Non-steady State Processes in a Plasma Pilot for Ignition and Flame Control

Yury D. Korolev, Igor B. Matveev

***Abstract* — The paper deals with investigations of gas discharge in a recently developed plasma pilot for ignition and flame control. The characteristic features of this discharge burning mode are extremely low current (about 0.1 A) and low average power (less than 100 W). However, ignition and flame stabilization in a wide range of equivalence ratio for air-hydrocarbon mixtures is demonstrated. The physical mechanism of ignition is associated with the non-steady state properties of discharge. At the low current level, discharge burns in a kind of glow mode and because of the glow-to-spark transition the high-current nanosecond pulses are superimposed on the glow plasma background. Then spark discharge initiates combustion process, which is efficiently sustained in the glow plasma.**

***Index Terms*—Plasma torches, combustion stabilization, glow-to-spark transition, plasma pilot.**

I. Introduction

Subject of the present paper is investigations of high-pressure gas discharge in the air-hydrocarbon mixtures as applied to the problem of ignition and flame stabilization. Although the idea of using spark discharge or various types of the steady state discharges (for example a kind of an arc) for the above purposes has a long history, investigations of discharges and development of novel ignition and flame control systems is still a progressing field of activity [1]–[4].

When we speak about the burning process initiation by gas discharge plasma we imply that plasma is generated in the local area of burner where combustion should occur. Combustion comprises of three temporal steps: ignition, flame stabilization, and reaction completion. Role of discharge at the ignition stage is to heat the gas to high temperature and generate chemically active radicals (O, H, OH, etc.), which provide a chain branching in the fuel oxidation reactions. Typical ignition time in favorable conditions falls on a scale 10^{-5} – 10^{-4} s. After that, flame can be stabilized and it propagates into a burner space with typical velocity less than several meters per second.

One of ignition methods would be using the spark discharge. As applied to the internal-combustion engines, typical energy that is dissipated in the spark discharge is about 50 – 100 mJ. In spite of the low level of energy, gas temperature, which can be achieved in the core of spark channel, seems to be rather high (more that 10000 K). The less diameter of streamer channel at the initial stage of spark discharge and the higher the discharge current, the higher temperature and degree of gas ionization is achievable [5]. Modern tendency in improving performance of internal-combustion engines is to enhance the spark power due to shortening the discharge time with simultaneous increasing the discharge current [2]. For example, with the spark current of about 200 A and pulse duration of about 100 ns, instant power in the spark reaches 10^6 W and the local gas temperature essentially exceeds 10000 K [5].

Hence, it is evident that the role of the spark method in starting burning process is to provide initial conditions in the local area. The main steps of combustion itself (ignition, flame stabilization, and reaction completion) run at the background of discharge afterglow, i.e. at the temporal stage when the spark current ceases and only discharge residual phenomena (shock wave, residual discharge plasma, heated gas, etc.) are available. This definitely means that the spark discharge is utilized for ignition only but not for the flame stabilization and sustaining combustion process at the later stages.

As an example of extreme case of using high current pulsed discharge is ignition in a supersonic flow [6], [7]. The authors had developed a system with dissipated energy up to 46 J, pulse duration of about 5×10^{-3} s and instant power of about 10^4 W. Plasma parameters in this system at the final temporal stage resemble those of an arc discharge rather than for a spark of short duration. However, the essence of physical mechanism for ignition is still being a pulsed impact at the local area of the burner and continuation of combustion process on afterglow stage.

The other type of igniters, that could be considered as an alternative to the above described pulsed ignition (spark plug) are systems based on steady state discharges, like an arc in various types of steady state plasmatrons [3], [8]–[10]. In such devices, the steady state gas discharge is sustained between two electrodes and the external gas flow is provided across the discharge area. A plasma torch, which forms in this case, is directed to the combustion chamber where burning of a fuel-air mixture has to be provided. Discharge plasma in such plasmotrons can be generated both in the conditions close to

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equilibrium state [3] and in the non-equilibrium conditions [8]-[10]. Typical average discharge power could be around 10^3 W and less. An efficient time for ignition with a use of plasmatrons is from several seconds to several tens of seconds [3], [8]. It becomes evident that such devices play not only a role of igniters at the initial stage of the process but also a role of the burning sustainers, i.e. supporting combustion in a pilot mode.

