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Simulator design for low pressure plasma discharges in planar geometry

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Abstract.   A design of a simulator code to determine the plasma characteristics in planar geometry discharges is presented. The experimentally obtained parameters are compared to the code predictions. The experimental plasma discharge characteristics were carried out using 99.99% nitrogen as the working gas at typical pressure values in the range 0.1–0.6 Torr. The simulator code was used to obtain the discharge current-voltage, showing compatibility with experimental values. The minimum breakdown voltage at the minimum gas pressure was also obtained. The relation between the discharge current at different anode-cathode distances was also determined.

Keywords: Plasma discharge, discharge Simulator, planar electrodes

1. Introduction

DC glow discharge at low pressure is one of the most familiar gas discharges with reasonable ionization fraction, and [1, 2]. The three basic regions in the glow discharges are the cathode region, the glow and the anode regions [3, 4]. The Paschen law is used to describe the mechanism of gas breakdown [5], in which the breakdown voltage is function of Pd, the product of the pressure and the electrode distance. Paschen law validity was confirmed for different DC discharge conditions as pressures, distances and electrode materials [6, 7]. It was also previously observed that there is departure from the Paschen law at small electrode gap separation [8, 9].

The inter-electrode voltage is an important parameter of gas discharge devices, which is necessary for the transition from non-self-sustaining discharge to self-sustaining one. Paschen discovered a law that the homogeneous field will be formed between the inter-electrodes after applying DC voltage to the two parallel plates, where the relation between the voltage and Pd determines the breakdown potential. If the gas components and electrode materials are definite, then the breakdown voltage, V_b, is a function of Pd under the cold electrode condition$(V \propto Pd)$. The Paschen's Law determines the minimum value, $(V_b)_{min}$ as a function of Pd at the minimum value of the voltage $\left(V_{(b)min} = f(Pd)_{Vmin}\right)$ when the numerical value of Pd is changed [10].

Plasma processing of materials is especially focused on the control of plasma parameters for improvement of the microstructure and properties of the thin films and various other materials that

have different applications, especially in aerospace industry to how to improve the hardness of spacecraft materials. Plasma has wide range of applications such as the activation of catalytic processes [11-15], surface treatment [16, 17], polymer based composite materials used in aerospace applications [18, 19], fabrication of microprocessors [20], medicine [21], nano-material synthesis [22] as well as many others. In case of polymers, which have vital role in aerospace materials, surfaces treated by plasma leaves active sites at the surfaces that are subjected to the aging as post reactions, and causes modifications during plasma exposure [23]. Numerous simulators have been developed for various fields of science particularly radiation and nuclear physics such as in [24, 25].

The main goal of this simulator's design is to obtain optimum operating parameters of the planar anode - cathode electrodes forming plasma. This enables setting up experiments to enhance the physical and chemical properties of different parts composing a fuel cell treated by plasma to enhance the use of fuel cells in space shuttles as a component of the electrical power system.

2. Simulator design and interface

The designed simulator has different input variables such as the gas type, electrodes geometries and the distances between electrodes, and uses the physical equations. The output is the relation of the input characteristic of the gas discharge inside the definite plasma source, and provides the Paschen parameters for the given input parameters. Figure 1 is a simple illustration of the input/out flowchart. It shows the input variables and the output results for the needed experiment set-up. Figure 2 shows the Simulator Graphical User Interface (GUI) of plasma source simulator with planar anode and cathode. This simulator was developed based on done Child – Langmuir equation for two planar plates in vacuum.

Child and Langmuir studied the space–charge limited emission for two infinite parallel plates at fixed voltage V_0 in vacuum separated by a distance d and developed the equation that relates the current density to the voltage. [26, 27]:

$$J = \frac{4\varepsilon_o}{9} \frac{V^{3/2}}{d^2} \left(\frac{2q}{m_e}\right)^{1/2}$$

(1)

Where J is the maximum current density, A/cm^2, permittivity ε_o is equal to 8.854x10^{-12} F/m, electric charge q equals q^*x1.602x10^{-19} AS, q^* is the charge state, atomic mass m equals ux10^{-24} g, u is the mass in atomic mass units, and V is the potential drop across the anode – cathode gap separation, d is the anode – cathode distance in meter.
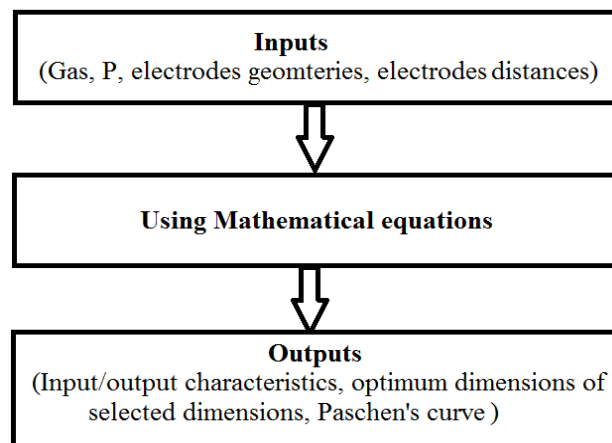
Inputs
(Gas, P, electrodes geomteries, electrodes distances)

