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# **CHALLENGES in HIGHER EDUCATION and RESEARCH in the 21st CENTURY**

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# ATMOSPHERIC PRESSURE PLASMA POLYMER MODIFICATION – NEW VISIONS, CHALLENGES AND SOLUTIONS

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A new development of the concept of using one-atmosphere barrier discharge plasma in the creation of technological plasma systems is proposed along with some new visions, challenges and solutions.

The concept of changing the electric load and the development of electric energy transformation in the plasma volume, when the polymeric material is introduced, is related to the basic technological characteristic of cold plasma treatment and modification – the variation of the volume and/or surface densities of the active power at loading the cold plasma generator/reactor system.

The plasma surface modification of highly-porous woven or non-woven textile materials is determined mainly: first, by the change in surface properties – in the topology and chemical functionality of the fibers, and second, by the modification of the highly-porous media itself, which is of decisive importance for its capillary activity.

*Keywords:* cold plasma reactor system, electrode edge effect, external characteristic, one-atmosphere air barrier discharge, plasma etching, plasma-chemical activation and grafting, plasma-chemical setting and plasma surface modification

## 1. Introduction

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

Characteristic to all types of barrier (corona) 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  $C_\delta$  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 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 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 task of the present work consists in studying the behavior of low-frequency (50 ÷ 60 Hz) air barrier discharge that burns under load – a high-porous non-woven textile media, in the volume of a cold-plasma generator system at atmospheric pressure – *one-atmosphere air barrier discharge (OAABD)*.

The technological modifications – physical and plasma-chemical etching, plasma-chemical surface activation and grafting, plasma chemical setting, or plasma-chemical surface modification, depend on voltage  $U_{gap}$  (RMS) applied

across the electrode system, on the geometry of the plasma generator system, and on the morphology and dielectric properties of treated polymeric material.

The present investigation should demonstrate how a high-porous non-woven textile medium, penetrable by the electric discharge burning partially in the capillary structure of this porous medium, influences the plasma-chemical process of its physicochemical modification.

## 2. Experimental Investigation

Experimental investigations [1-3], performed by us for a continuous period of time in connection with the manifestation of the load effect in a cold plasma reactor system, allow to seek a new technical solution in using the load effect for creating an effective cold plasma generator/reactor system.

Due to the considerable volume of the experimental investigation, the discussion of results is focused on the OAABD-discharge that burns in the plasma volume for constant thickness of dielectric barrier  $\delta = 3, 4, 5, 6, 7, 8$  and 9 mm, and for varying width  $b = 6, 9$  and 12 mm of plasma gap.

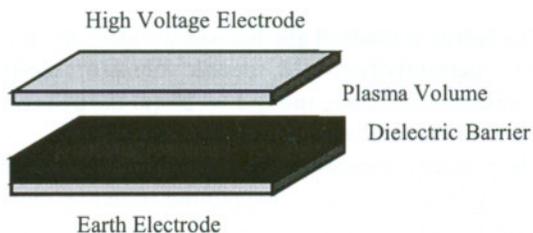


Figure 1. Type of plasma or OAABD-reactor system used in the experimental investigation.

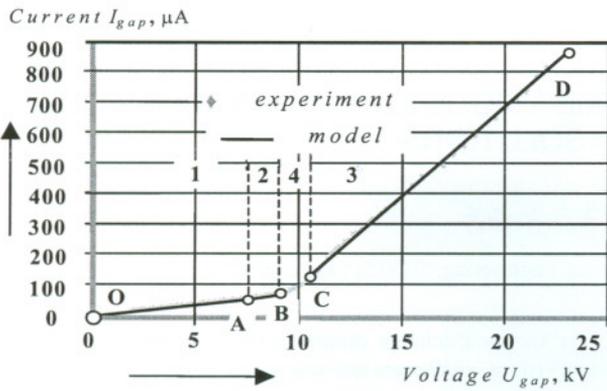


Figure 2. Stages of burning of one-atmosphere air barrier discharge (OAABD) represented by the linear sectors of the external characteristic, which expresses the relationship between the average value of current  $I_{gap}$  and the effective value of applied voltage  $U_{gap}$ . OA - non-operating linear sector; AB - first operating linear or  $O_2$ - sector; CD - second operating linear or  $N_2$ -sector; BC - non-linear transient sector of external characteristic.

