Glow-to-Spark Transitions in a Plasma System for Ignition and Combustion Control

Yury D. Korolev, Oleg B. Frants, Nikolay V. Landl, Vladimir G. Geyman, and Igor B. Matveev

***Abstract* — This paper deals with investigation of a new regime in a plasma ignition and flame control system as applied to air-hydrocarbon mixtures. The system is based on design of a classical high-current arc plasmatron. As compared with a thermal plasmatron mode, an averaged discharge current in the described device has been decreased to about 0.1 A. Although average power dissipated in the discharge does not exceed 200 W and averaged gas temperature at the plasmatron exit for typical regimes of the discharge operation in air is less than 500 K, the device demonstrates reliable ignition and flame stabilization in a wide range of equivalence ratios. Physical mechanism of ignition is associated with the non-steady state properties of discharge. At a low current level, the discharge burns in a kind of glow mode, and because of the glow-to-spark transitions, the high-current nanosecond pulses are superimposed on the glow plasma background. Then the spark discharge initiates combustion process, which is efficiently sustained in the glow plasma.**

***Index Terms*—Combustion stabilization, glow-to-spark transition, ignition, plasma torches.**

I. Introduction

ALTHOUGH the direction of activity associated with usage of a spark discharge or various types of the steady state discharges (for example a kind of an arc) for ignition and flame control has a long history [1]–[4], investigations of discharges and development of novel ignition systems is still a progressing area of research and development.

One of the well-known ignition methods is based on usage of a spark discharge. Modern tendency in improving performance of the spark ignition systems is to enhance spark power due to shortening the discharge time up to about 100 ns and even less [2], [5], [6] with simultaneous increasing of the discharge current. In such nanosecond regimes of operation, the expenditure of energy for ignition can be minimized.

It is evident that the role of the spark method in starting burning process is to generate chemically active radicals at initial period of time. The further steps of combustion itself 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 flame stabilization and sustaining combustion process at the later stages.

The other types of igniters that could be considered as an alternative to the spark ignition are systems based on steady state discharges, such as an arc in various types of steady state plasmatrons [3], [7], [8]. In such devices, the steady state gas discharge typically burns in external gas flow, and a high-temperature plasma torch is directed to the combustion chamber where burning of fuel-air mixture has to be provided. Typically, the steady state arc plasmatrons need more average electric power to operate as compared to the spark plugs. Nevertheless, the evident advantage of the plasmatron lies in the fact that it plays not only a role of igniter at the initial stage of the process, but also a role of the burning sustainer, i.e. supporting combustion in a continuous mode.

In this paper, we describe a specific regime of gas discharge, which combines both the advantages of nanosecond spark ignition and steady state burning sustaining at the later temporal stages. In this discharge regime, due to the glow-to-spark transitions, the high current spark pulses with duration of about 100 ns are superimposed on the non-equilibrium plasma of a glow-type discharge. Both ignition and flame control are demonstrated for the air-propane mixtures in a wide range of equivalence ratio with extremely low average power dissipated in the discharge. The principal physical properties of the discharge are also discussed.

II. Experimental Arrangement and Conditions of Discharge Burning in Plasmatron

The experiments on ignition and flame control have been carried out as applied to air-propane mixtures with a plasmatron-type igniter [3]. Experimental arrangement and method of measurements are shown schematically in Fig. 1.

Output voltage of a dc power supply V_0 is applied between cathode and anode via the ballast resistor R_b and coaxial cable (inner electrode is the cathode and outer electrode is the anode). If the voltage of the power supply is high enough, then the very first breakdown occurs over the shortest pass in the gap between coaxial parts of cathode and anode. Under the effect of gas flow, the discharge plasma can be shifted to the plasmatron exit aperture. In these conditions, at later stages

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Y. D. Korolev, O. B. Frants, N. V. Landl, and V. G. Geyman are with the Institute of High Current Electronics, Russian Academy of Sciences, Tomsk 634055, Russia (e-mail: korolev@lnp.hcei.tsc.ru).

I. B. Matveev is with Applied Plasma Technologies, Falls Church, VA 22046 USA (e-mail: i.matveev@att.net).

(after the very first breakdown) the plasma column becomes attached to the end of the cathode. Typical gas flow across the aperture is from 0.1 to 1.4 g/s and typical diameter of the plasmatron exit aperture is from 4 to 5 mm.

In the experiments, we recorded the current through the discharge gap (R_S is the current shunt) and the discharge burning voltage V_G. The discharge images at different temporal stages had been taken via the plasmatron exit aperture by means of CCD camera.

