XXXIX INTERNATIONAL SCIENTIFIC CONFERENCE ON INFORMATION, COMMUNICATION AND ENERGY SYSTEMS AND TECHNOLOGIES

iCEST 2004

Proceedings of Papers

Volume 2

Bitola, 2004

XXXIX INTERNATIONAL SCIENTIFIC CONFERENCE ON INFORMATION, COMMUNICATION AND ENERGY SYSTEMS AND TECHNOLOGIES

-ICEST 2004-

Procedings of Papers – Volume 2 of 2 volumes

Editor:	Prof. Dr. Cvetko Mitrovski
Technical Editor:	Pargovski Jove
Published by:	Faculty of Technical Sciences, Bitola, Macedonia
Printed by:	MIKENA, Bitola, Macedonia
Total print run:	260

ISBN: 9989-786-38-0

CIP – Каталогизација во публикација
Матична и универзитетска библиотека
“Св. Климент Охридски”, Битола

621.391:004(063)(082)
007.52(063)(082)
004.22(063)(082)
621.397.3:004(063)(082)
621.396.67(063)(082)
004.738.5(063)(082)

INTERNATIONAL scientific conference on information, communication and energy systems and technologies (39 ; 2004 ; Bitola)
ICEST 2004 : proceedings of papers / XXXIX International scientific conference on information, communication and energy systems and technologies ; [editor Cvetko Mitrovski]. - Битола : Технички факултет, 2004. – 2 св.
(XVI, 422 ; XVI, 422 стр.) : илустр. ; 28 см

Библиографија кон трудовите. – Регистар

ISBN 9989-786-38-0
1. Gl. Stv. nasl. 2. Mitrovski, Cvetko
а) Електроенергетски системи – Зборници б) Кодирање – Зборници в) Дигитална обработка на сигнали – Зборници г) Антени – Зборници д) Интернет – Зборници ѓ) Индустриска електроника – Зборници
COBISS.MK-ID 17470017

Dear Colleges,

On Behalf of the Technical Program Committee I was given the pleasure to wish you a welcome on the International Scientific Conference on Information, Communication and Energy Systems and Technology, **ICEST 2004**, which will be held from June 16 through 18, 2004 at the Winter-Summer Tourist Centre “Pelister” near Bitola.

The Conference is organized by the Faculty of Technical Sciences at the Saint Kliment Ohridski University of Bitola, Faculty of Electronics at the University of Nis and by the Faculty of Communications and Communication Technologies at the Technical University of Sofia, in cooperation with IEEE sections of Macedonia, Serbia and Montenegro, and Bulgaria. This year, the Faculty of Technical Sciences-Bitola has an honor for first time to be a host of the Conference under the ICEST acronym and we shall do our best to fulfill the standards established by our partners on the previous two ICEST Conferences.

This year, the Conference Program includes 222 papers for oral and poster presentation which are going to be presented by more than 150 participants of the Conference. Therefore the participants will have rather busy schedule, which I sincerely hope, won’t affect their presentations. I also hope that the Conference will be the place where you can strengthen the collaboration among the institutions and the countries you are representing by sharing your ideas and your scientific results.

At last I want to express my gratitude to all our sponsors that has enabled the organization of this conference.

I wish you all a pleasant and a fruitful work on the ICEST-2004!

Assoc. Prof. D-r Cvetko Mitrovski
Conference Chairman

iCEST 2004

XXXIX INTERNATIONAL SCIENTIFIC CONFERENCE ON INFORMATION, COMMUNICATION AND ENERGY SYSTEMS AND TECHNOLOGIES

organized by

Faculty of Technical Sciences
University “St. Kliment Ohridski”, Bitola, Macedonia

Faculty of Communications and Communications Technologies
Technical University of Sofia, Bulgaria

Faculty of Electronic Engineering
University of Niš, Serbia and Montenegro.

with support of

- Ministry of Education and Science Macedonia
- Macedonian Science Society-Bitola
- ETAI Macedonia
- ALCATEL Macedonia

in cooperation with

- IEEE Macedonia Section
- IEEE Bulgaria Section
- IEEE Serbia and Montenegro Section

ICEST HISTORY

The ICEST Conference appears to succeed a series of conferences started from 1963 at the Technical University of Sofia under the name "Day of the Radio". In 1977 the name of the Conference was changed into "Communication, electronic and computer systems".

