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A Multi-Mode Plasma Pilot

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This paper describes a new type of plasma ignition and flame control system. The main features of the plasmatron operation modes are extremely low average current (about 0.1 A) and low average power (less than 100 W). However, it 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 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. The plasma pilot based on this principle is described.

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 long history, investigations of discharges and development of novel ignition systems is still a progressing area of research and development[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 three temporal steps, namely 1) ignition, 2) flame stabilization, and 3) reaction completion. The role of discharge at the ignition stage is to heat the gas to high temperature and generate chemically active radicals, which provide chain branching in the fuel oxidation reactions. Typical ignition time in favorable conditions falls on a scale of 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 the widely used ignition methods is the spark discharge. As applied to the internal-combustion engines, the typical energy that is dissipated in the spark discharge is about 50 – 100 mJ. In spite of low level of energy, gas temperature, which can be achieved in the core of spark channel, seems to be rather high (more that 10,000 K). The smaller the 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 the internal-combustion engines is to enhance spark power due to shortening the discharge time with simultaneous increasing of the discharge current[2].

Hence, it is evident that the role of a spark method in starting burning process is to provide initial conditions in a local area. The main steps of combustion itself (ignition, flame stabilization, and reaction completion) are 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 type of igniters, that could be considered as an alternative to the above described pulsed ignition is systems based on steady state discharges, such as an arc in various types of steady state plasmatrons[3,6,7]. In such devices, the steady state gas discharge is sustained between two electrodes and an external gas flow is provided across the discharge area. A plasma torch, which forms in this case, is directed to the combustion chamber where

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burning of a fuel-air mixture has to be provided. Typical average discharge power could be around 10^3 W or less. An efficient ignition time by plasmatrons is from several seconds to several tens of seconds. It becomes evident that such devices play not only a role of igniters at the initial stage of the process, but also role of the burning sustainer, *i.e.* supporting combustion in a pilot mode.

Until present, the main discharge phenomena in the arc plasmatrons was interpreted in the framework of a steady state approach[6,7,8]. It means that discharge is considered as a steady state object, whose physical properties and ability to initiate the combustion process are determined by the average discharge current and discharge burning voltage. In our recent works[9,10] we have demonstrated that the most efficient regimes of a plasmatron operation correspond to the conditions when the nanosecond spark discharge pulses are superimposed on a non-equilibrium plasma of a glow-type discharge. This principle has been used in development of a novel type of igniter and plasma pilot. The main features of discharge operation in such a plasma pilot are described in this paper.

II. Main Idea of a Non-Steady Plasmatron Operation

In general case any type of plasma igniter represents a gas-discharge gap with a presence of gas flow across the electrode system, which is connected to high-voltage power supplier. This situation is shown schematically in Fig. 1.

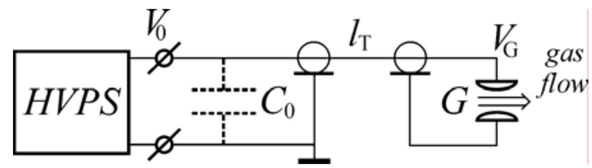


Fig. 1. Schematic of an electric circuit for powering the ignition gap.
G – ignition gap located in the combustion chamber; *HVPS* – high-voltage power supply connected to the gap by means of the cable l_T, C_0 – additional capacitor bank that can be inserted into the circuit.

We can use, for example, *DC* power supplier (*HVPS*) with a voltage high enough to initiate the static breakdown in the gap *G*. If current from *HVPS* is rather large (about 4 A and more), a kind of arc discharge in a gas flow appears in the gap. Actually, in this regime we will have well-known ignition and combustion sustaining system based on steady state arc plasmatron[3]. Typical discharge burning voltage in such a plasmatrons is less than 300 V, and typical average power is about 1 kW or larger. Because of such units are widely used, our interest in this paper is in ignition by means of the nanosecond current pulses.

It can readily be seen that the same electric circuit is applicable for formation of the nanosecond current pulses directly in the gap *G*. To do this we should decrease current from the power supplier to level of less than 1 A. Situation in the discharge gap and in the electric circuit will change radically which is illustrated schematically in Fig. 2.