The temporal development of the discharge phenomena is determined by the gas flow and a current, which is delivered from power supply. Changing of the output voltage V_0 and the ballast resistor R_b allows us to change the current. Such an electric circuit (with the ballast resistor) is not optimal from viewpoint of technical applications, since a considerable fraction of total power is dissipated in the resistor R_b. However, this circuit offers a possibility to operate with a prescribed current value which is convenient in physical investigations and in interpretation of the obtained data. Let consider some limited cases of the discharge regimes after the very first breakdown.

The well-known regime of arc plasmatron corresponds to a current from power supply larger than $i \approx 5$ A. After the very first breakdown, a spark channel arises at the coaxial part of the electrodes. As far as this channel is sustained by a rather large current, the spark discharge transforms into the steady state arc with distictively expressed cathode spot and with low discharge burning voltage. Due to the turbulent gas flow, the discharge channel is shifted to a position as shown in Fig. 1. This means that at the later stages of the discharge operation the arc channel is attached to the end of the cathode. Typical discharge burning voltage in such conditions $V_G = 150 - 200$ V, average power dissipated in plasma is about 1 kW, and average gas temperature is up to 3000 K [7].

The other limited regime of operation is associated with the conditions as the current i from power supply is extremely low [9]. Situation in the discharge gap and in the electric circuit will change radically which is illustrated schematically in Fig. 2.

The discharge phenomena in the plasmatron gap and in the electric circuit are developing by the following way. At initial instant of time $t = 0$ (when the power supply is switched on) the capacitance C of the coaxial cable starts charging through the ballast resistor R_b so that voltage at the gap V_G gradually increases during the time interval from $t = 0$ to $t = t_1$. When voltage V_G reaches the static breakdown value $V_G = V_S$ (in our conditions $V_S < 10$ kV) the very first breakdown in the plasmatron gap occurs, the spark discharge arises, and total capacitance C discharges through the gap in an oscillatory mode. Thus, due to the spark, the capacitance C is discharged completely and the oscillatory spark current of a short duration with a value of several ten amperes appears in the plasmatron. (As far as the current duration is much less than the charging time interval $(0 - t_1)$, this current is schematically shown in Fig. 2 as a spike at instant t_1).

The gap behavior at the next charging cycle of the

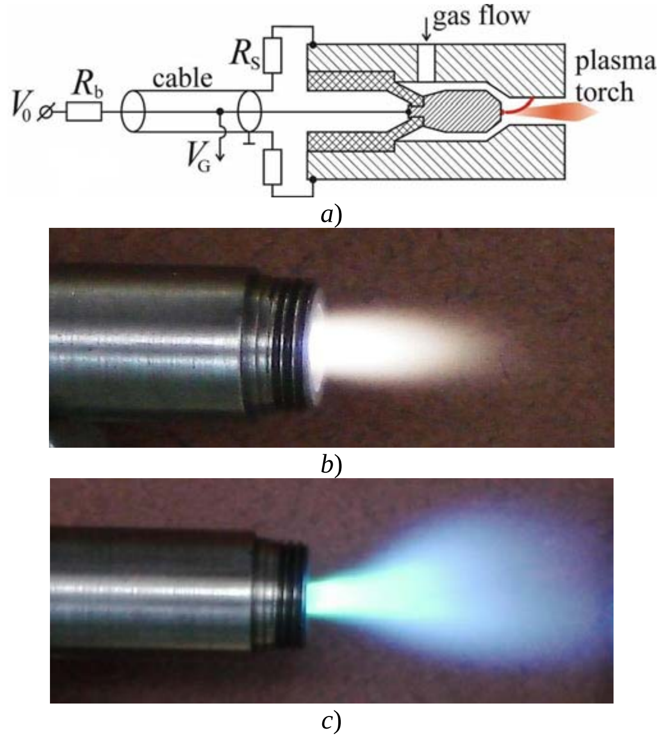


Fig. 1. Experimental arrangement for ignition and flame control in plasmatron (*a*) and typical photographs of the flame in air (*b*) and air-propane mixtures (*c*). Voltage V_0 of negative polarity is applied to the cathode via the ballast resistor R_b (R_S is the low-resistive current shunt).

