Application of Arc-Driving Discharge to Igniting

K. Korytchenko\(^1\), V. Lisovskiy\(^2\)

\(^1\)Kharkiv Institute of Armored Forces by National Technical University “KhPI”, Kharkiv, Ukraine
\(^2\)Kharkiv National University, Kharkiv, Ukraine

Abstract: A problem of increasing the volume of a thermal ignition source is solved through acting on a gas discharge process according to the following prescriptions. The first prescription is to provide a predominant deposition of discharge energy in a gas-discharge gap. This is accomplished through optimizing the parameters of the capacitive discharge circuit as well as the length of the discharge gap. According to the second prescription the plasma parameters have to be made closer to the thermal equilibrium ones during the spark evolution. In order to fulfill these prescriptions we employ a high-voltage driving pulsed arc, where the voltage applied across the discharge gap is controllably changed. We present an explanation of the fast expansion rate of the visible part of a spark channel at the initial stage which is not associated with the propagation of an intense shock wave.

Keywords: arc driving discharge, ignition, detonation initiation.

1. Peculiarity of the ignition

The increase of flame propagation velocity can be achieved through growth of a burning surface. Such an increase can be attained due to multiplying the volume of a thermal ignition source at the initial stage of a spark ignition. Presently widely spread automobile ignition systems use an induction coil. These systems create a high temperature discharge channel, the diameter of which, as a rule, amounts to about 0.1 mm. A length of the spark channel comprises from 1 to 5 mm depending on the condition of discharge ignition. Thus, the volume of the thermal source in such systems does not exceed 0.05 mm\(^3\). The new system producing a driving pulsed arc is offered in this report. It permits to create an efficient thermal source, the volume of which exceeds 5 mm\(^3\) with the energy deposition about 1 J.

High efficiency of the designed system is achieved due to the change of the voltage applied across the discharge gap during the pulsed arc development. Influence of the driving discharge on the efficiency of the energy deposition into the channel allows for a following simplified explanation. An energy input into the discharge channel is determined by the equation:

\[
Q = u i t = [E l ] [\sigma E \pi R^2] t,
\]

where \(u\) is the voltage applied to the gap, \(i\) is the discharge current, \(\sigma\) is the plasma conductivity of the channel (assuming a uniform distributing of the conductivity across the channel cross-section), \(R\) is the channel radius, \(E\) is the electric field strength, \(l\) is the gap length, \(t\) is the time. We know that the reduction of the strength \(E\) leads to the falling of the conductivity \(\sigma\). Therefore, if an energy source has the sufficient power to obtain a high discharge current \(i\) and the strength \(E\) is decreasing, the current increase is achieved due to the growth of the channel radius \(R\). Thus, due to the driving strength there is an increase in the fraction of the deposited discharge energy due to the volume increase of the thermal ignition source.

2. Calculation of driving strength

A way of how the drive of the electric field strength influences the discharge process is presented in papers [1, 2]. It is shown that the forced change in the field strength inside the pulsed arc by an external electric circuit involves:

1) a rise in a resistance of the discharge channel by diminishing the plasma conductivity;
2) an increase in a rate of gas heating by the discharge current due to the growth in electron-ion collision rate;
3) an approach of the ionization degree of the plasma to the thermally equilibrium one through limitation of the electron temperature.

Therefore the drive of the field strength into a pulsed arc allows not only fulfilling the growth condition of the energy fraction deposited into the discharge gap but it advances the efficiency of the electric energy transformation into thermal one of the gas-discharge environment.

The following assumptions were employed to calculate the required dynamics of changing of the electric field strength to drive the pulsed arc into the ignition systems. All discharge energy will be directly transformed into heat if there is an electron energy balance when a quantity of electron energy obtained from the electric field during electron motion between collisions with an ion of an atom or a molecule will be fully transferred to the ion via their elastic collision. A formula of the strength calculation that was obtained in paper [2] using this assumption is given by:

\[
E = 1.79 \cdot 10^{-15} \cdot n_e \cdot \ln \Lambda \cdot \frac{\frac{1}{A} \sqrt{(T_e - T_i)T_e}}{T_e^2},
\]

where \(E\) is the electric field strength [V/cm], \(T_e\) is the electron temperature [eV], \(T_i\) is the temperature of heavy particles (atoms, molecules, ions) [eV], \(n_e\) is the electron density [cm\(^{-3}\)], \(\ln \Lambda\) is the Coulomb logarithm, \(A\) is the mass...
of the ion in atomic mass units

