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Computational Study of Charge Density Produced in N_2:H_2 Plasma Actuator

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Abstract

Numerical simulation of charge density produced in plasma actuators is dependent upon the development of models dealing with electrical properties. The main aim of this work is to investigate the characteristics surface charge density and space charge density of DBD plasma actuator. A simple design of surface dielectric barrier discharge plasma actuator is used in the study. The discharge gas was N_2:H_2 mixture with applied voltage equal to 1.5 kV. A theoretical plasma model is used to establish the charge density details. Results show that surface charge density increased in value and spread in width alone the exposed electrode as the voltage increased and reached to the amplitude value.

Keywords: Plasma actuator, Space charge density, Surface charge density, COMSOL multiphysics

Introduction

One of the most common devices used for plasma generation is the DBD plasma actuator. It offers several practical benefits such as: It contains no moving mechanical parts, it is weight too low, low power consumption, no need to combustible fuel, offers versatility in design and geometry, and it permits real-time control since it has a relatively high frequency response [1]. Generally, geometrical properties of plasma actuator are electrodes width which is typically of a few mm, the gap between encapsulated and gas exposed electrode which is also in order of few mm and in some studies set to be zero and a dielectric material such as Teflon, glass or kapton. Plasma actuator could be single or double or multi electrodes due to the study purpose. Due to its low cost and simplicity, plasma actuator used in many applications. It is used in solution of the problem of flow separation on air vehicles [2], enhance the aerodynamic flow control of air planes [3], produce and speed up ionic wind [4-7]. Many models have been investigated to simulate plasma actuator applications such as Monte carlo method with particle-in-cell [8], Navier-Stokes equations in addition with electric model [9], lumped element model plus Navier-Stokes equations [10], Surrogate model and fluid model [11-13]. Each of these models study the plasma actuator parameters as geometrical design, electrical parameters and plasma characterizations to find the best actuation process. Charge density considered to be one of the important parameters in studying plasma diagnostics and behavior. Many researches had been done where charge density considered. Alexander and Eugene studied the charge density fluctuations in order to explain the detachment of dust particles from the surface [14]. Shen et al studied the effect of relative permittivity of materials on the charge density distribution for different time periods [15]. Pedro and Anne studied the surface charge density profile for different material permittivity [16]. In the present work, surface charge density behavior and space charge density distribution along the simulated dbd plasma actuator for different simulation time were done. The plasma actuator considered is N2:H2 actuator with 50 % for each.

Materials and methods

As Known, surface dielectric barrier plasma actuator consists of 2 electrodes 1 exposed to the applied voltage and a covered electrode. A dielectric material separated between electrodes. Generally, high voltage with several kV and number of Hz is applied to the exposed electrode and produces barrier discharge on the dielectric surface in the region above the lower electrode. The result of the discharge is electrohydrodynamic force generated which acting on the discharge gas and a plasma flow is induced as shown in **Figure 1**.

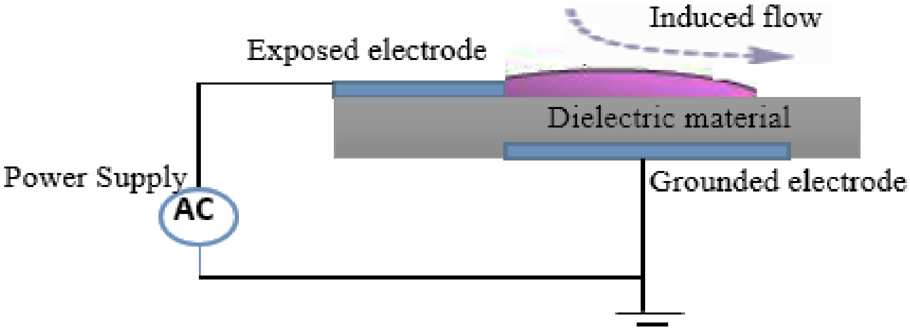


Figure 1 Schematic Diagram of DBD plasma actuator.

In the present work, the dielectric barrier plasma actuator is simulated in a domain area of 0.5×1 mm^2 space as a rectangular domain. The electrodes length is 0.014 mm thick and 0.4 mm long. The buried electrode is grounded while negative or positive constant voltage is applied to the exposed electrode. A voltage of −1.5 kV was applied as negative input voltage. Initial values of electric field intensity and potential obtained for the initial condition. Initial conditions for discharge initiations is electron number density of 10^{10} m^{-3}, gas temperature is 300 K, and the pressure is 1 atm.

