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CONTENTS

ENERGY CHARACTERISTICS AND PARAMETERS OF NON-UNIFORM (PIN-TO-PLANE) DIELECTRIC BARRIER DISCHARGE

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Abstract. Interesting types of *DBD* in ambient air at atmospheric pressure for the generation of non-thermal plasma on dielectric surfaces were investigated. *Pin-to-plane dielectric barrier discharge* was sustained in the electrode configurations combining electrode components of both corona and *DBD* – metallic pins or triangle spikes electrode, situated single- or double-in-line and metallic plate electrode covered with a dielectric barrier. It was investigated experimentally the burning mode of this new discharge in ambient air. The discharge behavior with single- and double-in-line spikes high voltage electrode was discussed. The *pin-to-plane DBD* is a new *DBD*-based discharge rich in energy that produces a lot of chemically active centers on the wood surface by functionalization (oxidation).

Keywords: burning voltage, critical parameters, dielectric barrier discharge, non-uniformity, operating area, single- and double-in-line spike electrode.

INTRODUCTION

The surface properties are determined by a thin layer of molecular dimensions and can be changed without influencing the bulk properties of the low surface energy materials. Paper, fibers and other cellulosic materials are mostly characterized by non-polar chemically inert surfaces with surface energy in the 20÷40 mN/m range. In general, wood (cellulosic) materials are wetted by liquids when the surface energy of the wood surface exceeds the surface energy of the liquid. The surface energy of common organic solvent is lower than that of the wood, therefore paints, inks, adhesive and impregnating solution based on organic solvents are successfully applied to wood and cellulosic materials. Environmental requirements call for a replacement by water-based paints, inks and bonding agents. Flame retardency is accomplished by capillary impregnation with water solution containing different kind of flame retardants. Because of the high surface tension of water (72.1 mN/m) a treatment of low energy surface is necessary to improve their surface energy.

Low surface energy impedes surface contamination and allows easy cleaning, but it complicates such processing as printing, coating, sticking, impregnation, etc. Various processes have been developed for surface treatment to enhance adhesion and capillary activity, such as mechanical treatment, wet-chemical treatment, exposure to flames, and cold (non-thermal) plasma treatment in atmospheric dielectric barrier discharge (*A-DBD*).

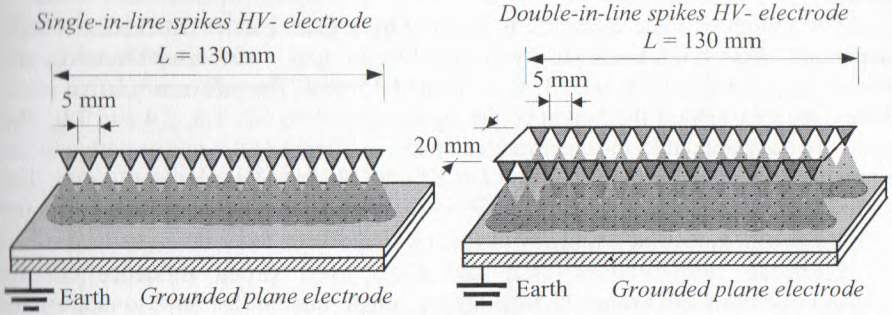


Figure 1. Electrode configurations of dielectric barrier discharge (*DBD*): **a** -*pin-to-plate DBD* with *single-in-line* spikes electrode (*SILS electrode*); **b** – *pin-to-plate* DBD with *double-in-line* spikes electrode (*SILS electrode*).

Plasma surface treatment of dielectric surfaces at atmospheric pressure with *alternative current barrier corona* (*AC-BC*) or *pin-to-plane DBD* were published recently (*Akishev* et al, 2002; *Radu* et al, 2003). These discharges were sustained in the electrode configuration combining the electrode elements of both:– a pins (spike) electrode came from corona discharge, and a plate electrode covered with a dielectric barrier came from *A-DBD*. The authors experimentally and theoretically investigated the burning mode of this pin-to-plane *DBD* in ambient air at atmospheric pressure. Diverse applications including the functionalization demand a solid physical and chemical understanding of the operational principals of such discharges.

The effect of plasma surface treatment and pre-treatment depends on the energy input into the plasma-chemical surface (or volume) process. For the energy flow on a resting substrate surface, the dosage D is used: $D = (P\,t)/A$, (W sek)/m^2 or J/m^2, where P is the real power introduced into the discharge, W; A is the substrate (electrode) surface, m^2; and t is the process duration of the, sek. If the substrate surface is moving with linear velocity ϑ, m/sek, for the absorbed energy flow the dosage D is used: $D = P/(b\,\vartheta)$, J/m^2, where b is the treated surface width, m. The real power P introduced into the discharge is an important parameter to achieve desired surface chemistry for the both surface material operations and it characterize the result of the chemical interaction of non-thermal plasma with the low energy treated surface.

The aim of this paper is the experimental study of energy characteristics and parameters of a special *pin-to-plane DBD* with different electrode configuration, Fig. 1.

EXPERIMENTAL INVESTIGATION

The *pin-to-plate DBDs* are typical discharges with expressed local non-uniformity closeness high-voltage electrode that consists a lot of pins (spikes) arranged the length of electrode according two way – *single-in-line* or *double-in-line*, Fig. 1a and b. An alumina profile is used for making the two studded high voltage electrode configurations with *single-in-line* (*SIL*) and *double-in-line* (*DIL*) arranged spikes, Fig. 1.

The grounded plate electrode is covered by a glass barrier (thickness: 3 mm) and separated form high electrode by a variable air gap – the inter-electrode gap distance d is varies on five levels: 3, 6, 9, 12 and 15 mm. The relevant relative inter-electrode distances toward the height of the spikes are – 0.6, 1.2, 1.8, 2.4 and 3.0. The distance between the double-in-line arranged spikes is 20 mm or 4.0 units relative to the spike height. The length of the *SILS*- and *DILS* high voltage electrodes is 130 mm. The electrodes are energized by a high voltage power supply with typical voltages in the 1÷20 kV range and industrial frequency (50 Hz), [1, 2].

Electrode configurations *SILS* and *DILS* exert strong influence on the breakdown conditions and avalanche to streamer transformation that have to modify not only the *DBD's* volt-ampere characteristic, ignition U_b voltage, and critical parameters of operating sub-area, [1], but the energy effectiveness operational parameters of the operational (real power-voltage) characteristics - $P = \varphi(U_{RMS})$, $d = const$.

The static volt-ampere characteristics of *pin-to-plane DBDs* have been plotted experimentally, linear polygonal discharge models have been worked out in accordance with a well known method for a minimal coefficient of linear correlation, not less than 0.9900, and then all the electrical parameters – burning voltage U_b and ignition parameters (voltage U_{ig} and current I_{ig}) of the *DBDs* operating areas - first and next ones, have been calculated, [2].

