Majlesi Journal of Electrical Engineering **Vol. 17, No. 1, March 2023**

Optimization of Electricity Consumption using Dielectric Barrier Discharge Method (DBD)

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Received: 17 November 2022 Revised: 6 December 2022 Accepted: 25 January 2023

ABSTRACT:
Dielectric Barrier Discharges (DBDs) are self-sustaining electrical discharges in electrode configurations containing an insulating material in the discharge path. Dielectric barrier discharge is considered a new method to produce plasma, which is of interest to researchers in various fields. In this article, electrical breakdown and plasma formation with argon atmospheric pressure gas are simulated. To avoid the complexity of the problem and faster convergence, the simulation has been done in one dimension. It has been shown that the optimization of a plasma reactor depends on the distance between the electrodes and the gas flow rate. By changing different discharge gaps, the gap has been optimized and as a result, optimized power consumption has been achieved.

KEYWORDS: Dielectric Barrier Discharge, Plasma, Power Systems, Finite Element Method, Ionisation.

1. INTRODUCTION

Recently, plasma based technologies have been used for a wide range of applications, such as textile, electronics, sterilization of medical equipment, wound healing, packaging in the food industry, agriculture, dental applications as dental caries, elimination of biofilms, sterilization of living tissue with the potential to kill various types of bacteria, viruses and so on, surface treatment and activation, and excimer formation[1-3].

To enhance the surface energy of substrates such as dielectrics or polymers, their surface should be modified by plasma treatment. Surface treatment by Plasma is one of the most versatile techniques in surface modification, without changing the surface properties[4]. Plasma can be defined as ionization of a feed gas that produces positive and negative ions, electrons, UV photons, along with active free radicals[5]. Atmospheric pressure plasma devices (also referred to as non-thermal or low-temperature or cold plasma) can be defined as remote plasma sources operating at Atmospheric Pressure (AP) and moderate gas temperature[5]. Non-thermal plasma reactors working at atmospheric pressure have gained a lot of interest due to their numerous applications. The use of Dielectric Barrier Discharge (DBD), is one of the promising technologies for producing cold atmospheric plasmas. This type of discharge where at least one of the electrodes is covered with a dielectric material, prevents the formation of an arc discharge. The electrical energy injected to a DBD plasma system is mainly transferred to energetic electrons, while the neutral gas remains closest to ambient temperatures than the heavy particles that are at room temperature.

The discharge gap width can be varied from less than 0.1 mm to about 100 mm, and applied frequency from below line frequency to several MHz[6].

There are various types of Dielectric Barrier Discharge (DBD) with different configurations. These plasma systems are driven by micro-waves, RF, AC, or pulsed power supply in the presence of gas feeds, such as noble gases (He and Ar) or mixture of noble gases [1]. Due to the surface charge accumulation on dielectric parts, the dielectric counteracts the external applied electric field. This leads to the self-limitation of discharge current and prevents the transition of discharge into the arc[1].

In order to optimize a DBD system, it is important to calculate the power consumed over a wide range of discharge conditions, to clarify that there is an optimal discharge gap for material treatment.

This work investigates the analysis of a DBD reactor with both of the circular flat electrodes covered with dielectric materials to optimize various characteristics of the system, such as average power consumption, for surface processing. Indeed, the main goal of the research described in this work is to obtain an optimal value of reactor gap for average power consumption in the proposed DBD system.

Paper type: Research paper
DOI: 10.30486/mjee.2023.1975011.1024
How to cite this paper: N. Dadashzadeh, **"Optimization of Electricity Consumption using Dielectric Barrier Discharge Method (DBD)"**, *Majlesi Journal of Electrical Engineering*, Vol. 17, No. 1, pp. 117-121, 2023.

2. STRUCTURE AND EQUATIONS

In our proposed model, simulation of electrical breakdown of an atmospheric pressure gas is demonstrated. Since electrical breakdown of a gas is a complicated process, a 1D model is considered. Fig.1 (a) shows the schematic diagram of the 3D structure of the designed DBD and Fig.1(b) shows the 1D discharge geometry of the simulated DBD

To highlight the physics of the breakdown process, this simulation uses a simple argon chemistry which keeps the number of species and reactions of species to a minimum. As the voltage applied to the top plate of DBD system increases, a strong electric field is formed in the gap between the two plates. Any free electrons in the gap are accelerated due to electrical field and if the electric field is strong enough, they may gain enough energy to cause ionization. The result of ionization is a cascade effect where the number of electrons in the gap increases exponentially on a nanosecond time. Electrons created via electron impact ionization rush towards one of the dielectric plate’s surfaces, in the opposite direction to the generated electric field. An equal number of ions are also generated in the gap during electron impact ionization (the number of electrons and ions must be in equal pairs to preserve the overall charge balance). The ions rush toward the opposite plate in the same direction as the electric field. As a result, surface charge accumulation with opposite sign is formed on both dielectric plates. This leads to the electric field to become shielded from the gas filled gap. Indeed, the electric field across the gap cannot exceed the value of breakdown electric field, which is highly dependent on the working gas. Surface charge accumulation temporarily terminates the discharge process until the electric field reverses direction and the discharge process repeats in the opposing direction.

