Comparison of conditions of direct detonation initiation by spark with one by pulsed arc according to the gradient mechanism of Ya.B. Zeldovich

Korytchenko K.V., Poklonskiy E.V., Galak O.V.
Faculty of military education of NTU «KhPI»
Kharkov, Ukraine

1 Introduction

Repetitive detonation initiation by low input of electric energy is a main problem required as a solution to create pulsed detonation devices. According to the data acquired both theoretically and experimentally by different authors, the critical energy of detonation initiation into stoichiometric oxygen-hydrogen mixture at a room temperature and atmospheric pressure is proved to range from 0.5 to 2 J. Thus, in spite of the fact that detonation initiation by spark discharge in this mixture by atmospheric pressure can be achieved when total electric energy stored into high-voltage capacitor exceeds 200 J [1], the researches connected with direct initiation of detonation by the electric discharges continue. Correspondingly, there appears a question about the reasons of low efficiency of spark discharge applied to detonation initiation.

Ya.B. Zeldovich and others explained the reason of the detonation initiation into piston engines by means of a gradient mechanism [2]. The initiation in this case is caused by the nonuniform temperature profile accidentally appearing in the mixture into combustion chambers. In other words, it means that quite a large volume of the combustible gas having higher temperature than the temperature of another one appears into the chamber. As a result it can cause a «simultaneous» self-ignition of the mixture into the large volume and subsequent pressure increase in this volume cannot be compensated by the gas-dynamic expansion due to the large scale of the combustion zone. Recently this mechanism has been used to initiate a detonation by nanosecond discharge. The energy of such discharge is deposited into a large gas-discharge volume. But, due to low specific power of energy input which can be entered by a nanosecond discharge, detonation initiation takes place via formation of a gradient of ignition delay times resulting in acceleration of chemical reactions into the large volume in this case. It means that indirect initiation of detonation is carried out. The power of energy input by high-voltage pulsed arcs is higher in few orders of magnitude than the one by nanosecond discharges. While applying the technology of pulsed arc, a large gas-discharge channel is obtained by low deposition of the electric energy [3]. Therefore the analysis of conditions of direct detonation initiation by the pulsed arc according to the gradient mechanism is done in the paper. The discharge features allowing initiating a detonation by the gradient mechanism are found.

2 An analysis of mechanism of detonation initiation by spark discharge

Correspondence to: entropia@rambler.ru

We will consider the process of detonation initiation by a powerful spark discharge in high-pressure gas (atmospheric pressure and higher). The formation of the weakly ionized current-conducting channel on small discharge gap is known to be provided by streamer or avalanche mechanisms of break-down where the initial channel radius equals about 1 mm. It is accepted that the subsequent development of process of ionization-overheated instability leads to the gas density drop in the central part of the channel which results in conductivity and temperature increase in this zone. The development of this process brings out the contraction of the discharge current; i. e. the discharge current is concentrated into the channel, the radius of which, as a rule, does not exceed 0.1 mm. This process is the initial stage of transition from spark to the arc. The increasing in the specific power of the energy input results in the rising of pressure into the formed channel and it causes subsequent development of a gas-dynamic process of shock-wave expansion of the channel. Reduction in gas density occurs behind the wave front thus creating conditions to ionize the gas in low-density region. So, an expansion of the current-conducting channel is provided by the process of the gas-dynamic expansion of the channel. The subsequent energy input into the discharge channel results in maintenance of the shock wave intensity and when the intensity is sufficient the detonation initiation occurs into the fuel-air mixture.

It is necessary to know time dependence of the specific power depositing into a gas-discharge gap and time history of an area size of energy input (a radius of the current-conducting channel) to approach the conditions of a simulation with the real dynamics of energy input into the spark channel. These magnitudes were measured, for example, in works [4, 5]. As an example we will use the experimental results of the spark discharge by a condenser the capacity of which is 0.5 μF, the inductance of the discharge circuit is 2 μH, the voltage of the capacity charge equaled 15 kV. The spark was formed in air of atmospheric pressure. Thus we have the time dependence of specific power changing and time history of the radius of the current-conducting channel (table 1).