RESULTS AND DISCUSSION

The burning voltage U_b and ignition current I_{ig} calculated from discharge models, the real power P can be determined as a function of current I_{AVG} through the electrode configuration, or corresponding voltage drop U_{RMS} across the electrode cell, for all operating areas, [for $(I_{AVG} - I_{ig,\,AVG}) > 0$, or $U_{RMS} > U_{ig,\,RMS}$], after the next equation (*Filippov-Emeljanov*, 1958), Fig. 2:

$$P = U_b\,(I_{AVG} - I_{ig,\,AVG}),\ \text{W}. \qquad (1)$$

The real specific power p_0 (per one length of the high voltage electrode) is calculated from the real length of electrode configuration L = 0.130 m, Fig. 3:

$$p_0 = \frac{P}{0.130},\ \text{W/m (Wpm)}. \qquad (2)$$

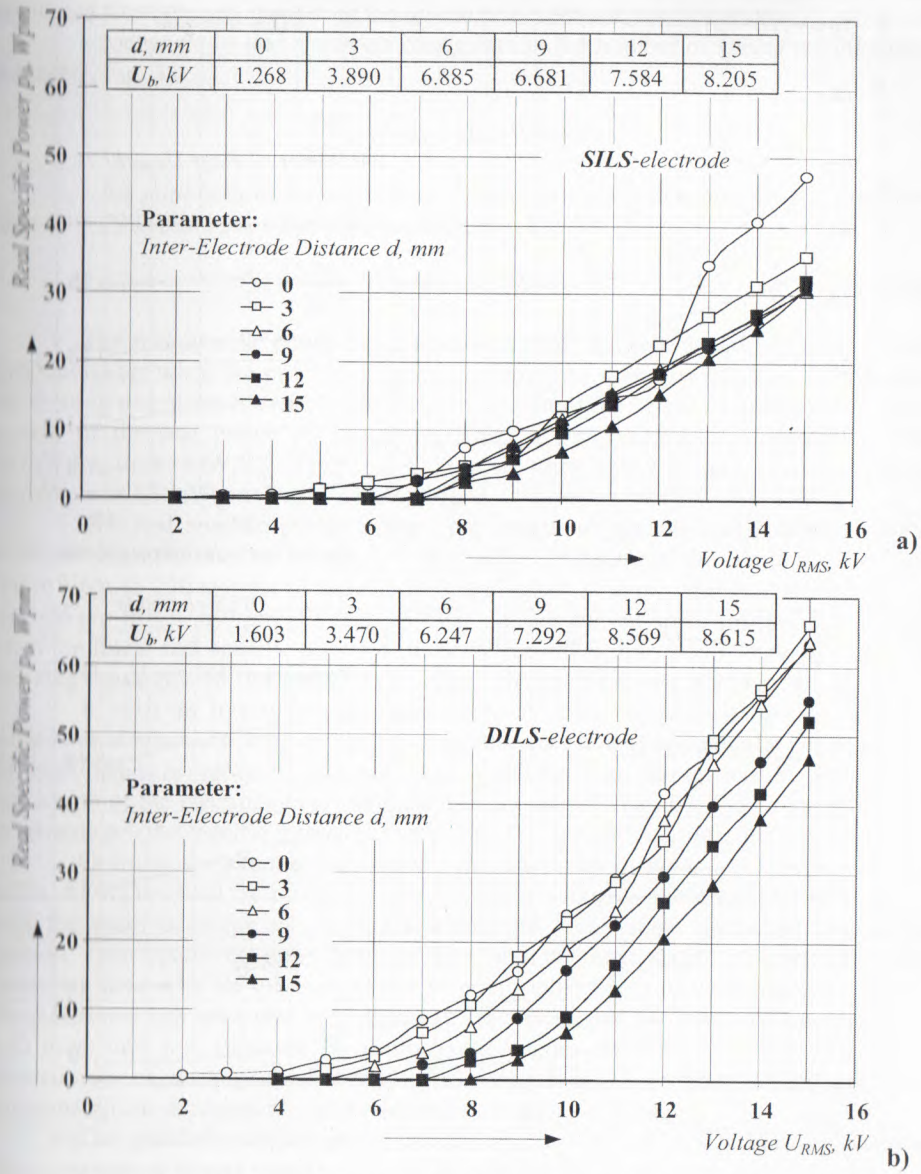


Figure 2. Families of energy efficiency characteristics of *pin-to-plate DBDs* $p_0 = f(U_{RMS})$, $d = const$, with electrode configuration: **a** – *single-in-line* spikes (*SILS*-) electrode; **b** – *double-in-line* spikes (*DILS*-) electrode.

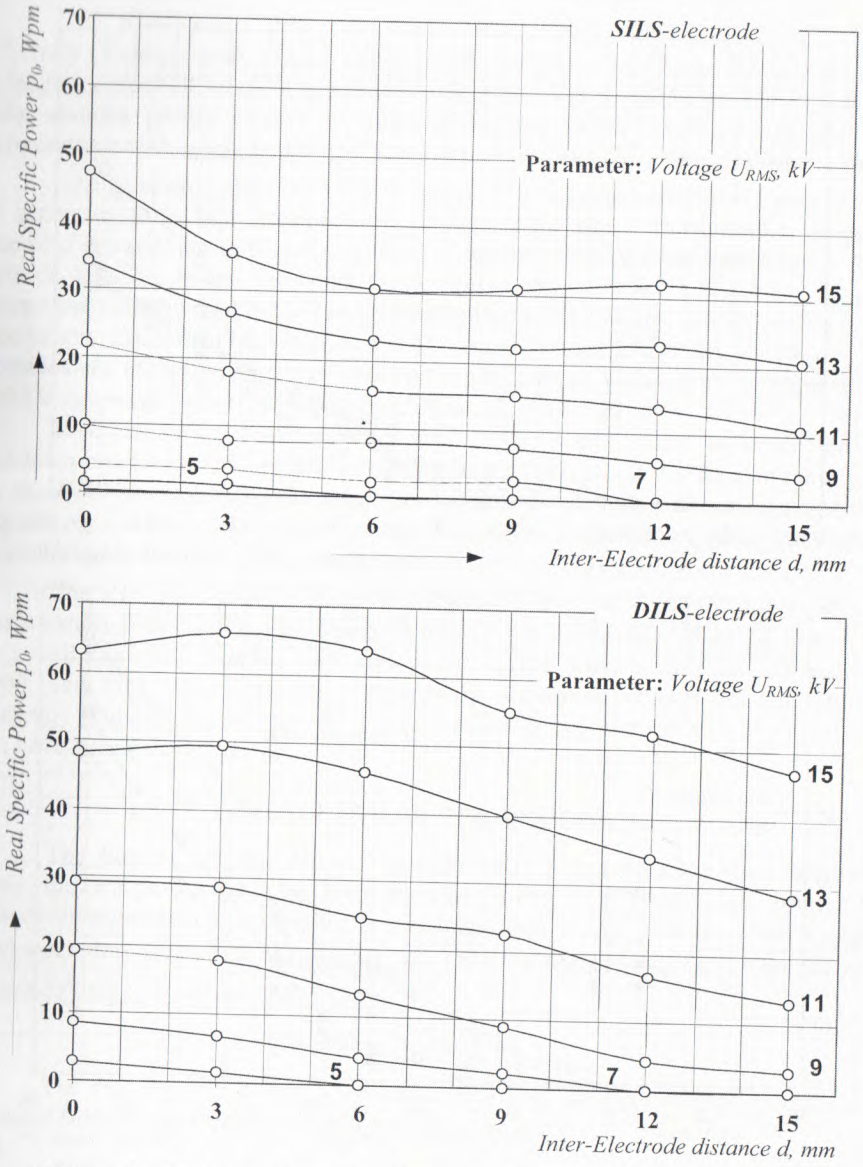


Figure 3. Families of energy efficiency characteristics of *pin-to-plane DBDs*: $p_0 = \varphi(d)$, $U_{RMS} = const$, with electrode configuration: **a** – *single-in-line* spikes (*SILS*-) electrode; **b** – *double-in-line* spikes (*DILS*-) electrode.