Currently, the main discharge phenomena in the arc plasmatrons are interpreted in the framework of a steady state approach [9], [10]. It means that the arc discharge is considered as a steady state object, whose physical properties and ability to initiate the combustion process are determined by average discharge current and discharge burning voltage. On our opinion, this supposition does not allow adequate description of the discharge main properties, especially for moderate average discharge current (less than 1 A). That is why this work objective is to investigate the non-steady state processes in low current discharge and to elucidate their role in combustion initiation and flame stabilization.

II. Experiments with a Steady State Plasma Pilot in a Low Current Mode

The advanced and widely used devices for plasma plum generation based on classical arc plasmatron are described in our previous papers [3], [8]. An operational principle for the plasmatron that has been used in present experiments together with the photograph of a plasma torch is shown in Fig. 1.

Voltage of DC power supply is applied between the cathode *1* and anode *2*. Breakdown occurs over the shortest pass in the gap between coaxial parts of cathode and anode. Due to the turbulent gas flow, the discharge channel is shifted to position as shown in Fig. 1, i.e. at the later stages of discharge operation the discharge channel is localized at the end of cathode. Typical diameter of the plasmatron exit aperture is from 4 to 5 mm and typical gas flow across the aperture is up to 1 g/s.

Detailed investigations and successful implementations for such type of plasmatron have been carried out in a regime of high-current arc (i = 4 – 8 A), when discharge burning voltage V_d = 150 – 200 V, average power dissipated in plasma is about 1 kW, and average gas temperature is up to 3000 K [3]. At these conditions discharge burns in a form of arc with distinctively expressed arc cathode spot attached to the end of cathode.

One of drawbacks of the steady state arc plasmatron is comparatively low lifetime of the electrode system. Recently we tested another discharge burning mode in the arrangement shown in Fig. 1 [8]. A distinctive feature of this mode is a decreased average current (less than 0.5 A), but an increased discharge burning voltage (more than 1 kV). Average power for such type of plasmatron is essentially less than 1 kW. Thus this device seems to be more suitable for sustaining combustion in the pilot mode. However, in some conditions this plasmatron is capable to be used for ignition purposes also. We have defined that the discharge operation modes in

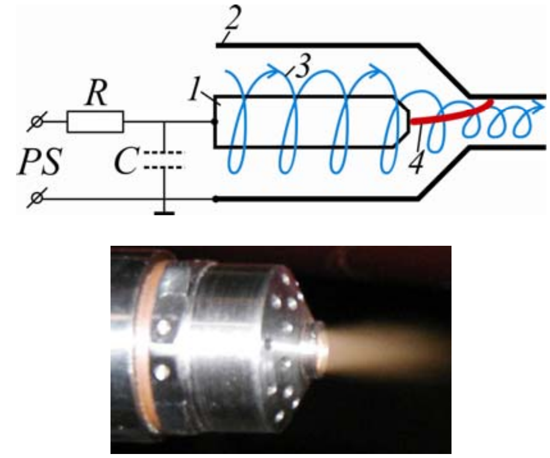

Fig. 1. Principle of operation for the steady state arc plasmatron and photograph of the plasma torch formed by the plasmatron. *1* – cathode, *2* – anode, *3* – swirling gas flow (air or air-fuel mixture), *4* – arc channel in a high current mode, *PS* – DC power supply, *R* – intrinsic resistance of the power supply, *C* – capacitance of the connecting cable.

these conditions have unusual features, which will be shortly described below.

Table I illustrates one of possible discharge modes for an atmospheric pressure air with different gas flows G(air) through the plasmatron. Discharge current here i_d and discharge burning voltage V_d, as it will be seen later, are the certain averaged values that are provided by the measurement devices of the power supply *PS*. The other notations in Table I are as follows: Q_d is the average power dissipated in discharge, W_d is the specific energy transferred for gas heating in supposition that power Q_d is totally expended for heating, ΔT_g is the estimated increase in of gas temperature in discharge.