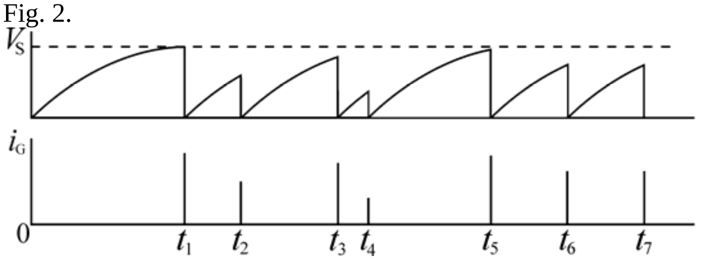


Fig. 2. Voltage at the ignition gap V_G and current through the gap i_G for the electric circuit shown in Fig. 1.
(The gap *G* does not completely recover its dielectric strength in a pause between high-current pulses).

It is appropriate to consider the main discharge behavior features by the following example. Let a total capacitance of the cable l_T and of the capacitor C_0 be equal to C = 3.3 nF. It could be achieved, for instance, with the cable l_T of a 3 m length and C_0 = 3 nF. If charging voltage V_0 = 10 kV, then a maximum energy stored in the capacitance C will be $W = CV_0^2/2$ = 165 mJ. Let charging the capacitance C is provided through the charging resistor R_b = 300 kΩ, *i.e.* maximum charging current from the power supply i = 33 mA and characteristic charging time $R_bC \approx 1$ ms.

The discharge phenomena in the gap and in the electric circuit are developing by the following way. At the initial instant of time $t = 0$, the charging process starts and voltage at the capacitance C (and at the gap G correspondingly) gradually increases during the time interval from $t = 0$ to $t = t_1$. When voltage V_G reaches the static breakdown value $V_G = V_S \approx 10$ kV, the very first breakdown in the gap *G* occurs, the spark discharge arises, and total capacitance *C* discharges through the gap in an oscillatory mode. Half a period of an oscillations can be roughly estimated as $T/2 \approx \pi(LC_0)^{1/2}$ = 150 ns, where L = 750 nH is the cable l_T inductance. Thus, due to the spark, capacitance *C* discharges completely and the oscillatory spark current of a short duration with value of several hundred amperes appears in the ignition gap. As far as current duration is much less than charging time interval (0 – t_1), this current is schematically shown in Fig. 2 as a spike at instant t_1.

Further development of the discharge phenomena in the ignition gap depends on: how fast the deionization processes after the instant t_1 proceed and how fast the gap recovers its dielectric strength. Recovery time, in particular, depends on the gas flow velocity across the gap. The higher velocity the faster the spark channel products are carried away from the gap and less the recovery time.

One of the cases corresponds to conditions when the recovery time is extremely short. In this situation after the very first breakdown (at instant t_1) capacitance C starts charging from the power supply repeatedly. Simultaneously, recombination of the spark discharge plasma takes place, and products of the electrode erosion and gas dynamics disturbances are carried out from the gap. As a result, gap recovers its dielectric strength during the charging process. Then, new breakdown occurs again at a voltage V_S close to the static breakdown voltage of the gap. The process has repeated and we have in the electric circuit a succession of high-current pulses, whose pulse repetition rate f is determined by the characteristic charging time ($f \approx 3/R_bC$).

Actually, the above-described regime of operation is rather evident and well known. This regime is normally used in high-pressure switching devices for different applications[5]. An important problem for switching devices is to enhance a pulse repetition rate. From our experience and prior works we can conclude that the pulse repetition rate of 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 we initiate the burning process 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[9,10] (see Fig. 2). The main idea of such regime is that the gap G should not recover its dielectric strength in the pause between high-current pulses, *i.e.* residual plasma from preceding discharge has to be available in the gap when successive spark discharge occurs.