The real specific power p_0 (per one spike of the high voltage electrode) was calculated from the real number of the investigate electrode configuration:

- for *single-in-line electrode configuration* the number of spikes is 200 spikes per meter, Fig. 3a:

$$p_S = \frac{p_0}{200}, \text{ W per spike (Wps);} \quad (3)$$

- for *double-in-line electrode configuration* the number of spikes is 400 (two rows with 200 spikes per meter) spikes per meter, Fig. 3b:

$$p_S = \frac{p_0}{400}, \text{ W per spike (Wps).} \quad (4)$$

The real specific power p_0 (per one meter of electrode length) of *pin-to-plane DBD* increases when the number of spikes is double by adding a new row of spikes to the existing one at the distance of 20 mm (or four times the height of the spike). But the growth of the real power p_0 is very different – for example, the growth is form 30 mWpm to 64 mWpm (6 mm, 15 kV); and other example: the growth is form 46 mWpm to 66 mWpm (3 mm, 15 kV), Fig. 3.

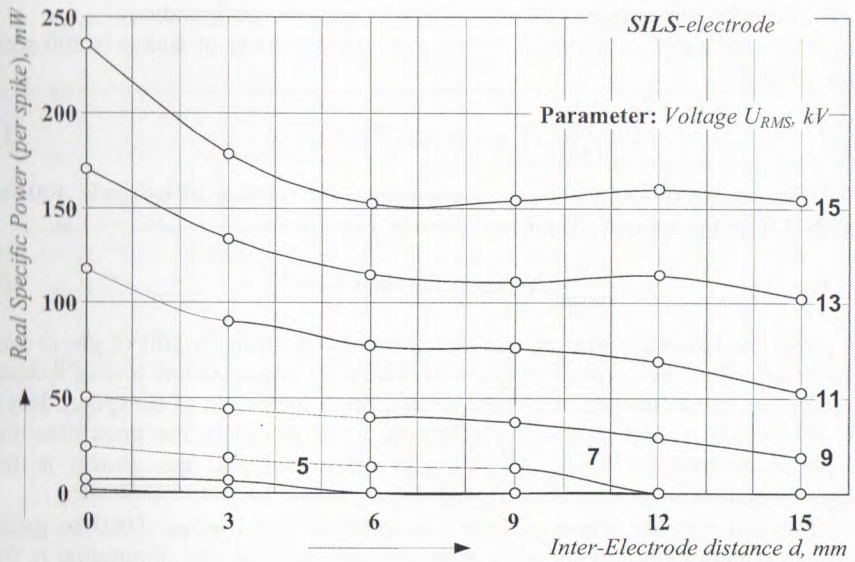
The real specific power p_S (per one spike) of *pin-to-plane DBD* in general decrease when the number of spikes is doubled – for example, the diminution is from 180 mWpm to 130 mWpm (3 mm, 15 kV); and other example: the diminution is form 160 mWpm to 130 mWpm (12 mm, 15 kV), i. e. the current spike loading p_S decrease when the linear real specific power p_0 increase by adding one parallel row of spikes or realizing the double-in-line spikes high voltage electrode pin-to-plane, Fig. 4.

It exist an interaction between the local spike microdischarges of adjacent spike lines at relatively large distances – four times the height of particular spike, for the different distances between electrodes, Fig. 4. If this examination will be applied for unit length of the electrode configuration (per one meter) then *DILS*-configurations has its advantage - the specific discharge real power P is higher with more then 50 %.

Ordinary the external volt-ampere characteristics of *plane-to-plane* (co-planar) *DBDs* are represented by polygonal linear models with tree sub-areas that correspond with the main development stages of discharges - the stage preceding the *DBDs* ignition, (non-operating area); and the first and the next stages of burning *DBDs* (operating area with its sub-areas). The external volt-ampere characteristics of *pin-to-plane DBDs* at low inter-electrode distances are represented by polygonal linear models with more then tree sub-area. By analogy, the energy efficiency or the technological characteristic of *pin-to-plane DBDs* $p_0 = f(d)$ or $p_S = \varphi(d)$, $U_{RMS} = const$, are presented by polygonal linear models with more than two operating sub-area.

The generalized real power model of *pin-to-plane DBDs* burning has the following special feature common for all *DBD*-based discharges:

i) the *pin-to-plane DBD* burns at a constant burning voltage, i. e. $U_b = \text{const}$, but the inter-electrode distance d does not significant influence on the change of the burning voltage and the real power P;



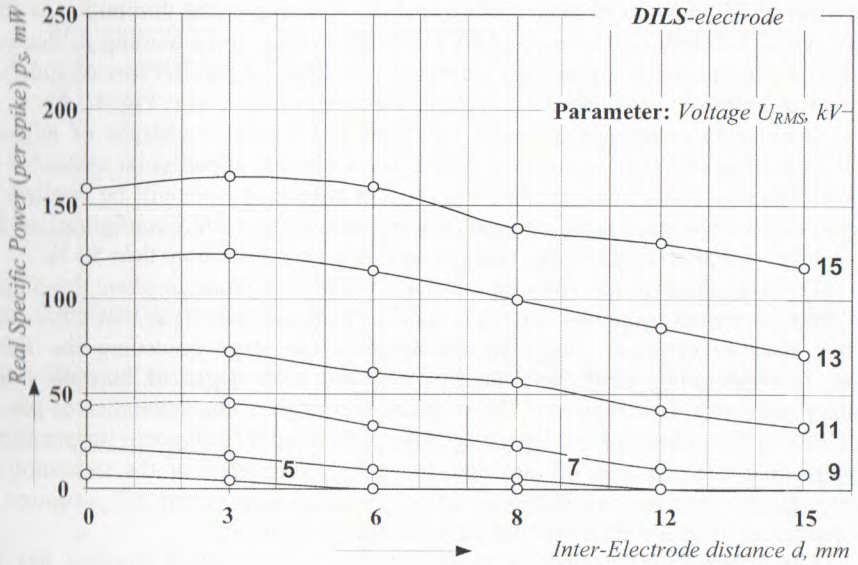


Figure 4. Families of technological pin-to-plane *DBDs* characteristics $p_S = \varphi(d)$, $U_{RMS} = const$, of the two investigated electrode configurations: **a** – *single-in-line* spikes (*SILS*-) electrode; **b** – *double-in-line* spikes (*DILS*-) electrode.

ii) the ignition of *pin-to-plane DBD* or the transitions to a new operating area are threshold processes occurring for certain critical parameters – ignition voltages and currents (U_{ig} and I_{ig}) - but the inter-electrode distance d does not significant influence on the change of the critical parameters U_{ig} and I_{ig} and the real power P;

iii) the *pin-to-plane DBD* have to be described by the linear relationship between the real power P and the *RMS* value of voltage – the coefficient of linear correlation gets values above 0.9900 at low inter-electrode distances – d ∈ [3÷15 mm] or $d^* = d/L \in [0.6 \div 3.0]$.