We can see that the average discharge current is less than 0.1 A, and an increase in gas temperature at the device outlet does not exceed 200 K. Then, based on generally accepted steady state approaches, it would be reasonable to suppose that we deal with a kind of glow discharge, whose average power is definitely not high enough to initiate combustion even for stoichiometric fuel-air mixture.

Nevertheless, when we add some propane flow to the plasma feedstock, gas mixture ignition occurs and propane flame appears. The corresponding data are presented in Table II. Here the average discharge current was maintained at a level of i_d = 84 mA and air flow was G(air) = 0.45 g/s (see the second line in Table I). The discharge parameters are given for different propane G(propane) flows. Parameter α shows air to fuel ratio and α = 1 corresponds to stoichiometric blend.

In spite of extremely low averaged temperature (see Table I), the process of propane burning is initiated in plasmatron and observed in a wide range of α ratio. For extremely high propane percentage (so-called rich mixture), when G(propane) is more than 0.3 g/s, the discharge is extinguished and flame disappears as well.

The data on discharge operation regimes in mixture

TABLE I
DISCHARGE PARAMETERS IN AIR

G (air), g/s	i_d, mA	V_d, V	Q_d, W	W_d, J/g	ΔT_g, K
0.22	84	560	47	214	200
0.45	84	630	53	120	115
0.75	84	840	70	95	90
1.12	84	960	80	70	66

TABLE II
DISCHARGE PARAMETERS IN THE AIR-PROPANE MIXTURE. G (AIR)=0.45 G/S

G (propane), g/s	α	i_d, mA	V_d, V	Q_d, W
0.02	1.45	84	740	62
0.041	0.7	84	800	67
0.062	0.47	84	850	71
0.082	0.35	84	920	77
0.10	0.29	84	920	77

TABLE III
DISCHARGE PARAMETERS IN THE AIR-PROPANE MIXTURE. G (AIR)=0.75 G/S

G (propane), g/s	α	i_d, mA	V_d, V	Q_d, W
0.02	2.5	84	840	70
0.041	1.22	84	860	72
0.062	0.8	84	910	76
0.082	0.6	84	930	78
0.10	0.5	84	950	80
0.12	0.4	84	980	82

propane-air for air flow G(air) = 0.75 g/s are shown in Table III. We can also see that the burning process is sustained in a wide range of α value (from 2.5 to 0.4). When the propane flow G is higher than 0.12 g/s, the flame disappears. However, it should be stressed that the reason for the flame disappearing lays in the fact that the discharge is extinguished, since the voltage of power supplier is not high enough to sustain the discharge in our experimental conditions.

It seems that ignition becomes possible only due specific regime of the discharge burning. In the conditions under discussion we deal with the essentially non-steady state discharge.

The characteristic feature of a high-pressure glow discharge is so-called glow-to-spark transition phenomenon [5]. It means that discharge burns in a glow mode only during limited time frame, after which micro-explosion at the cathode surface occurs, the arc cathode spot is initiated and the spark channel is attached to the spot [11], [12]. If current from the power supply is not high enough to sustain the arc spot at the cathode surface, the spot is extinguished and discharge starts burning again in the glow mode. With total current of about 0.1 A, typical lifetime of the arc cathode spot is less than 1 μs [11]. So, a steady state arc discharge is not able to be sustained with low current value.

Transitions from glow to spark and back happen on a nanosecond time scale. During the process of spark discharge formation a high-current peak with pulse duration from 10 to

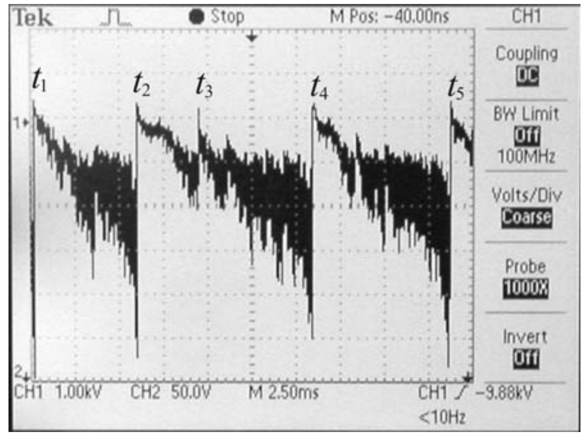

Fig. 2. Voltage at the gap of plasmatron illustrating the non-steady state behavior of the discharge at a low average current (i = 80 mA).

