance circuit breaker S_1.

3 Numerical investigation of the effect of bridging on the energy input

The developed spark discharge numerical model [5-7] allows calculating parameters of the shock wave generated in a spark for arbitrary circuits. It allows using electrical circuits with ideal and real elements. The parameters of the shock waves generated in oxygen environment at atmospheric pressure under various conditions of the spark gap commutation in RLC-circuit were compared. In the first case, the electric circuit was used for calculation (Fig. 3a). In this circuit, the branch R of the spark gap has no inductance. Therefore, when the ideal switch S is on, the current i_1 in the spark was interrupted momentarily. In the second case, a damped oscillatory discharge was studied. In the third case, the calculation is performed for the electrical circuit (Fig. 3b). The third case corresponds to the discharge of the real spark gap having an inductance L. In the first and third cases, closing of the switch S was performed at t = 1/4 T, where T is a discharge period.

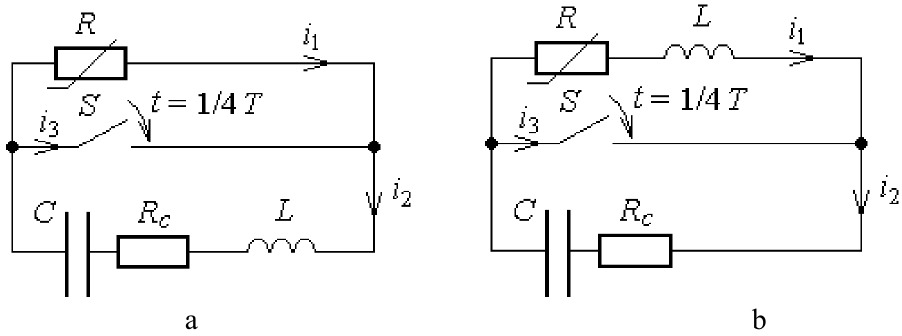

Figure 3. The circuits for ideal (a) and real (b) bridging of the discharge gap in RLC-circuit.

In all simulation cases, the discharge circuit parameters are equal to L = 1 μH, R_C = 0,01 Ohm, C = 0,25 μF, U_C = 15 kV. The length of discharge gap is equal to 5 mm. The time for switching S is equal to t = 1/4 T = 0,8 μs. The discharge currents in simulation cases at the time interval $0 \le t \le T/2$ were as follows (Fig. 4):

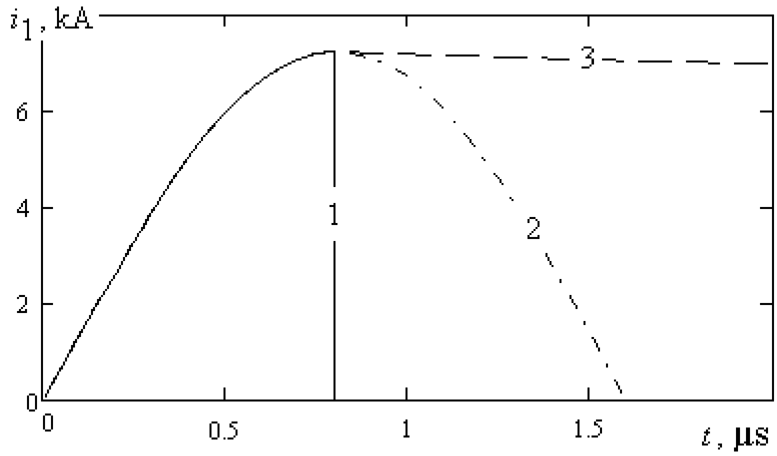

Figure 4. The discharge currents in simulation cases № 1, 2, 3.

The comparison of pressure and temperature achieved in the shock wave in accordance with the simulation cases № 1, 2, 3, are shown for the time t = 1/2 T_{RLC} = 1,6 μs. It was found that the pressure at the shock wave front in the first case is $p_{fr1} \approx 2{,}1$ MPa, in the second case it is $p_{fr2} \approx 2{,}6$ MPa, in the third case it is $p_{fr3} \approx 2{,}8$ MPa (Fig. 5). Thus, the temperature at the front of the shock wave in the first case reaches about $T_{fr1} \approx 1300$ K, and in the third case it reaches $T_{fr3} \approx 1600$ K. Therefore, bridging of the spark gap in paper [3] resulted in the increase of the shock wave intensity, even in comparison with the shock wave generated by the damped oscillatory discharge.

