Magnetron Dielectric Barrier Air Discharge at Low Frequency

Peter D. Dineff[1] and Dilyana N. Gospodinova[2]

***Abstract* – Dielectric barrier discharges that burn at atmospheric pressure and industrial frequency (50/60 Hz) are a good technological alternative to the *RF*- and glow discharges at low pressure (vacuum). The present investigation offers a new approach aiming at the creation of a new magnetron dielectric barrier discharge plasma system, intended for plasma-chemical treatment of low energy surface porous materials.**

***Keywords* – atmospheric-pressure glow discharge, dielectric barrier discharge, high-pressure low-frequency dielectric barrier discharge, plasma-chemical surface modification.**

I. INTRODUCTION

There are more than ten thousand (10,000) granted United States Patents which are related to the generation and applications of ozone. More than one hundred of these patents have been granted to innovative techniques of ozone generation, [2].

Ozone production is predominantly achieved by one of the following three groups of methods: electrical discharge methods, electrochemical methods, and ultraviolet (*UV*) radiation methods.

Electrical discharge methods, which are the commercial methods of widest use, have relatively low efficiencies (2 ÷ 10 %) and consume large amounts of electricity. The other two groups of methods (electrochemical and *UV*) are less cost-effective.

Because *ozone* is very reactive, it is also unstable. It cannot therefore be stored and has to be produced where and when it is needed. Ozone is produced from oxygen-containing gases in ozone generators by means of a *dielectric barrier discharge* (silent electrical discharge). All industrial-scale ozone generators make use of this method, [1, 2, 6, 7].

The *dielectric barrier discharge* (*DBD*) is an important type of alternating current (*AC*) glow discharge, operating at atmospheric pressure and in a lower frequency range (50 ÷ 60 Hz), where both electrodes, or at least one of them, are typically covered by a dielectric barrier, [6, 7].

As a result of applying an *AC* voltage to an electrode system with one or both electrodes covered by dielectric layer, a DBD appears in the gas gap. Such non-thermal or cold discharges are suitable for a wide range of applications, e. g. ozone generation, surface treatment and modification of plastic foils, textiles and even metals, pollution control, sterilisation, ultraviolet and vacuum ultraviolet light sources for laser pumping, *AC* plasma displays, and others, [2].

Basic designs of plasma-chemical reactors using DBDs are given in Fig. 1. While the *DBD* in Fig. 1a is determined mainly by discharge columns in the gas gap and surface discharges on the dielectric, the arrangement with extended surface electrodes, Fig. 1b, leads only to surface discharges along the dielectric surface. The packed bed reactor with dielectric pellets, Fig. 1c, includes both types of *DBDs*.

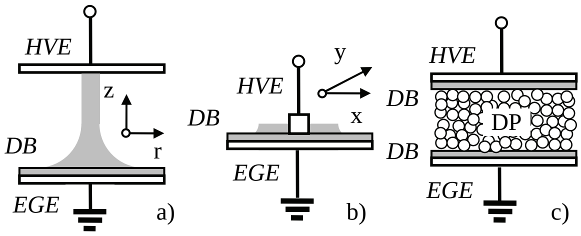

Fig. 1. Different types of DBDs arrangements: **a** - volume DBD plasma reactor, **b** - surface DBD plasma reactor and **c** - packed bed DBD plasma reactor.
HVE and *EGE* – high-voltage electrode and earth-grounding electrode; *DB* – dielectric barrier; *DP* – dielectric pellets.

In addition to applying an electric field (or difference of potentials) to a plasma reactor electrode system, a magnetic field can be also applied to a glow discharge. The most well-known discharge type with *crossed magnetic and electric fields* is the *magnetron discharge*. The electrons circulate in helices around magnetic field lines and give rise to more ionisation. Hence, magnetron discharges are typically operated at lower pressures and higher currents than conventional or normal and abnormal glow discharges, [1].

The theory of the *low-pressure magnetron glow discharge* was developed by *R. Redhead*, and the field of practical implementation is defined by the pressure; the discharge currents being 100 ÷ 200 mA/cm^2, [1].

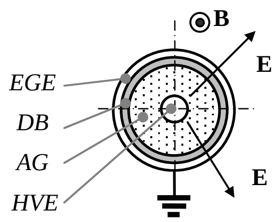

Fig. 2. Co-axial types (tube in tube) of a magnetron DBD plasma reactor with crossed magnetic **B** and radial electric fields **E**.
HVE and *EGE* – high-voltage electrode and earth-grounding electrode; *DB* – dielectric barrier; *AG* – air (discharge) gap.