100 ns is superimposed on the glow discharge current. Energy to the spark discharge is supplied from the capacitance of connecting cable C (see Fig. 1). In our conditions C = 300 pF, so that the delivered energy is at a level of 1 mJ and this energy is introduced into the spark channel for a time less than 100 ns.

Thus, the proposed ignition mechanism can be summarized as follows. When discharge in the plasmatron burns in a low-current glow-type mode, dissipated specific power is not enough to initiate the air-fuel mixture burning process. However, in this extremely non-equilibrium mode, the chemically active radicals with low density are generated in plasma. As on the background of glow discharge, the short duration spark channel arises, this channel becomes able to give origin to the ignition process. The temporal development of the ignition goes efficiently because of the surrounding medium represents not "cold gas", but low-density non-equilibrium glow discharge plasma where the chemically active particles are already available. In such conditions, even small energy dissipation in the spark channel seems to be sufficient to start the burning process.

The data that confirm correctness of the proposed concept are presented in Fig. 2. This figure shows typical voltage behavior at the gap under the conditions of Table I.

We can see that discharge does not burn in a steady state mode. At the instants t_1, t_2, t_3, t_4, and t_5 the abrupt voltage drop at the gap occurs. This means that the spark channel with high conductivity forms in the gap, which results in fast discharging the capacitance C. After each spark, the capacitance C starts charging again via resistor R, i.e. voltage at the gap gradually increases. During this stage, the residual discharge plasma is still available in the gap, so that the dielectric strength of the gap is not completely recovered. As a result, the micro-sparks are generated in the gap at the stage of capacitance charging. These micro-sparks do not provide complete discharging of the capacitance C, which is reflected as "noise" on the voltage waveform.

The experimental arrangement shown in Fig. 1 is not adjusted for recording the current and voltage waveforms with nanosecond time resolution. In this connection, we have carried out the measurements with a use of special set up that allows obtaining information on the discharge behavior on the nanosecond time scale. Results of these measurements confirm correctness of the proposed approach for the discharge phenomena interpretation.

III. Experimental Investigations of the Discharge Behavior with Nanosecond Time Resolution

Schematic of experimental arrangement is shown in Fig. 3. As a matter of fact, this is the generator of nanosecond pulses base on coaxial lines [5]. The electric circuit operates as described below. Under the effect of power supplier *PS* the pulse forming coaxial line l_f is charged to a voltage V_B via charging resistor *R* (C_1 is an intrinsic capacitance of power supply which maintains constant value of potential V_A). When breakdown in high-pressure spark gap *G* occurs an incident wave of amplitude $V_B/2$ propagates over the transmitting line l_t to the matched load $Z = 50\ \Omega$, where V_B is the voltage value to which the pulse forming line is charged, i.e. the breakdown voltage for gap *G*. In most experiments, length of the forming line l_f was equal to 40 cm that is the cable capacitance $C = 40$ pF. In some experiments, we used the line length of 90 cm. The spark gap *G* with an interelectrode distance of 0.2 mm operates in nitrogen at a pressure $p = 2$ bar.

In generally used cases, the described system operates in so-called *RC* generator mode. When voltage at the gap *G* reaches the static breakdown value, the spark gap is switched and nanosecond pulse appears on load *Z*. Process of charging the forming line and the gap breakdown repeats on and on. The *RC* characteristic time is selected in such a manner that the pause duration between the successive pulses allows the gap to recover its dielectric strength. This means that each breakdown occurs in the conditions as voltage V_B corresponds to the static breakdown voltage.