It was calculated using the experimental results (fig.1) that the time history of the energy input into the spark channel does not correspond to a sine-wave curve as it was considered in the work [1]. It is caused by reduction in the electric field strength into the arc column during the process of the spark evolution.

It is known that the increasing of the spark current during the discharge evolution into the gas happens both by an increase of conductivity of gas-discharge plasma and due to expansion of cross-section area of the conductive channel. As the channel expansion starts only when the channel temperature is growing, the rise of spark current is provided mainly due to increase of gas conductivity into the channel at the initial stage of the channel development. Therefore it is possible to assume that initially the energy input is carried out by the fixed channel radius. Subsequently, the radius of energy deposition is accompanied with the propagation of the shock wave front.

On the basis of an aforesaid it is possible, at a first approximation, to set the dynamics of energy input, depending both on the time and the radius, to model a detonation initiation in the hydrogen-oxygen mixture by this condenser and the foregoing parameters of the discharge circuit. In the calculations presented below the specific power of energy input into the spark was set the following way:

$$W(t,r)=\begin{vmatrix} W_0(t)/k \ if \ [t \le 10^{-7} \ and \ r \prec 2.5\cdot 10^{-4}] \\ \left[A\cdot t + B\cdot t^2 + C + D/t\right]/k \ if \ [10^{-7} \succ t \le t_d \ and \ r \prec \left[A1\cdot t + B1\cdot t^2 + C1 + D1/t\right] \\ 0 \ if \ t \succ t_d \end{vmatrix}, \quad (1)$$

where t_d is duration of a first quarter of the discharge period that in given example equals $t_d \approx 10^{-6}$ s; k is the coefficient featuring the ionization loss in the discharge; coefficients are $A = 6.9\cdot 10^{20}$, $B = 4.3\cdot 10^{26}$, $C = -3.1\cdot 10^{14}$, $D = 7.3\cdot 10^{7}$, $A1 = 1.85\cdot 10^{3}$, $B1 = -4.4\cdot 10^{8}$, $C1 = 1.5\cdot 10^{-4}$, $D1 = -8.3\cdot 10^{-12}$; $W0(t)$ is a time history of the specific power at the initial stage that was set as:

$$W_0(t) = \frac{E(t)\cdot i(t)}{\pi\cdot r_0^{\,2}} = \frac{\left[-1.4\cdot 10^{13}t + 1.5\cdot 10^{6}\right]\cdot\left[I\cdot\sin(\omega t)\right]}{\pi\cdot r_0^{\,2}}, \quad (2)$$

where *E(t)* is the strength of the electric field in the positive column of the arc channel; *I(t)* is an instantaneous value of the discharge current; *I* is a current amplitude; ω is a discharge period; r_0 is an initial radius of the channel that equals $r_0 = 2.5 \cdot 10^{-4}$ m.

As the presented mathematical model does not take into account the ionization loss in the discharge, there was a necessity to introduce the magnitude correction of the specific power by adding the correction coefficient *k*. The temperature of plasma in powerful spark discharges is known to reach about 1 eV (11610 K). Thus, the plasma is fully singly-ionized. For example, ionization potentials of atomic hydrogen and oxygen are 13.6 eV. Accepting that the share of the ionization loss in the spark discharge is 75 %, the coefficient, $k = 4$, is accepted in the calculations. The peak value of the specific power taking into account the ionization loss achieves $W_{\max} = 3.75 \cdot 10^8$ W/cm^3 in this case by an average value of the one equaling $W_{\text{mid}} = 4.9 \cdot 10^6$ W/cm^3 during the energy input.