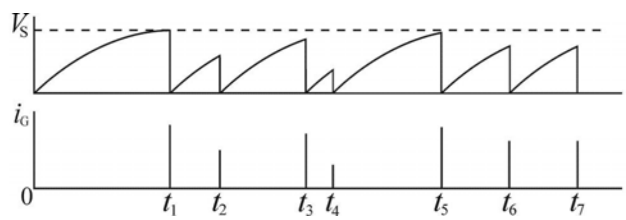


Fig. 2. Voltage at the plasmatron gap V_G and current through the gap i_G for the electric circuit shown in Fig. 1 in the conditions when the gap does not completely recover its dielectric strength in a pause between the high-current pulses.

capacitance C depends on how fast the deionization processes after the instant t_1 proceed and how fast the gap recovers its dielectric strength. One of the cases corresponds to conditions when the recovery time is essentially less than the characteristic charging time of the capacitance R_bC. In this situation, new breakdown occurs again at a voltage V_S close to the static breakdown voltage. The process is repeated and we have in the electric circuit a succession of high-current pulses, whose pulse repetition rate f is determined by the charging time ($f \approx 3/R_bC$).

Actually, the above-described conditions are rather evident and well known as applied to high-pressure switching devices for different applications [10]. An important problem for switching devices is to enhance a pulse repetition rate. From our experience, we can conclude that the pulse repetition rate up to 1 kHz is quite achievable. In principle, such regime of operation can be usable in the gaps for ignition and combustion sustaining. The essence of this regime is that the burning process is initiated by means of subsequence of high-current short-time spark discharges. However, the combustion is not sustained in the pause between the nanosecond pulses in this operation mode.

As applied to the subject of this paper, another regime of operation seems to be much more attractive [9], [11] (see Fig. 2). The main idea of such a regime is that the gap G should not completely recover its dielectric strength in the pause between the high-current pulses. Then the very first breakdown occurs at instant t_1 at the static breakdown voltage. After that, the voltage at the gap becomes zeroes and deionization of the gap is going on. Simultaneously the capacitance C is charging and the voltage at the gap V_G is increasing. As far as in the time interval ($t_2 - t_1$) the gap is not yet de-ionized completely, new breakdown at instant t_2 occurs at a lower voltage in comparison with the very first breakdown. The process is repeated and the values of breakdown voltages at the instants t_3, t_4, t_5, and so on are changed randomly.

The most attractive feature of the described regime lies in the fact that the combustion process is ignited due to the spark discharges and is additionally sustained in the pauses between pulses due to a low-current glow-type discharge. This is the principal idea that we propose for the plasmatron powering.

The range of experimental conditions for ignition and flame control in air-propane mixtures had been described in [9], [11]. The typical average discharge current was about 0.1 A and the average discharge burning voltage was from 0.5 to 1 kV. This means that an average power dissipated in the plasmatron gap amounted from 50 to 100 W. With a rather high gas flow (larger than 0.5 g/s), an increase in the gas temperature at the plasmatron exit due to dissipation of the discharge power does not exceed 200 K. Proceeding from general considerations, such average temperature is too low to initiate the burning process. However, in the air-propane mixtures with the air-to-fuel ratio α from 1.5 to 0.3 (α = 1 corresponds to stoichiometric blend) the flame is ignited and stably sustained. This becomes possible due to specific regime of the discharge operation when the high-current nanosecond spark pulses are superimposed on a background of glow-like discharge.

The experimental data on more detailed investigations of non-steady discharge behavior are presented below.

III. Non-Steady State Discharge Behavior in Air and Air-Propane Mixtures

Figure 3 illustrates the waveforms of voltage at the gap and current through the gap for the very first breakdown in plasmatron. As noted above, the very first breakdown occurs between the coaxial parts of electrodes (the instant of breakdown is marked in Fig. 3*a* as t_1). It is seen that the breakdown is accompanied by the sharp decrease in the gap voltage up to zeroes value. The capacitance of connecting cable C = 300 pF is discharge through the plasmatron gap in oscillatory current mode with a period of oscillation less than 100 ns (see Fig. 3*b*).

