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Numerical modeling of plasma Actuator at high pressure

Abstract. *In this work, we develop a physical model for an asymmetric dielectric barrier discharge (DBD) in air driven by nanosecond voltage negative pulse. This configuration has been proposed as actuators for flow control. We present a hydrodynamic model to approximate the evolution of charge densities. The model consists of the continuity equations for electrons, positive and negative ions coupled to Poisson's equation for the electric field. We use Scharfetter and Gummel schemes SG and SG0 schemes coupling at time splitting method to resolve the transport equations system. The Poisson's equation is resolved by the tridiagonal method coupled with the over-relaxation method to calculate the electrical field. The stationary spatial distribution of the electron and ion densities, the electric potential, and the electric field in a two-dimensional (2D) configuration are presented.*

Streszczenie. *W pracy przedstawiono model fizyczny asymetrycznego wyładowania barierowego dielektrycznego (DBD) napędzanego impulsem negatywnym nano-nanocząsteczkowym w powietrzu. Konfiguracja została zaproponowana jako siłowniki do sterowania przepływem. Przedstawiono model hydrodynamiczny przybliżający ewolucję gęstości ładunku. Model składa się z równań ciągłości dla elektronów, jonów dodatnich i ujemnych sprzężonych z równaniem Poissona dla pola elektrycznego. Używano schematy Scharfettera i Gummla Przedstawiono stacjonarny rozkład przestrzenny gęstości elektronów i jonów, potencjał elektryczny oraz pole elektryczne w konfiguracji dwuwymiarowej (2D).* ***Numeryczne modelowanie aktuatora plazmowego przy wysokim ciśnieniu***

Keywords: Plasma actuator, fluid model, charged particle transport, time splitting method, *Scharfetter and Gummel schemes*.
Slowa kluczowe: Napęd plazmowy, model płynów, transport cząstek naładowanych, metoda podziału czasu, schematy Scharfettera i Gummel.

Introduction

Flow control plasma actuator has been widely studied over the past two decades as a means to reduce drag and improve performance of aerodynamic bodies [1][2][3]. Recently, the most commonly used plasma actuator has become the sliding-dielectric barrier-discharge (SDBD). A typical configuration of the SDBD is indicating the geometrical parameters of interest for its operation. Plasma actuator consists of two electrodes attached to opposite sides of a dielectric sheet. When high voltage pulse sufficient amplitude is applied between the electrodes, the intense electric field partially ionizes the surrounding air producing no thermal plasma on the dielectric surface. The collisions between the neutral particles and accelerated ions generate a net body force on the surrounding fluid leading to the formation of an "ionic wind" [4]. The body force can be used to impart the desired flow control outcome on a given fluid system.

The numerical modeling of the plasma produced by a SDBD actuator to which a short high voltage pulse is applied is described in this work. This numerical model offers the advantages of a detailed description of the plasma, providing the spatial and temporal evolution of the charged species and allowing the computation of electro-hydrodynamic forces. However, these outputs are meaningful only if the model is able to describe the physics accurately. This last point is the main challenge with the numerical modeling of the plasma at atmospheric pressure, since the experimental validation is difficult to perform for other than very global characteristics of the plasma, such as the velocity of streamers or its spatial extent. In this paper, we outline a numerical simulation methodology for plasma actuators. The transport equations and Poisson's equation formed self-consistent model [5]. We use Scharfetter and Gummel schemes SG and SG0 [6] [7] [8]. Coupling at time splitting method [5] [8] [9] to resolve the transport equations system.

Description of Model

A simulation of DBD plasma actuator was performed on a two dimensional domain as shown in Figure 1. The medium was atmospheric air. A simplified air chemistry model, which consists of generic species of singly charged positive ions, negative ions, and electrons, was used. This configuration and the air chemistry were taken from Mamunuru and Kortshagen [10].

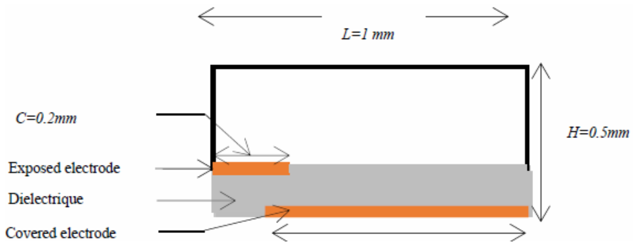


Fig. 1: Schematic view of DBD plasma actuator

Physical model

The SDBD model is based on a fluid description of electron and ion transport in air in the classical drift-diffusion and local field approximations, which are generally considered to be accurate enough for discharge models at atmospheric pressure.