Since 2000 it has become an international conference under the name EIST (Energy and Information Systems and Technologies). The first two EIST Conferences were organized by the Faculty of Communications and Communication Technologies, Sofia and the Faculty of Technical Sciences, Bitola.

In 2002 the Faculty of Electronic Engineering, Niš joined successfully the Conference organizers. Again, the Conference changed its name becoming ICEST (International Scientific Conference on Information Communication and Energy Systems and Technologies).

This year host of the ICEST conference is the Faculty of Technical Sciences, University "St. Kliment Ohridski", Bitola, Macedonia.

ORGANIZERS OF THE CONFERENCE

General Chairman:

C. Mitrovski	*University "St. Kliment Ohridski"- Bitola, Macedonia*

Vice Chairmen:

B. Milovanovic	*University of Niš, Serbia and Montenegro*
R. Arnaudov	*Technical University of Sofia, Bulgaria*

Members:

G. Dimirovski	*University of Skopje, Macedonia*
B. Dimitrijevic	*University of Niš, Serbia and Montenegro*
N. Dodov	*Technical University of Sofia, Bulgaria*
E. Ferdinandov	*Technical University of Sofia, Bulgaria*
M. Gusev	*University of Skopje, Macedonia*
Lj. Kocarev	*University of San Diego, USA*
Lj. Panovski	*University of Skopje, Macedonia*
V. Litovski	*University of Niš, Serbia and Montenegro*
M. Hristov	*Technical University of Sofia, Bulgaria*
L. Jordanova	*Technical University of Sofia, Bulgaria*
G. Milovanovic	*University of Niš, Serbia and Montenegro*
V. Milutinovic	*University of Belgrade, Serbia and Montenegro*
G. Stojanov	*Technical University of Sofia, Bulgaria*
M. Stojcev	*University of Niš, Serbia and Montenegro*
B. Spasenovski	*University of Skopje, Macedonia*
Lj. Trpezanovski	*University "St. Kliment Ohridski"- Bitola, Macedonia*
D. Velickovic	*University of Niš, Serbia and Montenegro*

ORGANIZING COMMITTEE

Chairman:

P. Mitrevski	*University "St. Kliment Ohridski"-Bitola, Macedonia*

Members:

M. Popnikolova-Radevska	*University "St. Kliment Ohridski"-Bitola, Macedonia*
I. Nedelkovski	*University "St. Kliment Ohridski"-Bitola, Macedonia*
G. Trombev	*University "St. Kliment Ohridski"-Bitola, Macedonia*
N. Acevski	*University "St. Kliment Ohridski"-Bitola, Macedonia*
D. Najdenov	*University "St. Kliment Ohridski"-Bitola, Macedonia*
B. Stevanovski	*University "St. Kliment Ohridski"-Bitola, Macedonia*
V. Ceselkoska	*University "St. Kliment Ohridski"-Bitola, Macedonia*
M. Kostov	*University "St. Kliment Ohridski"-Bitola, Macedonia*
M. Stojcev	*University of Niš, Serbia and Montenegro*
L. Lubih	*Technical University of Sofia, Bulgaria*
I. Docev	*Technical University of Sofia, Bulgaria*

CONFERENCE SECRETARIAT

M. Kostov	*University "St. Kliment Ohridski"-Bitola, Macedonia*
M. Atanasovski	*University "St. Kliment Ohridski"-Bitola, Macedonia*

Faculty of Technical Sciences, Bitola, Macedonia
I. L. Ribar, bb, 7000 Bitola
Phone:+389 47 207 701
Fax: +389 47 203 370

TECHNICAL SUPPORT

A. Kolevska	*University "St. Kliment Ohridski"-Bitola, Macedonia*
J. Pargovski	*University "St. Kliment Ohridski"-Bitola, Macedonia*

CONFERENCE INTERNET SITE

For further information, please visit the Conference Internet Site:

http://www. tfb.uklo.edu. mk/icest2004

TABLE OF CONTENTS

VOLUME 2

Control Systems and Robotics

Electronic Components, Systems and Technologies

Telecommunications Systems and Technology

Electrical Machines

Education Quality

Poster Session

Modeling The External Characteristic Of Cold-Plasma Reactors

Peter Dineff[1] and Dilyana Gospodinova[2]