This model is based on following linear equation for all operating areas - $P = D.U_{RMS} + C$, where D is the slope, W/V, and C– the intercept of the geometric line, W.

XPS- measurements have been used to study the resulting plasma-chemical modifications on the polymer surface. XPS analysis in this work was carried out using an photoelectron spectrometer VGS ESCALAB Mk II with Al Kα x-ray radiation ($h\nu$ = 1486.6 eV; *FWHM* = 0.5 eV). XPS instrument use soft x-ray (200÷2000 eV) radiation to examine core-levels.The angle between the incident X-ray directions and the observations (fixed by analyzer entrance slit) was 50^0. Used instrument accept samples: 10 x 10 mm. The minimum analysis area ranges are from 10 to 200 micrometers (μm).

XPS- analysis is a surface chemical analysis technique that can be used to analyze the surface chemistry of a material in its "as received" state, or after some treatment such as non-thermal plasma with *pin-to-plane DBDs* (only for one minute), for example. *XPS* detects all elements with an atomic number (*Z*) of 3 (*lithium*) and above. This limitation means that it cannot be detect hydrogen (*Z*=1) or helium (*Z*=2). Detection limits for most of the elements are in the parts per thousand ranges (0.1 atom % = 1 part per thousand = 1000 ppm).

Table 1. XPS- surface chemical analysis of surface plasma-chemically treated heart wood samples.

X-ray photoelectron spectroscopy (mono-Al Kα radiation)							
Douglas fir Wood Samples After DBD Plasma Treatment		*Operational Voltage Area Above U_b, kV*	*RMS Voltage U_{RSM}, kV*	*Specific Real Power P, Wpm²*	*Wood Surface Composition (1÷5 nm usually), at. %*		
					C	**O**	**N**
Pin-to-plate DBD	No.1	6.628	7.0	201.900	76.5	23.4	0.1
	No.2		9.5	855.400	83.0	16.8	0.2
	No.3	10.776	11.0	1230.000	84.9	14.6	0.5
Co-planar DBD	No.4	7.000	10.0	2.565	68.3	31.7	0.0
	No.5	11.920	15.0	56.037	69.1	29.9	1.0
K	No.6	-	-	-	**77.7**	**21.8**	**0.5**

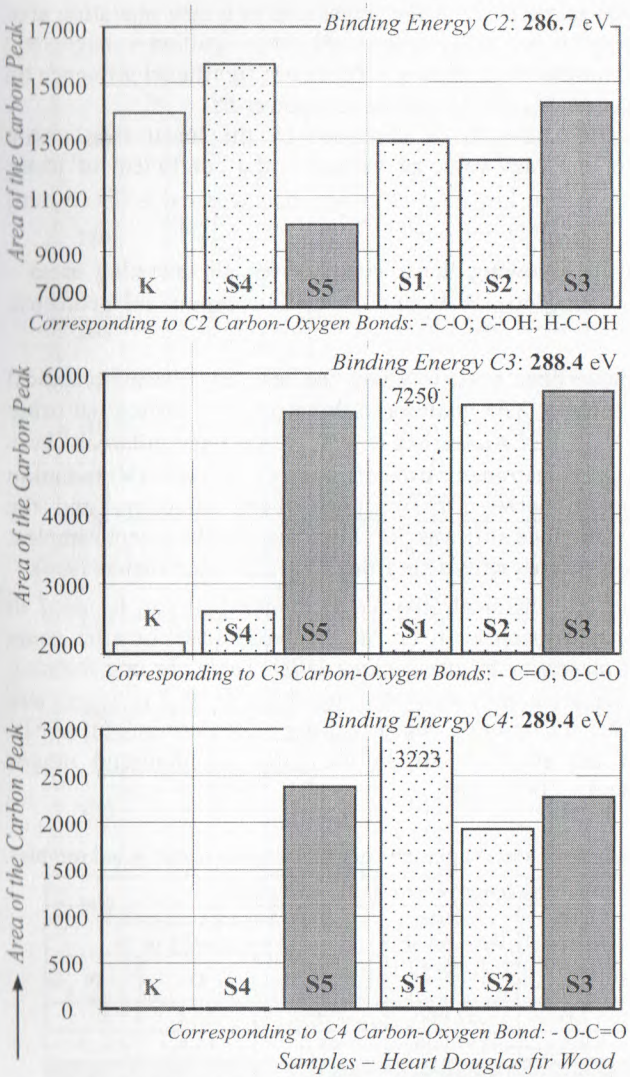


Figure 5. Carbon peak areas (in relative unit), or carbon-oxygen bonds quantity, of the typical for Douglas fir wood carbon peaks after *Kazayawoko*, 1998.

The presence of peaks at particular energies indicates the presence of a specific element in the sample under study - furthermore, the intensity of the peaks or the area under the peaks is related to the concentration of the element within the sampled region. Thus, the technique provides a quantitative analysis of the surface composition and in sometimes known by the alternative acronym, ESCA (Electron spectroscopy for chemical analysis).

Atoms of a higher positive oxidation state exhibit a higher binding energy due to the extra coulombic interaction between the photo-emitted electron and the ion core, Fig. 5.

This ability to discriminate between different oxidation states and chemical environments is one of the major strengths of the *XPS* technique.

As a result of the XPS measurements investigations the following main conclusions can be derived: i) the quantitative analysis of the surface composition shows that the main result of the plasma-chemical surface interaction is expressed by the different oxidation states C2, C3 and C4 of carbon; ii) the behavior of the *co-planar DBD*

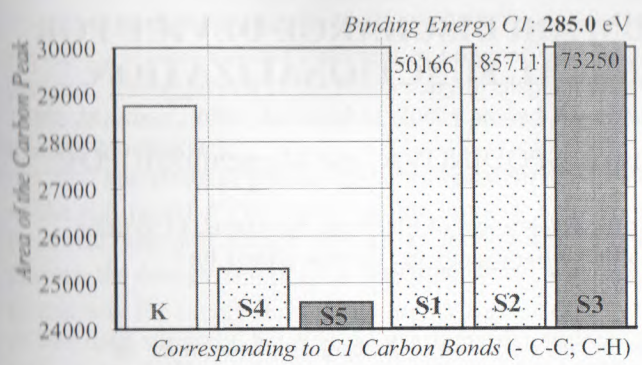


Figure 6. Carbon peak Cs1 area (in relative unit), or carbon bonds quantity, of the typical for Douglas fir wood carbon peak after *Kazayawoko*, 1998

is received as basis for comparison with the pin-to-plane DBD behavior: there are two operating sub-areas – the first from 7.000 to 11.920 kV and the second – above 11.920 kV, Table 1. The first operating area is characterized by prevalent single carbon-oxygen bonds while the second operating areas – by predominant double carbon-oxygen bonds, and O-C=O bond, that is not typical for the cellulose and the wood, Fig. 5; iii) the *pin-to-pin DBD* has also tow operating area – the first one from 6.628 to 10.776 kV, and the second – above 10.776 kV, but there is not predominant carbon-oxygen bonds – there are single, double and O-C=O bonds on the surface together, Fig. 5; iiii) it is possible to suppose that the *pin-to-plane DBD* create C-H bonds on the surface while the *co-planar DBD* sharply diminish the quantity of C-H and C-C bonds.

