FEATURES OF THE MICROSECOND PULSED DISCHARGE IGNITION IN OXYGEN IN A POINT-TO-PLANE CONFIGURATION

S.M. Mankovskyi, B.B. Kadolin, L.M. Zavada, V.I. Golota, M.O. Yegorov
National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
E-mail: svyatoslav@kipt.kharkov.ua

The results of investigations on electrodynamic characteristics of the pulsed barrierless discharge in the point-to-plane electrode system in oxygen under the combined negative voltage application to the point-electrode are presented. It was shown that parameters of the combined voltage have significant influence on conditions for the discharge ignition and, as a result, on efficiency of ozone synthesis in this discharge.

PACS: 52.75.−D, 52.77.−J, 52.80.HC, 52.90.+Z

INTRODUCTION

Over the last decade, ozone technologies have been widely used. However, the large-scale introduction of ozone technologies is restricted due to a high cost and operation complexity of the DBD ozone generators. Therefore, the development of ozone generators which are robust alternative to the regular DBD ozone generators is an actual task. The pulsed barrierless ozonizer with a point-to-plane electrode system is one of the promising directions of research [1]. According to [2], high-efficient ozone synthesis (2.5 kW·h/g) was reached for the pulsed corona discharge. Such result was obtained due to the application of high-voltage nanosecond pulses with a steep edge (less than 50 ns). These high-voltage nanosecond pulses provided significant overvoltage at the discharge gap and prevented the transition of discharge to a spark mode due to short pulse duration. However, up-to-date power supply units generating such HV-pulses are low-efficient and emit the high-level electromagnetic noise. This makes such power supply units inexpedient for the wide using in commercial ozonizers. On the other hand, it was shown that parameters of the first Trichell pulse significantly differ from pulse parameters of the steady-state pulse sequence [3]. Characteristic time for setting the Trichell pulse sequence is defined by the balance between the processes of negative ion formation in the Trichell pulses and their neutralization on the anode in the intervals between pulses. Therefore, it can be assumed that if the plasma chemical reactor (PCR) is fed with the high-voltage pulses of microsecond duration and high pulse ratio, the discharge breakdown will occur every time under the conditions of the first Trichel pulse, i.e. under the most favorable conditions for ozone synthesis. The high-voltage (up to 15 kV) high-efficiency power supply units, operating at the pulse repetition rate up to 20 kHz with pulse width of ~1 µs and efficiency factor up to 80%, have already been developed and are widely used. Therefore, the high-voltage microsecond pulses can be successfully exploited in the PCRs for ozone synthesis.

The goals of this article are: to study the electrodynamic characteristics of the microsecond pulsed discharge breakdown under the combined voltage application to the point-to-plane electrode system in oxygen-air gas mixture (93% O_2); to study the influence of HV-pulse repetition rate on the discharge breakdown voltage and on the discharge transition to the sparkover; to study the influence of low bias voltage on ozone synthesis efficiency.

1. EXPERIMENTAL SETUP

The experiments were carried out on the experimental setup that included: PCR-module, HV-pulse generator, oxygen generator AirSep-20 with the productivity up to 0.5 m^3/h, oil-less air compressor Atlas Copco LF 2-10 with the productivity of 11m^3/h at the pressure of 10 bars. Gas flow was measured by the flowmeter RM-0.25G. Output ozone concentration was measured by the ozone analyzer Teledyne Instruments 454-H with an effective measuring range of 0…200 g/Nm^3. Oxygen concentration was measured by the magneto-dynamic oxygen analyzer PMA-10. The HV-probe Tektronix P6015A with the bandwidth up to 75 MHz and current probe Tektronix CT1 with the bandwidth of 1.2 kHz…200 MHz were used to take measurement of HV-pulse characteristics. Signals from the probes were recorded by the 200 MHz oscilloscope Tektronix TDS 2024B.

The HV-pulse generator provided negative gaussian-shaped HV-pulses at resistive-capacitive load with the following parameters: the amplitude is up to 12 kV, pulse duration at the half-height is 0.7…1 µs, pulse repetition rate is 0.1…15 kHz. Maximum power consumption of the HV-pulse generator was 180 W with the efficiency up to 70%. Typical oscillogram of the HV-pulse at the reactive load is shown in Fig. 1.