Then the very first breakdown occurs at instant t_1 with voltage close to its static breakdown value. After that voltage at the gap becomes close to zeroes and deionization of the gap is going on. Simultaneously voltage at the gap V_G increases due to charging capacitor C. Thus, in the time interval ($t_2 - t_1$) gap is not yet de-ionized completely, so low current of a glow-like discharge is still flowing in the gap coursed by charging the capacitor C. As a result, new breakdown at instant t_2 occurs at the lower voltage in comparison to the very first breakdown. The process is repeated and the values of breakdown voltages at the instants t_3, t_4, t_5, and further are changed randomly.

The most attractive feature of the described regime lies in the fact that flame is not only ignited at the instants t_1, t_2, t_3, and on, but also additionally sustained in the pauses between pulses due to low-current of a glow-type discharge. This is the principal idea that we propose for the plasma pilot powering. The method allows us to combine direct nanosecond ignition in the discharge chamber with enhancing the burning process propagation over the combustion chamber after ignition. Experimental data in support of this concept and more detailed discussions are presented below.

III. Experimental Data in Support of the Method

The experiments on ignition and flame control have been carried out as applied to air-propane mixtures with a plasmatron-type igniter. Experimental arrangement and method of measurements are shown in Fig. 3. It could be seen that electric circuit is actually coincide with the schematic in Fig. 1.

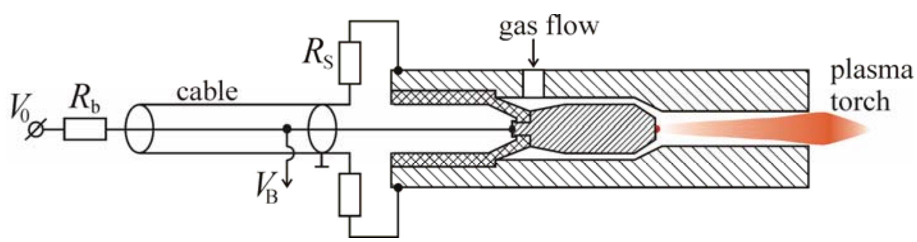


Fig. 3. Experimental arrangement for ignition and flame control in a plasmatron and for discharge investigations with a nanosecond time resolution. V_0 – output voltage of power supplier; R_b – ballast charging resistor; R_S – resistance of the shunt for current recording; V_B – voltage measured with high-voltage probe. Inner coaxial electrode is a cathode and outer electrode is an anode; typical length of cable is 3 m.

Voltage of the DC power supply V_0 is applied between a cathode and an anode. Typical gas flow across the aperture is up to 1 g/s. The very first breakdown occurs over the shortest pass in the gap between coaxial parts of cathode and anode. Due to the turbulent gas flow, discharge channel is shifted to the end of cathode. With a high discharge current (more than 4 A) we have typical regime of the arc plasmatron. The arc cathode spot is attached to the end of the cathode as shown in Fig. 3 (this regime is also described in details in Ref. 3).

To realize an idea of non-steady state nanosecond discharge powering, we decreased current from the power supply and increased voltage V_0. One of the possible discharge modes for an atmospheric pressure air with different gas flows G(air) through the plasmatron is illustrated in Table 1. Discharge current i_d and discharge burning voltage V_d, as it will be shown later, are certain averaged values that are provided by the measurement devices of the power supply. The other notations in Table 1 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 of the gas temperature due to discharge.

Table 1. 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

We can see that the average discharge current is less than 100 mA, average discharge burning voltage is higher than 500 V, and an increase of the gas temperature at the device outlet does not exceed 200 K. Then, 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 2. 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 1). 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 1), the process of propane burning is initiated in plasmatron and the propane flame is observed in a wide range of α ratios. 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.