Abstract – **The external or static volt-ampere characteristic describes the behavior of technological barrier discharge at diverse stages of development and application regimes. Various approaches to mathematical modeling of the external characteristic of cold plasma reactors creating plasma volumes and plasma surfaces for plasma surface modification of polymers and polymeric materials are examined.**

Keywords - **External characteristic, Cold-plasma reactor, One-atmosphere barrier discharge, Plasma surface modification.**

I. INTRODUCTION

Barrier discharges feature serious technological advantages determining their application to the technology of textiles and textile fibers, electronics and microelectronics, and printing industry [1].

Characteristic of all types of barrier discharges is the presence of one or two dielectric barriers separating the electrodes from the working medium.

This remains a purely external token of barrier discharges, as the dielectric barrier performs a quite essential part in discharge occurrence and burning, which is expressed by the following, [1, 2]:

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

❑ the barrier re-distributes the electric field intensity in the interelectrode space, loading electrically the working (gaseous or vaporous) medium, the intensity in this medium increasing ε_δ times with respect to the electric field intensity in the barrier, where ε_δ is the relative dielectric permittivity of the barrier material or it determines the critical parameters of barrier discharge: voltage of ignition U_{bd} and current of ignition I_{bd};

❑ the barrier determines the voltage of burning U_b of the discharge, which remains constant in the course of its burning and does not depend on the working voltage chosen.

! The multiple ionization-related and chemical processes going simultaneously during burning of the barrier discharge at atmospheric pressure present considerable problems not only in controlling of discharge, but also in describing its behavior, [2].

THE TASK of the present work is to use various approaches to modeling the behavior of a low-frequency (50 Hz) barrier discharge, which burns in the volume or on the surface of a cold-plasma generator system, under load or in the absence of a load, in air at atmospheric pressure (**760** ± 25 Torr, **1** atm), i. e. of a *one-atmosphere barrier discharge* (*OABD*).

The investigations are focused on two types of a cold-plasma reactor system:

♦ *the first one* representing two plane-parallel electrodes with a glass barrier between them, which create a plasma volume with relatively uniform distribution of the electric field between the glass barrier and one of the electrodes, i.e. a *one-atmosphere uniform barrier discharge* (*OAUBD*);

♦ *the second one* representing two plane-parallel electrodes, which embrace tightly the glass barrier in such a way, that solely on that side of the barrier, which looks at the comb-shaped electrode, there emerges a plasma surface with strongly non-uniform distribution of the electric field, i. e. a *one-atmosphere non-uniform barrier discharge* (*OANUBD*).

II. General formulation of the investigations

Our experimental investigations [2, 3, 5] performed during a continuous period of time allow to search for a new description of the behavior and control of the barrier discharge at atmospheric pressure, based on its external or static volt-ampere characteristic.

This characteristic expresses the relationship between the average value of current I_{gap} (*AV*) passing through the barrier discharge and the effective value of voltage U_{gap} (*RMS*) applied across discharge, Fig. 1.

Moreover, it turns out [2,3], that the external characteristic may be simulated by means of a broken-line polygon of three linear segments, each of them corresponding to one of the three development stages of the barrier discharge, Fig. 1:

♦ the stage preceding the ignition of the barrier discharge, namely the so-called free or non-operational 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 mostly containing nitrogen oxides.

At high values of linear correlation factor r_{pc} the linear law describes very well the individual sections of the external characteristic of barrier discharge. However, the transitional regions of the characteristic remain outside the scope of this description, because there is a smooth transition between each two adjacent regions, while the polygon simulating the characteristic represents a broken line.

Do the latter two stages (or regimes) of burning of the barrier discharge really exist? The answer is positive, because the analysis of the elementary processes clearly separates from each other the two air media, in which ozone and products of its decomposition are generated, [1]:

---

[1] Peter Dineff is with the Faculty of Electrical Engineering, Technical University of Sofia, Kliment Ohridski 8, 1000 Sofia, Bulgaria, E-mail: dineff_pd@abv.bg.

[2] Dilyana Gospodinova is with the Faculty of Electrical Engineering, Technical University of Sofia, Kliment Ohridski 8, 1000 Sofia, Bulgaria, E-mail: dilianang@abv.bg.

