XIII-th International Symposium on Electrical Apparatus and Technologies

SIELA 2003

PROCEEDINGS
Volume II

29 – 30 May 2003
Plovdiv, Bulgaria

ISBN 954-90209-2-4
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CHARACTERISTICS OF THE LOW-FREQUENCY CAPACITIVE DISCHARGE

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Abstract. The low-frequency electric discharge that burns at atmospheric pressure and industrial frequency (50/60 Hz) is represents a good technological alternative of the RF- and glow discharges at low pressure. Based on the external static characteristic of the discharge, basic electrical parameters are proposed, which are suitable for investigating and controlling the technological process of surface plasma-chemical modification.

Keywords: external (volt-ampere) static characteristic, high-pressure low-frequency discharge, plasma-chemical surface modification, surface current density, surface power density.

INTRODUCTION

The low-frequency capacitive discharge (LF-CD) at atmospheric pressure and industrial frequency (50/60 Hz) is the more and more frequently used alternative of glow and RF-electrical discharges in the technology of plasma-chemical surface treatment of polymers and polymer materials.

Burning of LF-CD discharge in air at atmospheric pressure is determined in the first place by the dissociation and ionization of oxygen and nitrogen i.e. by the production of ozone and the chemical active products resulting from its decomposition, and of the nitrogen oxides and their active oxidation. The variety of plasma-chemical processes is too much considerable and is an essential obstacle not only to accomplishing a general description of the technological process, but also to controlling the plasma-chemical modification.

Plasma-chemical processes going on in the LF-CD discharge are unambiguously connected with the development of electrical processes in the discharge. The external static characteristic of the LF-CD discharge that expresses the relationship between the average value of the electric current and the effective of the voltage applied can be used for explaining the electrical and plasma-chemical processes in the discharge.

Two characteristic operating sectors are observed on the external static characteristic of the LF-CD discharge. These operating sectors correspond to the behavior patterns of oxygen and nitrogen. We have shown the possibility to model these sectors by using a linear regression relationship.

THE TASK of the present work consists in the illustration of an original approach that allows describing and controlling the technological regimes of plasma-chemical modification through basic electrical characteristics of the LF-CD discharge.
THEORETICAL AND EXPERIMENTAL INVESTIGATIONS

The general view of the external static volt-ampere characteristic and straight-line operating sectors \( AB \) and \( CD \) are shown in Fig. 1a.

![Figure 1a. Characteristic sectors of the external volt-ampere characteristic of the LF-CD discharge, i.e. the relationship between the average current value \( I_{av} \) and the effective value of applied voltage \( U_{eff} \) (a): OA - non-operating sector; AB - first operating sector responsible for the electrical and chemical processes going on with the participation of oxygen; CD - second operating sector responsible for the electrical and chemical processes that go on with the participation of nitrogen; BC - transient region. Linear model of the external characteristic and critical electrical parameters (b) of the two transitions to the first (A-B) and second (C-D, point B = point C) operating sectors.](image)

Burning of LV-CD discharge is characterized by a constant voltage applied to the discharge or by a constant burning voltage \( U_g \) for the whole operating sector, irrespective of the values of supplied voltage \( U_{eff} \) and current \( I_{av} \). Each operating sector is characterized by its own voltage of discharge burning, i.e. \( U_{g,O} \) and \( U_{g,N} \), respectively. The two voltages are represented by their effective values in the same way as they take part in the volt-ampere characteristic. Actually, after discharge ignition they should be represented by their maximal values, \( \sqrt{2} \cdot U_{g,O} \) and \( \sqrt{2} \cdot U_{g,N} \), respectively, for the effective value is meaningless under these conditions.

The equivalent electric circuits of the LV-CD discharge for different stages of burning may be presented by using corresponding voltage sources substituting for the discharge gap. The air gap is substituted by two capacitors, \( C_{A,O} \) and \( C_{A,N} \), connected in series in such a way that at the first non-operating stage of discharge development the equivalent circuit consists of three capacitors connected in series, Fig. 2a. At the second stage, the discharge gap is substituted by the in-series connection of a source of voltage equal to the burning voltage \( U_{g,O} \) and capacitor \( C_{A,N} \), Fig. 2b. At the third stage, the discharge gap is substituted by only one voltage source \( U_{g,N} \), Fig. 2c.