The simulation study was done using COMSOL multiphysics plasma model [17]. This model is based on the use of Poisson's equation and on fluid equations for both electrons and ions. The plasma chemistry is necessary to added to equations, providing the production of the charged species, as well as secondary electron emission generated by ions impacting the gas interface. To stabilize convective effects, the model uses a Scharfetter-Gummel discretization. The discharge is generated by the electric potential that is applied to the anode boundaries. The applied potential equation is;

$$V = V_0 \tanh (t/\tau) \qquad (1)$$

where: V_0 is the amplitude to the potential (in V) wich is equal to 1.5 Kv.

The electrostatic field is computed using the following relation [15];

$$-\nabla.\varepsilon 0\ \varepsilon r\ \nabla V = \rho \qquad (2)$$

where: ε_0 , ε_r are the relative and dielectric permittivity respectively, V is the applied voltage and ρ represents
the space charge density.

The space charge density is estimated by depending on the plasma chemistry specified in the model using the equation;

$$\rho = \left(\sum_{k=1}^{N} z_n\, k_n - n_e\right) \qquad (3)$$

The boundary condition for surface charge accumulation on the dielectric surfaces is;

$$n\,(D1 - D2) = \rho_s \qquad (4)$$

where ρ_s represents the surface charge density, which is computed by the solution of the next down ordinary differential equation on the system surfaces:

$$\frac{d\rho s}{dt} = \text{n Ji} + \text{n Je} \qquad (5)$$

where $n \cdot J_i$ represents the normal component of the total ion current density at the wall, and $n \cdot J_e$ represents the normal component of the total electron current density at the wall.

The chemical reactions used for discharge gases were ionization, excitation, attachments and recombination reactions for both N_2 gas and H_2 gas.

Table 1 The chemical reactions used in the model.

Chemical reaction	**Type**
$e + N_2 \Rightarrow e + N_2$	Elastic
$e + N_2 \Rightarrow e + N_2s$	Excitation
$e + N_2s \Rightarrow e + N_2$	Super elastic
$e + N_2 \Rightarrow 2e + N_2^+$	Ionization
$N_2s + N_2s \Rightarrow N_2s + N_2$	Recombination
$e + H_2 \Rightarrow e + H_2$	Elastic
$e + H_2 \Rightarrow e + H_2s$	Excitation
$e + H_2s \Rightarrow e + H_2$	Super elastic
$e + H_2 \Rightarrow 2e + H_2^+$	Ionization
$H_2 + H_2s \Rightarrow H_2 + H_2$	Recombination

The simulation was done by extremely fine mesh of triangular shape with number of elements equal to 82524 elements, minimum element quality 0.7349 and average growth rate 1.135.

Results and discussion

Electrical charge accumulation on dielectrics (or space charge, as it is commonly referred to) can have dramatic effects. Thus, the electric field induced by the development of space charges is superimposed to the geometrical electric field applied to the material in its usual operating conditions. So, studying charge density can give a view to the electric field. **Figure 2** shows space charge density for different time steps. High net charge density forms on the edge of the exposed electrode at t = 0.15 ns. Since electric field intensity is high near the exposed electrode, electrons can obtain a great amount of energy from the electric field and as a result an electron avalanche take place. The electrons then accumulate along the dielectric surface. Spread of the region that contains high charge density when simulation time reaches to 0.3 ns. The potential is distorted due to the discharged gas on the dielectric material surface. As a result, the distorted potential produces high electric field intensity.