The modeling of the detonation initiation by the capacity discharge of foregoing parameters was made relating to the stoichiometrical hydrogen-oxygen mixture at the atmospheric pressure. The one-dimensional gas-dynamic system of equations for cylindrical symmetry completed by the state equation is applied in the calculations. Chemical reaction kinetics of hydrogen-oxygen combustion was adopted from work [6] and it included 17 direct reactions and 17 reverse one. A method of S.K. Godunov having the second order of accuracy was used in the calculation.

It is calculated (fig. 2), that the radius of a high-pressure area coincides with the radius of an energy input area at the initial stage of the channel expansion ($t = 0.1$ µs). Subsequently there appears a gap between the front of the shock wave and the energy input area or so-called «cover» of the current-conducting channel, that corresponds to experimental data [4, 5]. With the development of the spark channel an increase in the gap occurs. A chemical-energy release due to hydrogen combustion takes place namely in the area formed by the gap between the front shock wave and the energy input area. The area of the chemical-energy release is reflected in appearance of a temperature jump on the spatial distribution of the temperature in the discharge channel, the temperature of which corresponds to approximately 3500 K in the given example. Analyzing the energy state of the gas in the channel we will find out that endothermic reactions dominate in the discharge up to $t < 8 \cdot 10^{-7}$ s (fig. 3). As a result, the basic part of the deposited discharge energy is expended on dissociation of molecules of oxygen and hydrogen in the area of the energy input where the gas-plasma temperature exceeds 5 000 K that limits an increase in the intensity of the shock wave.

There is incongruity between the total energy of capacity discharge when detonation initiation takes place at experimental researches and the one at the calculated results. It can be caused by the difference between experimental conditions where gas-dynamic expansion of the spark channel corresponds to spherical symmetry due to the short gas-discharge gap and the modeling one. Nevertheless, the accepted model gives a qualitative description of mechanism of detonation initiation by the spark discharge adequately.

When the duration of the energy input and (or) the specific power fall down to the critical value, an initiation of detonation does not occur (fig. 4). In this case an increase of the pressure due to the combustion is compensated by pressure drop due to the channel expansion because of the small scale of the area where the chemical energy release takes place.

3 Detonation initiation by a gradient mechanism

A method of detonation initiation by a gradient mechanism (overall ignition) where there is a pressure balance in the discharge channel with ambient pressure during the process of the energy input is of scientific interest. It is similar to the process of the detonation initiation by deflagration to detonation transition in a detonation tube where the increase in pressure due to combustion is not compensated by the gas expansion because of the large scale of combustion zone. That leads to a rise of intensity of a compression wave which transforms into a detonation wave then.

In the case of detonation initiation by this mechanism, the requirements to the electric discharge, particularly in the specific power of the energy input into the discharge channel, change. For example, it is calculated (fig. 5) that the detonation initiation takes place in stoichiometric hydrogen-oxygen mixture of atmospheric pressure when the specific power of the energy input equals $W = 6000$ W/cm^3 which is three orders of magnitude lower than it is in the powerful spark discharges. The energy is deposited by the radius $r_{inp} = 1$ cm and the deposition time $t_{inp} = 0.1$ ms. Assuming that the strength of an electric field in the positive column of the discharge channel at given discharge duration is about $E = 10 \div 100$ V/cm, we get the required density of the discharge current, which is about $j = 60 \div 600$ A/cm^2. It is possible by such magnitudes of the current density in certain conditions to obtain electron emission from the cathode without the origin of cathode spots. It is one of main requirements for technical realization of the discharge energy input into a large volume. A magnitude of the discharge current ranges from $I = 180 \div 1800$ A in this case. Thus, evaluating the magnitudes of the strength of the electric field, the discharge current and the discharge duration, we come to the conclusion that driving of the parameters of energy input into the discharge channel is technically feasible.