Table 2. Discharge parameters in the air-propane mixtures. G(air) = 0.45 g/s

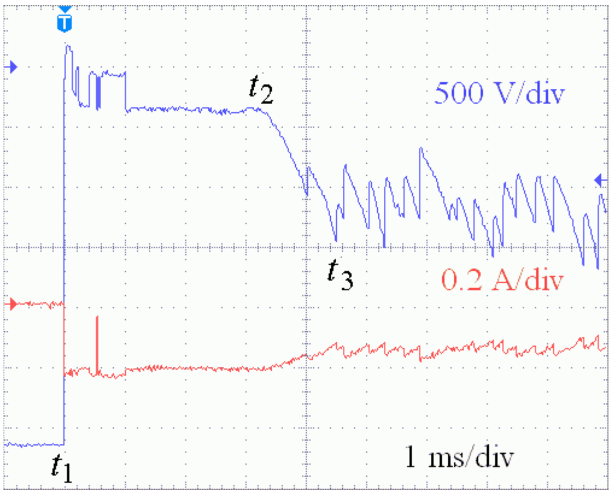
G (propane), g/s	α	i_d, mA	V_d, V	Q_d, W
0.02	1.45	84	740	62
0.041	0.7	84	800	67
0.062	0.47	84	850	71
0.082	0.35	84	920	77
0.10	0.29	84	920	77

It seems that ignition and flame sustaining become possible only due to specific discharge burning regime, which is shown schematically in Fig. 2. After the very first breakdown, the spark discharge of short duration arises in the plasmatron. If current from the power supply was high enough, then the spark discharge would be able to transform into a steady state arc with distinctively expressed cathode spot. However, in the conditions of low current, lifetime of the cathode spot is less than 1 μs[5]. The cathode spot is extinguished and in the pause between pulses (from t_1 to t_2) discharge is sustained in a low-current glow mode. The characteristic feature of a high-pressure glow discharge is so-called glow-to-spark transition phenomenon. It means that discharge burns in a glow mode only during limited time frame, after which micro-explosion at the cathode surface occurs, the cathode spot is initiated and the spark channel appears again. The moment of a new spark channel appearance is noted in Fig. 2 as t_2. Then the described cycle of events is repeated.

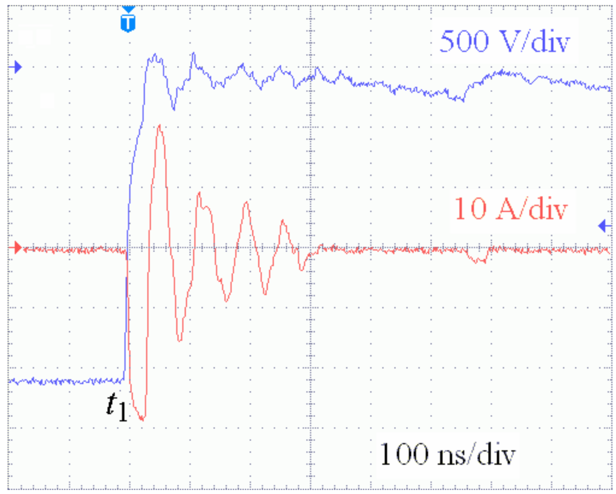
Transitions from glow to spark and back happen on a nanosecond time scale. During the spark discharge formation process a high-current peak is superimposed on the glow discharge current. Energy to the spark discharge is supplied from the capacitance of connecting cable (see Fig. 3). In our conditions C = 300 pF, so delivered energy i level is about 1 mJ and this energy is introduced into the spark channel during the time frame of about 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 burning process in the air-fuel mixture. 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 does not represent a “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.

Below we demonstrate some figures with the experimental data in support of the above-described concept. Figure 4 shows the waveforms for the very first breakdown in a plasmatron.



a)



b)

Fig. 4. Voltage and current waveforms for the very first breakdown in the plasmatron obtained with different time resolution (plasmatron design is shown in Fig. 3). Air flow through the plasmatron G(air) = 0.1 g/s (gas velocity v_{gas} = 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.