Subject of our interest is in another discharge burning mode. This mode can be achieved by an intentional decrease in the resistor *R* value in order to get succeeding breakdown for the conditions when the gap does not completely recover its dielectric strength, i.e. when plasma from a preceding pulse is still available in the gap. As described in Sect. II, just such a mode is distinctive for the low-current plasmatron shown in Fig. 1. The detailed investigations of the voltage and current behavior with nanosecond time resolution allowed us to clarify the main discharge features in these non-steady state conditions. In the experiments, we recorded voltages V_A and V_B at the points *A* and *B* of electric circuit (see Fig. 3) and current in the transmitting line l_t.

Examples of the current and voltage waveforms for $R = 155$ kΩ and $C = 40$ pF are shown in Fig. 4. It could be seen that the very first breakdown occurs at voltage $V_B = 2.2$ kV, which corresponds to static breakdown voltage of gap *G* (instant $t = 4$ µs). This breakdown results in a peak of spark current $i = V_B/2Z \approx 20$ A.

Demonstration of typical shape for this current peak is

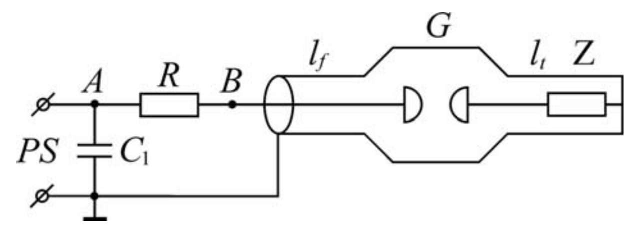

Fig. 3. Experimental arrangement for the discharge investigations with a nanosecond time resolution

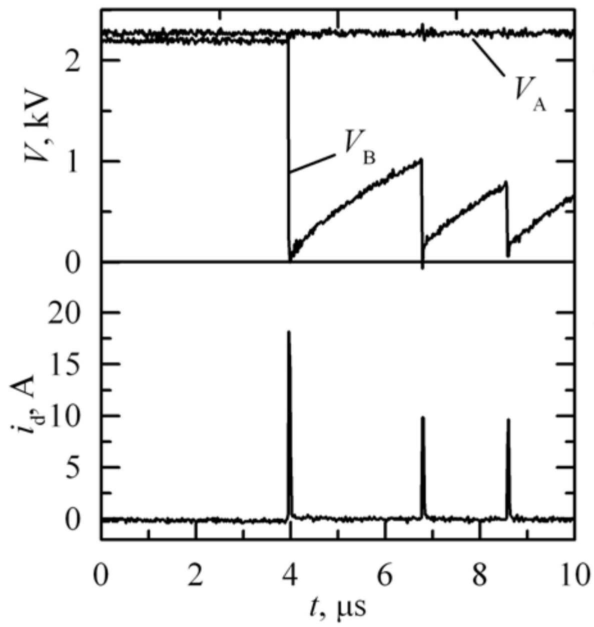

Fig. 4. Voltage and current waveforms for regime of high pulse repetition rate ($R = 155$ kΩ, $C = 40$ pF).

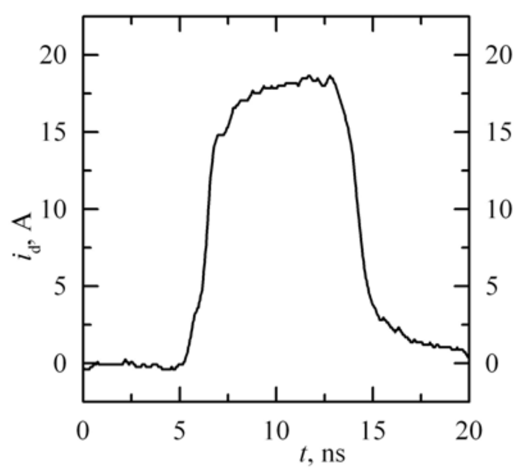

Fig. 5. Illustration of current waveform for a single current pulse. Charging voltage $V_A = 2$ kV, length of the charging cable $l_f = 90$ cm.

Figure 4 definitely shows that after the very first breakdown, the succeeding breakdowns occur at decreased voltages as far as the discharge gap is not de-ionized completely. Proceeding from the charging time of capacitance C we can roughly estimate that in the pause between the high-current nanosecond pulses the gap resistance is comparable with R and an averaged current via the gap is at a level of 10 mA. It is apparent that this current value could not be visible on the waveform in Fig. 4.