♦ *one of these*, a medium depleted of energy, is created in electric fields of low relative intensity *E/p*, favoring processes with larger cross-section of impact interaction – about 10^{-16} cm^2, i. e. ozone generation from molecular ions O_2^+, where two molecules of ozone O_3 correspond to one molecular ion O_2^+. A product of its rapid decomposition under conditions of α-impact ionization are the exited, chemically active oxigen (O_2^*) molecules (the so-called singlet oxygen);

♦ *the other*, energy-rich medium, is created in electric fields of higher relative intensity *E/p* and favors processes with smaller cross-section of impact interaction – about 10^{-18} cm^2, i. e. the generation of ozone O_3 from atomic ions O^- and O^+ through intermediate synthesis of negative O_3^- and positive O_3^+ ozone ions.

The energy–richer medium of higher values of the relative electric-field intensity *E/p* and plasma temperature creates conditions not only for rapid decomposition of ozone, but also for its inhibition in reactions with negative atomic ions O^-, with atomic oxygen *O*, or with nitrogen oxides NO_x. Such a medium is characterized by rapid depletion as regards the ozone and products of its decomposition. It is enriched with nitrogen oxides, [1].

This thesis is supported by the direct measurement of the ozone obtained in ozone-air mixtures in the two regimes of burning of the barrier discharge, [4].

The mathematical model thus obtained is based on its real reasons, moreover that experiments in modifying low-energy polymeric surfaces indicate different physico-chemical relations of materials in these two cases, [4].

This comes to show that there exist physical, chemical and technological reasons that make this model very useful. One-atmosphere barrier discharge can be simulated and controlled as a voltage-controlled current source.

At the same time *Zhiyu Chen* and *J. Reece Roth* [5] propose a new model of behavior of one-atmosphere barrier discharge based not on the linear law, but on a power one. The discharge current follows a power law, a characteristic of the voltage-current behaviour of a normal glow discharge (in vacuum). For example, the current-voltage relationship of various normal glow discharges in vacuum was $I \propto U^2$, $I \propto U^3$, and $I \propto U^9$.

Its output current follows the power law given by the following equation

$$I = 0\text{, for } U_{gap} < U_{bd} \tag{1}$$

$$I\,\alpha\,\left(U_{gap} - U_{bd}\right)^n\text{, for } U_{gap} \geq U_{bd} \tag{2}$$

where *n* is an integer that may range from 1 to 12 in different types of glow or barrier discharge plasma devices, U_{bd} - the voltage of breakdown.

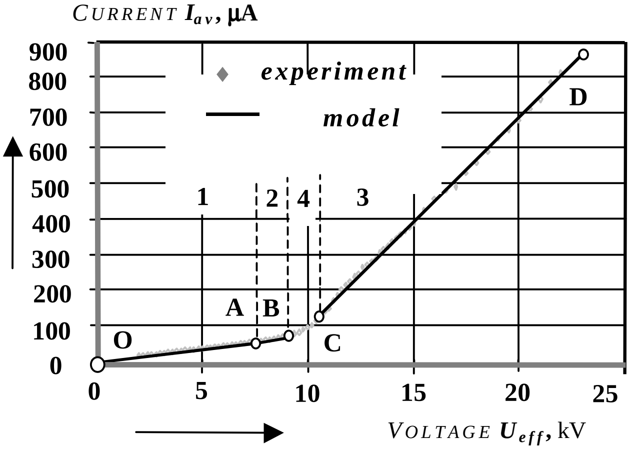

Fig. 1. Operating sectors on the external characteristic of one-atmosphere barrier discharge, namely the relationship between the average value of current I_{gap} and the effective value of applied voltage U_{gap}.

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

A power law, for which $U_{gap} < U_{bd}$ is set equal to zero, does not adequately simulate the behaviour of the one-atmosphere barrier discharge. The power law relates to the whole region of burning of barrier discharge, i. e. for $U_{gap} \geq U_{bd}$.

Furthermore, the authors also assume that the voltage of burning U_b of barrier discharge remains constant, irrespective of the value of voltage U_{gap} applied across discharge gap, and for this reason they also speak for one-atmosphere *glow* discharge plasma (*OAGDP*).