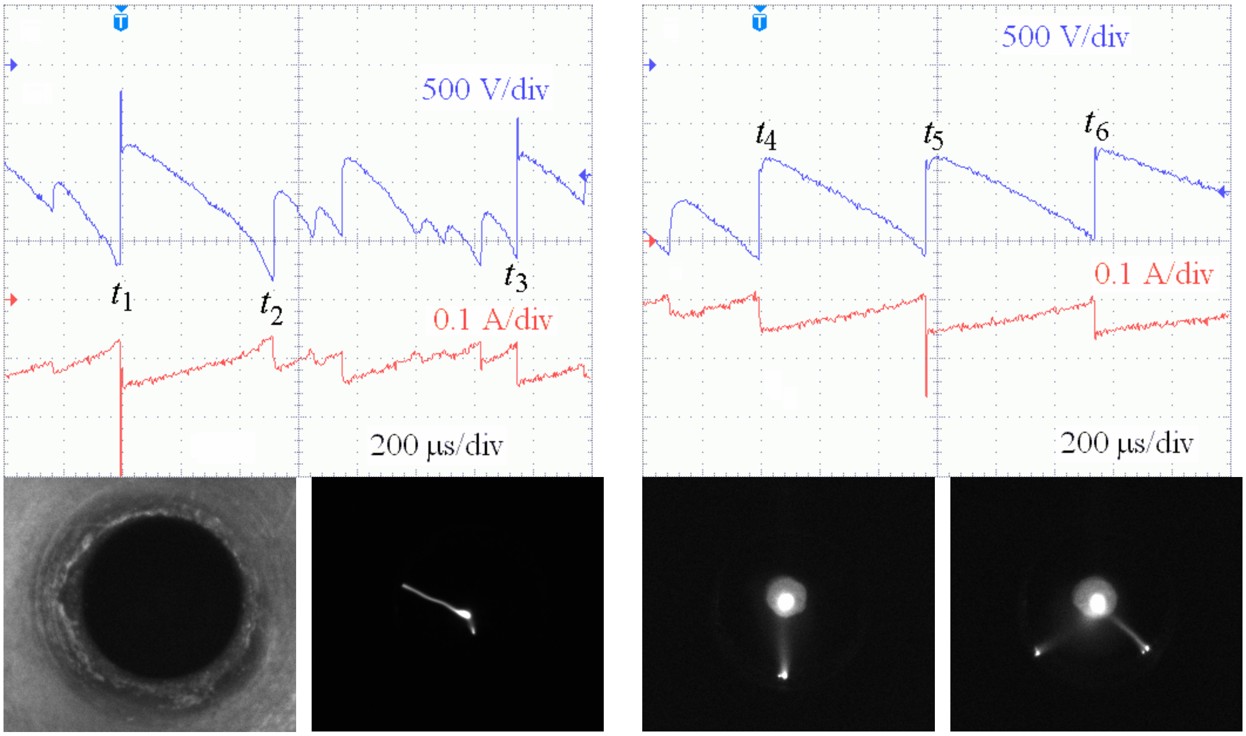
As noted above, the very first breakdown occurs between the coaxial parts of electrodes in plasmatron. In Fig.4 the instant of breakdown is marked as t_1. Figure 4*b* shows that breakdown is accompanied by the oscillatory current through the spark channel due to discharging capacitance of the coaxial cable. After the very first breakdown a kind of glow discharge with an average current of about 200 mA appears in the gap (see time interval from t_1 to t_2). This is not a steady state discharge stage. We can see the sharp voltage collapses at the waveform when glow-to-spark transitions occur and sharp increases of voltage when cathode spot is extinguished.

Under the effect of gas flow, discharge plasma is shifted to the end of cathode during the time interval from t_1 to t_2. After that, the discharge current starts flowing between the end of cathode and coaxial part of anode in the plasmatron exit. Length of the discharge plasma channel increases because of the gas flow through the plasmatron exit that leads to increasing the average voltage drop at the plasma column (time interval from t_2 to t_3). At the stage $t > t_3$ we can see a non-steady discharge behavior at the conditions when current attachment is localized at the end of the cathode. More detailed information about the stage $t > t_3$ is presented in Fig. 5.

The first from the left hand side photograph in Fig. 5 is the plasmatron exit picture. We can see here 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 channel location.