CONCLUSIONS

The present research formulates the problem of the pin-to-plane electrode configuration or the influence of the local non-uniformity of electrical field on the elementary processes in cold non-equilibrium plasmas, external electric characteristics and energy efficiency parameters. The *pins-to-plane DBDs* burns in every operating sub-area at constant burning voltages U_b, and the real power P is a linear function of RMS voltage drop across the electrodes. The linear functional subordination between the real power and RMS voltage is a distinguishing feature for all the *DBDs*. The *pins-to-plane DBDs* with higher energy suggest the through likely oxidation states of carbon at 286.7, 288.4 and 289.4 eV. It is one new different but very effective instrument for surface functionalization (oxidation) of wood (Douglas fir).

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NON-EQUILIBRIUM AIR DISCHARGE DEVICE FOR PLASMA-CHEMICAL FUNCTIONALIZATION

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Abstract. New types of *AC* dielectric barrier discharges in ambient air (at atmospheric pressure and room temperature) for plasma-chemical functionalization of low-energy surfaces were investigated. A combination between *dielectric barrier discharge* (*DBD*) at low (in vacuum), and high (atmospheric) pressure, was sustained in an electrode configuration combining electrode components of both – spiral electrode into a quartz (dielectric barrier) tube under low pressure in argon, and second spiral electrode outside tube in ambient air. It was investigated experimentally the burning behavior of this low-high pressure *DBD*. The low-high pressure *DBD* behavior under different pressure in so called vacuum electrode (argon) was discussed.

Keywords: burning voltage, critical parameters of ignition, dielectric barrier discharge, and low-high pressure dielectric barrier discharge.

INTRODUCTION

Low-temperature non-equilibrium plasmas are effective tools for surface treatment of various materials in micro-electronics, manufacturing and other modern industrial applications. The plasma-chemical surface influence of atmospheric pressure discharge presents advantages such as plasma treatment with cheap gas mixture or air, low specific energy consumption and short processing time.

Functionalization leads to formation of functional groups on the surface by chemical reaction between gas-phase species (*Chan*, 1994). Functionalization change, but mostly improves the wettability, the adhesion, lamination to other film, the printability and other coating applications, the capillary activity and impregnation of porous media (*Dineff*, 2004). In realty these different processes are not strongly separated, e.g. functionalization may include cleaning and sputtering. The depth scale of different processes are as follows: etching – 10÷100 nm; functionalization – 1÷5 nm, and coating - 10÷1 000 nm (*Behnisch*, 1994). The efficiency of various plasma components in surface functionalization is very different: ions and neutrals (kinetic energy: ~ 10 eV) components that cause chemical interactions in depth (monolayer); reactive neutrals (thermal energy: 0.05 eV) – chemical surface reactions and functional groups formation (depth: monolayer); electrons (kinetic energy: 5÷10 eV) – surface ionization and dissociation (depth: ~ 1 nm); photons (VUV: > 5 eV; UV: < 5 eV) – photochemical and secondary processes (depth: micron range).

The dielectric barrier discharge (*DBD*) seems to be the most promising plasma source for plasma-assisted treatment of polymer (and wooden) surfaces at atmospheric pressure. Investigations of the filamentary or disperse *DBD* (*Behnke*, 1996; *Dineff* et al, 1999; *Massines*, 2001; *Sonnenfeld*, 2001) proved the applicability of *DBD* for surface treatment techniques.

The effect of plasma chemical treatment depends on the real energy E (W sek) or the real power P (W) input into the process: $E = P\,t$, where t is the duration of the treatment, sek. For energy flow on an immobile substrate immersed in the discharge plasma, the dosage $D = (P.t)/A$ was used, J/cm^2, where A is the electrode surface, cm^2. In this way for energy flow on the barrier surface of a surface *DBD*, fig. 2a, the dosage D was used similarly, but A is the quartz barrier surface. The dosage is proportional to real power P. The real power is an important parameter of *DBD* to achieve desired surface chemistry or the quantity of gaseous product.

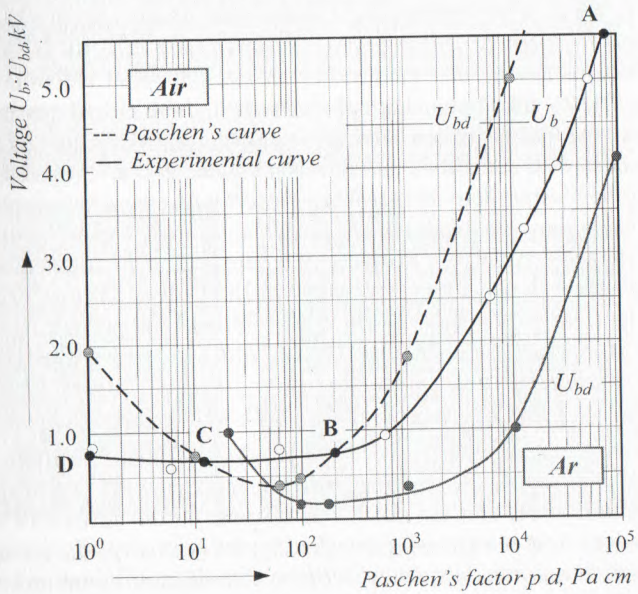


Figure 1. Burning voltage U_b of AC *DBD* in coplanar electrode configuration at electrode distance 0.6 cm and compensated edge effect as a function of pressure p, and Paschen's law (curve) for *DC* breakdown voltage U_{bd} in dry air, where p is the pressure, Pa; d – distance between electrodes, cm.

Special applications of *DBD* under low pressure (in vacuum) exist – the burning voltage drop across the inter-electrode gap is constant too during the discharge burning: $U_b = const$. The experimental results, presented by [1], enable as to show the burning voltage U_b of a *DBD* in coplanar electrode configuration as a function of the pressure, and to compare it with the breakdown voltage U_{bd} of dry air and argon (*Ar*), fig. 1.

The aim of this paper is the experimental investigation on the ignition and the burning behavior of a new type of *AC DBD* in ambient air at atmospheric pressure and room temperature for plasma-chemical functionalization of low-energy (polymeric) surfaces, fig. 3.

LOW-HIGH PRESSURE DIELECTRIC BARRIER DISCHARGE

A combination between *vacuum DBD* burning at low pressure (under 1 000 mbar), and *atmospheric DBD* burning under high pressure, was sustained in an electrode configuration combining electrode components of both – spiral electrode into a quartz tube (*quartz dielectric barrier*) was immersed in argon under low pressure. Second spiral electrode was arranged on the tube surface immersed in ambient air. It experimentally was investigated the ignition and burning behavior of this low-high pressure *DBD* (*LHP DBD*). The *LHP DBD* behavior under different pressure in so called vacuum electrode (under argon) was discussed. We take the view that the *LHP DBD* is a combination of two serially powered *DBDs* that burn in co-axial cylindrical electrode configuration, Fig. 2c: *the first DBD* burns among the windings of an external spiral electrode in ambient air at atmospheric (high) pressure, Fig. 2a; *the second DBD* burns among the windings of an internal spiral electrode in argon under low pressure, fig. 2b. The internal spiral electrode and the closed quartz tube under low pressure constitute the so called tubular vacuum electrode, Figs. 2d and e. Vacuum tubular electrodes with straight electrode was produced and investigated too, Fig. 2f.

