STUDY OF DUAL FREQUENCY RF AND RF/DC PLASMA DISCHARGES USED FOR SURFACE TREATMENT

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ABSTRACT

The low pressure RF discharges have found a wide application in plasma technologies for processing solid material surfaces. Recent measurements indicate that the performance of these discharges can be modified by the use of an extra auxiliary RF (dual-frequency discharge) or DC (RF/DC discharge) power source applied to the reactor electrodes [1-2]. In this paper the superposition of RF and DC voltages in two-electrode capacitive discharges and their applications for surface treatment and sterilization of medical devices are numerically investigated and dependencies of key plasma parameters on a reactor configurations are studied.

The discharge has been formed inside a tube, 5.5 cm in diameter and 4cm long. The two-dimensional (2D) self-consistent drift-diffusion fluid model is developed to describe the charged particle transport. The two-term Boltzmann approximation is used for calculating electron kinetic coefficients for the model. Axial and radial profiles of charged particles density, average energy of electrons, electric field and other parameters are obtained. The ion energy at the processed product and hence the surface temperature of the latter is evaluated. Numerical results are in a good agreement with experimental ones [3-4]. Advantages of dual frequency RF and RF/DC discharges versus RF capacitive discharges for the sterilization of medical products are shown.

1. INTRODUCTION

Nowadays capacitive radio frequency (RF) discharges are widely used in a number of applications, such as surface treatment, etching, sterilization and so on. Radio frequency discharges are well-studied both experimentally and theoretically. At the same time, most experimental reactors for surface treatment still meet the same problem – its effectiveness. It's well-known, that plasma parameters depends both on a reactor configuration (its dimensions, interelectode gap etc.) and on a power source parameters (voltage, frequency). The fact that surface treatment effectiveness in a number of applications depends on particle density and flux was confirmed in a number of papers in the past [5-7]. It was shown, that changing a configuration of a plasma reactor may significantly improve plasma parameters. The key question is how to configure a plasma reactor to effectively control both plasma particle density and energy profiles to get optimal parameters for different gas discharge applications.

In the recent years it was shown that usage of an extra RF or DC power source in a reactor configuration may significantly increase key plasma parameters and its effectiveness for different applications. A number of modelling studies have been published recently, where attempts have been made to investigate how key discharge parameters depend on a reactor configuration [7-8]. But some ambiguities still exist. When using two power sources, one electrode may be powered with two power sources or both electrodes may be excited by different power sources. One of the most important questions is how key plasma parameters depend on a power source-electrode connection configuration and its parameters. Dual-frequency discharge may significantly improve overall plasma reactors effectiveness in a number of applications, so theoretical study is an important task to be solved.

2. GENERAL CONDITIONS

Gas discharges and its parameters are studied in a cylindrical form reactor, filled with Ar, with parallel plate electrodes excited by two power sources, 5.5cm in diameter and 3cm long. Different configurations of a reactor electrodes excitation and power source parameters are observed. The pressure is kept in a range 50-500mToor (low-pressure gas discharge). A schematic illustration of a reactor configuration is presented in Fig. 1.

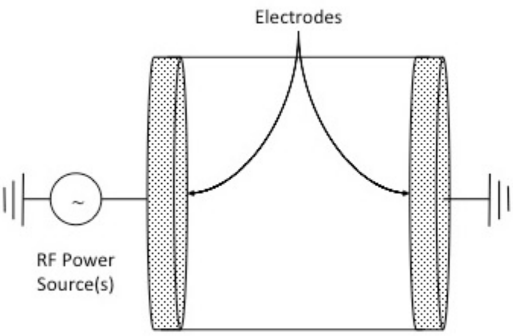

Fig. 1. Schematic illustration of a reactor configuration.

A number of reactor configurations are possible – both RF and DC power sources may be used, exciting different electrodes. For simplicity and conciseness, the present study is limited to the tree of them:

- One electrode is dually excited with two RF power sources and the other one is grounded;
- Two electrodes are excited with different frequencies and voltages of RF power sources;
- RF/DC power sources excite both electrodes.

In case of dual-frequency configuration, a sinusoidal waveform for both RF power sources is considered. The applied voltage to the electrode is a sum of two voltages (in case of both power sources applied to one electrode):

$$V = V_1 \cos(2\pi f_1 t) + V_2 \cos(2\pi f_2 t) \qquad (1)$$

where V_1, f_1, V_2, f_2 are the voltage amplitudes and frequencies respectively.