All subsequent considerations are made by using the demonstrated three equivalent circuits of the discharge and the plasma generator, Fig. 2.
The inclination of straight-line sectors in the external characteristic is determined by the capacitive reactances as follows, Fig. 2:

\[ C_{OA} = \frac{C_{\delta,O} C_{\delta,N} + C_b}{C_{\delta,O} + C_{\delta,N} + C_b}; \]
\[ C_{air} = \frac{C_{\delta,O} C_{\delta,N}}{C_{\delta,O} + C_{\delta,N}}; \]
\[ C_{OA} = \frac{C_{air} C_b}{C_{air} + C_b}. \]

\[ C_{AB} = \frac{C_{\delta,N} C_b}{C_{\delta,N} + C_b}. \]

\[ C_{CD} = C_b. \]

The basic electrical characteristics for sector AB and the critical parameters, namely the critical current \( I_{cr} \) and critical voltage \( U_{cr} \), may be wholly presented by the voltage of discharge burning \( U_{g,O} \):

\[ I_{av} = \omega C_{\delta,N} \left(U_{eff} - U_{g,O}\right); \]
\[ J_{\delta} = \frac{\omega C_{\delta,N} U_{g,O}}{S} \left(U_{eff} - \frac{\omega C_{\delta,N} U_{g,O}}{S} = BU_{eff} - A; \right) \]
\[ P = U_{g,O} (I_{av} - I_{cr}); \]
\[ p_a = \frac{U_{g,O}}{S} (J_{av} - J_{cr}) = \frac{\omega C_{\delta,N} U_{g,O}}{S} U_{eff} - \frac{\omega (C_{air} + C_{AB}) U_{g,O}^2}{S} = DU_{eff} - C; \]
\[ U_{cr,O} = \frac{C_{air} + C_{AB}}{C_{AB}} U_{g,O}; \]
\[ I_{cr,O} = \omega C_{air} U_{g,O}. \]

The external volt-ampere characteristic \( I_{av} = \varphi(U_{eff}) \) is presented as a polygon of three straight-line sectors, each of which corresponding to a different stage of the development of the LF-CD discharge, Fig. 1b. In such a way, the variation of voltage applied helps determine the existence limits of the plasma-chemical regimes of surface
helps determine the existence limits of the plasma-chemical regimes of surface modification, which correspond to the first sector \( AB \) and the second sector \( CD \), Fig. 1a.

The external volt-ampere characteristic \( I_{av} = \varphi(U_{eff}) \) depends on the active area of electrodes \( S \), which determines its applicability to the corresponding concrete electrode systems only. It is used with a scale change, namely \( J_{av} = I_{av}/S \), for plotting the new characteristic \( J_{av} = \xi(U_{eff}) \) that does not depend on the active electrode area \( S \) any more and has a universal character as concerns the electrical processes, for it takes into account the intensity of elementary processes going on in the discharge itself, equation 5.

The processes of dissociation and ionization as well as the plasma-chemical processes that depend on the foregoing ones have a threshold-like character. For instance, the plasma-chemical treatment in ozone- and oxygen-containing cold plasma starts only after the \( LF-CD \) discharge has ignited, i.e. upon attaining the critical parameters of current and voltage, \( J_{cr,O} \) and \( U_{cr,O} \), respectively, which are responsible for the first operating sector \( AB \), equations 8 and 9. The treatment in cold plasma containing nitrogen oxides, which is characteristic for the second sector \( CD \), starts only after reaching the critical electrical parameters corresponding to the new transition: \( J_{cr,N} \) and \( U_{cr,N} \).

The technological effect of the modification depends not on the value of current density \( J_{av} \) at a given time, but on the difference \( J_{av} - J_{cr,O} \). The specific quantity of electricity \( q_S = J_{av} - J_{cr} \), carried over by the discharge per a unit of time through a unit of active area of the electrodes, represents a measure for technological effectiveness of emerging plasma-chemical changes in the air and on the polymer surface treated.

