EXPERIMENTAL INVESTIGATION OF ARC COLUMN EXPANSION GENERATED BY HIGH-ENERGY SPARK IGNITION SYSTEM

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The results of an experimental investigation of an improved spark-capacitor ignition system are presented. The high-speed shooting and oscillography techniques were used. Influence of the ignition system parameters on a size of an ignition region, a time scale of spark energy input and discharge efficiency has been found out. The reason of the high spark efficiency has been explained. Variants of circuit diagrams generating a single arc pulse and double arc pulse have been tested.

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INTRODUCTION

Pulsed arc discharge is widely used as a reliable ignition source of lean fuel-air mixtures. Ignition reliability depends on a size of a high-temperature region [1]. The increase in an arc size achieves by growth of energy deposited into the spark discharge. Special automotive ignition systems are used to generate high-energy spark discharges [2].

There are some problems to design a high-energy spark ignition system. It is necessary to have high efficiency of a spark energy input when the total discharge energy achieves one Joule. It has to supply with a high voltage pulse (above 20 kV). The pulse frequency should be variable in a range from 10 Hz to 200 Hz. The main problem connected with the required efficiency due to a next reason. An active resistance of the pulsed arc cannel as an active load of the ignition system starts falling dramatically when the total energy grows. It changes a balance of energy input between the load (spark gap) and the discharge circuit of the ignition system.

Manufacturers present ignition system features [3]. But such parameters influencing on ignition reliability as a size of an ignition region, a time scale of a spark energy input and discharge efficiency are not given.

This work is focused on an experimental investigation of the mentioned parameters of an improved spark-capacitor ignition system [4-6].

EXPERIMENTAL SETUP

We use a special spark ignition system where the total ignition energy can achieve one Joule to generate pulsed arcs periodically. It has to note that the total spark energy of traditional automotive ignition systems is up to 50…200 mJ [7]. A circuit diagram of the improved spark-capacitor ignition system is given on Fig. 1.

The designed system initially generates a high-voltage pulse by a pulsed transformer *T* that leads to a spark breakdown. Then the system produces a current pulse by a capacitor C_1 connected in series with secondary winding of the transformer. Due to significant growth of the discharge current we have an arc formation. Next improving of the system was made. We added diode *VD* in parallel with the capacitor C_1 to form a single high-current pulse. A common energy source was used to charge the capacitors C_1 and C_2. We applied an IGBT-transistor generating time-limited one-polarity pulses to avoid an energy loss when a transformer core is saturated.

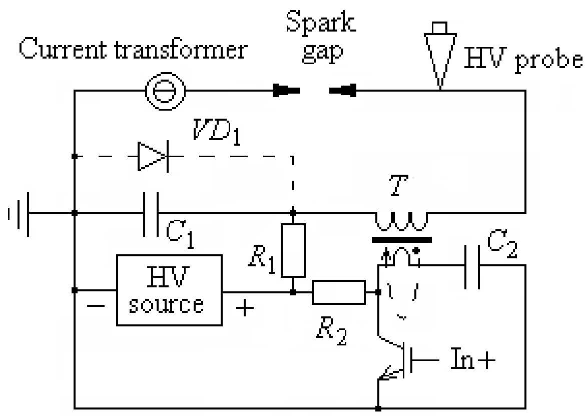

Fig. 1. A circuit diagram of the high-energy ignition system

We used a single turn high current transformer as the pulsed transformer. The turns ration was 90. It was used Hitachi Metals F1AH1122 transformer core. Wire diameter of the secondary winding was 1 mm. The secondary winding resistance was 124.5 mΩ. The DE-5000 LCR meter was applied to measure the transformer inductances. A magnetizing inductance of the primary winding was about 3.6…11.9 μH in the measured frequency range from 10 to 100 kHz. We cannot to find out a leakage inductance of the primary winding due to a testing error. A magnetizing inductance of the secondary winding was about 46…48 mH. The leakage inductance of the secondary winding was about 3.4…4.9 mH. Thus the transformer design (single turn transformer) allows achieving high magnetizing inductance and low values of leakage inductance.