3. MODEL

Assuming azimuthal symmetry due to the reactor configuration, all the basic equations are written down in cylindrical coordinates (r, z) (Fig. 2). The RF potential is obtained from the Poisson equation. To obtain the electron transport parameters (ETP) the local mean energy approximation coupled with two-term Boltzmann solver BOLSIG+ is used [9]. The Boltzmann solver runs only once to tabulate the ETP parameters.

The electron, positive and negative ions continuity and momentum transfer equations are derived within the framework of drift-diffusion approximation from the first and second moments of the Boltzmann equation respectively [8]. The third moment of the Boltzmann equation yields the mean energy balance equation for electrons.

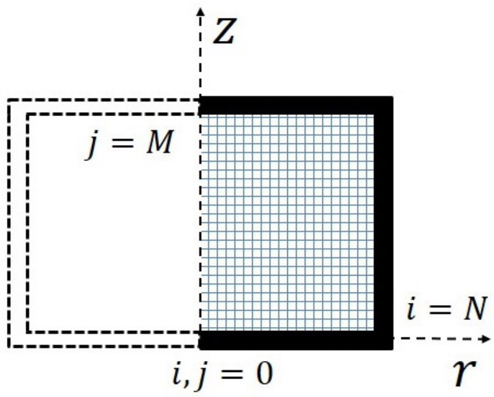

Fig. 2. Schematic illustration of r,z coordinates, boundaries and computational mesh.

First, second and third moments equations require a set of boundary conditions to be fully defined, which are well-described in a number of works [].

The equations are solved iteratively by using the Scharfetter–Gummel exponential discretization scheme. Poisson's equation is solved with a direct matrix method. Charged particle transport equations are splitted with a semi-implicit Crank-Nicholson method and Courant-Friedrichs-Lewy condition is applied to control a time step.

Equations are discretized using a second order finite difference representation. It should be mentioned, that basically 100x100 grid is used, further grid enlargement leads to substantial calculation time degradation with no great result improvement at the same time. At the same time, overall calculation performance may be significantly improved with the help of parallel and distributed computational code implementations.

4. RESULTS

As mentioned above, three reactor configurations are observed. For conciseness, all the results will be described in terms of density profiles.

It should be underlined, that the described task is a multi-model and multi-parameter one as it's necessary not only to solve model equations for a set of reactor configurations, keeping correct boundary conditions, but also to perform a set of calculations with different input data (e.g. power source parameters) to analyse the key dependencies and optimal plasma parameters for surface treatment. To perform a set of numerical experiments, required to extract necessary data, the "Virtual Discharge" modelling environment, coupled with ScopeShell [10] and Tadisys [11] systems is used.

It was shown that reactor configurations with two power sources may significantly improve overall plasma devices effectiveness. The influence of both power source parameters and its power-to-electrode connection configuration on key plasma parameters was studied. Two power sources with different connection configurations allow controlling both particles energy and flux separately and effectively. It should be mentioned, that classical one power source reactor configuration does not allow to manipulate both energy and flux, keeping it as optimal ones for different applications.

Power source parameters are V_1, f_1, V_2, f_2 - voltage amplitudes and frequencies for dual-frequency setup and V_{rf}, f_{rf}, V_{dc} for RF/DC configuration respectively.

Dual-frequency reactor configurations demonstrate strong density profiles' dependency on both power sources parameters and its connection to the reactor's electrodes. It was noticed, that when power source frequencies greatly differs, the configuration with one powered electrode gives significantly lower electron density profiles as compared with two excited electrodes configuration (Fig. 3).

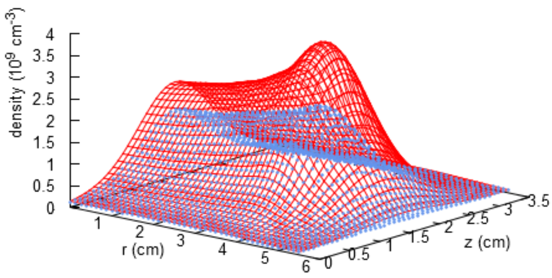

Fig. 3. Time-averaged electron density profiles for dually excited electrode configuration (dotted blue) and two powered electrodes configuration (solid red). Reactor configuration - p=500mTorr, $V_1 = 220V, f_1 = 4{,}52MHz, V_2 = 50V, f_2 = 45{,}2MHz$.

At the same time, when the higher RF power source frequency is constant and the lower RF power source frequency is increased, it was noticed, that dually excited electrode configuration gives higher electron density profiles.

RF/DC reactor configurations were also studied. An extra DC power source, applied to a reactor electrode, may significantly increase density profiles as compared with single RF power source configuration (Fig. 4).