Let consider a processes in the plasmatron, starting from the instant t_1. At this moment, 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. 5*a*. We can see the distinctively expressed cathode spot in the center of the frame (at the central part of the cathode end) and a bright filamentary channel 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, as a result of breakdown the complete voltage collapse at the gap takes place, and the breakdown itself is accompanied by oscillatory current whose waveform is similar to that shown in Fig. 4*b*.

After t_1 voltage at the gap increases *i.e.* the cable capacitance C is charging. At this stage, a glow-like discharge burns in the gap. The length of a plasma column is increasing due to gas flow, which leads to increasing the discharge burning voltage. At instant t_2 new transition from glow to spark arises. It is known[5] 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 conductivity of the filamentary spark channel. At the next temporal stage, the diffuse channel transforms into a high-conductivity spark channel if stored in the capacitor energy is sufficient for such transition. Hence, it can be concluded that for instant t_2 we have situation with so-called non-completed breakdown: the diffused channel has already appeared but transformation of the diffused channel into the high-conductivity stage has yet not occurred for this particular case. Note that the current spike for such type of non-completed breakdown has an aperiodic form (see Fig. 6).



(t_1) (t_4) (from t_5 to t_6)

a) *b*)

Fig. 5. Voltage and current waveforms for discharge in a plasmatron at the stage when discharge is attached to the end of the cathode and end-on CCD photographs of the discharge image.
R_b = 13.6 kΩ, C = 300 pF, V_0 = 3.0 kV. *a*) gas flow G(air) = 0.5 g/s (v_{gas} = 20 m/s); *b*) G(air) = 0.1 g/s (v_{gas} = 4 m/s).

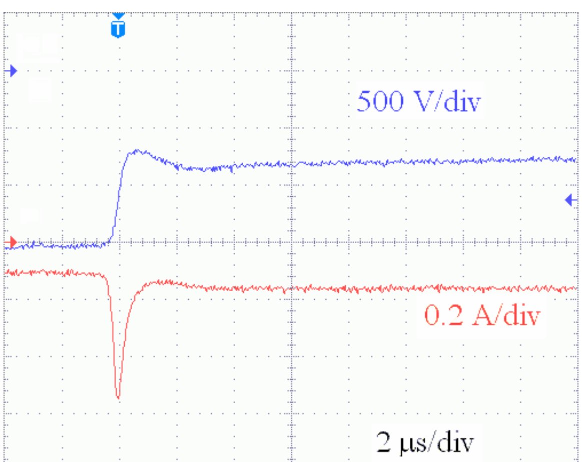


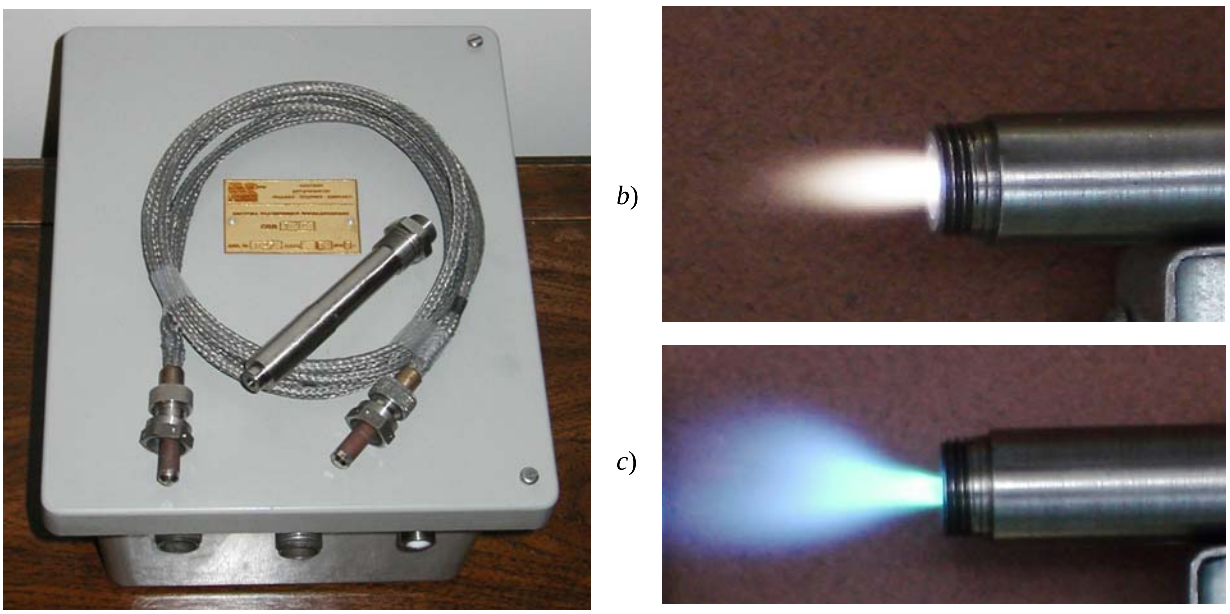
Fig. 6. Illustration of the voltage and current waveforms for non-completed transition from glow to spark in a plasmatron. R_b = 13.6 kΩ, C = 300 pF, V_0 = 3.0 kV, gas flow G(air) = 0.1 g/s (v_{gas} = 4 m/s).