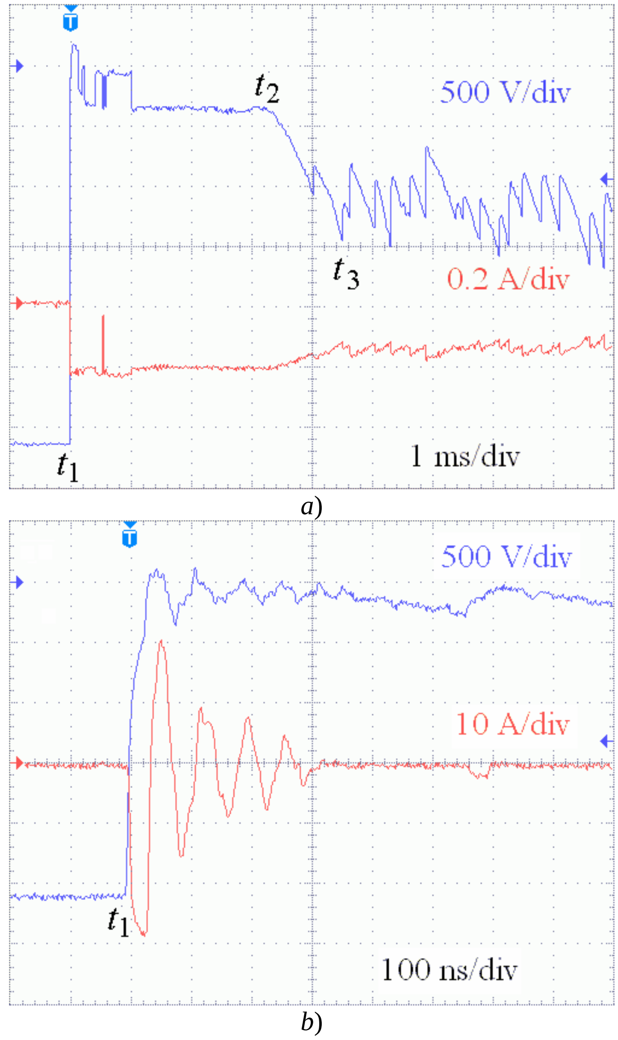


Fig. 3. Voltage and current waveforms for the very first breakdown in the plasmatron. Air flow through the plasmatron G(air) = 0.1 g/s (gas velocity v = 4 m/s); capacitance of the cable C = 300 pF; ballast resistor R_b = 13.6 kΩ. *a*) V_0 = 3.2 kV; *b*) V_0 = 2.7 kV.

When the capacitance C becomes completely discharged, the current delivered by the power supply $i = V_0/R_b \approx 0.24$ A. On the one hand, a part of this current flows through the residual plasma of the spark discharge. On the other hand, in the course of the gap deionization, some fraction of the current is consumed for charging the capacitance C. As a result the voltage V_G increases up to V_G = 350 V, and a kind of glow discharge with a current i = 0.2 A appears in plasmatron.

From Fig. 3*a* we can see that the glow discharge is not sustained in a stable regime. At some instants of time, due to the glow-to-spark transitions, the sharp voltage collapses are observed. However, with a low current V_0/R_b from power supply, the discharge is not able to burn in an arc regime. Correspondingly, the discharge transforms into glow mode again (the voltage V_G abruptly increases up to 350 V). The glow-to-spark transition phenomenon will be discussed in detail later. Here, based on Fig. 3*a*, we want to pay attention to role of gas flow in the plasmatron.

Due to the gas flow, the discharge plasma is shifted to the end of the cathode. This process goes at the temporal stage ($t_2 - t_1$). Note, that with enhancing the gas velocity, the time interval ($t_2 - t_1$) is shortened. After the instant t_2, the discharge current starts flowing between the end of cathode and coaxial part of anode in the plasmatron exit cavity, as shown schematically in Fig. 1*a*. Characteristic feature of the gap geometry lies in the fact that the discharge channel is attached to a central part of the cathode end. However, the anode attachment of the channel is not strictly localized on the anode surface. Under the effect of the gas flow, an anode spot (a point of current attachment at the anode) is able to be displaced over the anode surface in the direction of plasmatron exit. Because of the displacement of the anode spot, the length of the discharge plasma channel increases with time, so that the average voltage drop at the plasma column increases (time interval from t_2 to t_3). In some sense the principal features of the discharge behavior at this stage resembles that for so-called "gliding arc" [8], [12], [13].

At the stage $t > t_3$ we can see a non-steady discharge behavior, which (at the time scale of 1 ms/div) looks like a kind of "noise" at the voltage waveform (Fig. 3a). The nature of this "noise" is discussed below.

Current and voltage waveforms jointly with the discharge images obtained by CCD camera are shown in Fig. 4. The left side photograph is the plasmatron exit picture taken along the plasmatron axis. Area of a dark circle here is the anode exit aperture. The cathode end is located inside the aperture. This picture is presented for convenience, as we want to understand the plasma column location and attachment of the current at the cathode and at the anode surfaces.

Let us consider the processes in plasmatron, starting from some point of time, which is marked in Fig. 4 as t_1. Remind that at this stage the current plasma column is attached to the cathode end. Low-density plasma fills the plasmatron anode cavity and forms the plasma torch (see Fig. 1*a*). Current to the anode is partly carried due to this plasma torch. However, the current attachment at the anode is not uniform. There exists an anode spot at the anode surface, i.e. a considerable fraction of total discharge current to the anode closes to the spot. As it will be seen later, just before the instant t_1, the regime of discharge burning corresponds to a glow-type discharge.