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The great concentration of gas particles at high pressure that determines the small average length of free path and high frequency of collisions between gas particles, does not speak of successful application of the *magnetron effect* to *DBDs*, i. e. for an atmospheric pressure glow discharge. An argument to this statement is the absence of concrete investigations in this field, despite of the great interest regarding *DBD* plasma technologies, [2].

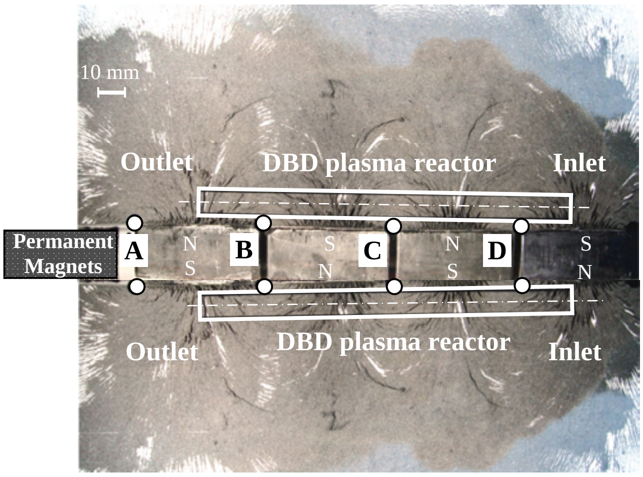

Fig. 3. *MDBD* plasma reactor with two co-axial discharge tube – graph of the magnetic flux density of an open magnetic system with four alternating permanent magnets poles arranged in line.

The TASK of the investigation presented consists in identifying the magnetron atmospheric pressure *DBD*, while observing the well-known definition of the magnetron effect with crossed magnetic and electrical fields.

The idea for realization of a *magnetron DBD* (*MDBD*) is demonstrated in Fig. 2: for the existing cylindrical symmetry of the electric field **E**, the magnetic flux density **B** should be directed along the electrode axis, i. E. Perpendicularly to the cross-section plane.

II. EXPERIMENTAL INVESTIGATIONS

Preliminary experimental investigations carried out on the selection of a source of permanent magnetic field and determination of the magnetic flux density **B**, at which the magnetron effect exhibits itself**,** indicate that:

- the magnetron effect exhibits itself at relatively strong magnetic fields, i. e. at B > 0.2 T;

- the necessary geometry of the magnetic field can be structured by means of permanent magnets.

- it is not possible to create a permanent magnetic field (B = const) along the entire length of the discharge tube (of the plasma reactor).

For the purposes of the investigation, two types of devices having different structure of the permanent magnetic field have been created:

- *MDBD* reactor with an open magnetic system with alternating poles of the permanent magnets arranged unilaterally to the discharge tube in one or two layers, Figs. 3 and 4;
- *MDBD* reactor with an open magnetic system with alternating poles of the permanent magnets arranged to the discharge tube in one line, Fig. 5.

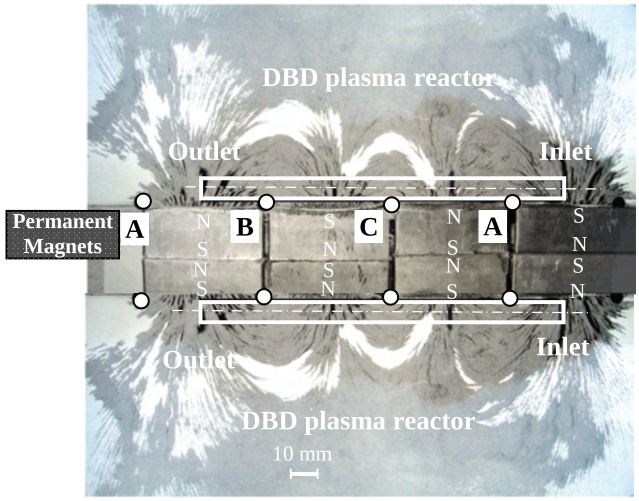

Fig. 4. *MDBD* plasma reactor with two co-axial discharge tube – graph of the magnetic flux density of an open magnetic system with four alternating poles of the permanent magnets arranged in two layers.