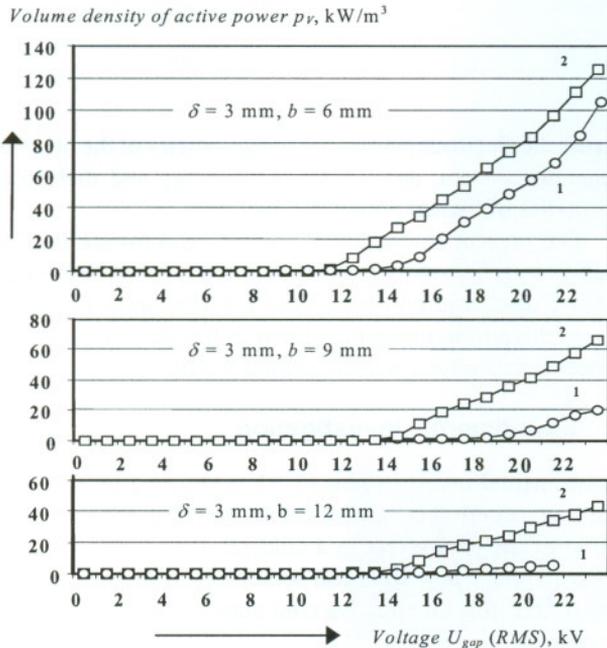


Figure 3. Variation of the volume density of active power  $p_V$  of an one-atmosphere air barrier discharge (OAABD) with voltage  $U_{gap}$ , applied across the electrodes, for various values of plasma gap  $b$  and the same thickness  $\delta$  of the glass barrier. 1 - no-load (idling) operation of the plasma generator system; 2 - operation of the plasma generator system under load.

The barrier is made of alkaline silicate glass and having dielectric permittivity  $\epsilon = 10$ , specific volumetric electrical resistance  $\rho = 10^9 \Omega m$ , and  $\text{tg } \delta = 25$  (at  $20^\circ C$ ), which is located in the inter-electrode space, Figure 1.

The plasma generator operates in idling regime, i. e. in free or non-influenced operating regime, where no material to be plasma-treated is placed into the plasma volume.

The external or voltage-current characteristic of the barrier discharges is determined experimentally.

It expresses the relationship between the average value

of electric current  $I_{gap}$  (AV) flowing through the barrier discharge and the effective value of voltage  $U_{gap}$  (RMS) applied across the discharge gap -  $I_{gap}(AV) = \varphi[U_{gap}(RMS)]$ , Figure 2.

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, Figure 2, [2,3]:

- the stage preceding the ignition of the barrier discharge, or the so-called free or non-operating discharge 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, Figure 1.

The external characteristic of one-atmosphere barrier discharges is used for determining the basic technological characteristics of discharges.

The surface density of power  $p_S$ , in  $W/m^2$ , and the volumetric density of power  $p_V$ , in  $W/m^3$ , are used as a basic technological characteristics for the purpose of comparison.

Power factor  $\cos \varphi$  is used for determining what part of the electric power consumed is transformed into plasma-chemical surface modification of the polymeric material.

The electric loading of the plasma gap is realized by treating a sample of non-woven textile on the basis of polyethylene terephthalate (PET) in its space. The textile sample has area mass  $500 \text{ g/m}^2$ , linear mass 15 tex and fiber length 45 mm and is of the Geotextile brand produced by Non-Woven Tex-tile Ltd., Sofia, Bulgaria.

### 3. Results and Discussion

The volumetric density of the active power  $p_\theta$  is considered as a characteristic of a process of surface plasma modification that characterizes the intensity of the technological process.

Changing the voltage  $U_{gap}$  (RMS) applied across the discharge gap, controls the intensity of the plasma-chemical process, Figure 3.

Loading the discharge gap or the working plasma volume by introducing the high-porous non-woven material to be treated exerts considerable effect on improving the technological characteristic of the cold-plasma generator system. The load effect turns out to be of essential importance for the operation of the plasma system: the increase in the volume density of active power  $p_V$  under system loading with respect to that for the operation in idling regime is considerable, Figure 3.

Loading the cold plasma generator in the treatment of high-porous non-woven media leads to considerable increase in its specific active power  $p_V$ .

This fact indicates that plasma-chemical processes inside the porous structure of the non-woven textile material