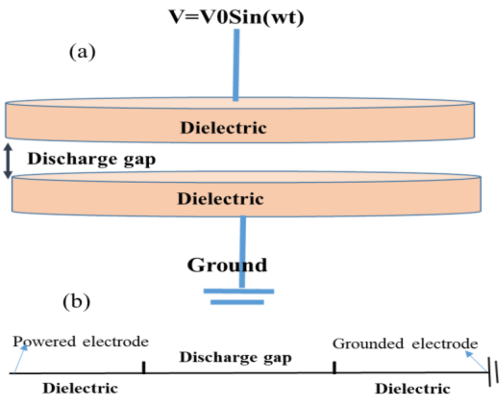

Fig. 1. (a) Schematic figure of the 3D structure of the designed DBD (b)The 1D discharge geometry of the simulated DBD.

The plasma is driven by a sinusoidal RF alternating voltage power supply with a frequency of 51 kHz (Table 1). When the applied voltage which must exceed the breakdown voltage of the gases is achieved, the gases lose their dielectric properties and turn into conductors[7]. Based on the electric equivalent network model, the values of electron density and mean electron energy are computed by solving a pair of drift diffusion equations.

Table .1. Values of applied voltage, frequency, diameter of the electrode and thickness of the dielectric layers.

Parameter	Value
Applied voltage	-800sin(wt)
RF frequency(f)	51e3[Hz]
Angular frequency	2*pi*f
Plate diameter	0.12mm

$$\frac{\partial}{\partial t}(n_e) + \boldsymbol{\nabla} \cdot [-n_e[(\mu_e \cdot \boldsymbol{E}) - D_e \cdot \boldsymbol{\nabla} n_e] = R\ _e \quad (1)$$

$$\frac{\partial}{\partial t}(n_\varepsilon) + \boldsymbol{\nabla} \cdot [-(n_\varepsilon(\mu_\varepsilon \cdot \boldsymbol{E}) - D_\varepsilon \boldsymbol{\nabla} n_\varepsilon] + \boldsymbol{E} \cdot \Gamma_e = R_\varepsilon \quad (2)$$

The convective effect of electrons due to fluid movement is neglected. Electron diffusion is calculated from the following equation.

$$De = \mu_e T_e \quad (3)$$

$$\mu_\varepsilon = 5/3\mu_e \quad (4)$$

$$D_\varepsilon = \mu_\varepsilon T_e \quad (5)$$

Assuming that "M" is the reactions related to the growth and decay of the electron density and "P" is the number of inelastic collisions of electrons. Considering "P >>M", we have:

$$R_e = \sum_{j=1}^{M} x_j\, k_j \quad (6)$$

Where "xj" is the mole fraction of the target species in the discharge process for reaction z, "kj" is the reaction rate coefficient and "N" is the total number density of neutral particles. Electron energy loss is obtained by summing the collision energy losses in all reactions:

$$R_\varepsilon = \sum_{j=1}^{P} x_j\, k_j N_n n_e \Delta\varepsilon_j \quad (7)$$

In the above equation, "$\Delta\varepsilon_j$" is the energy loss from reaction "j". The ratio of constants is calculated with the following integral:

$$k_k = \gamma \int_0^{\infty} \varepsilon\, \sigma_k(\varepsilon) f(\varepsilon) d\varepsilon \qquad (8)$$

In the above equation, "$\gamma = \sqrt{2q/m_e}$ ", " m_e "electron mass" ε " energy, "σ_k " Collision cross section, "f" is a function of electron energy distribution.

The static electric field is calculated from the following equation.

$$-\nabla \cdot \varepsilon_0 \varepsilon_r \nabla V = \rho \qquad (9)$$

$$\rho = \sum_{K=1}^{N} z_K\, n_k - n_e \qquad (10)$$

Space charge density is automatically determined based on plasma chemistry and the formula above.

3. BOUNDARY CONDITIONS

Due to the random movement of electrons in the chamber, they disappear in several free paths upon hitting the wall, and free electrons are formed again due to the effects of secondary diffusion, which leads to the following boundary condition:

$$\mathrm{n} \cdot \Gamma_e = (1/2) V_{e.th} n_e - \sum_P \gamma_P\, (\Gamma_P . \mathrm{n}) \qquad (11)$$

nd, the electron energy flux is calculated as follows:

$$\mathrm{n} \cdot \Gamma_\varepsilon = (5/6) V_{e.th} n_\varepsilon - \sum_P \varepsilon_P \gamma_P (\Gamma_P . \mathrm{n}) \qquad (12)$$

The second term on the right side of equation 11 represents the increase of electrons due to secondary emission effects. " γ " represents the secondary diffusion coefficient. The second term in equation 12 shows the energy flux of secondary emission. "ε " represents the average energy of secondary electrons.