Technological magnetron *DBD* devices with permanent magnets represent a space structure consisting of anisotropic strontium permanent magnets Sf: 80 x 57 x 12 mm (*Magnit* Ltd., Permik, Bulgaria): $H_C \geq 224$ kA/m; $B_r = 0.37$ T; $(BH)_{max} \geq 24$ kJ/m^3; $\mu_r = 1.2$; $T_Q = 735$ K; $\rho_V = 10.6$ Ωm; $\delta = 4.5 \div 5.0$ g/cm^3; $\delta l = (9 \div 15)\ 10^{-6}$; 55 HRC. They are suitable for making devices with an open magnetic system or with large air gaps.

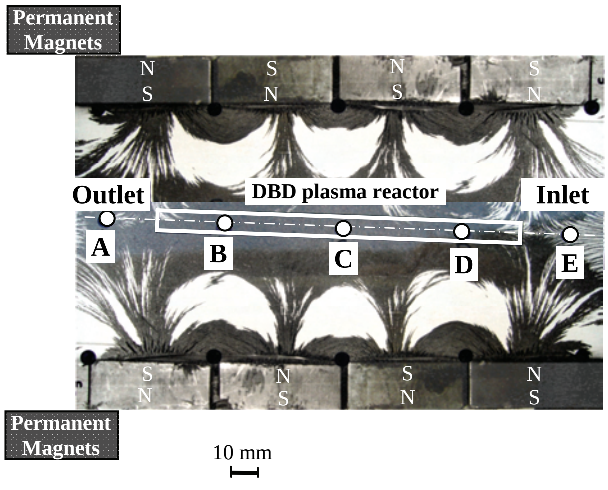

Fig. 5. *MDBD* plasma reactor with two co-axial discharge tube – graph of the magnetic flux density of an open magnetic system with alternating poles of the permanent magnets arranged bilaterally to the discharge tube in one layer.

Two design structures of magnetron BDB plasma reactors examined experimentally are shown schematically on the picture of the magnetic field obtained by means of fine ferromagnetic powder, Figs. 3, 4, and 5.

Figs. 3 and 4 show the same structure of an *MDBD* ozone generator – A55 and A75, their only difference being in the double volume of the four pole groups, which increases the maximum value of magnetic flux density **B** measured at designated points, namely *A*, *B*, *C*, and *D*. Measuring is carried out with a specialized instrument featuring an accuracy class of 0.5. In the first case, Fig. 3, the measured magnetic flux density is 55 mT, while doubling the magnetic mass of pole groups, Fig. 4, increases this value to 75 mT (i. e. by 36 %).

In the second examined structure of an *MDBD* ozone generator – B16, the arrangement of magnetic poles is realized in accordance with the so called quadrupled scheme that defines a maximally long sector with crossed magnetic and electric fields along the device's central axis, Fig. 5. However, the value of the maximum magnetic flux density **B** is lower, namely 16 mT.

Along the device there are periodically alternating areas, where the magnetic and electric fields cross each other.

The dielectric barrier is a quartz tube with internal diameter ∅ 8 mm. A resistive wire of FeCrAl ($\rho = 1.35 \times 10^{-6}\,\Omega$m) having diameter ∅ 0.20 mm is stretched along its axis. The second electrode is placed from outside by winding on the tube.

The elementary processes (impact dissociation, impact ionization, secondary electron emission from the cathode, chemical reactions) that are effected in the discharge gap play a different role as regards ozone generation: on one hand, O_2^*, O_2^+, O_2^-, and O_2 help generating ozone, and on the other hand, N, N*, NO_2, and NO support its inhibition. In general, it is possible to form two modes of *DBD* burning: a mode of generating ozone and products of its decay, and a mode of generating nitrogen oxides NO_x, Fig. 6.