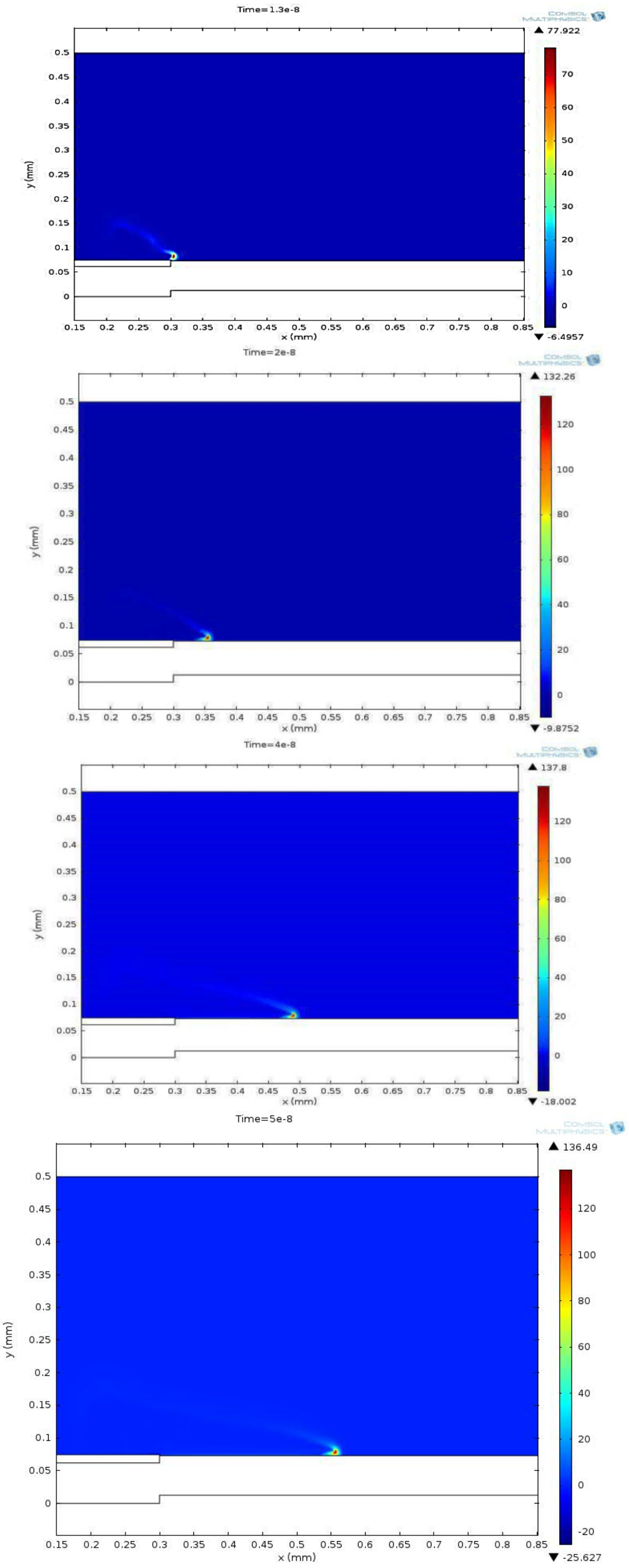
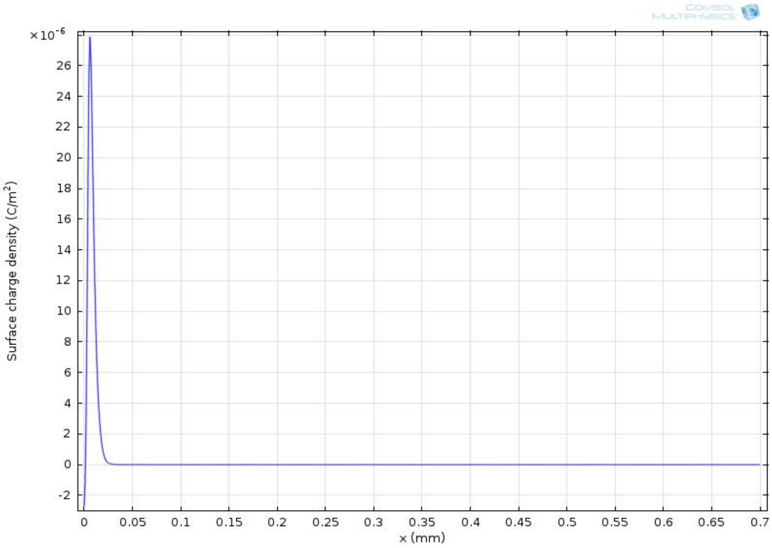
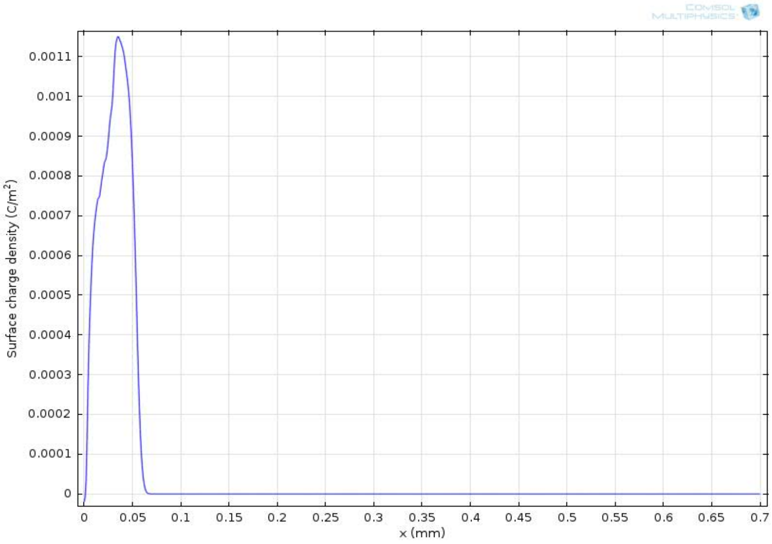


Figure 2 Space charge density (C/m^2) distribution in the simulation domain.