At the instant t_1, the glow-to-spark transition occurs with formation of a high-conductivity channel. CCD frame of this channel taken with exposition time of 1 μs is shown in Fig. 4. We can see the distinctively expressed cathode spot (*1*) in the center of the frame (at the central part of the cathode end) and a bright filamentary channel (*2*) attached to the anode. It should be stressed that here we are talking about so-called completed breakdown of the gap (or completed transition from glow to spark). In other words, because of breakdown, the high-conductivity channel results in the complete voltage collapse at the gap, and the breakdown itself is accompanied by the oscillatory current whose waveform is similar to that shown in Fig. 3*b*.

After t_1 voltage at the gap increases i.e. the cable capacitance C is charging. At this stage, a glow-type discharge with anode spot burns in the gap. Due to gas flow, the anode spot and the glow discharge plasma column is shifted in

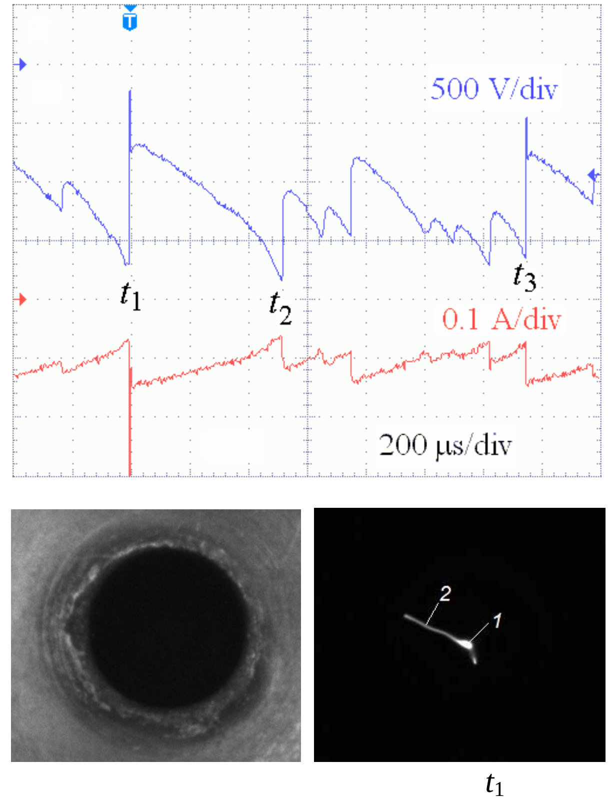


Fig. 4. Voltage and current waveforms for discharge in plasmatron at the stage when discharge is attached to the end of the cathode and CCD photograph of the discharge image. R_b = 13.6 kΩ, C = 300 pF, V_0 = 3.0 kV, gas flow G(air) = 0.5 g/s (v = 20 m/s).

(*1*) – the cathode spot in the case of completed glow-to-spark transition; (*2*) – the filamentary spark channel.

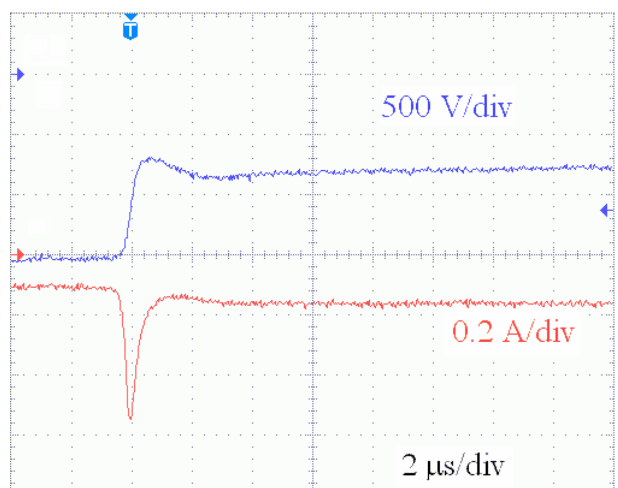


Fig. 5. Typical voltage and current waveforms for non-completed transition from glow to spark in plasmatron. R_b = 13.6 kΩ, C = 300 pF, V_0 = 3.0 kV, gas flow G(air) = 0.1 g/s (v = 4 m/s).

direction of the plasmatron exit. Since the anode spot intercepts a noticeable fraction of current we can conclude that the length of discharge column increases, which leads to increasing the discharge burning voltage.