Completed and non-completed transitions appear randomly. For example, at instant of time t_3 we have completed breakdown again. With low gas velocity non-completed breakdowns appear more frequently than for enhanced velocity. In Fig. 5*b* we can see non-completed transitions at the instants of t_4, t_5, and t_6. The CCD frames show that the discharge image for this regime is essentially different than that for the spark discharge (see frame t_1). The glow-type discharge occupies at the cathode end area of about 1 mm in diameter. The estimates with taking into account gas heating show that the current density at the cathode in glow stage approximately coincides with normal glow discharge current density.

Each glow-to-spark transition is accompanied by appearing new diffuse channel with new current attachment at the anode surface. This fact is clearly illustrated by CCD image with exposition time from t_5 to t_6. Here we can see two diffused channels: one of them appears at instant t_5 and another at instant t_6.

IV. Multi-Mode Plasma Pilot Based on the Above Described Principle

From the above-said it is understandable that the plasmatron-type system can be used both in the regime of arc discharge and in the regime of non-steady state discharge when the nanosecond pulses are superimposed on a glow stage of discharge burning. This idea has been realized in the multi-mode plasma system (MMPS) that has been developed by Applied Plasma Technologies on the basis of described investigations. This system is shown in Fig. 7.



b)

c)

a)

Fig. 7. Multi-mode plasma pilot system: *a*) engine kit; *b*) thermal mode of operation (arc discharge) with air feedstock; *c*) non-steady state mode of operation with propane/air feedstock gas.

The MMPS allows operating in a well-known thermal arc mode[3]. In this case a plasma feedstock gas flow is heated to high temperature due to dissipation of the discharge power. Typical average power for the purpose of ignition and flame control here is at the level from 0.6 to 1.2 kW. The preferable gas is air, as far as any propane or methane concentration leads to soot formation in the cathode area, which disturbs the plasmatron operation. Systems with thermal plasma have been used with pressure differential from 25 mm of H_2O to 1500 mm H_2O and flow rate from 0.01 to 1 g/s in gas turbine engines. This air flow can be supplied by gas turbine itself due to aerodynamic resistance of its combustor. The plasma torch, generated in the described regime, is shown in Fig. 7*b*.

Another mode of the MMPS is based on a non-steady state discharge. The power supply, in which current is limited by a special electric circuit with internal inductance, provides discharge powering. In this case MMPS works in the regime when nanosecond pulses are imposed on the glow-type discharge. Average power delivered to the gas feedstock from discharge is normally less that 200 W. However, a high temperature at the plasmatron exit could be achieved due to propane or methane injection into the plasma gas. Very important feature of this regime is that there is no soot formation and the electrode system lifetime, as far as the plasmatron in whole, is two orders of value higher than that for the arc plasmatron. The flame at the plasma pilot exit with propane feeding into the arc chamber is shown in Fig. 7*c*.

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