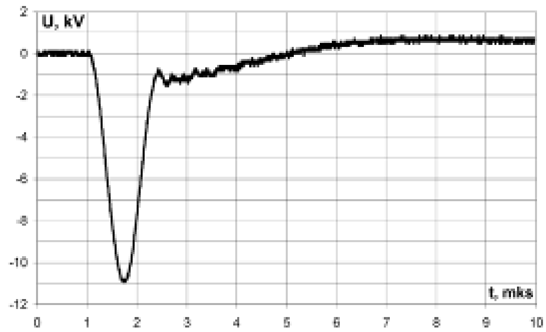


Fig. 1. Typical oscillogram of the HV-pulse

Electrical diagram of the experimental setup is shown in Fig. 2. The *bias circuit* provides on the discharge gap the low negative DC bias voltage U_{DC} up to 600 V at the inter-pulse periods. The *bias circuit* was formed by the HV-capacitor *C* and the group of HV-diodes *D.*

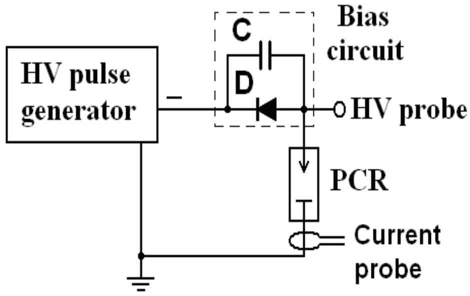


Fig. 2. Electrical diagram of the experimental setup

The PCR-module consisted of two PCRs connected in-parallel in the supply circuit and in-series along the gas flow line. Each PCR was a point-to-plane electrode system. Anode was a hollow stainless steel cylinder (500 mm length, 38 mm inner diameter, 0.5 mm tube wall thickness) with an inner cartridge made of graphite foil TMG-F/B2 (0.35 mm thickness). On the axis of the cylinder there was a sectioned cathode with 43 star-like cathode sections (26.5 mm diameter) separated by 10 mm bushings. Each cathode section had fifteen radial equidistant cogs with 0.5×0.5 mm cross section. If there is no discharge, the PCR is an air capacitor with the capacitance of 55 pF. Oxygen enriched air mixture with 93% oxygen and –73°C dew point was used as plasma-forming gas. Gas flow rate through the PCR module was 2 LPM.

2. EXPERIMENTAL RESULTS

The dependence of electrodynamic characteristics of the discharge and ozone synthesis efficiency on DC bias voltage was studied. As a PCR is a resistive-capacitive load with changing impedance, the HV-pulse amplitude at the equivalent capacitive load was fixed as constant for the whole range of the pulse repetition rate to match the experimental results properly. During the experiments, the oscillograms of voltage and current pulses were recorded at the applied low negative DC bias voltage U_{DC} = 0…600 V. The HV-pulse repetition rate was varied within the range of f = 0.5…15 kHz. Readings of output ozone concentration at all investigated values U_{DC} and f were gathered.

The oscillograms of voltage and current at the DC bias voltage U_{DC} = 500 V and pulse repetition rates f = 0.5; 1; 3; 5; 9; 11; 13 and 15 kHz are shown in Fig. 3.

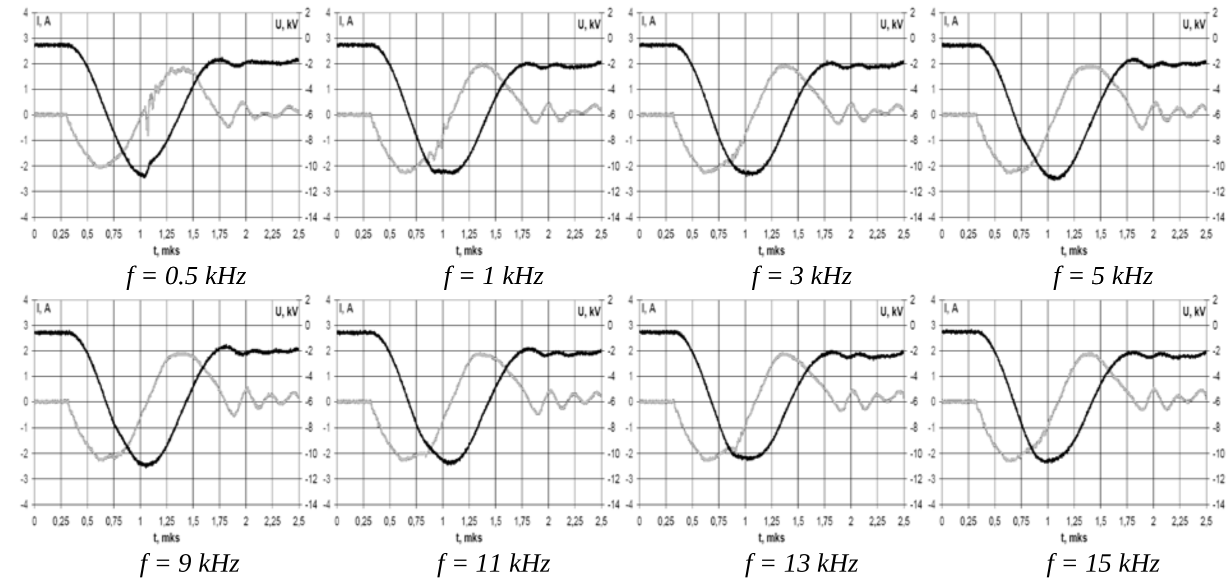
There are specific distortions on the current and voltage waveforms that related to the discharge breakdown and to the conduction current flowing. Specific break on the leading edge of the HV-pulse or close to the maximum corresponds to the discharge breakdown voltage U_B.