As the discharge take place, the dielectric surface locally accumulates positive charges that screens the cathode from the anode and propagates the discharge to the right, following the electric field lines. The body force is created by the positive space charge density at the head of the moving front. As the moving front propagates, it leaves behind a surface charge density on the surface of the dielectric. **Figure 3** shows the surface charge density along the plasma actuator simulation domain. In a perfect conductor, the surface charge density obtained from Gauss's law, and is directly relative to the normal component of the electric field at the surface. It is clear from figure that, as discharge take place, the surface charge accumulated on the surface of the electrode and spread along space and value on the electrode path. This surface charge density increased and create higher electric field values inside dielectric barrier. This is due to the fact that the charge density related to the electric field via Poisson's equation. Increasing simulation time shows that as time increasing the surface charge density spreads widely on the dielectric surface. From figure, surface charge density reaches maximum value equal to 1.1×10^{-3} C/cm^{-3}. Higher surface charge density will make higher electric field and as a result higher body force produced.





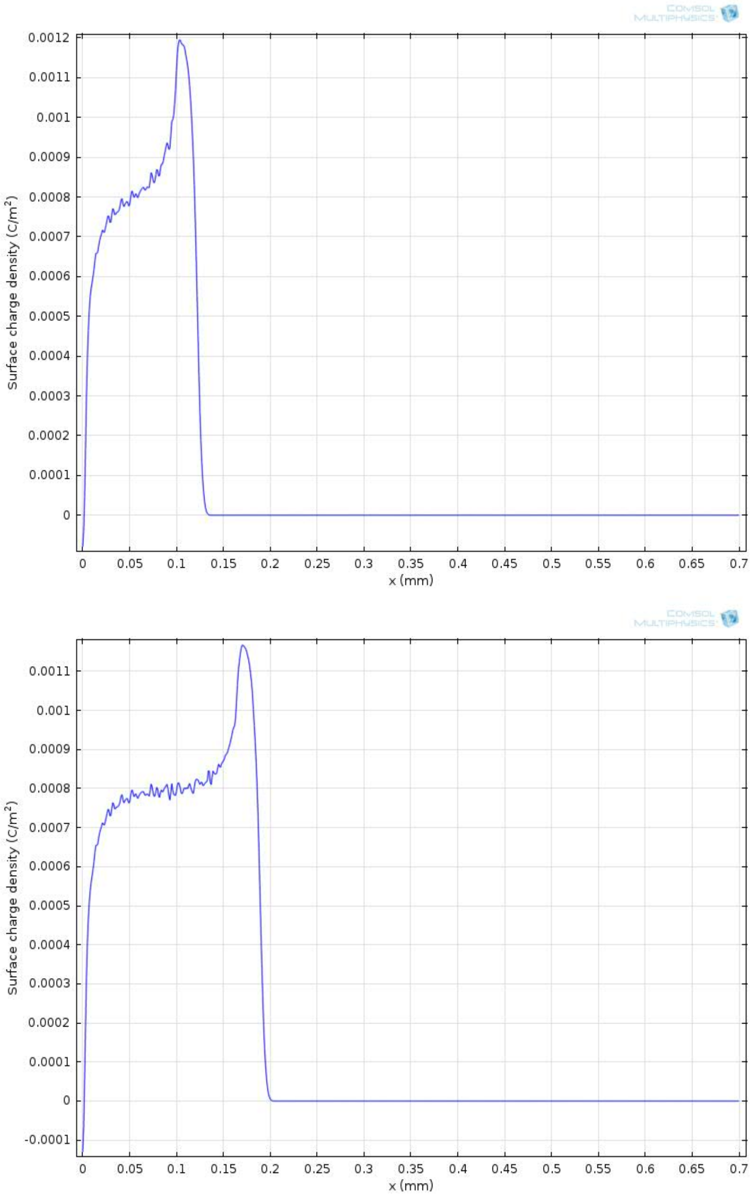


Figure 3 Surface Charge Density (C/m^2) in the simulation domain.

Conclusions

Studying the charge density distributions and behavior is an important point, Since the force generation is dependent on charge density (or electric field) and the evolution of it is to assess the performance of the DBD actuator. In the current paper, the discharge plasma actuator was modeled in accordance with reference model with radial arrangement of electrodes in Comsol Software. The plasma actuator of simple design was chosen in the research with N2:H2 mixture to study the evolution of charge density. In the studied results, the space charge density initiated at the edge of the exposed electrode and spread along the dielectric material surface as the discharge take place. Also, surface charge density increased in value and reaches maximum value equal to 1.1×10^{-3} C/cm^{-3}. From results also, it spreads in width alone the exposed electrode as the voltage increased and reached to the amplitude value. This means that, this charge accumulated on the dielectric surface will cause an initiation of electric fields in the dielectric barrier.

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