One Atmosphere Barrier Discharges With Electrode Edge Effect

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Abstract - **A new development of the concept of using strongly non-uniform fields in the creation of technological plasma systems at atmospheric pressure is proposed.**

Experimental investigations showing the effectiveness of electrode systems, for which the length of the electrode corona-forming line is introduced as a parameter, are considered. In other words, the degree of influence exerted by the edge effect upon static characteristics of the discharge and electrical characteristics of the plasma system is taken into account.

Keywords - **Electrode edge effect, external characteristic, cold plasma reactor system, one atmosphere air barrier discharge, plasma surface modification.**

I. INTRODUCTION

Barrier discharges at atmospheric pressure (**760** ± 25 Torr, **1** atm) have serious technological advantages, which impose their application to the technology of textiles and textile fibers, electronics and microelectronics, printing industry [1, 4].

Characteristic to all types of barrier discharges is the presence of one or two dielectric barriers that separate the electrodes from the working medium. This remains a purely external trait of barrier discharges, as the dielectric barrier performs a very essential part in the occurrence and burning of the discharge, [1, 2]:

❑ the barrier with its capacitance C_δ plays the role of a reactance, i. e. of a capacitive, ballast reactance $X_C = \omega^{-1} C_\delta^{-1}$, that limits the increase in the electric current during discharge burning;

❑ the barrier re-distributes the electric field intensity in the inter-electrode space by electrically loading the working air gap and determining the critical parameters - ignition voltage U_{bd} and ignition current I_{bd} of the barrier discharge;

❑ the barrier defines the voltage of burning U_b of the discharge, which remains constant during its burning and does not depend on selected working voltage.

! The multiple ionization and chemical processes going simultaneously during barrier discharge burning at atmospheric pressure create considerable difficulties nor only in controlling the discharge, but also for the description of its behavior, [2].

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The TASK of the present work consists in studying the behavior of low-frequency (50 Hz) air barrier discharge that burns without any load in the volume or on the surface of a cold-plasma generator system at atmospheric pressure - *one-atmosphere air barrier discharge* (*OAABD*).

The investigations are mainly focused on three types of cold plasma reactor systems:

❒ *the first one* representing two flat-parallel electrodes with a glass barrier between them, that creates a plasma volume with relatively uniform distribution of the electric field between the glass barrier and one of the electrodes, i. e. with suppressed electrode edge effect - *one-atmosphere uniform barrier discharge* (*OAUBD*);

❒ *the second one* representing a cold plasma reactor system, analogous to the *OAUBD*- reactor system, with a barrier and air gap placed in series between the two electrodes, but having a comb-shaped high-voltage electrode with strongly expressed electrode edge effect resulting from the increased length of the edge contour line - *one-atmosphere edge effect serial barrier discharge* (*OAEESBD*);

❒ *the third one* representing two flat-parallel electrodes that embrace tightly the glass barrier in such a way, that a plasma surface with the participation of the electrode edge effect is created only on that side of the barrier, which looks at the comb-shaped electrode, and the air gap turns out to be connected in parallel to the dielectric barrier - *one-atmosphere edge effect parallel barrier discharge* (*OAEEPBD*).

A comparative investigation is conducted by using the external static characteristic and the electric and technological characteristics of one atmosphere air barrier discharges, which result from the former one [3].

II. Experimental investigations

Experimental investigations [2, 3, 5], performed by us for a continuous period of time in connection with the manifestation of electrode edge effect in a cold plasma reactor system, allow to seek a new technical solution in using the electrode edge effect for creating an open (or single-side) cold plasma reactor system.

The *OAUBD*- plasma reactor system has electrodes, for which the electrode edge effect is neutralized by means of appropriately made chamfers along the external contour line of each electrode, i. e. by using the well-known *Rogovski's electrodes.*

In the other plasma reactor systems examined - *OAEESBD* and *OAEEPBD*– this effect is not compensated for. On the contrary, the edge effect is made stronger by introducing a comb-shaped high-voltage electrode consisting of alternating 4-millimeter-wide elementary electrodes separated from each other by an air gap of the same width, Fig. 1.

The *OAEESBD*- and *OAEEPBD*- plasma reactor systems differ from each other in the organization of the inter-electrode space – in the first case the barrier and plasma gap are placed in series between the electrodes, Fig. 1b, and in the second case – in parallel, Fig. 1c.