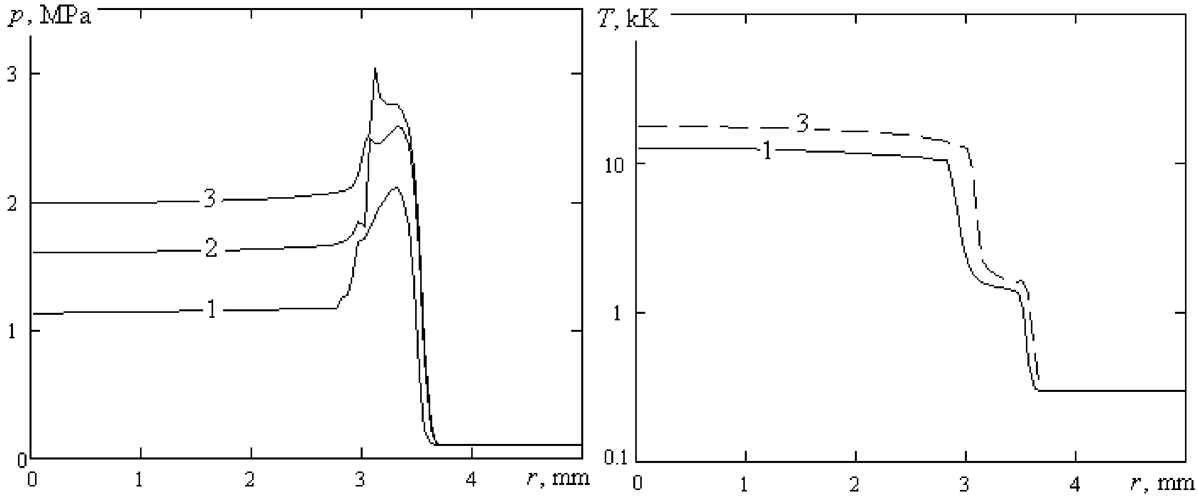

Fig.5. The distribution of pressure (left) and temperature (right) in simulation cases № 1, 2, 3 to the time t = 1,6 μs.

The difference in the intensity of the shock waves is explained by the difference of energy input into the spark channel after ¼ of the discharge period under different conditions of commutation (Fig. 6). It was found, that by the time t = 1,6 μs, which corresponds to a half-period discharge, the energy input into the spark channel in the third case is more than 50% greater than the energy input in the first case.

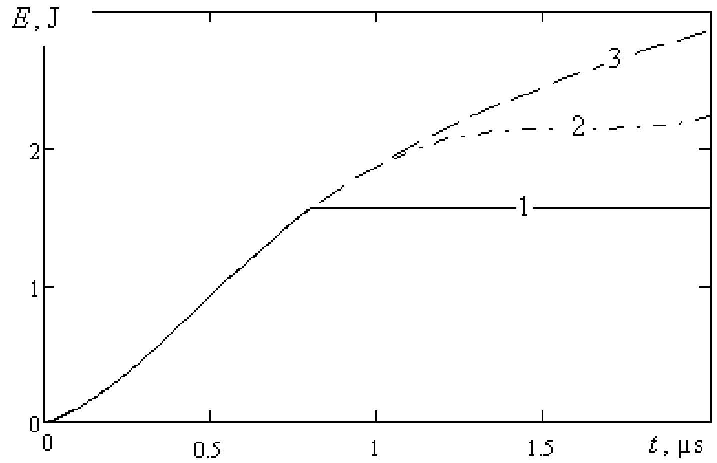

Figure6. The dynamics of energy input into the spark in simulation cases № 1, 2, 3.

The obtained results show that the spark gap bridging in accordance with the circuit presented in [3] at ¼ of the damped oscillatory discharge period led to an increase in the intensity of the shock wave. Therefore, the conclusion presented in paper [3], that the time t_{ef} for effective energy input is equal to ¼ of the damped oscillatory discharge period is an open question.

4 Numerical investigation of the effective energy input time for detonation initiation in spark discharge

The investigations were carried out for stoichiometric mixture of hydrogen and oxygen under normal conditions. The calculation of detonation initiation was performed for the electrical circuit with the following parameters. The capacitance of the capacitor was 2 μF. The initial voltage of the capacitor charge was 15 kV. The active circuit resistance was 0.1 ohms. The inductance of the discharge circuit was 0.9 μH. The length of the discharge gap was 3.5 mm.

The numerical simulations were carried out in accordance with the model of detonation initiation by spark discharge [5-7], which was improved due to consideration of slow vibrational excitation of molecules behind the shock wave front. The problem was solved in cylindrical symmetry.

The calculations were carried out at different time values of discharge interruption. It was found, that detonation initiation occurs even in case of discharge interruption in 1.1 μs. The results of calculation for this time of interruption are presented in (Fig. 7). Initiation is observed at the output of the detonation wave to the fixed parameters and considerable distance of the detonation front from the high-temperature area. It was found that the effective energy of initiation is 6.5 J/cm.