At HV-pulse repetition rate f up to 2.5 kHz, there are a sharp break on the voltage waveform (at 10…11 kV) and multiple pulsations in the current waveforms are observed at the same time. These pulsations can be explained by non-simultaneous discharge ignition in the different point-to-plane electrode cells along the multipoint electrode area.

As the pulse repetition rate f increases over 3 kHz, the point of discharge ignition time becomes less noticeable in the oscillograms, pulsations of the discharge conduction current are merged and localized in time and the discharge ignition occurs at lower voltage (8…9 kV). If the pulse repetition rate f increases over 11 kHz, the discharge ignition and the discharge current occur at increasingly higher voltage (10…11 kV).

At all other investigated values of DC bias voltage except U_{DC}=0 V, the discharge breakdown voltage U_B varied with the HV-pulse repetition rate f in similar way.

It's essential to note that the HV-pulse amplitude could be reduced by up to 700 V due to the discharge current flowing.



f = 0.5 kHz *f = 1 kHz* *f = 3 kHz* *f = 5 kHz*

f = 9 kHz *f = 11 kHz* *f = 13 kHz* *f = 15 kHz*

Fig. 3. Oscillograms of voltage (black) and current (grey) at the DC bias voltage U_{DC} = 500 V and HV-pulse repetition rates f = 0.5; 1; 3; 5; 9; 11; 13 and 15 kHz

The dependence of the discharge breakdown voltage U_B on the pulse repetition rate f for the given DC bias voltage U_{DC} = 0…600 V is shown in Fig. 4.

It should be noted that in case U_{DC} = 0 V, the discharge breakdown voltage does not depend significantly on HV-pulse repetition rate f. If the applied DC bias voltage $U_{DC} > 0$ V, a "dip" on the dependence curve occurs (see Fig. 4). This "dip" expands and shifts to higher HV-pulse repetition rates f.

Together with oscillograms, values of the output ozone concentration were recorded. To estimate the efficiency of ozone synthesis in the discharge, ozone mass $m(O_3)$ (g) per HV-pulse was determined as the following:

$$m(O_3) = \frac{n(O_3) \times Q}{f},$$

where $n(O_3)$ is the output ozone concentration (g/m^3); Q is the gas flow rate through the PCRs (m^3/s); f is the HV-pulse repetition rate (Hz).

The dependences of output ozone mass per HV-pulse $m(O_3)$ on the HV-pulse repetition rate f for the given DC bias voltage U_{DC} = 0…600 V is presented in Fig. 5. The analysis of dependences on Fig. 5 shows that ozone mass per HV-pulse $m(O_3)$ monotonously decreases as the HV-pulse repetition rate f increases at the DC bias voltage U_{DC} =0 V.

It can be assumed that such ozone synthesis reduction is related to the increase of ozone concentration in the plasma-forming gas due to the increase in discharge specific power with HV-pulse repetition rate f [4]. If the applied DC bias voltage U_{DC} is nonzero, the dependence of ozone mass per HV-pulse $m(O_3)$ on the pulse repetition rate f has a nonmonotonic behavior. Moreover, for each specified DC bias voltage U_{DC} there is a certain range of HV-pulse repetition rate f, where efficiency of ozone synthesis is higher in comparison with the case when U_{DC} = 0 V. As a result, the increase of ozone output concentration $n(O_3)$ from 32 to 45 g/Nm^3 was obtained at the DC bias voltage U_{DC} = 500 V and the HV-pulse repetition rate f = 15 kHz. At the same time, power consumption for this case increased only by 10%.