It should be taken into account that density drop in the heating area from initial magnitude of $\rho_0 = 0.55$ kg/m^3 happened no more than in $3.5 \div 4.5$ times up to the instant of the ignition that corresponds to time of $t = 110$ µs. Therefore there was enough quantity of potential (chemical) energy in this area to obtain a pressure jump up to 10^6 Pa by «instantaneous» ignition that provides initiation of detonation in this case.

In the presented example the chemical energy is almost not released during the process of the electric energy input into the channel (fig. 6). But in 20 µs after the electric energy input is stopped, which corresponds to the calculation time of 120 µs, figures 5, 6, the quantity of chemical energy released by the mixture combustion starts exceeding the electric energy input.

The energy input to initiate the detonation by the pulsed arc were 1.88 J/cm at the calculated example that is comparable with the one by the spark discharge.

There is a critical size of the heating zone (a critical radius of the energy input) when the detonation initiation occurs by this mechanism. The critical energy of the detonation initiation is reduced while the radius of the heating zone approaches the critical radius. It is caused by rising of the mass of the heating gas when the scale of the ignition zone is increased and it is necessary to exceed the ignition temperature of the mixture.

The variants of thermal ignition realization into the large volume by the pulsed arc are described in work [3]. A concept of the increase in the ignition volume by using the identical quantity of electrical energy resides in the rise in the discharge current with the simultaneous reduction of the voltage supported to the discharge by the energy source. Ultimately, there is a reduction in energy loss out of the discharge gap i.e. in the electric circuit including loss in the anode and cathode layers. And there is a growing of share of the discharge energy transformed into a kinetic energy of gas directly. It results in increase in the discharge efficiency in the range of $20 \div 50$ % by such discharges. In contrast, the efficiency of the powerful spark discharges makes about 1 %. It should be noted that duration of pulsed arc discharges can be regulated by the high-current electronic switch if the voltage in a discharge circuit makes about 1000 V. Vs., a high-voltage spark discharge cannot be virtually realized with duration of the quarter of the discharge period by retaining the residual share of the discharge energy.

On the basis of abovementioned it is concluded that the most advanced way to solve the problem of repetitive detonation initiation by low input of electric energy is using the arc driving discharge in realization of detonation initiation by gradient mechanism.

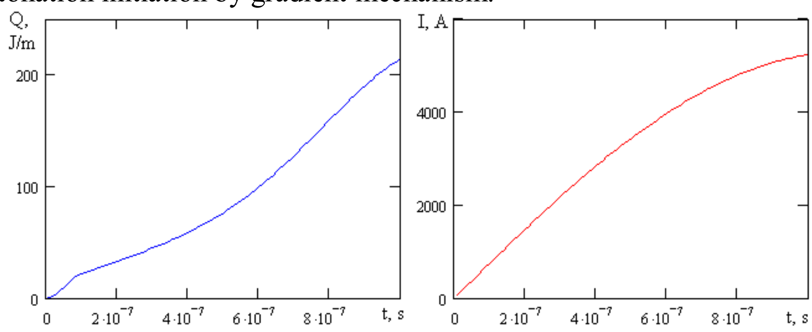

Figure. 1. Time dependence of energy input into the discharge channel (on the left) and dynamics of discharge current (on the right) received by the treatment of the experimental results [4, 5].