Using Mathematical equations

Outputs
(Input/output characteristics, optimum dimensions of selected dimensions, Paschen's curve)
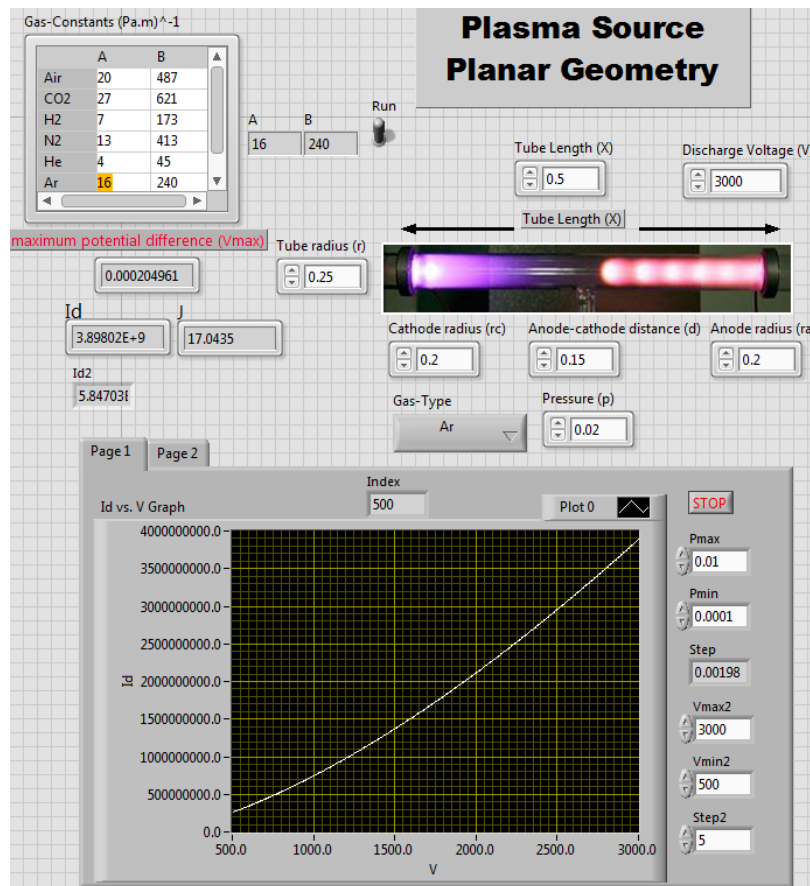
Figure 1. Simulator Flowchart.

Figure 2. Simulator Graphical User Interface (GUI) for planar geometry plasma source.

3. Simulator calculations

The plasma source consists of anode and cathode electrodes of planar shapes using pure aluminum material of purity equal to 99% placed inside a cylindrical quartz glass tube of 50 cm length and 36.5 cm diameter. The gap distance between the anode and cathode is kept constant at 10 cm. The anode and cathode were the same thickness and diameter equal to 0.7 cm and 7.5 cm, respectively. The discharge was operated using 99.99% nitrogen gas at typical pressure values in the range 0.1–0.6 Torr [28].

From experimental data, the designed simulator was used to calculate the current density to determine the discharge characteristics of formed plasma. The simulator was used to evaluate the relation between the discharge current, I_d versus the product of pressure and electrodes distance, Pd, at constant gas pressure, P, and constant anode – cathode distance, d.