The variation of the specific quantity of electricity \( q_{S,O} \) for the first operating sector \( AB \) may be described as a function of the voltage applied to the electrode system \( U_{cr,O} < U_{eff} < U_{cr,N} \) and the discharge burning voltage \( U_{g,O} \):

\[
q_{S,O} = J_{av} - J_{cr,O} = \frac{\omega}{S} C_{AB} \left(U_{eff} - U_{g,O}\right) = \frac{\omega}{S} C_{air} U_{g,O} \text{ or }
\]

\[
q_{S,O} = \frac{\omega}{S} C_{AB} U_{eff} - \frac{\omega}{S} \left(C_{air} + C_{AB}\right) U_{g,O} = BU_{eff} - \frac{C}{U_{g,O}}.
\]

The technologically effective specific quantity of electricity \( q_{S,O} \) may be also expressed by the surface density of active power \( p_a \), equation 7:

\[
q_{S,O} = \frac{p_a}{U_{g,O}} = \frac{1}{U_{g,O}} p_a = k p_a, \quad k = \text{Const},
\]

i.e. the variation of technologically effective specific quantity of electricity \( q_{S,O} \) is proportional to the surface density of active electric power \( p_a \).
Burning voltage $U_{g,O}$ has the meaning of a specific surface density of the active power of the LF-CD discharge, which is assigned to the technologically effective quantity of electricity carried over by the discharge per unit of time through a unit of active area of the electrodes, or the burning voltage is an intensive characteristic of the technological process:

\[
U_{g,O} = \frac{p_a}{q_{S,O}} = \frac{p_a}{J_{av} - J_{cr,O}}. 
\]

The low voltage of burning $U_{g,O}$ defines a large quantity of electricity $q_{S,O}$ carried over by the discharge through a unit of active area of the electrodes:

\[
k = \frac{q_{S,O}}{p_a} = \frac{1}{U_{g,O}} = \text{Const}.
\]

Four constants define the basic electrical and technological characteristics $J_{av}$, $p_a$, and $q_{S,O}$. These are $A$, $B$, $C$, and $D$. Constants $A$ and $B$ are determined on the basis of the experimentally obtained external static volt-ampere characteristic, while the rest of them are obtained from $A$ and $B$ by using the following basic relations in accordance with equations 5, 7, and 11:

\[
\frac{A}{D} = 1; \quad \frac{A}{B} = \frac{D}{B} = U_{g,O}; \quad \frac{C}{D} = \frac{C}{A} = U_{cr,O} = \left(1 + \frac{C_{air}}{C_{AB}}\right)U_{g,O}
\]

It is sufficient to know four quantities $A$, $B$, $U_{g,O}$, and $U_{cr,O}$, in order to plot the basic electrical and technological characteristics of the LF-CD discharge for the first operating sector of the discharge’s external static characteristic.

Analogous considerations are applied to describing the second operating sector of the external static characteristic, with the only differences that there exist different coefficients $A^*$ and $B^*$, different critical voltage $U_{cr,N}$ and different burning voltage $U_{g,N}$ of the LF-CD discharge.

Fig. 3 illustrates the variation of burning voltage $U_{g,O}$ of the LF-CD discharge, which is characteristic for the first operating sector $AB$, with the variation of the parameters assumed, namely the thickness $\delta$ of the glass (alkaline glass) barrier and the size $b$ of the air gap. The discharge is burning between two rectangular electrodes placed in a flat-parallel manner in a virtually uniform field.

Discharge burning voltage $U_{g,O}$ varies within rather wide limits, remaining between 2.5 and 10.0 kV in a rather large region of the factor space. There are, however, two regions, in which the burning voltage attains up to 20 kV, Fig. 3.
CONCLUSIONS

The present investigation demonstrates the importance of the basic electrical characteristics, namely discharge burning voltages $U_{g,O}$ and $U_{g,N}$, for the integral characterization of its technological behavior in the two main technological regimes.

The specific quantities of electricity $q_{S,O}$ and $q_{S,N}$ together with the surface density of active power $p_a$ may be considered electrical parameters suitable for describing the technological behavior of the LF-CD discharge in the corresponding regime of burning.

Figure 3. Variation of burning voltage $U_{g,O}$ for first operating sector $AB$ of the external static characteristic of LF-CD discharge with the variation of barrier thickness $\delta$ and size $b$ of the gap between electrodes.

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