Capacitance of the capacitor C_1 was variable and equaled 1, 1.5, and 3.3 µF to change the total discharge energy Q_t. The capacitor was charged to an initial voltage 600 V.

We used a high-speed digital camera MS70K to investigate an arc column expansion generated by the designed system. A recoding speed was from 15.000 to 38.600 fps. The discharge was generated in atmospheric pressure air. The spark gap length was about 5 mm.

Discharge current and arc voltage were measured by a current probe Honeywell CSNM 191 and a voltage probe Tektronix P6015A. Amplitude and form of discharge current were varied by changing of a schematic diagram of the discharge circuit and circuit parameters. Influence of a discharge current pulse form on the arc column expansion was determined by correlation of the arc images with the discharge current. It was assumed that a lighting region in photo images corresponds to a high-temperature region (Fig. 2). A size of a high-temperature region was found out by a diameter D of the lighting region.

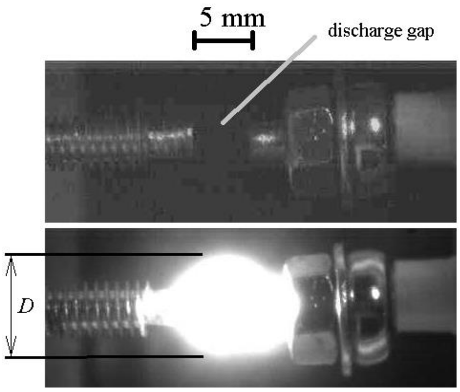

Fig. 2. Views of the discharge gap and pulsed arc

The average velocity u_{arc} of the arc column expansion was estimated via dividing an arc radius change by a time of an arc evolution extracted from high-speed imaging. A time integral of the electric power was calculated to find out the energy input in pulsed arc. A resistance of pulsed arc was estimated using experimental results of voltage and current time histories.

EXPERIMENTAL RESULTS

Current and voltage waveforms of the electrical discharge when diode *VD* is disconnected are given (Fig. 3). The capacitance of capacitor C_1 equaled 3.3 µF. We observed next stages of the discharge. The spark starts from breakdown. Then we have a time delay of an arc pulse. Such a delay caused by the transformer core saturation process because it changes an inductance of the secondary winding and an inductive reactance of the discharge circuit correspondingly. Following rapid discharge of the capacitor C_1 leads to an arc pulse generation. Then we observed a current restriction named a current pause. The transformer core remagnetizing is the reason of the pause. Second arc pulse happens after that.

It was found out that the arc delay time depends on polarity of the high voltage pulse in relation to polarity of capacitor C_1. If polarities are opposite the arc delay time exceeds about 50…100 µs. In another case we had the delay reduction about 10…15 µs. It means that the high-voltage breakdown pulse accelerates the core saturation.

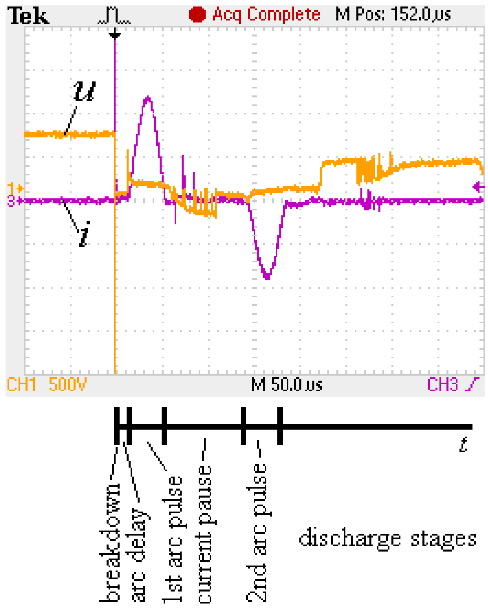

Fig. 3. Current i and voltage u waveforms of the electrical discharge when diode VD is disconnected and corresponding discharge stages (i – 50A/div)

The voltage waveform of the breakdown stage is given (Fig. 4). A linear rise in a voltage means a correct design of the transformer *T*. Duration of the high-voltage pulse was about 1 µs. Amplitude of the voltage pulse generated by the system is about 20 kV but the breakdown happened when the voltage exceeded 12 kV at given case (see Fig. 4).