At instant t_2 new transition from glow to spark occurs. In this particular case, we deal with the so-called non-completed transition or non-completed breakdown of the gap. Such type of transition results in the situation when the gap conductivity sharply increases as compared to glow regime but the high-conductivity channel (like shown in Fig. 4) has not formed. Note that the current spike for the non-completed breakdown has an aperiodic form (see Fig. 5). Completed and non-completed transitions appear randomly. For example, at instant of time t_3 we have completed breakdown again. With low gas velocity, the non-completed breakdowns appear more frequently than for enhanced velocity.

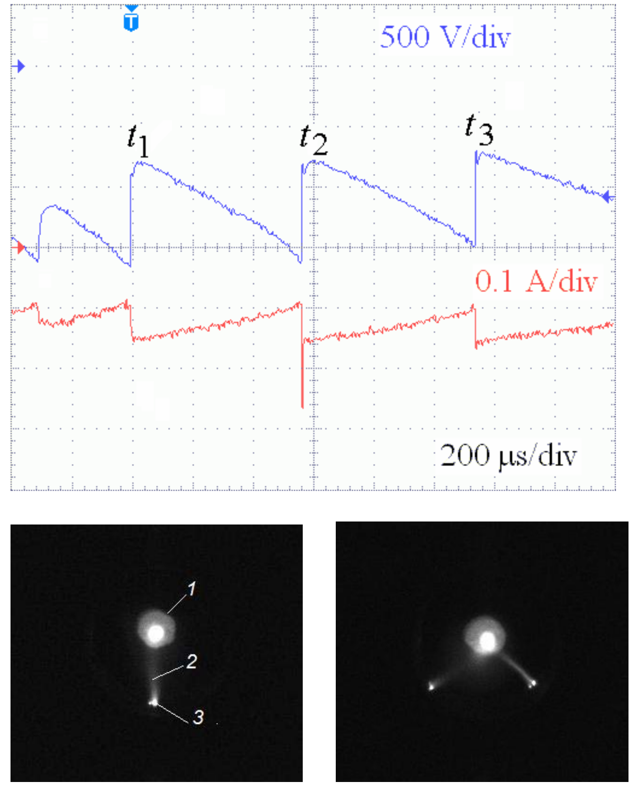
It is known [14] – [16] that glow-to-spark transition is initiated due to development of instability in the near-cathode region. As a result of the instability, the cathode spot arises and a diffuse channel sprouts from the spot. Conductivity of the diffuse channel is higher than that for glow discharge column but lower than the conductivity of the filamentary spark channel. At the next temporal stage, the diffuse channel transforms into a high-conductivity filamentary spark if the energy stored in the capacitor is sufficient for such transition. Hence, it can be concluded that the so-called non-completed breakdown actually represents the case when the diffused channel has already appeared but transformation of the diffused channel into the high-conductivity stage has not occurred.

The above said is illustrated by the waveforms and the photographs of the discharge image in Fig. 6. We can see here the non-completed transitions at the instants t_1, t_2, and t_3. The left photograph corresponds to exposition time Δt between t_1 and t_2. It reflects the discharge luminosity after the non-completed glow-to-spark transition occurred at instant t_1.

Exposition time for the right photograph is selected in such a manner to demonstrate the end of the stage ($t_3 - t_2$) and the beginning of stage $t > t_3$. Correspondingly, we see at the photograph two diffused channels. One of them appeared due to glow-to-spark transition at instant t_2 and another appeared due to the same type of transition at instant t_3.

The CCD frames show that the discharge image for this regime is essentially different from that for the spark discharge. The intensity of image luminosity is much lower than that for the photograph in Fig. 4. At the cathode surface we discern the low-luminosity area of about 1.1 mm in diameter (*1*). This area can be treated as a place of attachment for the glow-type discharge. A bright corn inside this area is a luminosity of the spark cathode spot that appeared in initial stage of the glow-to spark transition. Beside that, at a background of the diffuse channel (*2*), we can see the anode spot (*3*).

Proceeding from the total discharge current and the discharge area at the cathode surface, we are able to estimate an average current density and compare it with a current density of normal glow discharge. To do this we should know the so-called effective gas pressure in the gap or, which is the same, the pressure reduced to gas temperature. The point is that the gas in the discharge area is heated and the gas particle density is lower than in normal conditions. The effective pressure is determined from well-known relation:



Δt = 700 – 800 μs Δt = 1500 – 1600μs

Fig. 6. Voltage and current waveforms for discharge in plasmatron and CCD photograph of the discharge image for the case of non-completed glow-to-spark transition. R_b = 13.6 kΩ, C = 300 pF, V_0 = 3.0 kV, gas flow G(air) = 0.1 g/s (v = 4 m/s).
(*1*) – area of the current attachment at the cathode for glow-type discharge; (*2*) – diffused channel of non-completed breakdown; (*3*) – anode spot at non-completed breakdown

$$p_{\mathrm{eff}} = p_0 \frac{T_0}{T} \qquad (1)$$

where p_0 = 760 Torr, T_0 = 300 K, and T is the gas temperature in the discharge area.