But a calculation of strength according to this formula is possible only if the plasma parameters are measured. Therefore, we additionally used the Sakha equation (2) permitting to compute densities of molecular and atomic ions, the state equation (3) of singly-ionized quasi-neutral plasma and the equation (4) to calculate a thermal dissociation process that is presented below [3]:

\[
n_c = [K \cdot N \cdot \frac{g_a}{g_n} \cdot \frac{T_c^3}{T} \cdot \exp(-\frac{I}{T_c} \cdot \text{eV})]^{\frac{1}{2}}, (2)
\]

\[
N = \frac{(p / kT) - n_c(T_c + T)}{T},
\]

\[
\frac{N_d^2}{N_{at}} = \frac{g_d^2}{g_{at}} \cdot \frac{M_d^{\frac{1}{2}} \cdot \nu}{4 \cdot J_A \cdot \sqrt{\pi k T}} \cdot e^{-U/kT}, (4)
\]

where \( K = 6.06 \cdot 10^{21} \text{ cm}^{-3} \cdot \text{eV}^{-\frac{3}{2}} \); \( g_a \) and \( g_n \) are statistical weights of an ion and an atom (molecule), respectively; \( I \) is an ionization potential of an atom (molecule); \( k \) is the Boltzmann constant; \( U \) is the dissociation energy of the molecule; \( \nu \) is the molecule vibration frequency; \( J_A \) is the moment of inertia; \( g_A \) and \( g_{A2} \) are statistical weights of an atom and a molecule; \( M_d \) is an atomic mass.

Possibility of application of the equations related to highly-ionized plasma is checked via comparison of the frequency of elastic collisions of electrons and atoms (molecules) with the frequency of elastic collisions of electrons with ions using an equation:

\[
N \cdot \sigma_{el} << n_e \cdot \sigma_{cul}, (5)
\]

where \( \sigma_{el} \) is the cross-section of elastic collisions of electrons with atoms (molecules), \( \sigma_{cul} \) is the cross-section of Coulomb collisions.

A system of equations (1-4) was solved using an iteration method. A solution was found as dependence of the electron temperature on the temperature of ions with the given electric-field strength and pressure in the discharge (fig. 1).

The solution region is limited by equation (5) to minimal and maximal electron temperature. Falling of the temperature leads to a decrease in the electron density \( n_e \). Growth of the temperature causes a reduction of the cross-section \( \sigma_{cul} \) of Coulomb collisions. So, there is a range of the gas temperature where the balance between electron energy received from the field and energy losses via Coulomb collisions is achieved. From the analysis of terms of the balance establishment, the requirements of the electric-field drive in the pulsed arc were produced to ignite (fig. 2) or to initiate a detonation (fig. 3).

Verification of electron energy fraction lost via the Coulomb collisions is made depending on the ratio of the field strength to the atom (molecule) density. Program «Bol-sig+» [4] solving Boltzmann equation was used for the calculation where a gas temperature, influence of collisions between electrons and electron density are taken into account. Collisions of electrons with ions were added in...
the calculation by insertion of a separate species, the cross-section of which corresponds to Coulomb collisions with oxygen ions. Oxygen atoms were inserted as a separate species among molecules and their ions by introduction of proper collision cross-sections of the atomic excitation levels. It was accepted that the gas temperature equals $T = 2500$ K, the ionization level equals 10% for the calculation results presented (fig. 4). It was found that the fraction $\delta$ of the energy lost via elastic electron-ion collisions becomes dominant as compared with the losses via other excitation processes when the ration $E/N$ is reduced.

It should be noted that the Boltzmann equation can not be solved when the curve of collision cross-section is falling. The cross-sections of Coulomb collisions correspond to such type of the curves specifically. Increase in the electron velocity (their temperature) must be compensated by the growth of the elastic collision rate via a rise of the ion density in this case.

It should be noted that it is needed to use electric circuits where there is a drive of the voltage applied across the discharge gap to affect the electric field in the positive column of the arc. For example, the electric circuit presented in paper [5] allows driving the voltage partially. The high-speed photography of the discharge development showed that during the high-current stage of the discharge the diameter of the channel visible area approaches 3 mm in air of atmospheric pressure with the about 1 J energy deposition into the discharge (fig. 5). Velocity of channel expansion was about 100 m/s during the stage of pulsed arc development.

It was experimentally confirmed that the volume of the thermal ignition source is substantially multiplied at a motor-car spark-plug (fig. 6). The working frequency of the designed ignition system is more than 200 Hz.

