High-voltage pulsed driving arc applied to ignition and detonation

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1 Problem statement

The increase of velocity of flame propagation can be achieved through growth of burning surface. Such increase can be attained due to multiplying the volume of a thermal ignition source at the initial stage of a spark ignition. At the present time widely-spread automobile ignition systems use an induction coil. These systems create a high temperature discharge channel, the diameter of which, as a rule, makes about 0.1 mm. A length of the spark channel achieves from 1 to 5 mm depending on the condition of discharge ignition. Thus, the volume of thermal source in such systems does not exceed 0.05 mm^3. The new system producing of driving pulsed arc is offered in this work. The system allows effectively creating the thermal source, the volume of which is more than 5 mm^3 by energy deposition about 1 J.

One of ways of practical application of pulsed arcs of high and superhigh pressures are ignition systems of fuel mixtures. It is necessary using discharge created by the systems to provide the reliable ignition as diluted mixtures as enriched one by the different engine behavior. And periodic creation of a large volume of thermal sources of self-ignition is required to this effect. Minimization of energy expended on forming of the sources is expedient.

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

$$Q = u \cdot i \cdot t = [E \cdot l] \cdot [\sigma \cdot E \cdot \pi R_c^{\,2}] \cdot t,$$

where u is a voltage applied to the gap, i is a discharge current, σ is a plasma conductivity into the channel (assuming of uniform distributing of the conductivity in the channel cross-section), R_c is a radius of the channel, E is a strength of the electric field, l is length of gap, t is a time. It is known that reducing of the strength E leads to the falling of the conductivity σ. Therefore, if an energy source has sufficient power to obtain a high discharge current i and the strength E is decreased, growth in the current is achieved due to rise in radius of the channel R_c. Thus, due to strength driving there is increase in the share of the discharge energy deposited on multiplying of volume of thermal ignition source.

Development of pulsed arc takes place in the conditions of electric field changing into the positive column of arc. Such change affects establishment of current meaning of electron temperature,

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depending on which balance of an energy deposition into the different types of excitations of atoms (molecules) is coming. Thus, it is possible a realization of a condition when a main part of discharge energy is directly deposited into the required type of excitations of atoms (molecules) via influence on the field strength of the pulsed arc.

2 Calculation of the voltage driving

Obviously, a maximal size of the discharge channel using as the thermal source will be realized if all discharge energy will be directly transformed into a heat. This requirement can be attained if there is an electron energy balance when a quantity of electron energy obtained from the electric field during a motion of electron between collisions with an ion of an atom or a molecule will be fully transferred to the ion via their elastic collision. This condition was applied to calculate the required dynamics of changing of the electric field strength to drive the pulsed arc into the ignition systems. It was used the mentioned equation of electrons energy balance, a state equation, Sakha equation to get the closed equation system. A process of dissociation was taken into account too. A two temperature model of the highly-ionized plasma was used where there is a difference between the electrons temperature and ions one. An average mass of ions depending on a current gas condition was put into an equation of frequency of elastic electronic-ionic collisions. The electrons temperature was put in equalization of Sakha and expression of coulomb logarithm. The temperature of the heavy gas components was used to calculate a degree of gas dissociation. Possibility of an application of the equations related to highly-ionized plasma is checked via a comparison of the frequency of elastic collisions of electrons and atoms (molecules) with the frequency of elastic collisions of electrons with ions. Dates of cross-section of elastic collisions of electrons with the molecules of oxygen were adopted from a work [1].
The process of electrons attachment to the molecules of oxygen was not taken into account.
Results of the calculations related to the discharge into oxygen of atmospheric pressure show that the foregoing balance of energy transition from the electrons to the ions is achieved into the cold gas by the field strength equaled about 400 V/cm (fig. 1). Growth of ions temperature by this value of the field strength is possible in conditions of the mentioned balance presence when the gas temperature is less than 4700 K. Reducing of the field strength leads to expansion of temperature range where the balance is present. But a low value of the range increases. Falling of the strength also causes a decline of difference between the electrons temperature and the ions one.