Surface plasma activation (*SPA*) device with one surface-plasma activation applicator was produced for *Sheniang institute of chemical technology* (*Liaoning, China*) and was investigated, Fig. 2g. The applicator holds two vacuum tubular electrode powered on $U_{pk} = 7$ kV at 30 kHz, fig. 2h.

Vacuum tubular electrodes under different low-pressure have been made purposely for this project by *European Lighting Industry* Ltd., Sliven, Bulgaria.

EXPERIMENTAL INVESTIGATION

The atmospheric low frequency *DBD* electrode configuration consists of two cylindrical co-axial electrodes separated by a dielectric barrier – the internal electrode is made as a metallic tube, and the other – as a spiral on the surface of the quartz tube, Fig. 2a. The edge effect is as usually detached by the geometry of electrodes.

The vacuum low frequency *DBD* electrode configuration consists of two cylindrical co-axial electrodes separated by a dielectric barrier - the internal electrode is made as a spiral on the inside surface of the tube, and the external – as a metallic tube, Fig. 2b. The combined low–high pressure *DBD* electrode configuration consists of two cylindrical co-axial spiral electrodes arranged at the two side of the quartz tube - internal and external, Fig. 2c.

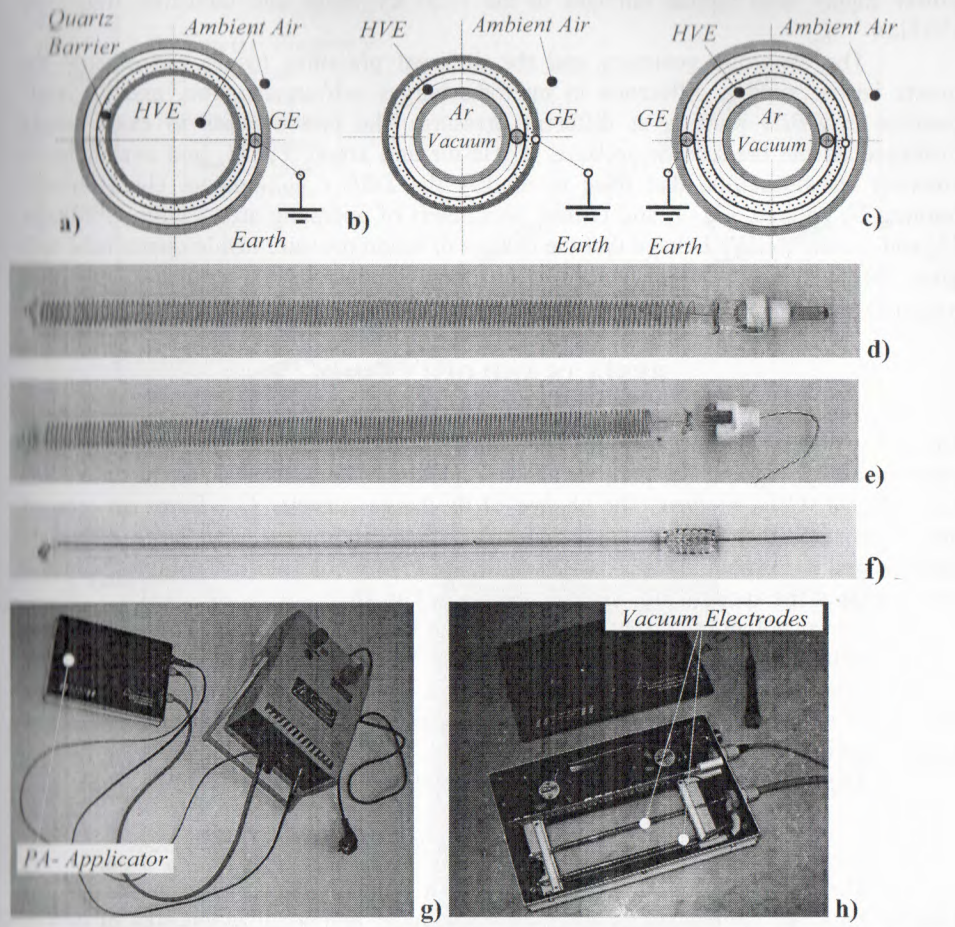


Figure 2. Schematic of the electrode configurations of low-high pressure dielectric barrier discharges: **a** – typical co-axial cylindrical electrode configuration of dielectric barrier discharge (*DBD*) with external spiral earthed electrode at high (atmospheric) pressure; **b** – co-axial cylindrical electrode configuration of *DBD* with internal spiral electrode at low (in vacuum) pressure; **c** – combined low and high pressure *DBD* with vacuum tubular electrode; **d** and **e** - vacuum tubular electrodes including an internal spiral metal electrode and a tubular quartz barrier under vacuum inside; **f** - vacuum tubular electrode with straight internal metal electrode; **g** – surface plasma activation (*SPA*) device with surface plasma activation applicator, made for *Sheniang Institute of Chemical Technology*, Liaoning, China; **h** – plasma activation applicator (*PAA*) with two vacuum electrodes. Vacuum electrodes have been made purposely for this project by *European Lighting Industry*, Ltd., Sliven, Bulgaria.

The dielectric tube is filled with argon under low pressure. The pressure range is: 1, 100, 200, 400, 800, and 900 mbar. The electrodes are energized by a high voltage

power supply with typical voltages in the 1÷20 kV range and industrial frequency (50 Hz).

The electrode geometry and the different pressures inside and outside the quartz barrier need a difference in microdischarges self-organization, and "crystal" patterns in *DBDs* burning at different pressure. The pressure has to exert strong influence on the breakdown voltages U_{bd} in air and argon, Fig. 1, and avalanche to streamer transformation that have to modify the *DBD's* volt-ampere characteristic, burning U_b voltage, Fig. 1, and critical parameters of operating area - ignition voltage U_{ig} and current I_{ig}. We believe that the change of argon pressure inside quartz tube will give rise to the typical influence on electrical characteristics, critical or ignition parameters, and real power of *LHP DBDs*.

RESULTS AND DISCUSSION

The statical external, or volt-ampere, characteristics $I_{AVG} = f(U_{RMS})$ of *LHP DBDs* for different argon pressure ($p = const$) in the quartz tube have been plotted experimentally, Fig. 3a. The data are shown replotted as current-pressure characteristics $I_{AVG} = f(p_{Ar})$, $U_{RMS} = const$. The change of discharge currents I_{AVG} forms an area of argon pressures that correspond to effective chemical process with large discharge currents and corresponding real power in the two *DBD* cold plasma volumes – inside and outside of the vacuum high voltage electrode, Fig. 3b.