For detailed investigations of current and voltage behavior in pauses between pulses, we used a special electric circuit. This circuit cuts off the peaks of high current so that we have a possibility to send the signal from transmitting line to oscilloscope and to record the current in the transmitting line at a level of 0.1 A and less. The experimental data presented below had been obtained by this method.

Current and voltage waveforms containing information on discharge behavior after the high-current pulses for different V_A values are shown in Figs. 6 and 7.

When we increase voltage V_A or decrease the ballast resistance R we increase the discharge current from the power supplier *PS*, i.e. increase the current between pulses. This fact is definitely seen from comparing the data in Fig. 6 and in Fig. 7. The less discharge current in the time interval between the pulses the larger breakdown voltage in conditions under consideration and the larger the pause duration between spark discharges.

In terms of physical mechanism of current passage in the pause between pulses, the discharge at this temporal stage can be defined as a kind of glow. In general, this definition is correct and reflects the principal properties of discharge. Nevertheless it would be more strictly to precise that we deal with ignition of the spark channel in decayed plasma from preceding discharge. Actually, addressing to Fig. 7, we can see that the discharge current decreases while the voltage at the gap (because of charging the capacitance C from power supplier) increases. What this means is the gap resistance increases with time from extremely low value to approximately R_g = 100 kΩ just before the new spark ignition. In other words for the case under discussion the discharge in time interval between pulses burns in a mode of decayed plasma where the processes of recombination in plasma column are prevailed over the process of ionization.

The transition from glow type discharge to spark occurs due to development of instability in the near cathode region. As a result of the instability the cathode spot arises and the spark channel sprouts from the spot [11], [12]. For our case (Fig. 7) the energy for cathode spot and spark channel formation is delivered by the capacitance of the pulse forming line, C = 40 pF. Stored in this capacitance energy is rather low (5 μJ). However, this energy is sufficient to provide the glow-to-spark transition process and to form the spark channel with a current of about 5 A.

With the charging resistor R = 20 kΩ, it becomes possible to reach the discharge current $i \approx 0.1$ A in the time interval between pulses. This regime is typical for the plasmatron whose operational features were discusses in Sect. II. A great variety of the transient processes in the discharge in the pause between the pulsed has been observed in this mode. The next figures (from Fig. 8 to Fig. 10) show typical versions of the transient processes under these conditions.

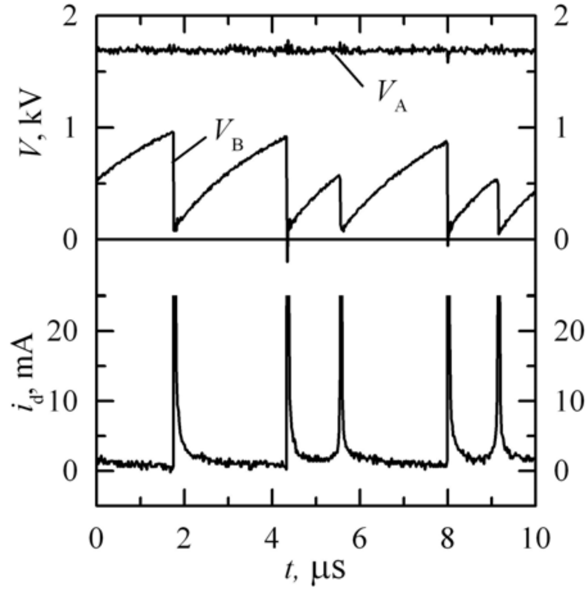

Fig. 6. Illustration of current behavior in a pause between pulses of spark discharge (formation of the spark channel in decayed plasma). R = 89 kΩ, V_A = 1.7 kV.