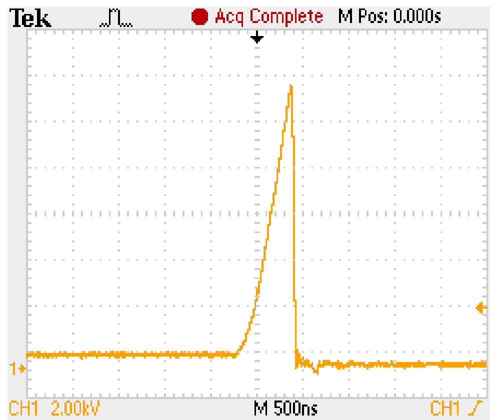

Fig. 4. The voltage waveform of the breakdown stage

We found out that sometimes the second arc pulse was absent. We think it happened due to plasma relaxation process during the current pause that led to an electrical conductivity disappearance.

The total time of the ignition pulse including the current pause was about 170…200 µs when diode *VD* was disconnected.

Current and voltage waveforms of the electrical discharge when diode *VD* is connected are given (Fig. 5).

The capacitance of capacitor C_1 was 3.3 µF for given result. We have three stages in this case. An arc stage corresponds to a one-polarity current pulse.

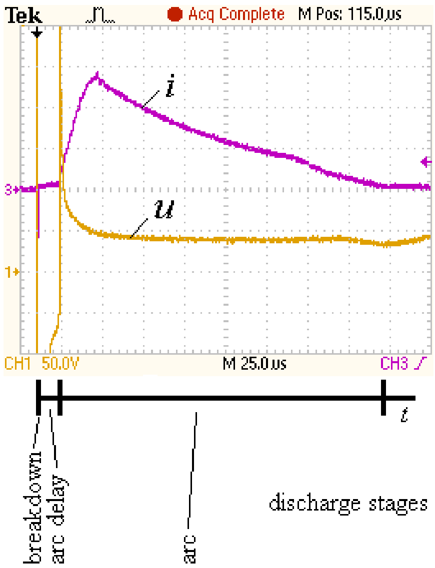

Fig. 5. Current i and voltage u waveforms of the electrical discharge when diode VD is connected and corresponding discharge stages (i – 50 A/div)

The total time of the ignition pulse when diode *VD* was connected was about 125…200 µs depending on the capacitance of the capacitor C_1. The total time grows when the capacitance increases.

An analysis of the high-speed photo images gave a good repetition of a pulsed arc evolution when the discharge conditions are similar. A comparison of the pulsed arc evolution when diode *VD* was disconnected and 3.3 µF condenser was used is presented (Fig. 6). There is a difference at 129.9 µs, but it can be explained by a difference in an initial time of a spark shooting and by a restriction on the recoding speed.

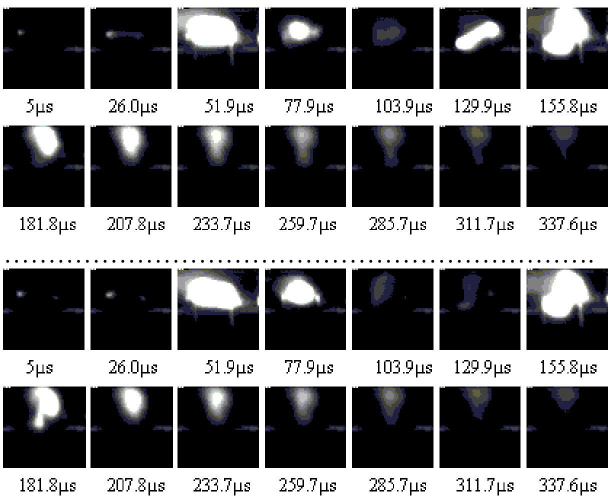

Fig. 6. The pulsed arc images of the two discharges when diode VD was disconnected

Obviously, an evolution of the high-temperature region depends on the current waveform. The current pulses have corresponded arc images.

The influence of the capacitance C_1 on the size of a high-temperature region can be observed in the Fig. 7. The diode *VD* was connected in this case.