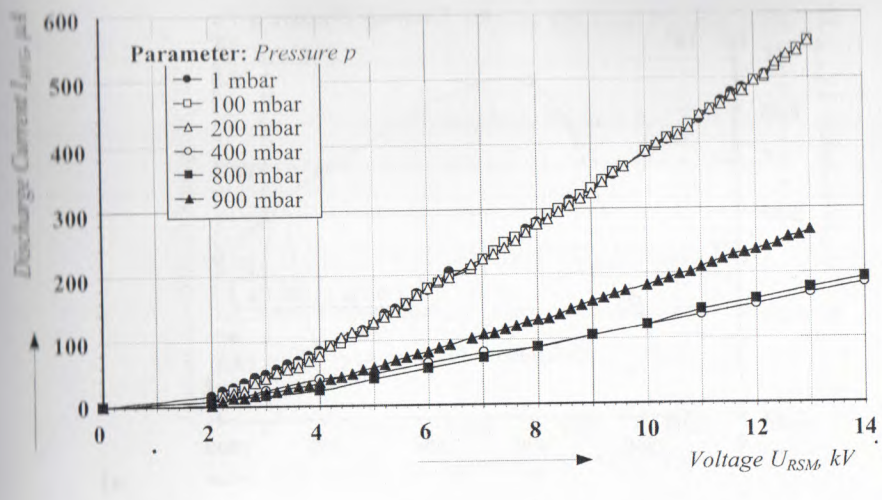
Linear polygonal discharge models have been worked out in accordance with [2], for a minimal coefficient of linear correlation, not less than 0.9900, and then all the electrical parameters of the *DBD* operating areas have been calculated and figured as function of argon pressure – burning voltage $U_{b,\,RMS}$, Fig. 4, ignition or critical voltage $U_{ig,RMS}$, and ignition current $I_{ig,\,AVG}$, Fig. 5.

The real power of *LHP DBDs* is given by (*Filippov and Emelianov*, 1958):

$$P = U_{b,\,RMS}\left(I_{AVG} - I_{ig,\,AVG}\right).$$

The real power P was figured as a function of argon pressure p at $U_{RMS} = const$. An interesting for the plasma-chemical functionalization area of power efficiency was formulated between 400 and 800 mbar: the real power P in this interval of argon pressure is higher - more two times above, than other pressures, Fig. 6.

From an operational viewpoint, the higher real power P correspond to higher discharge current I_{AVG}, or the high real powers require high discharge currents. No other *DBD* configuration studied to date shows such a behavior – most *DBD* configurations studied show that the burning voltage $U_{b,\,RMS}$ and the ignition current $I_{ig,\,AVG}$ have the important influence on real power P. Figures 4a and 5b show weak burning voltage and ignition current deviations as a function of argon pressure for a large interval of pressure change. The change of argon pressure p in the vacuum high voltage electrode has not significant influence on the burning voltage and the ignition parameters of *LHP DBD* but it increases the real power P by increasing the discharge current I_{AVG}, Figs 3b and 6.



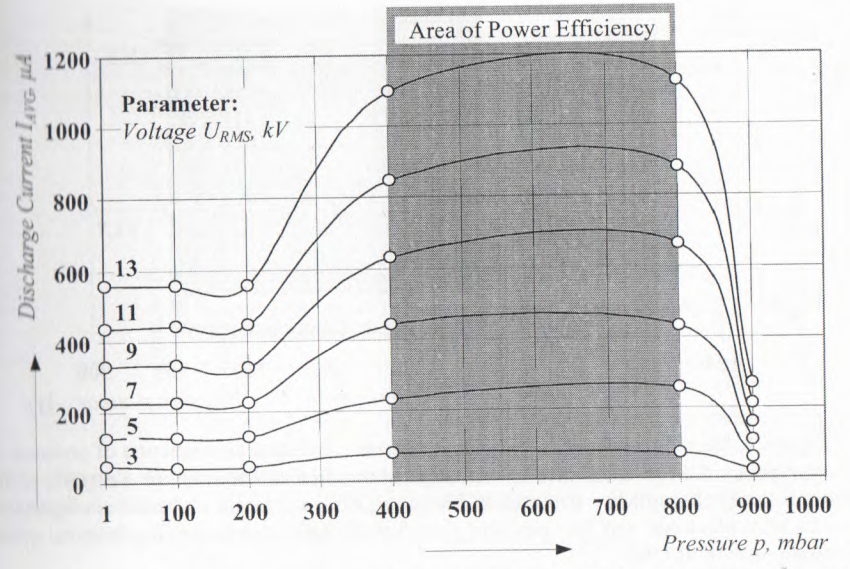
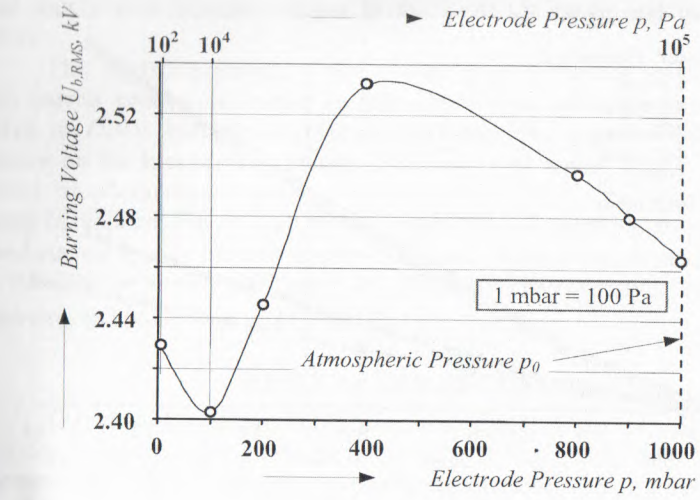


Figure 3. Statical volt-ampere characteristic $I_{AVG} = f(U_{RMS})$, $p = const$ (**a**) of co-axial cylindrical spiral electrode configuration of *DBD* with vacuum electrode under low pressure p inside (argon), and ampere-pressure characteristic $I_{AVG} = \varphi(p)$, $U_{RMS} = const$ (**b**). The area of power efficiency presents conditions for capacity real power.



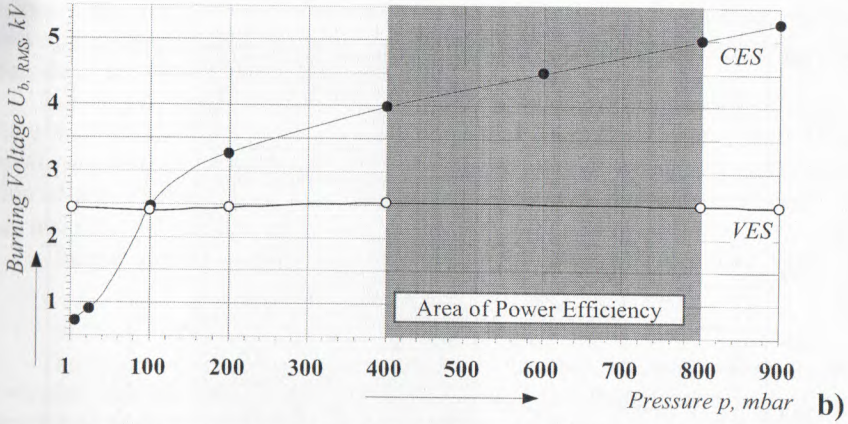
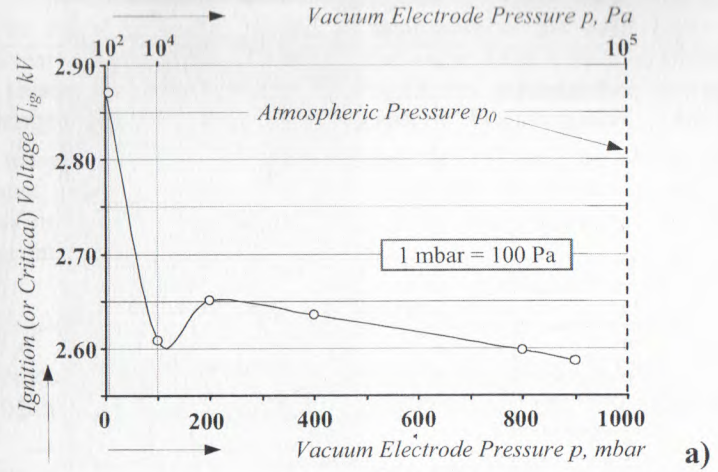