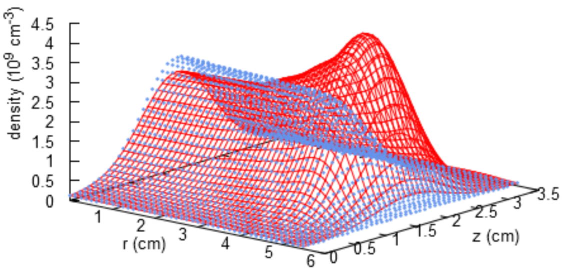

Fig. 4. Time-averaged electron density profiles for single RF power source configuration (dotted blue) and RF/DC power sources configuration (solid red). Reactor configuration - p=500mTorr, $V_{rf} = 220V, f_{rf} = 13{,}56MHz, V_{dc} = 200V$.

Generally, when applied voltage V_{dc} increases, the plasma density decreases and the plasma sheath thickness greatly enlarges (so plasma bulk thickness reduces respectively). A density reduction in the center of the reactor can be observed.

Obtained results are helpful and may be used for effectiveness analysis of plasma devices used for surface treatment, including sterilization of medical devices. As mentioned above, its well-known, that particle energy and flux parameters play key role in gas discharge effectiveness in surface treatment applications. So the key aim is to find out the best reactor configurations and setups for different applications. Performed sets of calculations and numerical experiments have shown that an extra RF or DC power source usage is an effective way to optimize gas discharge parameters and get its values, that are not achievable with classical one power source configurations. Obtained results are in a good agreement with experimental ones, but at the same time give a significantly wider set of data, that cannot be obtained experimentally due to diagnostic devices limitations.

5. CONCLUSION

In the present paper two power sources reactor configurations (both dual RF and RF/DC) have been studied theoretically with developed two-dimensional fluid model. A number of numerical experiments with different input data have been performed to analyse the dependency of key gas discharge plasma characteristics on reactor and applied power sources configurations.

The numerical results allow us to conclude that both electrode configurations and power sources parameters (voltage amplitude and frequency) have a pronounced influence on discharges characteristics: plasma density and ionization rate, sheath thickness, potential etc. The obtained profiles were compared to the experimental results and found to be in a good agreement with them. Obtained numerical results have been used for experimental plasma sterilization devices development and its effectiveness improvement.

The obtained results are the base for our future physical studies. Developed theoretical approach and two-dimensional model may be used for studying a number of other reactor configurations, including three RF or dual-RF/DC power sources setup, that may give new theoretical results extremely useful for further work on experimental devices improvement.

5. REFERENCES

[1] A. Salabas, R. Brinkmann, Plasma Sources Sci. Technol. 14, 53-59, 2005

[2] E. Kawamura, A. J. Lichtenberg, M.A. Lieberman,PlasmaSourcesSci.Technol.,17: 045002, 2008

[3] V. A. Lisovskiy, N. D. Kharchenko and V. D. Yegorenkov J. Phys. D: Appl. Phys. 43 425202, 2010

[4] V. A. Lisovskiy, N. D. Kharchenko and V. D. Yegorenkov, J. Phys. D: Appl. Phys. 41 125207, 2008

[5] M. Moisan, J. Barbeau et. al. Pure Appl. Chem. 73 N 3, 349-358, 2002

[6] G. Wenig, P. Scheubert, P. Awakowicz Surface and Coatings Tech. 174 482−486, 2003

[7] V. Milosavljevic, A. R. Ellingboe, C. Gaman, J. V. Ringwood. J. Appl. Phys. 103 083302-083302- 083310, 2008

[8] P. Diomede, S. Longo, D. Economu et al, J. Phys. D: Appl. Phys. 45 175204, 2012

[9] Bolsig+ http://www.bolsig.laplace.univ-tlse.fr

[10] D. P. Kostomarov, F. S. Zaitsev, A. G. Shishkin, and S. V. Stepanov. “The ScopeShell Graphic Interface: Support for Computational Experiments and Data Visualization”. Moscow University Computational Mathematics and Cybernetics. Vol. 34. Pp. 191-197. 2010.

[11] D. P. Kostomarov, F. S. Zaitsev, A. G. Shishkin, S. V. Stepanov, and E. P. Suchkov. “Automating Computations in the Virtual Tokamak Software System”. Moscow University Computational Mathematics and Cybernetics. Vol. 36. Pp. 165-168. 2012.

[12] A. Salabas, G. Gousset and L. L. Alves Plasma Sources Sci.Technol. 11 448, 2002

[12] Y. P. Raizer, N. Shneider and N. A. Yatsenko Radio Frequency Capacitive Discharges (Boca Raton, FL: CRC Press), 2005