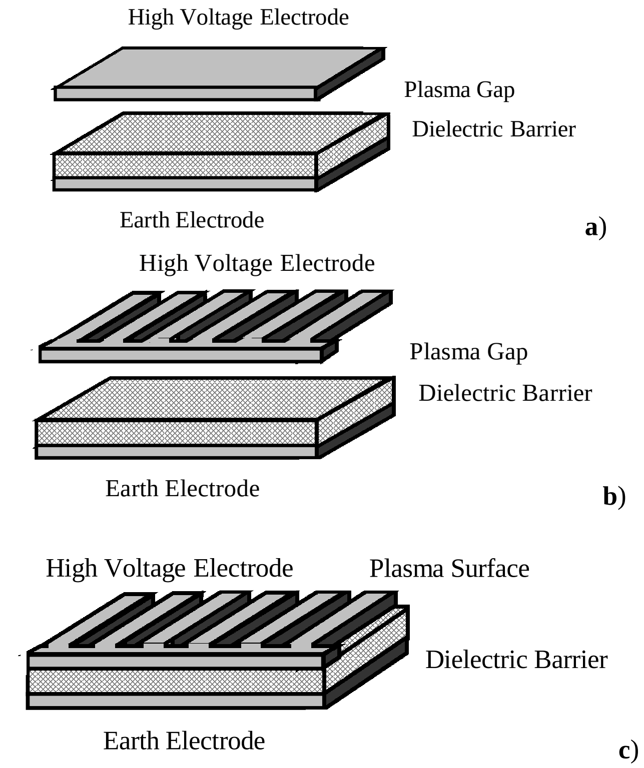

Fig. 1. Types of plasma reactor systems used in the experimental investigation: a - one atmosphere uniform barrier discharge (*OAUBD*); b - one atmosphere edge effect serial barrier discharge (*OAEESBD*); c - one atmosphere edge effect parallel barrier discharge (*OAEEPBD*).

The external or voltage-current characteristic of the barrier discharges is determined experimentally. It expresses the relationship between the average value of electric current I_{gap} (*AV*) flowing through the barrier discharge and the effective value of voltage U_{gap} (*RMS*) applied across the discharge gap - $I_{gap}\,(AV) = \varphi\;[\;U_{gap}\,(RMS)\;]$, Fig. 1.

The external characteristic is represented by a broken-line polygon of three linear sectors, each of them corresponding to one of the three development stages of the barrier discharge, Fig. 2 [2, 3]:

♦ the stage preceding the ignition of the barrier discharge, or the so-called free or non-operating regime;

♦ the first stage of burning, which corresponds to the formation of cold ozone- and oxygen-containing plasma;

♦ the second stage of burning, which corresponds to the formation of cold plasma containing mostly nitrogen oxides (NO_x).

For high values of linear correlation factor r_{pc} the linear law describes very well the individual sectors of the external characteristic of barrier discharge.

A generalized model of burning of the one atmosphere barrier discharge is created under the following conditions:

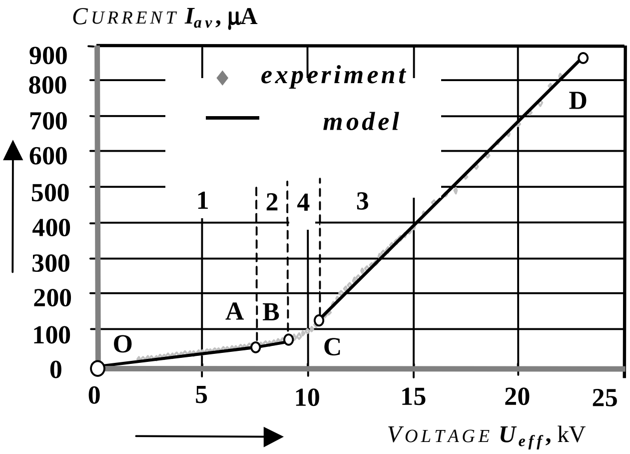

Fig. 2. Operating sectors of the external characteristic of one atmosphere barrier discharge, which represents the relationship between the average value of current I_{gap} and the effective value of applied voltage U_{gap}.