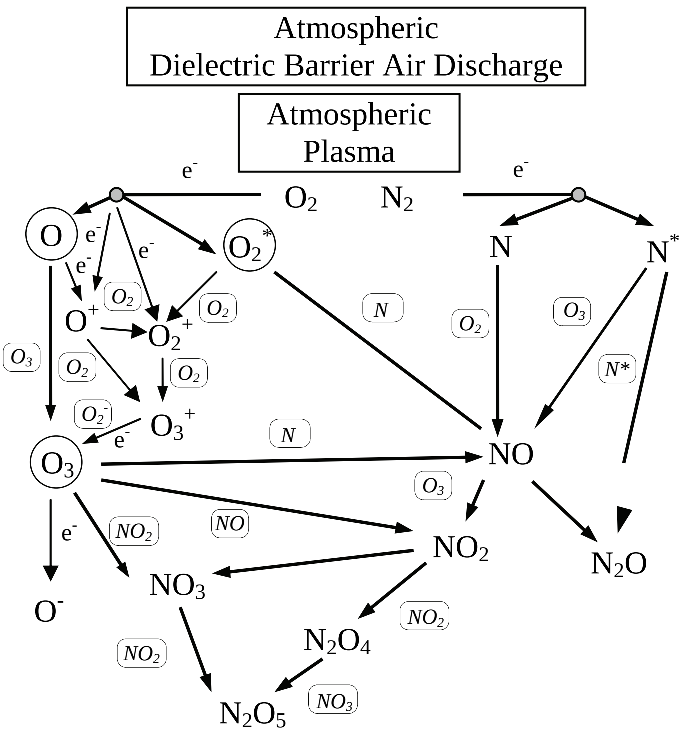

Fig. 6. Schematic presentation of the primary processes of impact electron ionization (e$^-$) and of the chemical transformations that on one hand generate ozone, and on the other hand inhibit it.

The external (volt-ampere) characteristic of *DBD*, presenting the relationship between the average value of discharge current I_{av} and the effective value of the voltage applied across the discharge gap U_{eff}, reflects the existence of two characteristic modes of DBD burning, Fig. 7, [3, 4, 5].

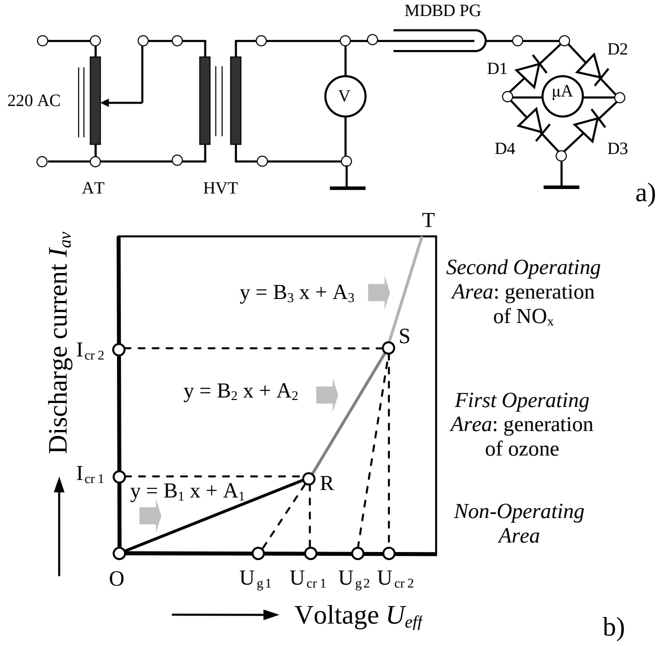

Fig. 7. Electric circuit of the experimental MDBD plasma generator (PG) (**a**) and volt-ampere characteristic (**b**).
AT – transformer for voltage regulation; *HVT* – step-up transformer; *D1*, *D2*, *D3* and *D4* – diodes allowing direct measurement of the average value of discharge current I_{av}.

III. RESULTS AND DISCUSSIONS

Experimentally plotted external characteristics of both discharges, *DBD* and *MDBD*, are shown in Figs. 8, 9 and 10 for each investigated structure of ozone generators.

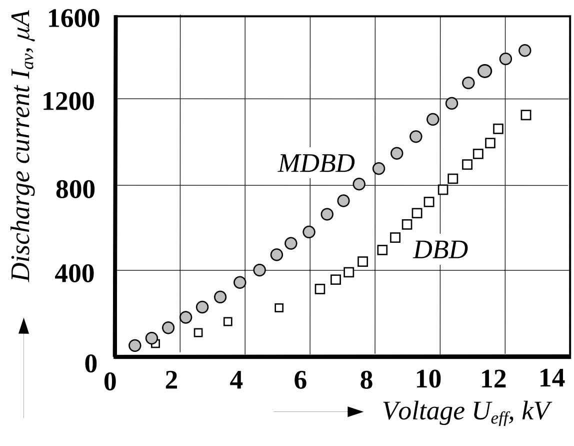

Fig. 8. Volt-ampere characteristics of *DB*- and *MDB*-discharges of the plasma generator A55.