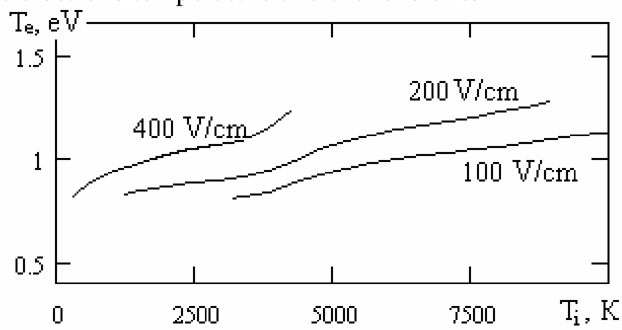

Fig. 1. Difference between the electrons temperature T_e and the ions one T_i by different field strength into the environment of oxygen of atmospheric pressure

Lowering of the field strength leads to restricting of electrons density. Thus, the quantity of the discharge energy expended on gas ionization declines (fig. 2). But it requires to be done in the conditions of growth of gas temperature and in such way that plasma remained highly-ionized. So, the strength reducing provides minimization of energy expended on forming of the thermal ignition sources. The curve of electrons density tends to decreasing when the gas temperature grows up to 2500 K, i.e. it starts during the dissociation process. It caused by exceeding of an ionization potential of atoms of oxygen comprising with the potential of the molecules. Nevertheless, frequency of elastic electronic-ionic collisions is at least one order of magnitude greater than collisions frequency of the electrons with atoms and molecules in the conditions of growth of the dissociation level. That means the plasma remains highly-ionized.

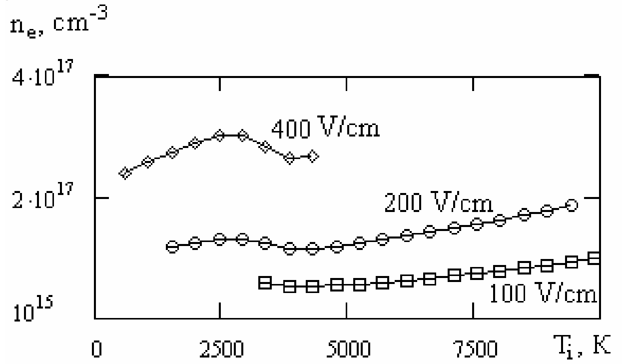

Fig. 2. Calculated change the electrons density by growth of gas temperature

Studding the calculated results concerning of oxygen discharge environment by atmospheric pressure, it have been gotten a dependence (fig. 3). Following the dependence, a creation of large volume of thermal ignition sources is achieved by the minimum quantity of electric energy input.

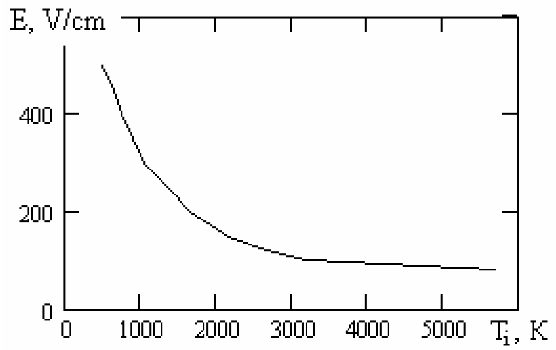

Fig. 3. Required dynamics of change the field strength into the column of arc depending on the gas temperature

It should be noted that it is needed to use electric circuits where there is a drive of the voltage supported to the discharge gap to affect on the electric field into positive column of the arc. For example, the electric circuit presented in work [2] allows driving the voltage partially.
The high-speed photography of development of the discharge created by the designed system and which is obtained into air environment and atmospheric pressure showed that the visible cannel diameter achieves a size of 3 mm during a high-current stage of the discharge by the energy input equaled about 1 J (fig. 4.). Velocity of channel expansion was about 100 m/s during the stage of pulsed arc development.

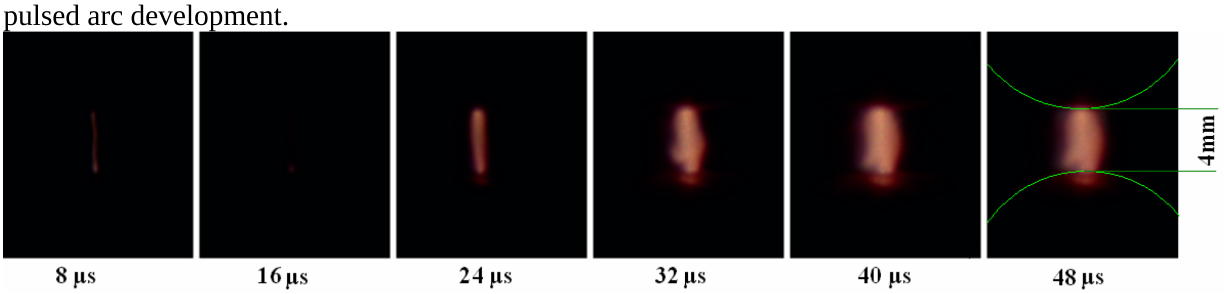

Fig. 4. The high-speed photography of the arc driving discharge

It was experimentally confirmed the volume of the thermal ignition source is substantially multiplied at a motor-car spark-plug (fig. 5). The working frequency of the system can be more than 200 Hz.