OA - non-operating sector; *AB* – first operating sector – cold technological plasma containing ozone and products of its decomposition; *CD* - second operating sector – cold technological plasma containing nitrogen oxides; *BC* – transient area.

❏ the barrier discharge, similarly to the normal glow discharge in vacuum, burns at a constant value of the voltage of burning, i. e. $U_b = const$;

❏ the barrier discharge ignition represents a threshold process that occurs at specific critical parameters - ignition voltage U_{bd} (*max*) and ignition current I_{bd} (*av*).

The external characteristic of one-atmosphere barrier discharges is used for determining the basic technological characteristic of discharges. As different plasma reactor systems are compared: on one hand *OAUBD* and *OAEESBD* creating plasma volumes, and on the other hand OAEEPBD that creates a plasma surface, the surface density of power p_S in W/m^2 is used as a basic technological characteristic for the purpose of comparison.

The experimental investigations are conducted with a barrier representing a plate of thickness $\delta = 3$ mm, made of alkaline silicate glass and having dielectric permittivity $\varepsilon = 10$, volumetric specific electric resistance $\rho = 10^9$ Ωm and $tg\delta = 25$ (at 20 ^{0}C).

II. Results and Discussion

The basic parameters of first operating sector *AB* of the external characteristic are given in Table 1 for the three plasma reactor systems.

Table 1.

Plasma reactor system	Intercept A, µA	Slope B, µA/kV	Correlation coefficient r_C	C_{bar}, pF
OAUBD	- 716	119	0.97669	1922
OAEESBD	- 836	164 (38%)	0.99036	1922
OAEEPBD	- 455	350 (194%)	0.99838	536

The rate of relative increase of current *B* in µA/kV grows up considerably – with about 38 percent – as a result of increasing the electrode contour line or intensifying the edge effect, i. e. due to the adoption of a comb-shaped electrode instead of the plane-shaped one, Figs. 1a and 1b.

The influence of the edge effect is more strongly expressed in the *OAEEPBD*- reactor system, where the rate increase observed is already 194 percent, Table 1.

The parameters of the second operating sector *CD* of the external characteristic of investigated plasma reactor systems are given in Table 2. The *OAEESBD*- plasma reactor system has no expressed second (*CD*) sector in the region of voltage investigation – up to 17 kV (*RMS*).

The rate of relative increase of the current in the second operating sector *CD* of the *OAEEPBD*- reactor system grows up with about 82 percent with respect to that of the basic *OAUBD*-reactor system.

Table 2.

Plasma reactor system	Intercept A, μA	Slope B, μA/kV	Correlation coefficient r_C
OAUBD	- 1580	219	0.99961
OAEESBD	-	-	-
OAEEPBD	- 1145	399 (82 %)	0.99864

The calculated values of the voltage of discharge burning for the first operating sector *AB* and the critical parameters of the first (*AB*) and second (*CD*) operating sectors of the external characteristic are shown in Table 3. Voltage of burning U_b of *OAB*- discharges decreases considerably with increasing the length of the electrode contour line and adopting the *OAEEPBD*- reactor system.

Table 3.

Plasma reactor system	U_b, kV	U_{bd} (1), kV	I_{bd} (1), μA	U_{bd} (2), kV	I_{bd} (2), μA
OAUBD	6.000	7.995	238	8.655	317
OAEESBD	5.088	5.700	101	-	-
OAEEPBD	1.302	3.014	599	14.002	4441

The calculated values of capacitance C_{pl} of the plasma region for the two operating regions of the external characteristic of the barrier discharges examined are given in Table 4.

Table 4.

Plasma reactor system	C_{pl} (*AB*), pF (mode of connection)	C_{pl} (*CD*), pF (mode of connection)
OAUBD	541 (serial)	1303 (serial)
OAEESBD	835 (serial)	-
OAEEPBD	705 (parallel)	879 (parallel)