Characteristics and a part of the critical parameters of the examined design structures of ozone generators A55, A75, and B16 are determined numerically and given in Table 1.

Comparing the two realizations of the first design structure, A55 and A75, creates the impression of clearly expressed shifting of the volt-ampere characteristic to the left, i. e. to higher currents; the larger shifting being observed for the stronger magnetic field, and this being valid for both operating areas, Table 1.

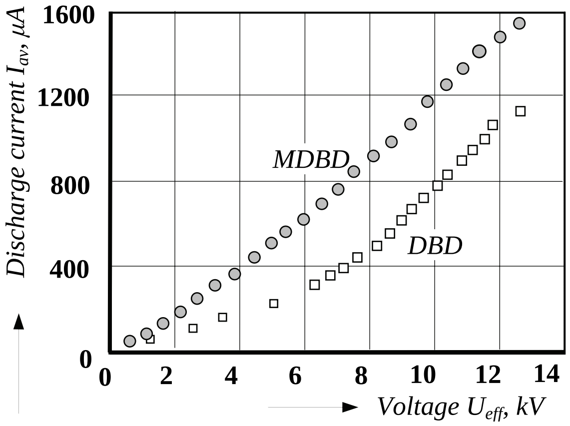

Fig. 9. Volt-ampere characteristics of *DB*- and *MDB*-discharges of the plasma generator A75.

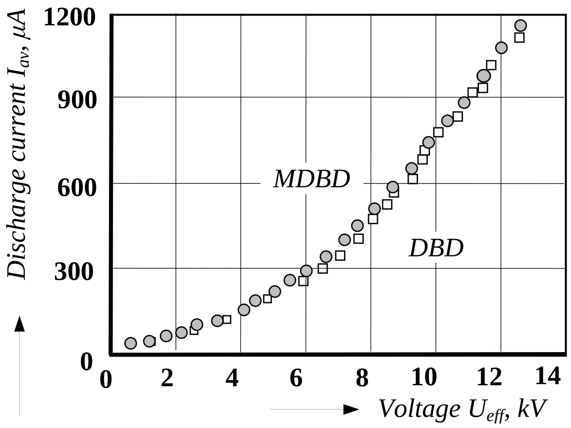

Fig. 9. Volt-ampere characteristics of *DB*- and *MDB*-discharges of the plasma generator B16.

TABLE I

Design Structure Type	**DBD**	**MDBD A75**	**MDBD A55**	**MDBD B16**
Correlation coefficient r_2, -	0.999	0.9986	0.9971	0.982
Correlation coefficient r_3, -	0.999	0.9962	0.9974	0.982
Critical voltage U_{cr1}, kV	2.237	6.269	4.2963	5.416
Critical current I_{cr1}, μA	185.8	255.6	368.6	235.4
Burning Voltage U_b, kV	0.69	3.34	4.37	1.64
Slope B_2, μA/kV	84.3	41.6	87.0	4.7
Slope B_3, μA/kV	120.0	134.5	138.9	113.6
Intercept A_2, μA	-2.8	-5.5	-5.2	14.8
Intercept A_3, μA	-82.7	-587.6	-228.2	-379.6

The intensity of the permanent magnetic field exerts substantial influence on *MDBD* characteristics.

IV. CONCLUSION

Based on the experimental investigations performed on various design structures of *MDBD* ozone generators, it is possible to derive the following main conclusions:

- the magnetron effect can be used in creating *MDBD* plasma technological systems;
- the impact of the magnetron effect is expressed by totally shifting the characteristic the left, while the critical ignition voltage of the discharge increases significantly, which also defines the high critical ignition current;
- using permanent magnets in the creation of *MDBD* plasma technological systems turns out to be a good solution that allows designing compact and efficient generators of ozone and cold plasma at atmospheric pressure;
- the developed magnetic system of the *A* type (A55 and A75) can be used not only in the considered case of volume *DBD* plasma reactor; it can also find an equally good application in the creation of surface *MDBD* plasma reactors;
- the combination of a magnetic system and two electrode systems can be considered a design module that is in position to produce complex MDBD plasma generators by repetition.

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