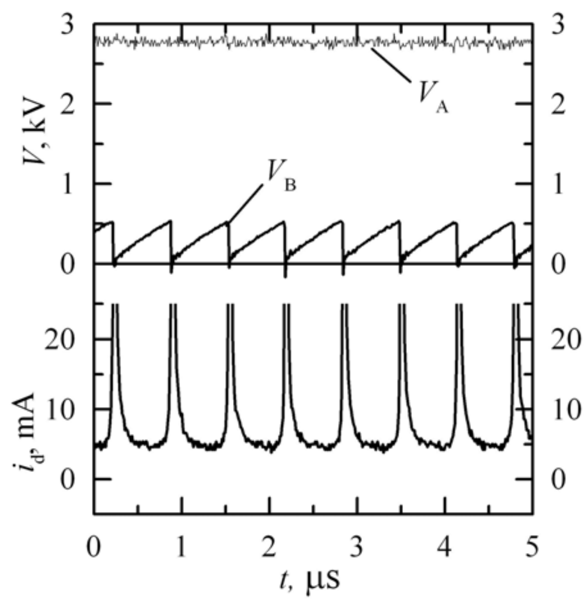

Fig. 7. Illustration of current behavior in a pause between pulses of spark discharge (formation of the spark channel in decayed plasma). R = 89 kΩ, V_A = 2.8 kV.

Figure 8 shows the case when during some time interval the discharge burns in a form of arc discharge with distinctively expressed cathode spot. This stage lasts from t = 0 to t = 200 ns. It could be seen that the discharge burning voltage is extremely low and the discharge current is determined by the charging resistor R. As we mentioned earlier, arc with low

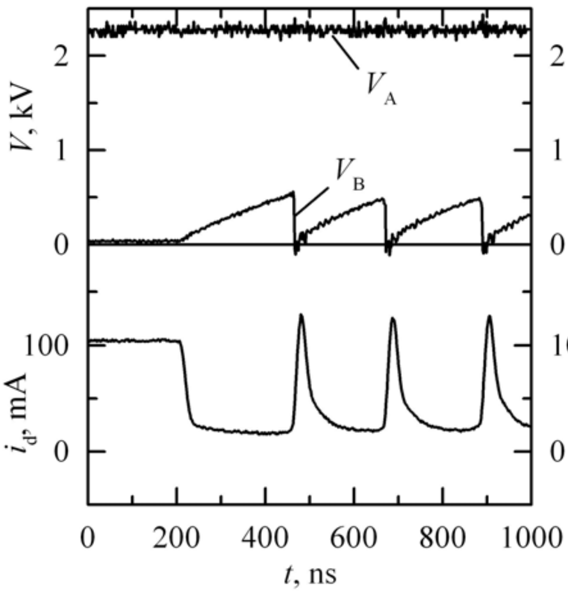

Fig. 8. Illustration of current behavior in a pause between pulses of spark discharge (temporal stages of the arc discharge with cathode spot and spark formation in the decayed plasma). R = 20 kΩ, V_A = 2.25 kV.

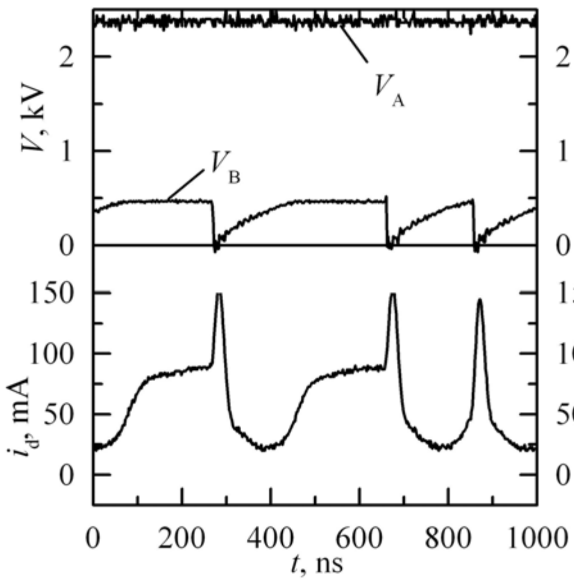

Fig. 10. Illustration of current behavior in a pause between pulses of spark discharge (temporal stages of the glow discharge, glow-to-spark transition, and formation of spark in the decayed plasma). R = 20 kΩ, V_A = 2.4 kV.