In the conditions of Fig. 6, the gas velocity is lowest, so that the gas temperature at the plasmatron exit, measured by thermocouple, achieves T = 1000 K. In the discharge area the gas temperature has to be higher. An upper estimate of the temperature can be made from the relation:

$$T = T_0 + \frac{Q}{C_p G}, \qquad (2)$$

where Q is average power dissipated in the discharge (the product of the average discharge current by the average discharge burning voltage), C_p is the specific heat of air, G is the gas flow velocity.

Then, with a use of (2) for the conditions of Fig. 6, we readily obtain T = 1900 K.

Let us take for definiteness T = 1200 K that corresponds to p_{eff} = 190 Torr. The current density at the cathode surface at the time interval Δt from 700 to 800 μs is estimated as j = 8.3 A/cm^2. The current density reduced to pressure will be j/p_{eff}^2 = 230 A/cm^2 ×Torr^2. Such a value exactly coincides with a normal current density of the glow discharge in nitrogen and air [14].

The cathode voltage drop for normal glow discharge in air is about 250 V. Then, from the voltage waveform in Fig. 6 we can estimate that, at the time stage from 700 to 800 μs, the discharge burning voltage $V_G \approx 1250$ V. This means that the voltage drop at the plasma column $V \approx 1000$ V, and the reduced electric field at the plasma column $V/p_{eff}d \approx 13$ V/cm×Torr (where the length of the plasma column is taken as d = 0.4 cm). Such a value is quite reasonable for glow discharge in air. Hence, we can conclude one more that at the stage between non-completed breakdowns we deal with a glow-type discharge.

Figure 7 demonstrates an example of the waveforms and discharge images for air-propane mixtures at the stage when discharge is attached to the cathode end. As a whole, the discharge behavior in the mixture has the same features as for air.

For example, the gas velocity in the conditions of Fig. 7 is rather large. Then, the characteristic time of increasing the length of the plasma column at the glow stage becomes smaller as compared to data in Fig. 6. The discharge also burns in non-steady regime and the non-completed and completed glow-to-spark transitions are observed in the gap.

When gleaning the waveforms for Fig. 7, we intentionally selected the time intervals when most of transitions from glow to spark are non-completed. Beside that, we used a large exposition time Δt for CCD camera in order that the exposition time overlaps a large number of the glow-to-spark transitions. The corresponding photographs of the discharge image clearly illustrate that each transition is accompanied by appearing the new diffused channel. The larger the number of transitions during the exposition time the more channels at the photograph we can see.

IV. Conclusion

The data of this paper are the results of investigation of a new regime in a plasma ignition and flame control system as applied to air-hydrocarbon mixtures. The system is based on classical high-current arc plasmatron. However, an average discharged current has been decreased essentially which results in specific regimes of the discharge burning.

The discharge burning regime can be referred to as a kind of glow discharge with random transitions from glow to spark. Two types of transitions have been observed: completed and non-completed transitions. For the case of completed transition a high-conductivity spark channel appears in the gap, and for non-completed transitions the diffuse channels arise.

The above discharge demonstrates efficient ignition and flame control at extremely low average power, dissipated in the discharge.

The 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 burning process in air-fuel mixture. However, in this extremely non-equilibrium mode, the chemically active