Surface charge accumulation is added to the both dielectric surfaces that are adjacent to the discharge gap where the plasma is generated by way of the following boundary condition:

$$n \cdot (D1 - D2) = \rho_s \qquad (13)$$

Where ρs indicates the surface charge density, which is calculated by solving the following distributed ODE on the surfaces:

$$\frac{\mathrm{d}\rho_\mathrm{s}}{\mathrm{dt}} = \mathrm{n} \cdot \mathrm{J_i} + \mathrm{n} \cdot \mathrm{J_e} \qquad (14)$$

The term n · Ji indicates the normal component of the total ion current density at the wall, and n · Je indicates the normal component of the total electron current density at the wall. The discharge process is formed by a sinusoidal potential applied to the exterior boundary of one of the dielectric plates.

Plasma chemistry

Since only a handful of reactions and a few species need to be considered, Argon gas is attractive to be used in a benchmark problem. The list of chemical reactions considered is as follows: (7)

Table. 2. The reactions of electron with argon gas (excited argon atoms Ar*, argon atom Ar, singly ionized argon atom Ar+)

Reaction	Formula	Type	Δε(ev)
1	e+Ar=>e+Ar	Elastic	0
2	e+Ar=>e+Ars	Excitation	11.5
3	e+Ars=>e+Ar	Superelastic	-11.5
4	$e+Ar=>2e+Ar^+$	Ionization	15.8
5	$e+Ars=>2e+Ar^+$	Ionization	4.24
6	$Ars+Ars=>e+Ar+Ar^+$	Penning ionization	-
7	Ars+Ar=>Ar+Ar	Metastable quenching	-

4. SIMULATION RESULTS

Due to the fact that it is easier to analyze the results of one-dimensional problem by extruding the solution into two dimensions, 1D analyzes are performed. The extra dimension represents time. In finite element method analyses, this is accomplished by adding a Parametric Extrusion 1D data set. The surface plot is convenient because it can be immediately seen that how the variables of interest evolve over time.

It can be seen from Fig. 2 that there is a much stronger electric field in the dielectric materials than in the discharge gap. This is because the surface charge accumulated on the dielectric plates surfaces tends to shield out the electric field.

Fig. 3 shows electron density versus the gap spacing for DBD with dielectric constant of 10 when reactor gap is varied from (a)0.05mm to (b)0.1mm.

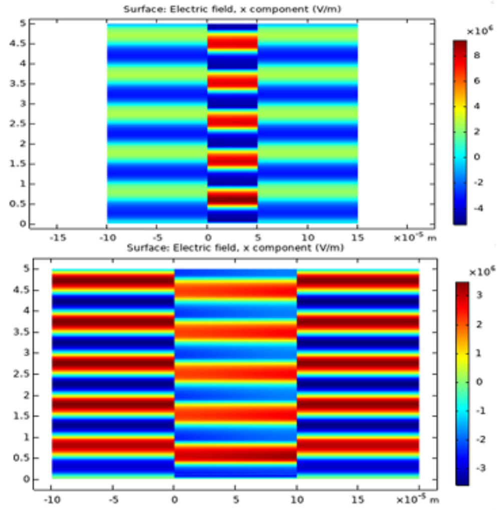

Fig. 2. Electric field across the gap (x-axis) vs. time (y-axis).

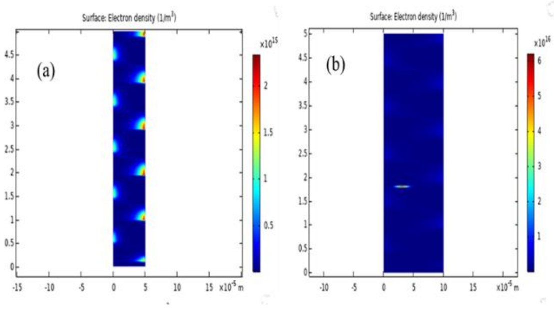

Fig. 3. Electron density versus the gap spacing for DBD with dielectric constant of 10 when reactor gap is varied: (a)0.05mm (b)0.1mm.

According to Fig. 4, the mass fraction of excited argon atoms is plotted by varying the discharge gap. The excited species have a much longer lifetime in the discharge gap than the electrons and ions. This is due to the fact that the primary mechanism for destruction of excited argon species is de-excitation upon contact with the wall. The electrons and ions reach the wall very rapidly due to migration mechanism whereas the excited argon atoms can only reach the wall via diffusion phenomenon. It is also clear from Fig. 4 that the discharge process reaches a periodic steady state solution after only two RF cycles.