For the established linear relationship between the average value of current I_{gap} (*AV*) and the effective value of applied voltage U_{gap} (*RMS*) capacitance C_{pl} of the plasma region may be calculated by first determining the total capacitance C_Σ, and then for a known, i. e. measured (at 50 Hz) capacitance C_{bar} of the glass barrier the capacitance C_{pl} of the plasma region is determined depending on the manner of connecting the barrier and plasma region, C_{bar} and C_{pl}: in series (eq. 2) or in parallel (eq. 3):

$$C_\Sigma = \frac{1}{2\sqrt{2}} \frac{\pi}{\omega} \frac{I_{gap}}{U_{gap}}, \ \omega = 2\pi f = 314 \, (50 \text{ Hz}); \qquad (1)$$

$$C_{pl} = \frac{C_\Sigma C_{bar}}{C_{bar} - C_\Sigma}; \text{ or} \qquad (2)$$

$$C_{pl} = C_\Sigma - C_{bar} \qquad (3)$$

The basic technological characteristic of the discharge – the relationship between surface density of active power p_S and applied voltage U_{gap} – is obtained on the basis of the experimentally determined external characteristic.

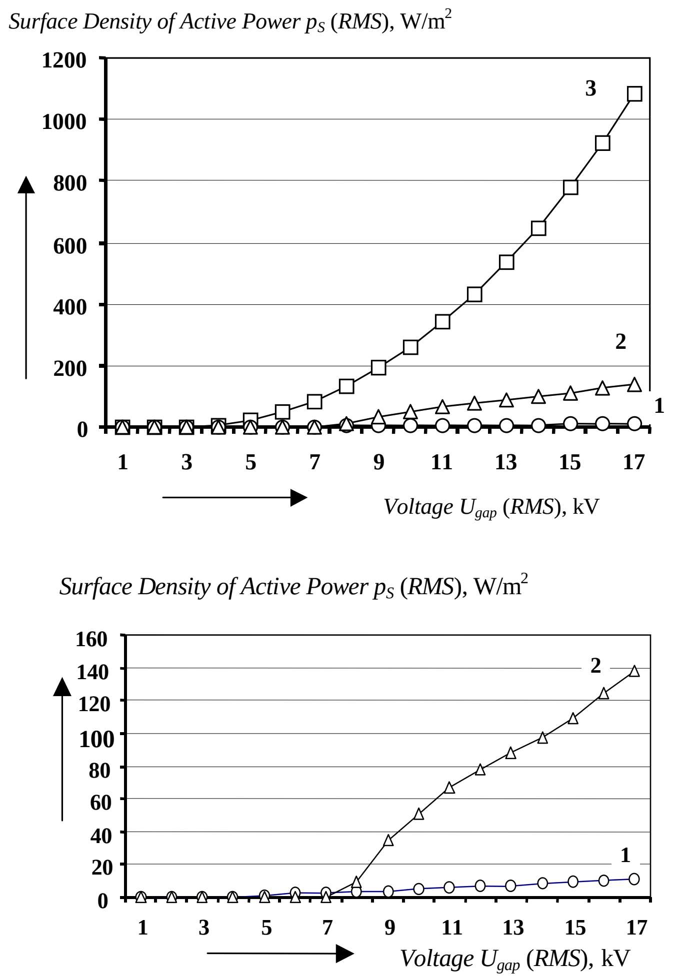

Fig. 3. Variation of surface density of active power p_S with applied voltage U_{gap}: **1** - *OAUBD*-reactor system; **2** -*OAEESBD*-reactor system; **3** - *OAEEPBD*-reactor system.

The surface density of active power p_S of the *OAEEPBD*-reactor system is conditionally determined for the geometrical area, on which the plasma layer is conditionally distributed. This means that the plasma active area includes also the areas between the elementary electrodes of the system. It is this approach only that allows making comparison between electrode systems with uniform and strongly non-uniform electric fields.

In such a way it is possible to compare different plasma generator systems, i. e. to compare plasma systems creating plasma volumes like the *OAUBD*- or *OAEESBD*- systems with plasma systems creating plasma surfaces like the *OAEEPBD*- system.