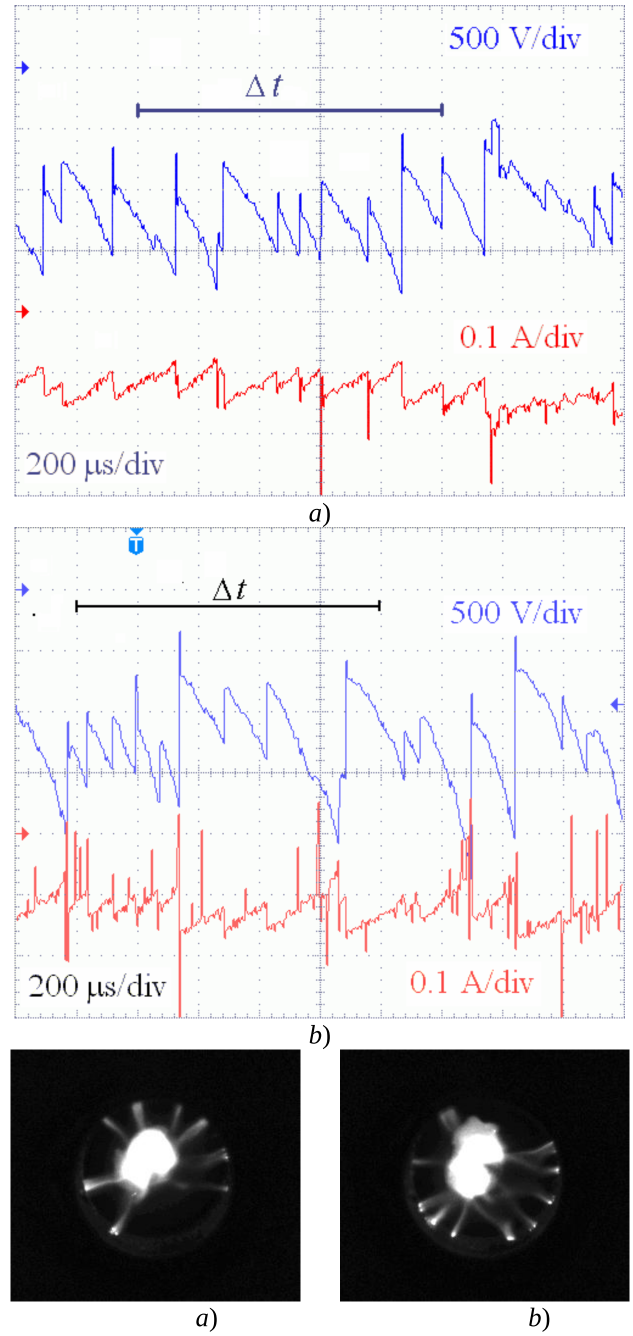


Fig. 7. Voltage and current waveforms for discharge in air-propane mixture and CCD photograph of the discharge image with a large time exposition (exposition time Δt is marked at the waveforms). R_b = 13.6 kΩ, C = 300 pF, V_0 = 3.0 kV. G(air) = 1 g/s (v = 20 m/s, G(propane) ≈ 0.01 g/s.

radicals with low density are generated in plasma. As on the background of glow discharge, the short duration spark or diffused 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.

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Yury D. Korolev was born in the U.S.S.R. on February 18, 1945. He received the degree and the Ph.D. from Tomsk State University, Tomsk, Russia, in 1967 and 1973, respectively, and the D.Sc. degree in physics from the Institute of High Current Electronics, Russian Academy of Science, Tomsk, in 1985.

Since 1977, he has been with the Institute of High Current Electronics, Russian Academy of Sciences, where he is currently the Head of the Low-Temperature Plasma Laboratory. He is also a Professor with Tomsk State University. His current research interests include fundamentals of a gas discharge and applications of high- and low-pressure discharges.

O. B. Frantz was born in the USSR on February 17, 1964. He received the M.S. degree in physics from the Physics-Technical Department, Tomsk Polytechnical Institute, Tomsk, Russia, in 1990. After graduation, he joined the Institute of High Current Electronics, Russian Academy of Sciences, Tomsk, Russia. His current research interests include gas discharge and the pseudospark switches.

N. V. Landl was born in the USSR on October 22, 1978. He received the M.S. degree in physics from the Department of Physics, Tomsk State University, Tomsk, Russia, in 2002. After graduation, he joined the Institute of High Current Electronics, Russian Academy of Sciences, Tomsk, Russia. His current research interests include gas discharge and the pseudospark switches.

V. G. Geyman was born in the USSR on September 6, 1960. He received the M.S. degree in physics from the Department of Physics, Tomsk State University, Tomsk, Russia, in 1983. After graduation, he joined the Institute of High Current Electronics of Russian Academy of Sciences, Tomsk. His current research interests include the physics of pulsed gas discharge and the discharge applications.

Igor B. Matveev was born in Russia on February 11, 1954. He received the Master of Science degree in mechanical engineering from Nikolaev Shipbuilding Institute, Nikolaev, Ukraine, in 1977 and the Ph.D. degree in 1984. His Ph.D. theses was entitled "Development and Implementation of The Plasma Ignition Systems for Naval Gas Turbines." From 1977 to 1990 was a Researcher, Teacher and Associate Professor with Nikolaev Shipbuilding Institute. In 1990, established a privately owned company Plasmatechnika (Ukraine) for development and mass production of plasma systems. Since 2003 he has been with Applied Plasma Technologies, Falls Church, VA, where he is the President and CEO.