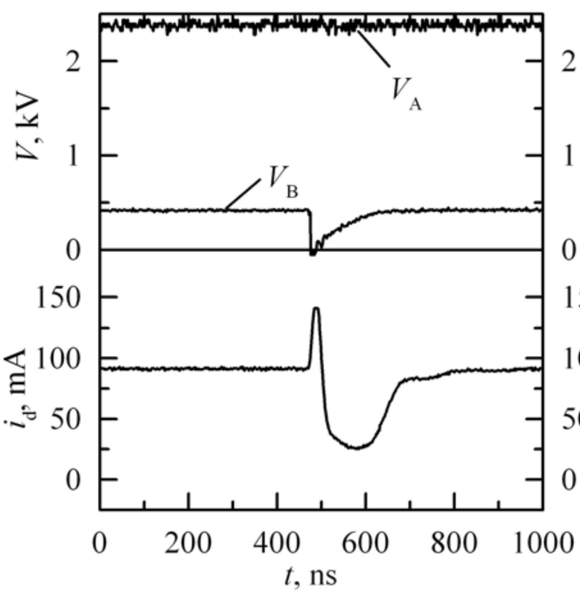

Fig.9. Illustration of current behavior in a pause between pulses of spark discharge (temporal stage of glow discharge and glow-to-spark transition). R = 20 kΩ, V_A = 2.4 kV.

current is not able to burn during a long time, as far as the lifetime of the cathode spot is limited [11], [12]. Then at instant t = 200 ns the cathode spot decays, the gap conductivity sharply decreases, and the discharge current falls abruptly to a value of 15 mA. The discharge starts operating in a kind of glow mode. After that, the voltage at the capacitance C is increasing and when it reaches a value of 500 V new spark channel is ignited. It could be also noted that in terms of our preceding consideration the further stages in Fig. 8 (after t = 200 ns) are characterized as a spark channel formation in decayed plasma.

Another version of the discharge behavior can be observed at the same conditions (Fig. 9). Here we see the glow-to-spark transition process in its “pure” form. Actually, from t = 0 to t = 470 ns a steady state glow discharge exists in the gap. As distinct to the regime of decayed plasma, this discharge with a current value of 90 mA is characterized by constant burning voltage $V_d \approx 400$ V. The glow-to-spark transition is accompanied by fast discharging of the capacitance C. When the capacitance is charged repeatedly, we observe that the glow discharge is established in the gap again (time interval from t = 700 ns to t = 1000 ns). It is evident that later on the glow discharge will transform into the spark again.

Figure 10 shows the situation when during the time interval of 1000 ns we can observe both the “pure” form of the glow-to-spark transition and formation of the spark channel in the decayed plasma. From t = 100 ns to t = 280 ns the glow discharge burns in the gap. At instant t = 280 ns the glow-to-spark transition occurs and when voltage at the capacitance increases repeatedly, the discharge continues to burn in the glow mode. After the time t = 670 ns we observe situation as the spark channel forms on background of the decayed plasma.

IV. Conclusion

High-pressure discharge in a new plasma pilot for ignition and flame control has been investigated. The main operational features of this discharge burning mode are low average current (about 0.1 A) and low average power (less than 100 W). The principal features of such type of discharge can be understood only on the basis of a concept that the non-steady state processes play a decisive role both in discharge operation and in combustion initiation.

High-pressure discharge with low current is not able to burn in the arc mode with a steady-state arc cathode spot. Lifetime of this spot at the cathode surface is limited, so discharge transforms into a glow regime of burning. However, the glow discharge is not stable due to the glow-to-spark transition phenomenon.

At the temporal stage, when discharge in the plasmatron burns as a kind of glow, dissipated specific power is not enough to initiate combustion of the air-fuel mixture. However, at this extremely non-equilibrium conditions the chemically active radical are still generated in plasma. When a spark channel of short duration arises on the background of glow type discharge, this channel is able to give origin to ignition. In such conditions the combustion process goes on efficiently, because of surrounding medium is not a "cold gas" but low-density gas discharge plasma. So, even a small portion of energy in the spark channel could be sufficient to light flammable blend and enhance combustion.

The above properties of discharge provide ignition at extremely low average power dissipated in the plasmatron as compared to the classical plasmatrons with the steady state arcs.

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