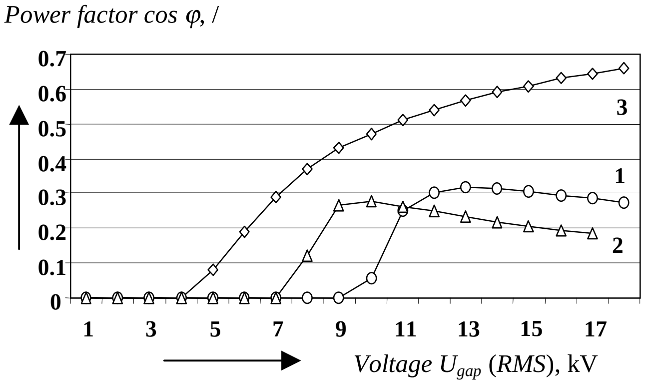

Fig. 4. Variation of power factor cos φ with the voltage applied across the discharge gap in different plasma generator systems: **1** - *OAUBD*; **2** - *OAEESBD*; **3** - *OAEEPBD*.

An even simplified analysis of technological characteristics clearly indicates that increasing the non-uniformity of the electric field in the discharge gap through the participation of an edge effect, i. e. through the increase of the high-voltage electrode perimeter – in the case of a comb-shaped electrode, Fig. 1, combined with adopting a parallel configuration of the dielectric barrier and plasma volume instead of the series scheme of placement of the dielectric barrier and plasma volume, provides the greatest possibilities for improving the external characteristic of the barrier discharge and the technological characteristic of the plasma generator system, Fig. 3.

The two plasma generator systems *OAUBD* and *OAEEPBD* are virtually incomparable: the value of surface density of active power p_S, which is acquired by *OAEEPBD* at voltage within $5 \div 6$ kV, is attained by *OAUBD* only at 17 kV (*RMS*), Fig. 3.

Increasing surface density p_S more than ten times, Fig. 3, may provide a much more intensive and energy-effective technological process of surface plasma-chemical modification of low-energy materials. In this case, the surface active power density represents a quantitative measure for the topological (etching) and chemical (activation, netting, polymerization) modifications of the surface of polymeric materials.

The energy-related effectiveness of plasma-chemical processes is different for the individual plasma generator systems, Fig. 4.

It is known that the power factor cos φ represents a measure for the effectiveness of the process of transforming the electric energy into another type of energy – in this case into the energy of chemical and physical modifications of the surface. The *OAEEPBD* technological plasma system ensures values of power factor, e. g. 0.65, which remain unattainable for the classical corona and barrier discharge plasma systems. Moreover, the energy-related effectiveness of technological regimes at relatively low voltages is strongly increased.

III. Conclusion

The experimentally plotted external characteristic of one atmosphere barrier discharge with industrial frequency (50 or 60 Hz) in the region of burning may be successfully used in the analysis of plasma generator systems, which are very different externally, even in the case when one system creates a plasma volume, and the other a plasma surface.

Increasing the degree of non-uniformity of the electrical field by changing the perimeter of the high-voltage electrode, i. e. by intensifying the impact of the edge effect, along with adopting a parallel circuit of connecting the dielectric barrier with the air gap, turns out to be an efficient way for magnifying the technological potentials and the energy-related effectiveness of plasma generator systems.

Using the *OAEEPBD*- plasma reactor system in the practice of plasma and plasma-assisted chemical surface modification of materials reveals a new opportunity for creating technologically effective plasma systems.

This type of reactors enables even more effective application not only at increased and high frequencies, but also at *RF*-frequencies.

References

[1] P. Dineff. Electrotechnology. Introduction to Electrotechnology. Technical University, Sofia, Bulgaria, **2000** (in Bulgarian).

[2] P. Dineff, D. Gospodinova. Energy-effective plasma-chemical surface modification of polymers and polymeric materials at atmospheric pressure. International conference MEDPOWER'02, November 04-06, **2002**, Athena, Greece, Proceedings, pp. 1124-1128.

[3] P. Dineff, D. Gospodinova. Electric Characteristics of Barrier Discharge. XXXVI. International Scientific Conference on Information, Communication and Energy Systems and Technologies "ICEST '2003". Sofia, Bulgaria, October 16-18, **2003**. Proceedings, Heron Press. Ltd., pp.442-445.

[4] T. Vladkova, P. Dineff, D. Gospodinova. Wood Flour: A New Filler for Rubber Processing Industry. II. Cure Characteristics and Mechanical Properties of NBR Compounds Filled with Corona-Treated Wood Flour, J. Appl. Polym. Sci., **2003,** 91(2), p. 883-889.

ACKNOWLEDGEMENT

This research was financially supported by Ministry of Education and Sciences (MON) - Project MU-TN-1201 / 02.