In the present work it is made an attempt to transfer the new relationship found between the instantaneous values of current and voltage onto the simulation of the experimentally obtained external characteristic or between the average value of current I_{gap} and the effective value of voltage U_{gap}. This is a possibility of obtaining a unitary controlling model for the whole region of burning of barrier discharge.

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

❏ 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 ignition of barrier discharge represents a threshold process occurring for certain critical parameters – the voltage of ignition U_{bd} (*max*) and current of ignition I_{bd} (*AV*), this determining the necessity that the description of discharge in the stage of burning is governed by eq. 2;

❏ the barrier discharge may be described in the whole region of burning or individually in each of the two sub-regions of burning;

❏ the generalized equation of barrier discharge burning, governed by the power law, is of the following form:

$$\frac{I_{gap} - I_{bd}}{\left(U_{gap} - \frac{U_{bd}}{\sqrt{2}} \right)^{n}} = B \qquad (3)$$

where I_{gap} (AV) is the current through the barrier discharge; U_{gap} (RMS) – the voltage across discharge gap; I_{bd} (av) and U_{bd} (max) – the critical ignition parameters of discharge; $n \geq 1$ – the exponent; B – a constant determining the increase of discharge current.

❑ the generalized equation includes in itself the linear law of variation as a particular case at $n = 1$:

$$\frac{I_{gap} - I_{bd}}{\left(U_{gap} - \frac{U_{bd}}{\sqrt{2}} \right)} = B = tg\alpha \text{ , or} \qquad (4)$$

$$I_{gap} = B\,U_{gap} + A \text{ , at} \qquad (5)$$

$$A = I_{bd} - B\frac{U_{bd}}{\sqrt{2}} . \qquad (6)$$

II. RESULTS AND DISCUSSION

A. General presentation of the regions of burning

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

External characteristics of the type $I_{gap}\,(AV) = \varphi\,[\,U_{gap}\,(RMS)\,]$ are obtained experimentally for two types of plasma generator systems:

♦ *the first one* having a virtually uniform electric field of a one-atmosphere uniform barrier discharge – the so-called *OAUBDG*-system; and

♦ *the second one* having a non-uniform electric field of a one-atmosphere non-uniform barrier discharge – the so-called *OANUBDG*-system.

The *OAUBDG*-system creates a plasma volume between the glass barrier and one of the two planar metal electrodes of area $S = 651.5\ cm^2$ and shape reducing the edge effect, the thickness of the plasma region being $H = 6\ mm$. The barrier capacitance is $C_\delta = 1192\ pF$, measured at industrial frequency.

The *OANUBDG*-system creates a plasma surface on one of the two flat metal electrodes of area $S = 480\ cm^2$ that embrace tightly the glass barrier. The discharge burns on the side to the electrode made in the form of a comb with width of *4 mm* of its constituent elementary electrodes and a distance of *4 mm* between each two of them. The discharge burns on the dielectric barrier itself – between the elementary electrodes. The barrier capacitance is $C_\delta = 536\ pF$ measured at industrial frequency.

The experimentally obtained external characteristics (for both plasma systems) permit applying both approaches to modeling in no-load regime.

The linear model for the ozone-oxygen region of burning the barrier discharge has the following parameters in accordance with eq. 5, Table 1.

TABLE 1.

SYSTEM	**B**, µA/kV	**A**, µA	***U_bd***, kV	***I_bd***, µA	*Correlation Coefficient r_{lc}, /*
OAUBDG	19.58	- 0.55	7.700	151	0.999375
OAUNBDG	349.7	- 455	3.014	599	0.998380

The linear model for the second region (that of the nitrogen oxides) of discharge burning has the following parameters in accordance with eq. 5, Table 2.

TABLE 2.

SYSTEM	**B**, µA/kV	**A**, µA	***U_bd***, kV	***I_bd***, µA	*Correlation Coefficient r_{lc}, /*
OAUBDG	26.82	- 62.5	11.92	250	0.993858
OAUNBDG	399.0	- 1145	14.00	4441	0.998640

The model generalized according to the power law for the whole region of discharge burning has the following characteristical parameters in accordance with eq. 3, Table 3.

TABLE 3.