The system was tested on a piston engine. It was obtained that changing of the energy deposition from 20 mJ to 200 mJ leads to a slight increasing into motor speed. Preliminary results have shown that turning moment rises on 10 % in some regimes (fig 6).
It is necessary a slight growth of the strength to initiate a detonation into fuel-oxygen mixture (fig 7).

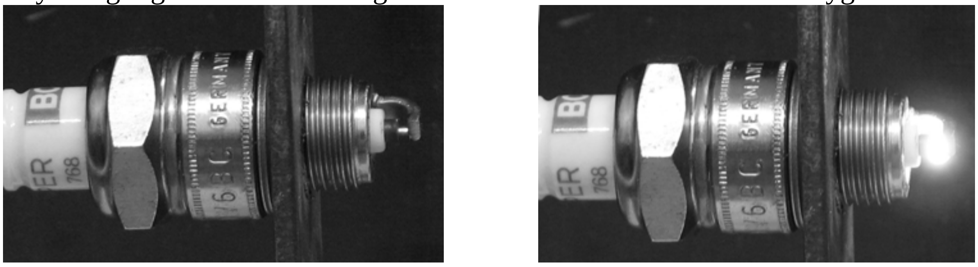

Fig. 5. Comparison of the discharges: spark of traditional ignition system is presented on the left; arc-driving discharge is presented on the right

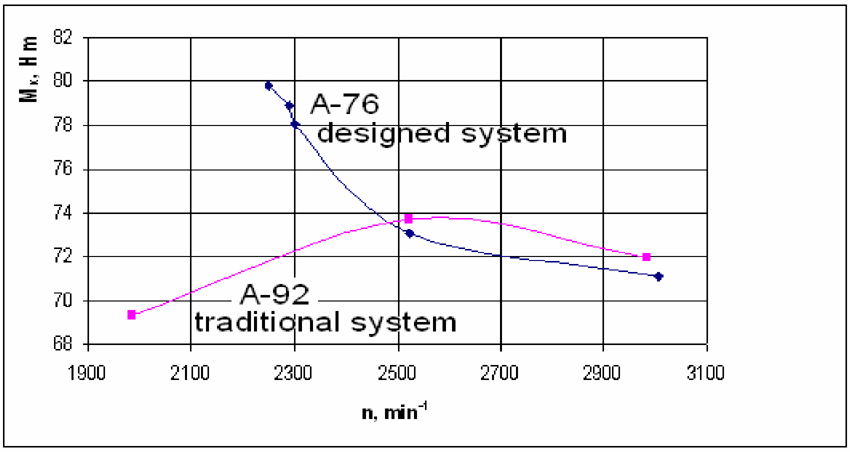

Fig 6. Dependence of turning moment on motor speed

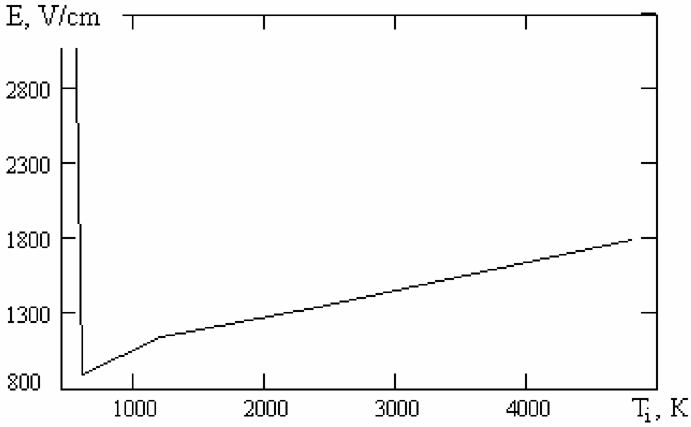

Fig. 7. Required dynamics of change the field strength into the column of arc depending on the gas temperature to initiate a detonation into fuel-oxygen mixture

References

[1] Hagelaar GJM, Pitchford LC (2005) Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models. Plasma Sources Sci. Techn. 14: 722.

[2] Dovbnya A, Korytchentko K et al. (2003) Dynamics of energy release in a low-voltage pulsed arc in air. Technical Physics. 48(12): 1586.