Surface density of active power  $p_s$ , W/m<sup>2</sup>

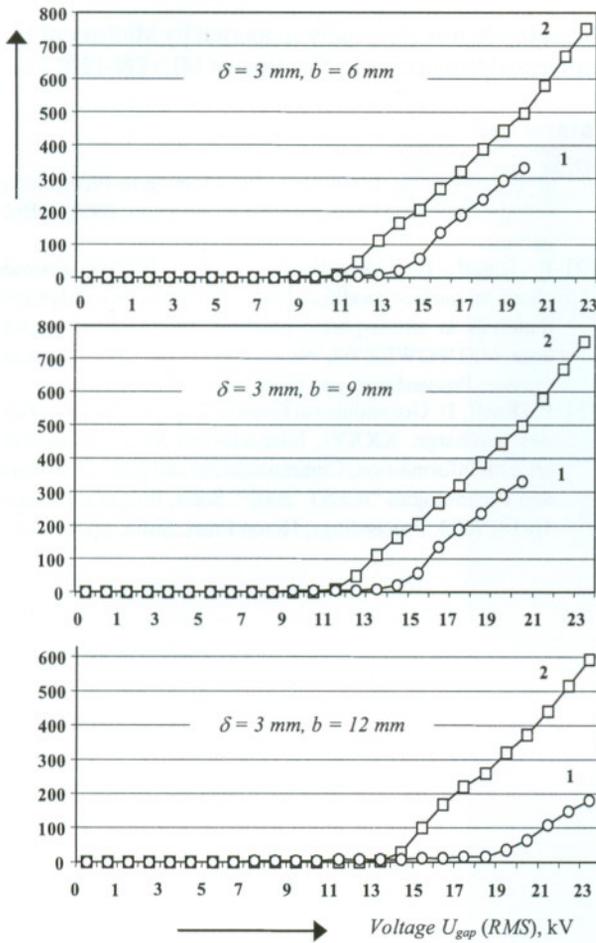


Figure 4. Variation of the surface density of active power  $p_s$  for a one-atmosphere air barrier discharge (OAABD) with voltage  $U_{gap}$ , applied across the electrodes, for various values of plasma gap  $b$  and for the same thickness  $\delta$  of the glass barrier. 1 – no-load (idling) operation of the plasma generator system; 2 – operation of the plasma generator system under load.

evolve much more intensively than those in the air medium at idling operation of the generator, the discharge gap of  $b = 6$  mm conditioning the attainment of the maximum value of specific active power  $p_V > 120$  kW/m<sup>3</sup>, Figure 3.

It is found a fact being of practical interest, that irrespectively of the operation regime of the plasma generator – at no load or under load, – the highest value of specific active power  $p_V$  is obtained for a glass barrier of thickness  $\delta = 3$  mm and a width of the discharge gap  $b = 6$  mm.

Power Factor  $\cos \varphi$ , /

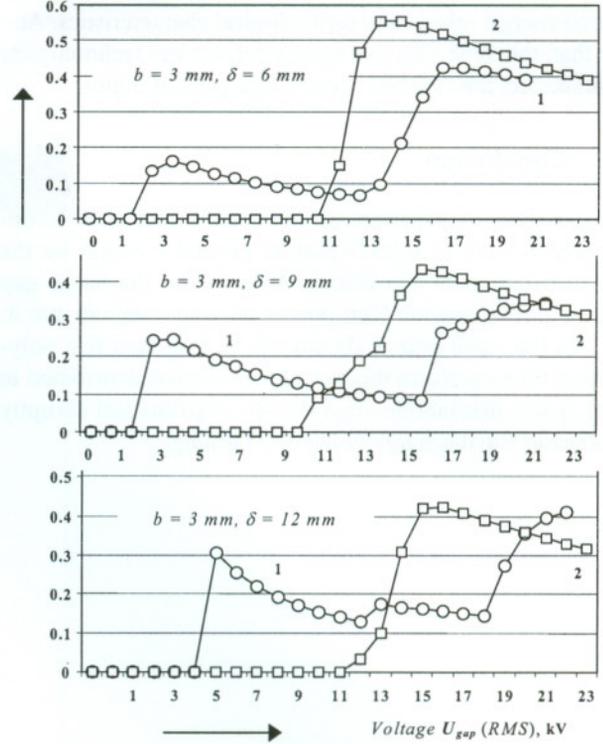


Figure 5. Variation of power factor  $\cos \varphi$  of an one-atmosphere air barrier discharge (OAABD-) generator at no load (1) and under load (2) with voltage  $U_{gap}$ , applied across the electrodes, for various values of plasma gap width  $b$  and the same thickness  $\delta$  of the glass barrier.

Also the results obtained with respect to the surface density of active power  $p_s$  can be considered in an analogous way, Figure 4.

Under the same circumstances the maximal specific power  $p_s$  of the plasma generator attains up to 750 W/m<sup>2</sup> under load.

The parameters of burning and critical parameters of the OAABD-discharge demonstrate again essential differences, which are due to the specific loading of the discharge gap under load, Table 1.

Investigating the power factor  $\cos \varphi$  shows once again the advantage of the load effect at OAAB-discharge – in treating high-porous materials values too high for this process are attained:  $\cos \varphi \approx 0.55$ , Figure 5.

It is experimentally found that there is a considerable difference between the idling regime and that under load for the OAABD-plasma generator.

Table 1. Behaviour description of one-atmosphere air barrier discharge

OAABD	Thickness of dielectric barrier $b$ , mm	Voltage of burning $U_b$ , kV	Critical or ignition discharge parameters			
			Voltage $U_{bd}$ (1), kV	Current $I_{bd}$ (1), $\mu$ A	Voltage $U_{bd}$ (2), kV	Current $I_{bd}$ (2), $\mu$ A
Under load	6	10.37	10.85	171	—	—
	9	11.90	12.30	155	—	—
	12	11.60	12.04	151	—	—
Non-load	6	1.36	7.70	151	342	-4328
	9	5.08	13.30	225	188	-3172
	12	2.14	10.93	183	51	-573

Moreover, it turns out that the load regime has very good energy-related and technological characteristics. And at that, the most effective energy-related and technological parameters are attained at discharge gaps of 6 mm.

#### 4. Conclusion

A possible explanation of the load effect that is observed for the *OAABD*-plasma generator might be the re-distribution of the electric field in the discharge gap upon introducing the high-porous polymer medium into it.

In the same time it should not be forgotten that polymeric fibers perform the part of a collector, distributed in the space, that inhibits high-energy electrons and abruptly increases the discharge voltage of burning.

#### Acknowledgement

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