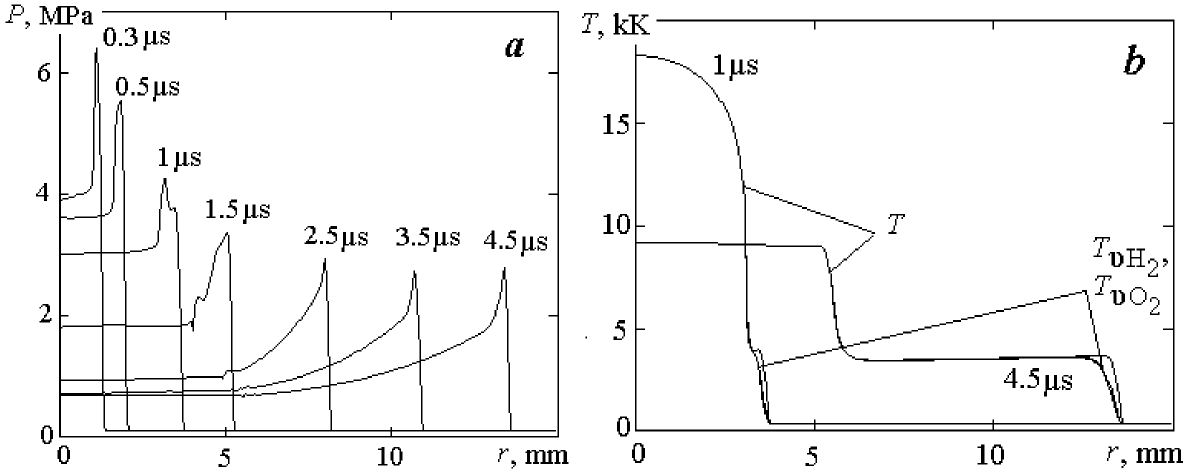

Figure.7. The time histories of pressure (a) and temperature (b): T_υ is vibrational temperature.

It should be noted, that ¼ of the discharge period equals to 2.2 μs for the studied electrical circuit. In the simulation case, detonation initiation is achieved at the time of interruption of 1.1 μs, which is equal to 1/8 of the discharge period. It is assumed that this time value corresponds to the critical time of detonation initiation. It is also assumed that the critical time is related to the time of shock wave separation from the conductive spark channel to the width of vibrational relaxation or length of the detonation cell. The width of this field requires further clarification.

The obtained result can be explained as follows. The amount of energy introduced into the spark discharge depends on the form of discharge current. For detonation initiation, the critical energy should be introduced for the critical time τ. Therefore, detonation initiation by spark discharge is influenced only by the form of the curve in the time period that doesn't exceed the critical time. The energy which is introduced into the spark channel after the critical time has no influence on the shock wave intensity. Hence, if ¼ of the discharge period exceeds the critical time of detonation initiation, in practice detonation initiation is achieved by increasing the capacitor charge voltage. The increase of capacitor charge voltage *U* provides the increase in the amplitude of the discharge current and the growth of energy input into the spark for the critical time τ (Fig. 8).

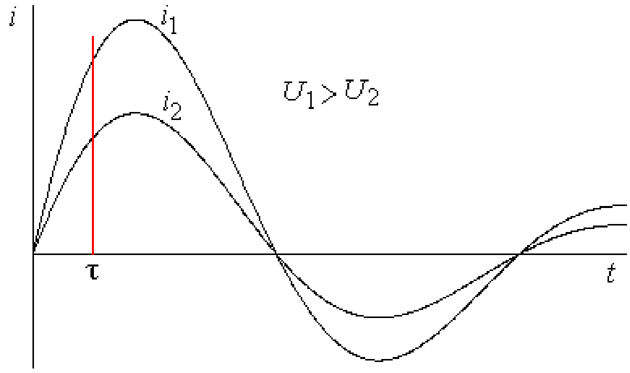

Figure. 8. Correlation between critical time τ and discharge currents.

Therefore, the time t_{ef} of effective energy input is equal to ¼ of the damped oscillatory discharge period only if ¼ of the discharge period is equal to the critical time τ of detonation initiation.
The developed detonation initiation model can be used for increasing efficiency of the spark detonation initiation.
We express our gratitude to prof. J. Lee for permission to use the results of his research [3] and to prof. E. Petersen for permission to use his kinetic model of hydrogen combustion for our numerical simulation.

References

[1] Kamenskihs V, Dick Ng, Lee JHS. (2010) Measurement of critical energy for direct initiation of spherical detonations in stoichiometric high-pressure H_2-O_2 mixtures. Combustion and Flame. 157: 1795.

[2] Zhang Bo, Dick Ng, Lee JHS. (2012) Measurement of effective blast energy for direct initiation of spherical gaseous detonations from high-voltage spark discharge. Shock Waves. 22(1): 1.

[3] Knystautas R, Lee JHS. (1976) On the effective energy for direct initiation of gaseous detonations. Combustion and flame. 27.: 221.

[4] Kamenskihs V, Lee JHS. (2009) Measurement of critical energy for direct initiation of spherical detonations in stoichiometric high-pressure H_2-O_2 mixture. Proc. 22nd ICDERS. P. 157.

[5] Korytchenko K, Poklonskii, Krivosheyev P. (2014) Model of the Spark Discharge Initiation of Detonation in a Mixture of Hydrogen with Oxygen. Russian Journal on Physical Chemistry B. 8(5): 692.

[6] Korytchenko K et al. (2013) Numerical simulation of gas-dynamic stage of spark discharge in oxygen. Problem of atomic science and technology. 4: 155.

[7] Korytchenko K, Golota V, Kudin D, Rodionov S. (2013) Spark discharge detonation initiation. Proc. 24th ICDERS. Rep.26.