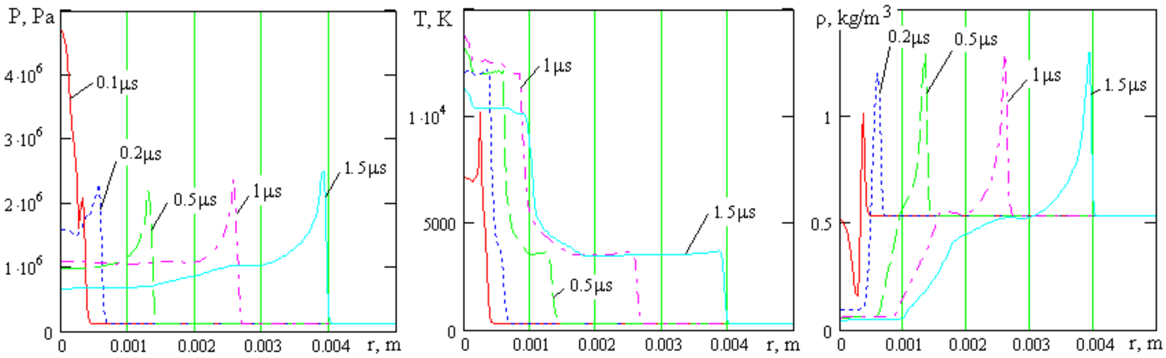

Figure 2. Dynamics of pressure, temperature and density profile histories calculated by the specific power is defined by the equations (1, 2) where the coefficient equals $k = 4$ and the time of energy input is $t_d = 10^{-6}$ s.

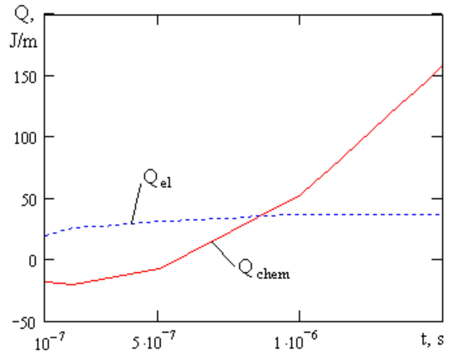

Figure. 3 Time histories of quantities of energy which correspond to one quarter of the deposited electric energy $1/4Q_{el}$ and absorbed (released) energy Q_{chem} of the chemical reactions according to calculated results on the figure 2.

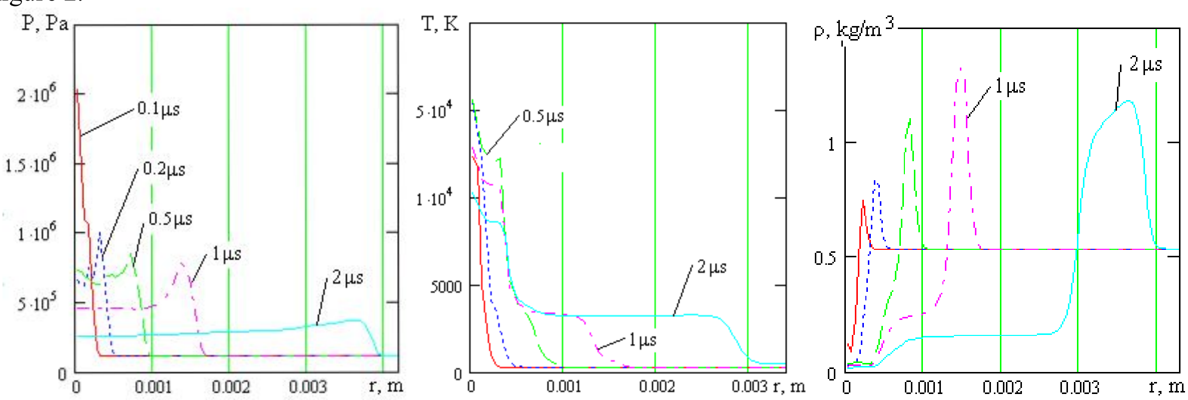

Figure 4. Dynamics of pressure, temperature and density profile histories calculated by the specific power is defined by the equations (1, 2) with the coefficient equaling $k = 5$ and $t_d = 5 \cdot 10^{-7}$ s.