SYSTEM	***U_bd***, kV	***I_bd***, µA	INTEGER n, /	*Correlation Coefficient r_{lc}, /*
OAUBDG	7.700	151	1.5	0.99467
OAUNBDG	3.014	599	1.1	0.99934

In loading the *OAUBDG*-system almost the whole plasma volume is filled with the material to be treated; in this case this is a non-woven textile based on polyethylene terephthalate (PET) with area mass 500 g/m^2. For this type of textile load the external characteristic changes to a significant extent – the region of burning is a single one and corresponds to the first characteristic region of burning, Table 4.

TABLE 4.

SYSTEM - MODEL	**B**, µA/kV	**A**, µA	***U_bd***, kV	***I_bd***, µA	*Correlation Coefficient r_{lc}, /*
OAUBDG- Linear model	359.37	- 372	10.85	172	0.992730
SYSTEM - MODEL	**INTEGER** n, /		***U_bd***, kV	***I_bd***, µA	*Correlation Coefficient r_{lc}, /*
OAUBDG- Power law	1.47		10.85	172	0.999195

Analyzing the models obtained indicates that both approaches enable making a description of the process by regions of burning or for the whole region of burning at a relatively high value of the linear correlation factor. This makes possible the application of both approaches for the purposes of examining or controlling the technological process.

Describing fully the process of discharge burning by means of a single function is of great practical importance, as it allows investigating very easily the influence of various parameters of the plasma generator system upon exponent *n* as well as upon two parameters critical for the ignition - I_{bd} and U_{bd} , Table 3.

Moreover, this characteristic may be made linear by taking the logarithm of both sides of eq. 3:

$$lg\left(I_{gap} - I_{bd}\right) = n\ lg\left(U_{gap} - \frac{U_{bd}}{\sqrt{2}}\right) + lg\ B\ . \qquad (6)$$

The linear model is suitable for making an individual description for each of the two characteristic regions of burning of the discharge. This is especially imperative in the case of realizing a technology in only one of the two technological regions of burning.

A. Using the power law model for describing the individual regions of burning of the discharge.

The values of the linear correlation factor are not always high, i. e. above 0.96, all over the investigated region, Fig. 2.

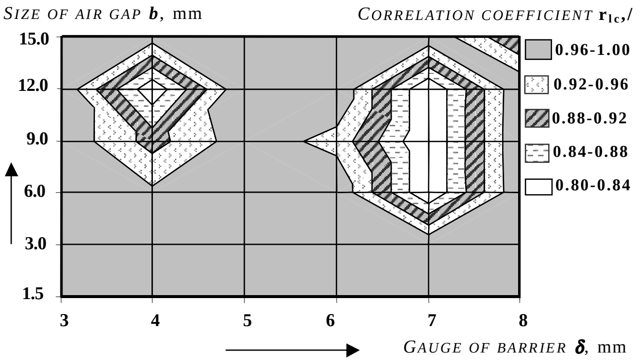

Fig. 2. There are regions in the space examined – thickness of the dielectric barrier δ and size of plasma volume b, of the first sub-region (or regime) of burning without load of the *OAUB*-discharge, in which linear correlation factor r_{lc} is of relatively low values, namely below 0.96.

This situation can be changed if using the generalized law for describing those individual regions of burning of the discharge, which are characterized by lower degree of linearity of the external characteristic.

As an example it is taken an *OAUBDG*-system with barrier thickness $\delta = 7\ mm$ and largest size of plasma volume $H = 9\ mm$, operating in a regime under load: treating PET non-woven textile with area mass $500\ g/m^2$ and thickness $5\ mm$. At $n = 1$ the linear correlation factor is relatively low, namely 0.9898, Table 6.

Verifying linear correlation factor r_{lc} for various values of exponent n indicates a new, higher value of $r_{lc} = 0.9960$ at $n = 1.66$, Table 6.

This is another possibility of describing more precisely the two technological sub-regions of burning of the one-atmosphere barrier discharge.

III. CONCLUSION

By using both methods investigated, it is possible to model successfully the experimentally obtained external characteristic of one-atmosphere barrier discharge with industrial frequency (*50* or *60* Hz) in the region of burning, either as a whole, or individually for each of its two parts.

TABLE 5.