Figure 4. Burning voltage U_b of dielectric barrier discharge as a function of pressure p: **a** - *VES* – co-axial cylindrical spiral electrode configuration of *DBD* with vacuum electrode under low pressure p inside (argon); **b** – comparison between *CES* – co-planar electrode configuration of *DBD* with inter-electrode gap low pressure p (air) and *VES* – the co-axial cylindrical spiral electrode configuration of *DBD*.

In order to characterize the increasing of real power of *LHV DBD*, a supposition was suggested: the *DBD* in argon under low pressure plays the leading part as an efficient *UV*-radiation source for the going ionizing and chemical processes in atmospheric plasma, and the atmospheric *DBD* plays the same part for the going ionizing and chemical processes in vacuum non-equilibrium and non-thermal plasma. If the pressure of argon in vacuum tube is varied the *UV*- radiation across the quartz tube exert influence on the going ionizing and chemical processes in atmospheric plasma: the manifestation of this influence was studied experimentally.



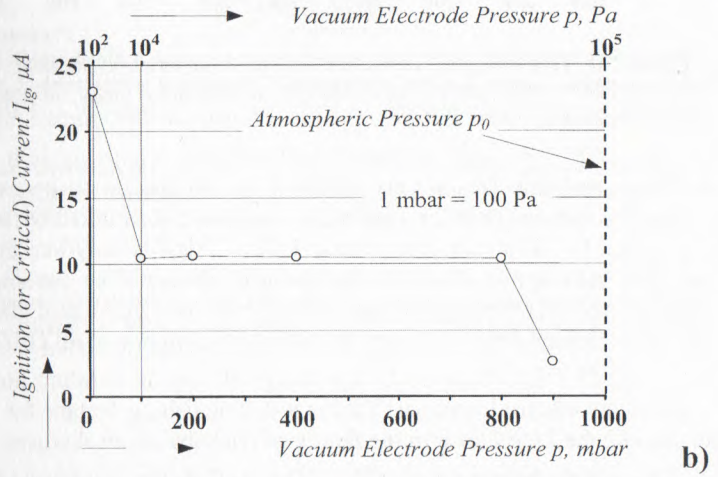


Figure 5. Ignition (or critical) parameters of a co-axial cylindrical spiral electrode configuration of *DBD*: **a** – ignition voltage U_{ig} of DBD; and **b** – ignition discharge current I_{ig} of *DBD* as a function of pressure p (argon).

CONCLUSIONS

As a result of the experimental investigations of *LHP DBD* with co-axial spiral electrodes, the following main conclusions can be derived:

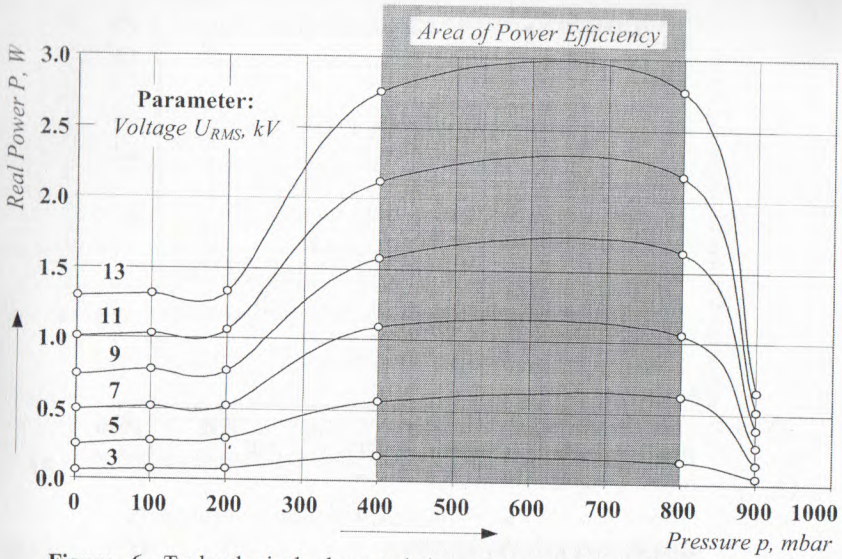


Figure 6. Technological characteristics of a co-axial cylindrical spiral electrode configuration of *DBD* – real power P as a function of pressure p under different voltage drops U_{RMS} across the electrode system, and area of power efficiency of *DBD* surface functionalization.

- The *LHP DBD* with electrode configuration containing is a typical *DBD*–based discharge and this fact is very good shown by the linear operational law for $I_{AVG} = f(U_{RMS})$, $p = const$. But the operating area is not constituted by more operating sub-areas, typical for co-planar atmospheric *DBDs*. There is only one operational area producing cold non-equilibrium and non-thermal plasma. The assumption that the combination of two *DBDs* energized and burning in serial *DBD*-based discharge is fully acceptable as a common *DBD* with properties that are common to all *DBD*;

- The *LHP DBDs* burn in the operating sub-area at constant burning voltages drop U_b across the electrode system. This is a distinguishing feature for all the *DBDs*. That fact put also the *LHP DBDs* in the family of *DBD*-based discharges;

- The specific behaviour of *LHP DBD* is well shown at different argon pressure in vacuum high-voltage electrode. The real power increases in the low pressure interval from 400 to 800 mbar following the change of discharge current. The change of argon pressure in the vacuum electrode has not significant influence on the burning voltage and the ignition parameters of *LHP DBD*. That's probably the effect of vacuum *DBD UV*- irradiation influence on atmospheric *DBD* across the quartz (dielectric) tube and vice versa.

- The *LHP DBD* created by the use of a specific vacuum high voltage electrode filled with argon under low pressure is a good technical decision because it suggests better discharge energy efficiency – higher discharge current and real power, and higher dosage of energy flow;

- The method of mathematical description of *DBD* static volt-ampere characteristics by linear polygonal models is applicable to the *LHP DBDs*. The coefficient of linear correlation gains values about unity: from 0.9978 to 0.9985 for different argon pressure. There is a strong linear functional subordination between the average of discharge currents and the *RMS* of voltages;

- The present experimental research formulates the problem of the vacuum electrode pressure (argon) influence on the elementary processes in cold non-equilibrium and non-thermal plasmas, external electric characteristics and power efficiency parameters.

ACKNOWLEDGEMENT

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