Figure (3) shows the relation between V_d in volt versus J in milliampere at d_{A-C} equal to 10 cm using nitrogen gas at P equal to 0.1 Torr. The current density increases by increasing the applied voltage. From experimental data [28], the discharge current increases with increasing nitrogen gas pressure and reaches 0.55 mA at $P = 0.1$ Torr. From simulator results J equals 0.23 mA/cm^2 at V equals to 480V, which is the experimentally obtained breakdown voltage. The current I_d is equal to 0.522 mA from the current density the 0.44 cm^2 area of the emitting cathode. The error between the I_d experimental and simulator data is 0.0272.
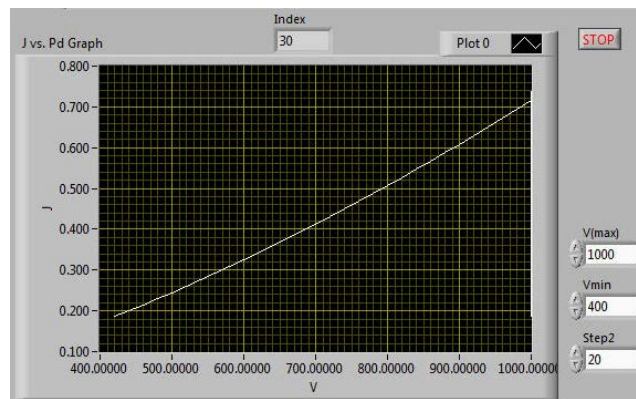
Figure 3. Simulated relation between discharge voltage versus current density at d_{A-C} = 10 cm.

Table (1) shows the simulator calculation of the discharge current corrected for each gas pressure and the minimum breakdown voltage compared to the experimental data. Figure (4) shows the relation between the simulated I_d values versus Pd using N_2 gas, where it is clear that the discharge current increased by increasing the gas pressure at constant distance between the anode and cathode.

Table 1. Simulated I_d (mA) for each Pd (Torr.cm) compared to experimental values.

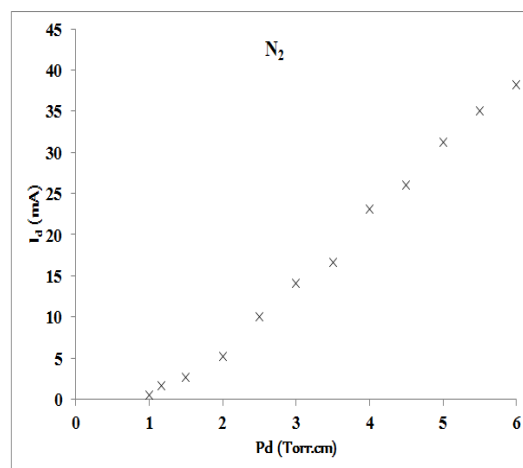| P (Torr.cm)	I_d (mA) – exp.	I_d (mA) - simulator
1.0	0.55	0.5228
1.5	2.7	2.6728
2.0	5.3	5.2728
2.5	10.0	9.9728
3.0	14.1	14.0728
3.5	16.6	16.5728
4.0	23.1	23.0728
4.5	26.0	25.9728
5.0	31.3	31.2728
5.5	35.1	35.0728
6.0	38.2	38.1728

Figure 4. Simulated discharge current versus Pd using nitrogen gas.

From figure (6) in [28], $V_{b\,(min)}$ and $Pd_{(min)}$ are equal to 458V and 1.17 Torr.cm respectively. Hence, a plot can be generated for the relation between d_{A-C} distances at the same pressure that equal to 0.117 Torr.
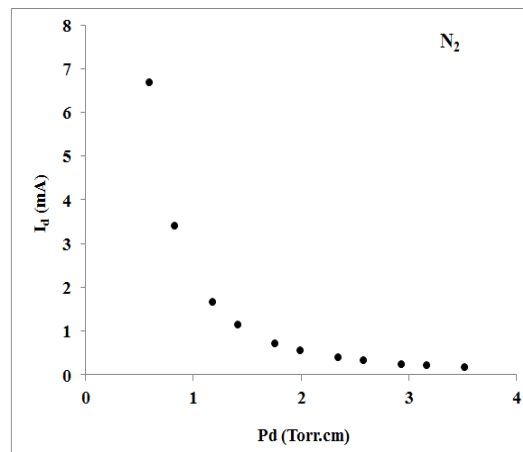

Figure 5. Simulated discharge current values versus pressure and different anode – cathode distances product using nitrogen gas.

Figure (5) shows the relation between the simulated I_d values versus Pd values at different anode - cathode distance using nitrogen gas. The discharge current is increased by increasing the distance between the anode and cathode at constant gas pressure, which is confirm with the Paschen's law.

4. Conclusion

Simulator of plasma source with planar anode and cathode is designed. By simulating the experimental data and making comparison. It is concluded that the simulator results are in good agreement with experimental data. The simulator can be useful in determining expected experimental data for a given configuration and operating parameters and to see the plasma characteristics before the experiment setup. Then, it is able to decrease a lot of efforts used to setup a definite experiment according to the type of required application.

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