SYSTEM - MODEL	**B**, μA/kV	**A**, μA	U_{bd}, kV	I_{bd}, μA	*Correlation Coefficient* r_{lc}, /
OAUBDG - Linear model	97.56	- 1079	12.56	146	0.9898
SYSTEM - MODEL	*Integer* n, /	**B**, μA/kV	U_{bd}, kV	I_{bd}, μA	*Correlation Coefficient* r_{lc}, /
OAUBDG - Power law	1.66	13.7	12.56	146	0.9960

The linear law that relates the average value of current I_{gap} through the discharge to the effective value of voltage U_{gap}, applied across discharge gap, is suitable for describing and controlling the burning of discharge in its two technological sub-regions, while the power law is more suitable for involving the whole region of burning of the barrier discharge.

However, the power law may be applied with the same success to certain cases, where a more precise description of behavior in the two sub-regions of burning is necessary.

In both cases, starting from the models of the external characteristic obtained as described and performing the necessary calculations, it is possible to determine the technological characteristic of the barrier discharge.

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**, Athens, 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.

[5] P. Dineff, R. Boshnakova**.** Production of Ozone-Air Gaze Mixture at Low Voltage Barrier Discharge. XI. Symposia with International Participation on Electrical Apparatus and Technologies "SIELA '95", Plovdiv, Bulgaria, June 01-02, **1995**. Proceedings, v.1, pp. 214-219 (in Bulgarian).

ACKNOWLEDGEMENT

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

One Atmosphere Barrier Discharges With Electrode Edge Effect

Peter Dineff[1] and Dilyana Gospodinova[2]

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].

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.

---

[1] Peter Dineff is with the Faculty of Electrical Engineering, Technical University of Sofia, Kliment Ohridski 8, 1000 Sofia, Bulgaria, E-mail: dineff_pd@abv.bg.

[2] Dilyana Gospodinova is with the Faculty of Electrical Engineering, Technical University of Sofia, Kliment Ohridski 8, 1000 Sofia, Bulgaria, E-mail: dilianang@abv.bg.

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.

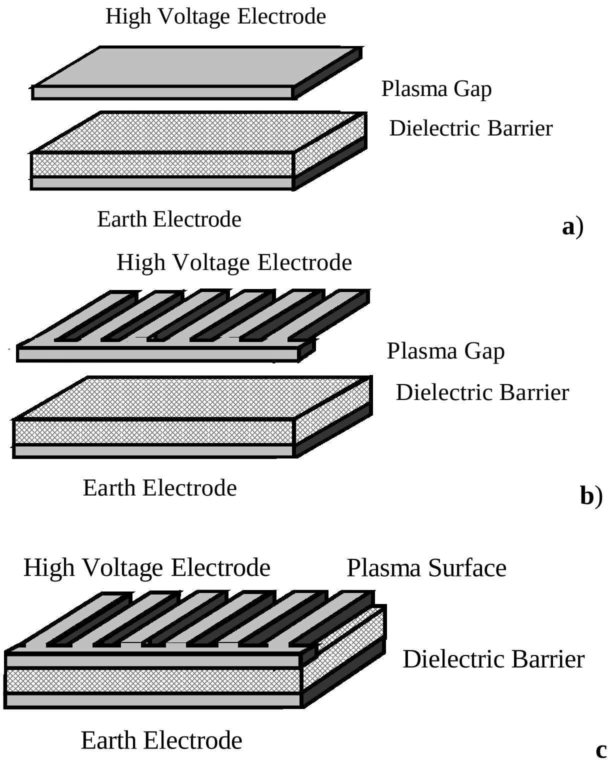

Fig. 1. Types of plasma reactor systems used in the experimental investigation: a - one atmosphere uniform barrier discharge (*OAUBD*); b - one atmosphere edge effect serial barrier discharge (*OAEESBD*); c - one atmosphere edge effect parallel barrier discharge (*OAEEPBD*).