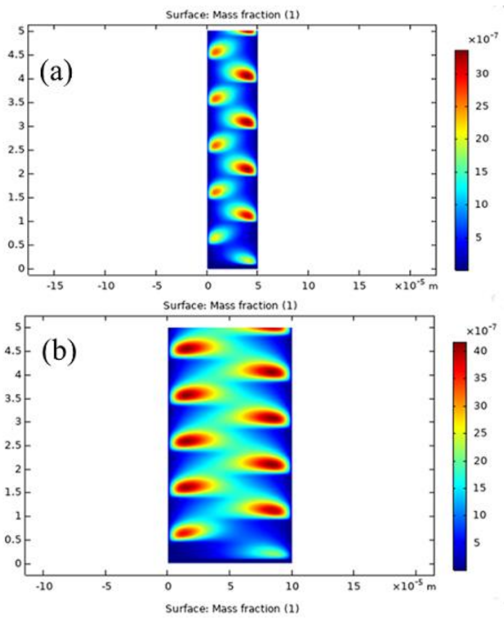

Fig. 4. Mass fraction of argon atoms.

According to the Fig. 5, plot of the total plasma current density (sum of the electron and ion current density), excluding the first RF cycle was demonstrated. Conservation of charge requires that the total current density be constant across the gap at any point in time.

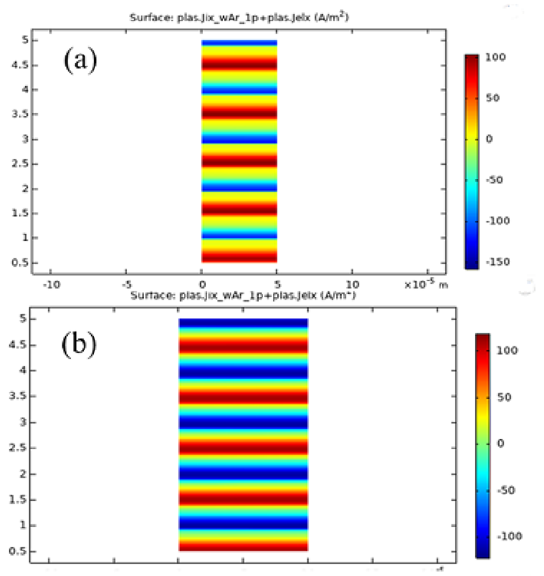

Fig. 5. Plot of the total plasma current density (sum of the electron and ion current density), excluding the first RF cycle. Conservation of charge requires that the total current density be constant across the gap at any point in time.

The instantaneously absorbed power in the generated plasma is demonstrated in Fig. 6. Time averaging this over 1 RF cycle leads to the power absorbed by the plasma. The absorbed power is different in first half cycle and the other half cycle. This difference is due to the fact that on the upper and lower plates, the secondary emission coefficients are different. According to Fig. 6 by increasing the gap total capacitive power deposition has been decreased therefore this is favorable in the designing of a DBD systems.

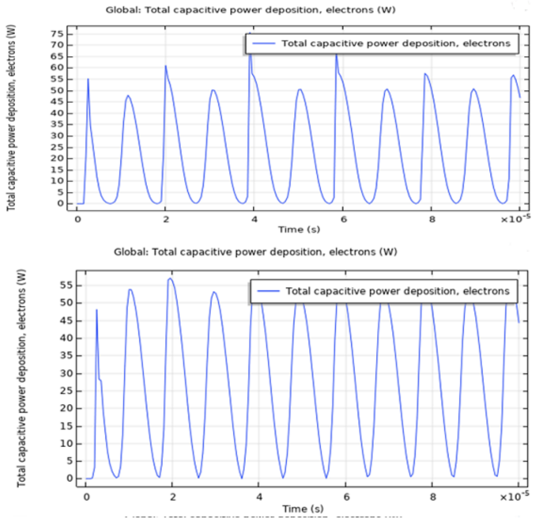

Fig. 6. Plot of power vs. time for the dielectric barrier discharge.

5. CONCLUSION

Dielectric barrier discharge assisted plasma technique is a novel green technique with high energy evolution. The developed DBD assisted plasma reactor is optimized using various diagnostic methods. Optimization of a plasma reactor depends on size, gap between the electrodes, gas flow rate and so on.

This paper simulates electrical breakdown and plasma formation in an atmospheric pressure gas of argon. Since electrical breakdown and generated plasma is a complicated process, a 1D model is considered. This model uses a simple argon gas, which keeps the number of species and reactions to a minimum value. By varying different discharge gaps, the optimized gap and therefore optimized power consumption was specified.

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