The system was tested on a piston engine “MeMTh”. Experimental investigations showed that changing of the energy deposition from 20 mJ to 200 mJ leads to a slight increase in the motor speed. Preliminary results demonstrate that turning moment rises by 10% at some operation mode (fig. 7).

3. Calculation of the length of the gas-discharge gap

Solving problems of an ignition and detonation initiation by an electric discharge in a gas, it is advisable to create mainly a gas-discharge plasma instead of erosion one. First, this allows increasing the life time of an initiation device due to a decrease in the electrodes erosion. Second, it spends much more energy for heating a solid than for increasing the gas temperature to the same temperature if the heating volumes are equal.

Obviously, putting the discharge electrodes closer leads to increasing the fraction of the erosion plasma. The quantitative estimation of the distance between the discharge electrodes that provides a condition of gas-discharge plasma formation is made as follows. It was assumed that an electrons energy has time to transform into a kinetic energy of the gas during a process of electron drifting into volume formed between the electrodes and filled by the gas if a length of the discharge gap is significantly more than a product of a time $\tau_{\text{rel}}$ of relaxation from electrons energy to kinetic energy of the gas and the drift velocity $v_d$ of electrons. That is a constraint is:

$$ l > v_d \tau_{\text{rel}}. $$

Derivation of the given equation is presented in paper [2] where the plasma was assumed to be highly ionized. The equation has the following form if the plasma is quasi-neutral:

$$ l > \frac{3.74 \times 10^{39} \cdot A \cdot E \cdot T_e^3}{n_e^2 \cdot \ln \Lambda} [\text{cm}], $$

The temperature of electrons reaches $T_e \approx 1 \div 2$ eV in a spark discharge. A density of electrons has an order about $n_e \approx 10^{16}$ cm$^{-3}$. Coulomb logarithm gains values in the range $\ln \Lambda \approx 5 \div 10$ for mentioned values of the density and the electron temperature. An average mass of ions is in the range $\Lambda \approx 16 \div 32$ relating to the discharge in oxygen. The electric field strength drops down to $E \approx 100 \div 2000$ V/cm at

![Fig. 5. High-speed photography of arc-driving discharge evolution](image)

Fig. 5. High-speed photography of arc-driving discharge evolution obtained by the mentioned circuit showed that during the high-current stage of the discharge the diameter of the channel visible area approaches 3 mm in air of atmospheric pressure with the about 1 J energy deposition into the discharge (fig. 5). Velocity of channel expansion was about 100 m/s during the stage of pulsed arc development.

![Fig. 6. Comparison of the discharges: spark of traditional ignition system is presented on the left; arc-driving discharge is presented on the right](image)

Fig. 6. Comparison of the discharges: spark of traditional ignition system is presented on the left; arc-driving discharge is presented on the right.
the first half-period of the current of a high-voltage capacitive discharge [6]. This strength appears at a stage of a spark channel expansion when the discharge current exceeds the order of tens amperes and growth in the current is limited by parameters of the electric circuit. If the electron temperature equals $T_e = 1$ eV, we get $n_e = 5 \times 10^{16} \text{ cm}^{-3}$, $A = 25$, $\ln \Lambda = 5$, $E = 2000 \text{ V/cm}$. The length according to equation (4) should be $l >> 0.3 \text{ cm}$ in this instance. If the input data are $T_e = 2$ eV, $n_e = 10^{16} \text{ cm}^{-3}$, $A = 16$, $\ln \Lambda = 10$, $E = 100 \text{ V/cm}$, the length is no less than $l >> 0.5 \text{ cm}$. Reduction in an electron density is caused by falling of a density of a gas-discharge environment in spite of electron temperature growing in given examples.

The calculated results show that it is necessary to use the discharge gap the length of which is more than 1 cm to form the gas-discharge plasma by the high-voltage capacitive discharge. The obtained results are in good agreement with results presented in paper [7] where a critical energy of detonation initiation did not depend on the form of electrodes and the gap in the case of the discharge length exceeded 1 cm.

We have to note that it is possible to form primarily a gas-discharge in the discharge gap of the small length when a discharge process is driven by changing the electric field strength in the arc channel.

4. Conclusion

A drive of the field strength into a pulsed arc according to the offered dependence allows not only to realize conditions of growth of the fraction of energy depositing in the discharge gap but it also raises an efficiency of an electric energy transformation into thermal one of gas-discharge environment. Due to the drive a rise of the volume of thermal ignition source is achieved.

References