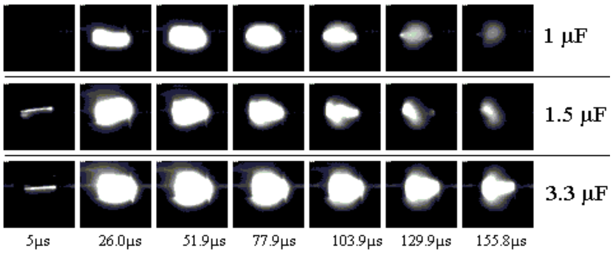

Fig. 7. The pulsed arc images by the different capacitance C_1

We think based on the experimental results that it is preferable to add diode *VD* in parallel with the capacitor C_1 to have a prolonged heating effect. It has to take into account instabilities of the 2nd arc pulse formation when diode *VD* is disconnected. More over the diode connection leads to a rise in the size of a high-temperature region by the equal total discharge energy.

The measured crude data of the pulsed arc discharges is presented Table.

The measured crude data of the pulsed arc discharges

C_1, µF/with or without diode	I_{max}, A	t_{arc}, µs	D_{max}, mm	u_{arc}, m/s	Q_{in}, mJ
3.3/-	120	180	5.2±0.6	98	250
1/diode	64	125	4.4±0.5	69	120
1.5/diode	80	150	4.8±0.5	79	170
3.3/diode	120	200	6.8±0.7	104	400

The spark-capacitor ignition system where the diode was not applied had lower efficiency than the system with the diode. It can be explained by an incomplete discharge of the capacitor C_1. The calculated efficiency of the system without the diode was about 42 %. The efficiency of the system with the diode was in a range from 65 to 70 %. We think that the high efficiency is achieved due to a value of the secondary winding resistance that was lower than the minimal resistance of the pulsed arc. For example, the minimal resistance was about 330 mΩ when 3.3 µF condenser was used. It is twice as large as the secondary winding resistance. A current density of the pulsed arc generated of the system with the diode was about 3.7…4.2 A/mm^2 when the discharge current had a maximal value. This data can be used to estimate the size of an ignition region when amplitude of the pulsed arc current is measured.

CONCLUSIONS

Obtained experimental data confirms that the improved spark-capacitor ignition system can increase the spark energy effectively. The efficiency of the system was in a range from 42 to 70 % depending on the circuit diagram. It was found out that a maximal diameter of the arc column generated by the designed system equals from 4.4 to 6.8 mm depending on the discharge current pulse form. An average velocity of the pulsed arc expansion was below the speed of sound. Duration of the high-voltage pulse was up to 1 μs. Duration of the current pulse was from 125 μs to 200 μs.

The obtained results can be used to improve features of the automotive ignition systems.

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ РАСШИРЕНИЯ ДУГОВОГО КАНАЛА В ВЫСОКОЭНЕРГЕТИЧЕСКОЙ ИСКРОВОЙ СИСТЕМЕ ЗАЖИГАНИЯ

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Представлены результаты экспериментального исследования усовершенствованной искро-конденсаторной системы зажигания. Использовались методы высокоскоростного фотографирования и осциллографического исследования. Выявлено влияние параметров системы зажигания на размер области воспламенения, динамику ввода энергии в искру и эффективность разряда. Обоснована причина высокой эффективности ввода энергии в искру. Проведено тестирование вариантов разрядной цепи, генерирующих одиночный и двойной дуговые импульсы.

ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ РОЗШИРЕННЯ ДУГОВОГО КАНАЛУ У ВИСОКОЕНЕРГЕТИЧНІЙ ІСКРОВІЙ СИСТЕМІ ЗАПАЛЮВАННЯ

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Наведено результати експериментального дослідження удосконаленої іскро-конденсаторної системи запалювання. Використовувалися методи високошвидкісного фотографування і осцилографічного дослідження. Виявлено вплив параметрів системи запалювання на розмір області запалювання, динаміку введення енергії в іскру та ефективність розряду. Обґрунтовано причину високої ефективності введення енергії в іскру. Проведено тестування варіантів розрядного кола, що генерують одиночний і подвійний дугові імпульси.