Comparison of the dependences in Figs. 4 and 5 suggests a correlation of ozone mass being produced per HV-pulse $m(O_3)$ with the discharge breakdown voltage. It is clearly shown that the "dips" in the curves for the discharge breakdown voltage U_B correspond to similar "dips" in the curves for the dependence of ozone mass per HV-pulse $m(O_3)$ on the HV-pulse repetition rate f. Maximum ozone mass per HV-pulse $m(O_3)$ is produced at the HV-pulse repetition rates f when the discharge breakdown voltage goes out of the right side of the "dip" to a quasi-constant level.

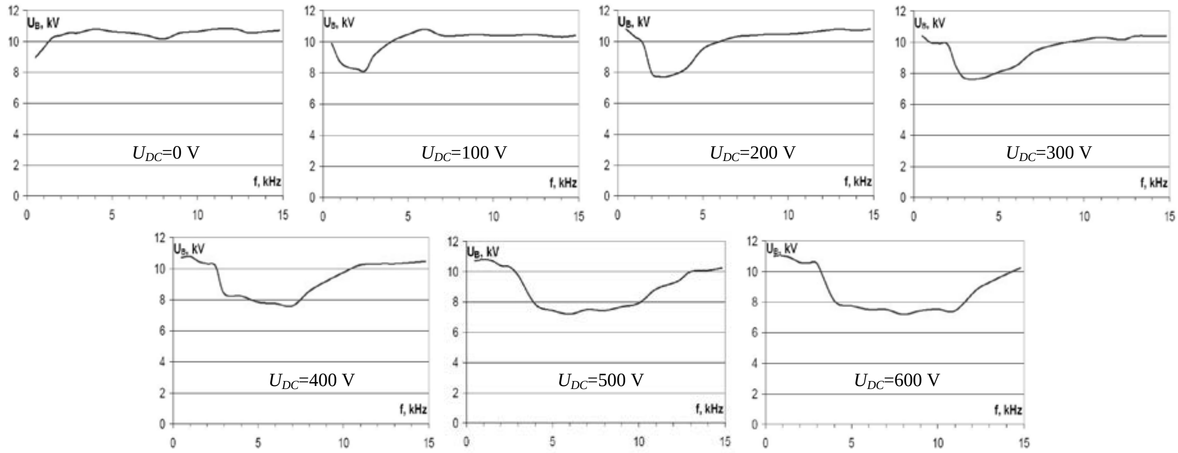


Fig. 4. The dependence of the discharge breakdown voltage U_B on the HV-pulse repetition rate for the DC bias voltage U_{DC} = 0…600 V

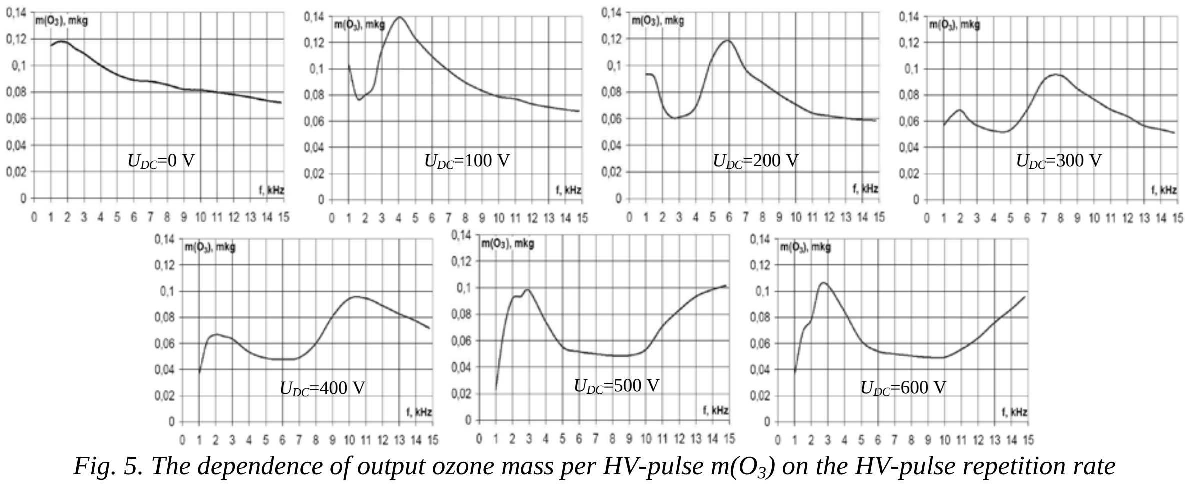


Fig. 5. The dependence of output ozone mass per HV-pulse $m(O_3)$ on the HV-pulse repetition rate for the DC bias voltage U_{DC} = 0…600 V