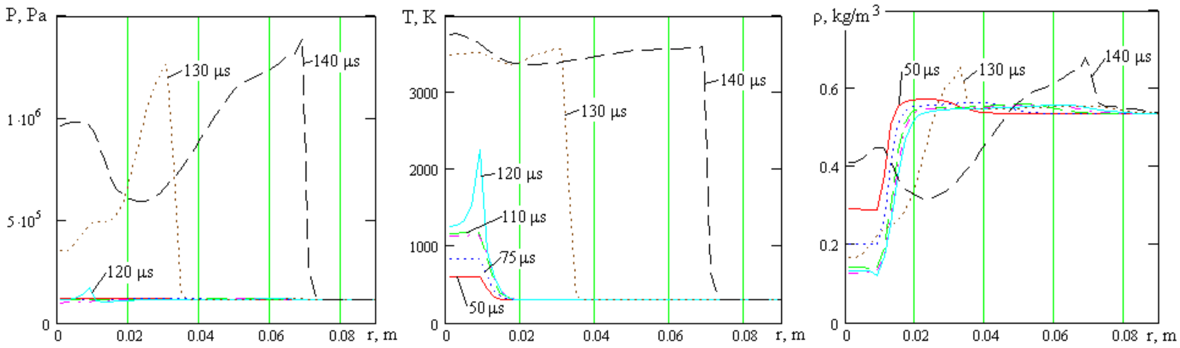

Figure. 5. Dynamics of pressure, temperature and density profile histories calculated by the specific power of W = 6000 W/cm^3 by the radius of the energy input of r_{inp} = 1 cm and the discharge duration of t_d = 0.1 ms.

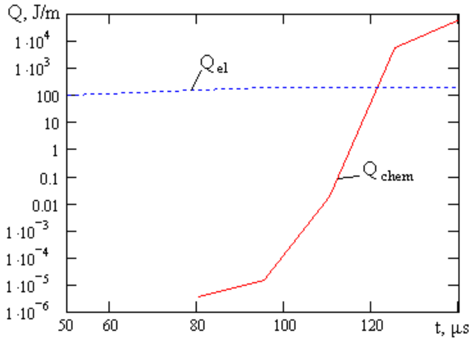

Figure. 6. Time histories of quantities of energy which correspond to the deposited electric energy Q_{el} and absorbed (released) energy Q_{chem} of the chemical reactions according to calculated results on the figure 5.

Table 1: Dynamics of changing of the discharge parameters (C = 0.25 µF, L = 2 µH, U = 15 kV) by data [4, 5]

Time, s	Current density, A/cm^2	Strength of the electric field, V/cm	Specific power, W/cm^3	Radius of the conducting channel, mm
10^{-7}	$3.8 \cdot 10^5$	1 270	$4.8 \cdot 10^8$	0.25
$2 \cdot 10^{-7}$	$2.4 \cdot 10^5$	715	$1.72 \cdot 10^8$	0.48
$5 \cdot 10^{-7}$	$1.3 \cdot 10^5$	550	$7.15 \cdot 10^7$	0.95
10^{-6}	$7 \cdot 10^4$	330	$2.31 \cdot 10^7$	1.55

Literature

[1] Kamenskihs V, Ng HD, Lee JHS. (2009). Measurement of Critical Energy for Direct Initiation of Spherical Detonations in Stoichiometric High-Pressure H_2-O_2 Mixtures. Proc. 22nd ICDERS.: 157.

[2] Zeldovich YaB et al. (1970). Development of detonation in a non-uniformly pre-heated gas. Acta Astronaut. 15: 313.

[3] Korytchenko KV et al. (2008). Control of a pulsed arc discharge for effective heating of a gas. Technical Physics. 53(4): 415.

[4] Abramson IS, Gegechkori NM. (1951). Oscillographic investigation of spark discharge. Journal of Experimental and Theoretical Physics. 21(4): 484.

[5] Gegechkori NM. (1951).Experimental investigation of channel of spark discharge. Journal of Experimental and Theoretical Physics. 21(4): 493.

[6] Murray S. (2001). Explosion Physics - Fundamentals and Current Developments. Professor I.I. Glass 6th Memorial Lecture.