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 - $I_{gap}\left(AV\right)=\varphi\ [\ U_{gap}\left(RMS\right)\ ]$, 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:

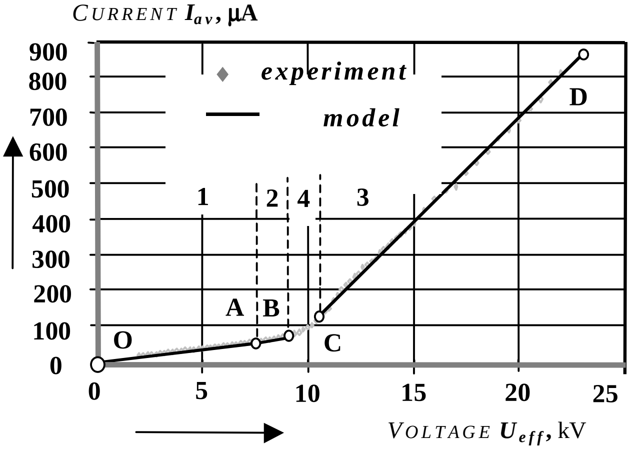

Fig. 2. Operating sectors of the external characteristic of one atmosphere barrier discharge, which represents the relationship between the average value of current I_{gap} and the effective value of applied voltage U_{gap}.

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):

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

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

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

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.

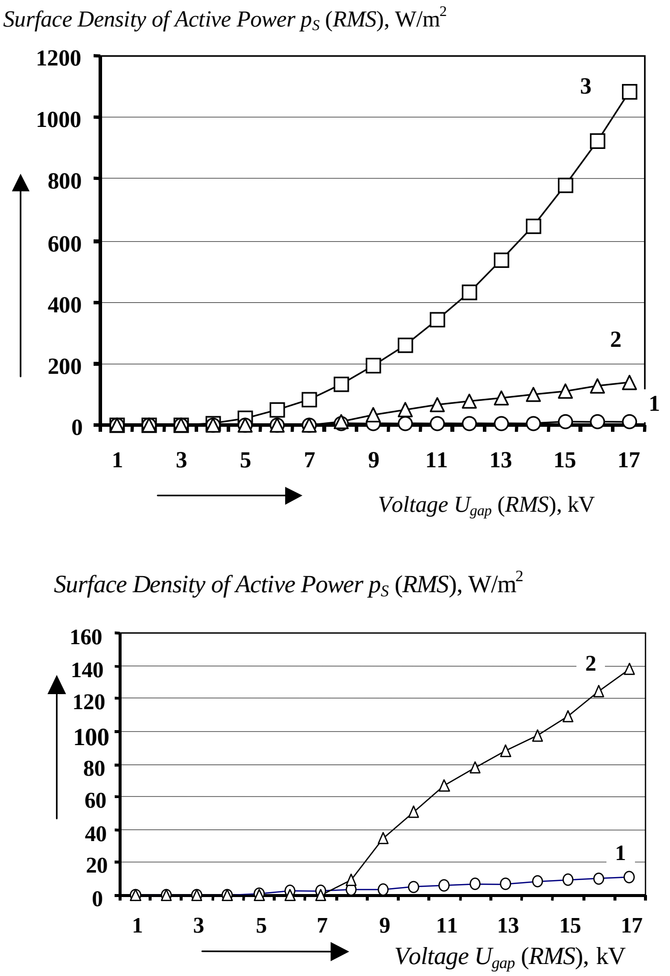

Fig. 3. Variation of surface density of active power p_S with applied voltage U_{gap}: **1** - *OAUBD*-reactor system; **2** -*OAEESBD*-reactor system; **3** - *OAEEPBD*-reactor system.

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.

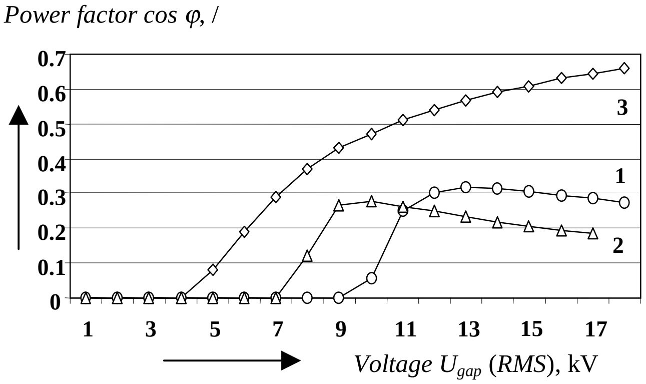

Fig. 4. Variation of power factor cos φ with the voltage applied across the discharge gap in different plasma generator systems: **1** - *OAUBD*; **2** - *OAEESBD*; **3** - *OAEEPBD*.

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 ÷ 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.

AUTHOR INDEX