Also, the dependence of the discharge breakdown voltage U_B for the HV-pulses with different amplitude applied to the discharge gap at the given pulse repetition rates f and DC bias voltage U_{DC} was studied. It was found that the discharge breakdown voltage U_B for the sub-microsecond pulses does not depend on the amplitude of HV-pulses. At the same time, it should be noted that the low negative DC bias voltage U_{DC} prevents the discharge transition to a spark mode and allows to significantly extend the operating range for the HV-pulse amplitude. It allows to apply more power to the discharge and, therefore, to improve the output ozone productivity of PCR.

CONCLUSIONS

The effect of application the DC bias voltage in intervals between HV-pulses on characteristics of the barrierless gas discharge in oxygen with a point-to-plane electrode system has been studied. Bias voltage has an effect on discharge formation conditions. This influences the discharge breakdown voltage and, as a result, the plasma chemical processes in the discharge. It was shown that there is an optimal bias voltage for efficient ozone synthesis by the discharge. This optimal bias voltage magnitude depends on the HV-pulse repetition rate. Under the optimal both a bias voltage and a HV-pulse repetition rate the output ozone concentration can be increased by 20…40% with an increase in power consumption up to 10%.

Other important effect of the combined voltage application is the possibility to extend the HV-pulse amplitude range in which the discharge operates without transition to a spark mode.

The research was partially supported by STCU project #P658.

REFERENCES

1. V.I. Golota, B.B. Kadolin, V.I. Karas', I.A. Paschenko, S.G. Pugach and A.V. Yakovlev. Ozone synthesis in atmospheric pressure needle-to-plane gas discharge // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Acceleration Methods"*. 2000, № 4, p. 254-257.
2. S.V. Korobtsev, D.D. Medvedev, V.M. Shiryaevski. Ozone generation in the impulse corona discharge in the non dry air // *25 All Russian seminar "Ozone and Other Ecologically Safe Oxidizes. Science and Technologies"*. M.: "MSU", June 5, 2003, p. 31-35.
3. Y.S. Akishev, M.E. Grushin, I.V. Kochetov, A.P. Napartovich, N.I. Trushkin. An establishment of regular Trichel pulses in a negative corona in air // *Plasma Phys. Rep. (11)*. 1999, № 25, p. 922-927.
4. V.I. Golota, L.M. Zavada, O.V. Kotyukov, O.V. Poliakov, S.G. Pugach. Ozone synthesis efficiency upgrading in the pulsed point-to-plane gas discharge // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Acceleration Methods"*. 2006, № 5, p. 91-94.

Article received 05.06.2018

ОСОБЕННОСТИ ЗАЖИГАНИЯ МИКРОСЕКУНДНОГО ИМПУЛЬСНОГО РАЗРЯДА В КИСЛОРОДЕ В СИСТЕМЕ ИГЛА-ПЛОСКОСТЬ

С.Н. Маньковский, Б.Б. Кадолин, Л.М. Завада, В.И. Голота, М.А. Егоров

Представлены результаты исследований электродинамических характеристик импульсного безбарьерного разряда в системе электродов игла-плоскость в кислороде при использовании комбинированного питания с отрицательным потенциалом на игольчатом электроде. Показано, что параметры питания существенно влияют на условия зажигания разряда и, как следствие, на эффективность синтеза озона в данном разряде.

ОСОБЛИВОСТІ ЗАПАЛЮВАННЯ МІКРОСЕКУНДНОГО ІМПУЛЬСНОГО РОЗРЯДУ В КИСНІ В СИСТЕМІ ГОЛКА-ПЛОЩИНА

С.М. Маньковський, Б.Б. Кадолін, Л.М. Завада, В.І. Голота, М.О. Єгоров

Представлено результати досліджень електродинамічних характеристик імпульсного безбар'єрного розряду в системі електродів голка-площина в кисні при використанні комбінованого живлення з негативним потенціалом на голчатому електроді. Показано, що параметри живлення істотно впливають на умови запалювання розряду і, як наслідок, на ефективність синтезу озону в даному розряді.