Three types of charge particles are considered: electrons (index e in the equations below), one generic type of positive ions (index p), and one type of negative ions (index n).The continuity equations for electron, positive and negative ions are written, respectively, as:

$$\frac{\partial n_e}{\partial t} - \frac{\partial (n_e w_e)}{\partial \vec{r}} + \frac{\partial}{\partial \vec{r}}\left(D_e \frac{\partial n_e}{\partial \vec{r}}\right) = S_e \quad (1)$$

$$\frac{\partial n_p}{\partial t} + \frac{\partial (n_p w_p)}{\partial \vec{r}} + \frac{\partial}{\partial \vec{r}}\left(D_p \frac{\partial n_p}{\partial \vec{r}}\right) = S_p \quad (2)$$

$$\frac{\partial n_n}{\partial t} - \frac{\partial (n_n w_n)}{\partial \vec{r}} + \frac{\partial}{\partial \vec{r}}\left(D_n \frac{\partial n_n}{\partial \vec{r}}\right) = S_n \quad (3)$$

$$S_e = \alpha n_e |w_e| - \eta n_e |w_e| - B_{ep} n_p n_e + S_{ph} \quad (4)$$

$$S_p = \alpha n_e |w_e| - B_{ep} n_p n_e + S_{ph} \quad (5)$$

(6) $$S_n = \eta n_e |w_e| - B_{pn} n_e n_p$$

Ionization coefficient: α = 3.5 10^3 exp(-1.65 10^5 E-1) [11]
Attachment coefficient: η = 1.5 10 exp(-2.5 10^4 E-1) [11]
Velocity of electrons: w_e = -6.06 10 $|E|^{0.75}$ [12]
Velocity of positive ions: w_p = 2.43 E [11]
Velocity of negative ions: w_n = -2.7 E [11]
Diffusivity of electrons: D_e = 1800 cm^2/s [12]
Diffusivity of ions: D_p, D_n = -0.03 μ_{ion} cm^2/s [11]
Recombination coefficient: B_{ep} = 2 10^{-7} cm^3/s [10]
Recombination between ions: B_{pn} = 2 10^{-7} cm^3/s [10]
Photoionization source: Sph = 0 (negative pulse voltage)

The transport equations are coupled with Poisson's equation (Eq.7) for the electric field. The relative dielectric permittivity in the dielectric medium taken to be 5 (see figure 2) in the present work .

(7) $$\nabla^2 V = -\frac{e}{\varepsilon_0 \varepsilon_r}(n_p - n_e - n_n)$$

Boundary Conditions

The boundary conditions for the species continuity equations solved only in the region of the domain where air is present are tabulated in Table 1[15].

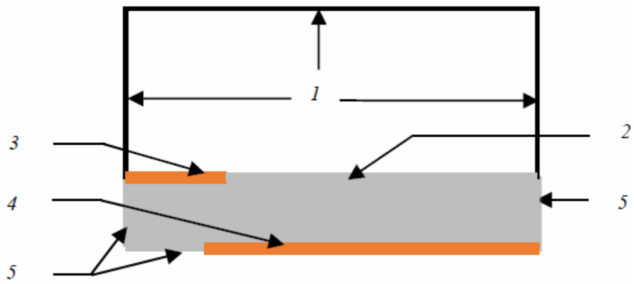


Fig. 2: Schematic representation of the used boundaries conditions

Table.1: Boundary conditions for continuity equations

Boundary	Electrons	Positive ions
1	Flux = 0	Flux = 0
2 / 3	Flux = $n_e v_e$	Flux = $n_p v_p$

The Poisson's equation is solved in the air as well as the dielectric regions; its boundary conditions are tabulated in Table 2. The boundaries are numbered in Figure2 [18].

Table.2: Boundary conditions for Poisson's equation

Boundary	Boundary condition
1 / 5	V = newman condition [15]
3	$V = V_{app}$
4	$V = 0$
2	$\nabla^2 V = \frac{e}{\varepsilon_r}(n_i - n_e) + \frac{e}{\varepsilon_r}\sigma\delta_s$ [16]

The continuity equations and Poisson's equation are solved simultaneously, subject to the above boundary conditions. An initial uniform background density of 10^5 cm^3 is set for all species**.**

Numerical methods

The numerical scheme adopted in our model is similar to that described by SCHARFETTER and GUMMEL SG in the context of particle transport [13]. The transport equations (Eq.1, 2, and 3) are discretized by a finite difference method (Eq.8) using an exponential scheme. In this paper, we combine between the SG and the SG0 scheme whose are presented by Kulikovsky [14].

(8) $$\frac{n^{k+1}_{i,j} - n^k_{i,j}}{\Delta t} + \frac{\Phi^k_{i+1/2,j} - \Phi^k_{i-1/2,j}}{\Delta x} + \frac{\Phi^k_{i,j+1/2} - \Phi^k_{i,j-1/2}}{\Delta y} = S^k_{i,j}$$

The calculated flux by SG scheme is given by the following expression:

(9) $$\Phi_{i+1/2} = \frac{D_{i+1/2}}{h_i I_0}(n_i - e^{\alpha} n_{i+1})$$

With: $h_i = x_{i+1} - x_i$, $\alpha = \frac{\mu h_i E_{i+1/2}}{D_{i+1/2}}$ and $I_0 = \frac{e^{\alpha} - 1}{\alpha}$

When: $h_i << \frac{2D_{i+1/2}}{\mu|\Delta E_i|}$

The calculated flux expression is given by the improved scheme of order 0; SG0 as follows:

(10) $$\Phi_{i+1/2} = \frac{D_{i+1/2}}{h_v I_0}(n_G - e^{\alpha_v} n_D)$$

With: $h_v = \sqrt{2\ \varepsilon\ D_{i+1/2} h_i / |v_{i+1} - v_i|}$, $\alpha_v = -\frac{h_v v_{i+1/2}}{D_{i+1/2}}$, and

$$I_0 = \frac{e^{\alpha_v} - 1}{\alpha_v}$$

ε is the interpolation factor that must be between 0.01 and 0.02 [20]

The densities n_G and n_D at the virtual nodes are given by the following expressions:

(11) $$n_G = \left(n^k_i + 1\right) e^{a(x_G - x_i)} - 1$$

(12) $$n_D = \left(n^k_i + 1\right) e^{a(x_D - x_i)} - 1$$

With: $a = \frac{1}{h_i}\log\left(\frac{n^k_{i+1} + 1}{n^k_i + 1}\right)$,and $\begin{cases} x_G = (x_i + x_{i+1} - h_v)/2 \\ x_D = (x_i + x_{i+1} + h_v)/2 \end{cases}$

Time splitting method

The numerical resolution of the transport equations of our 2D self-consistent fluid model is laborious. In this section, we use the SCHARFETTER and GUMMEL algorithm coupled to the time splitting method for the numerical solution of the transport equations. The splitting methods are well-known to solve this kind of multidimensional and multi-physical problems. In effect, the equations written initially in 2D are transformed into one-dimensional equations in each spatial direction [13].So by using this time splitting method, it is possible to find firstly $n^k_{i,j}$ for time step k with no knowledge of the numerical approximation, then for the new time step $(k+1)$ and finally calculate $\Phi^k_{i,j}$ using the solution that has already been computed for $n^k_{i,j}$.

The two-dimensional resolution of equation (8) is performed using the time splitting method [9]:

(13) $$\frac{\partial n(x,y,t)}{\partial t} + \frac{\partial \Phi(x,y,t)}{\partial x} = 0$$

(14) $$\frac{\partial n(x,y,t)}{\partial t} + \frac{\partial \Phi(x,y,t)}{\partial y} = 0$$

(15) $$\frac{\partial n(x,y,t)}{\partial t} = S(x,y,t)$$

Solving the Poisson equation is usually one of the most expensive parts of simulations of density models for SDBD discharge. The Poisson's equation is most often discretized in a 2D cartesian grid by using central finite difference scheme [6].

(16) $$\Delta V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}$$

(17) $$\frac{\partial^2 V}{\partial x^2} = \frac{V_{i-1,j} - 2V_{i,j} + V_{i+1,j}}{\Delta x^2}$$

(18) $$\frac{\partial^2 V}{\partial y^2} = \frac{V_{i,j-1} - 2V_{i,j} + V_{i,j+1}}{\Delta y^2}$$

The resulting linear system is then solved using iterative methods from the Successive Over-Relaxation (SOR) family [19].

Results and discussions

The SDBD actuator was simulated numerically for the following conditions. The geometry of the computational domain is: dielectric layer of thickness 0.1 *mm*, total height of the computational domain of 0.5 *mm* and total length equal of 1 *mm*. The length of the upper electrode was 0.2 *mm* and the length of the lower electrode was 0.85 mm (see figure1). The resolution of the continuity equation is done for the number of points n_x= 301 along the propagation axis, and n_y= 201 in the transverse direction. A Gaussian negative pulse of 3.5 kv amplitude is applied to the exposed electrode. A typical applied voltage pulse is shown in figure 3.The number of the point following the time n_t=1000.

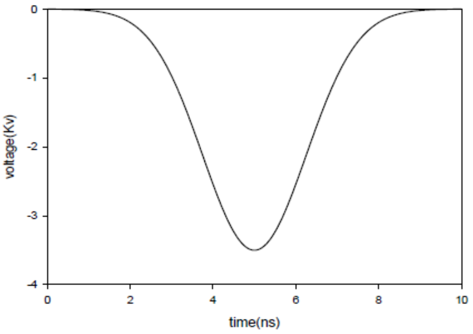
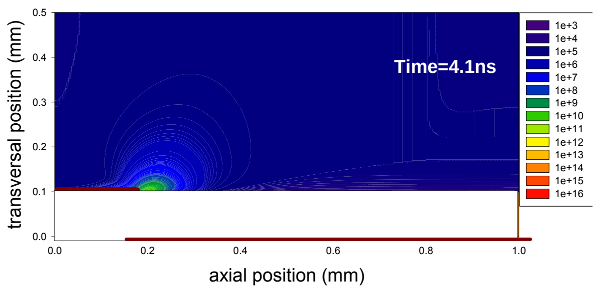


Fig. 3: applied voltage as a function of time

The electric potential produces an anode directed streamer where electrons are emitted from the exposed electrode.

The plasma ignites at a lower electric field value in this instance. Figure 4 shows the space distribution of the positive ion density for a negative pulse at different time.

It is seen that the discharge light up not at the edge of the exposed electrode but on the dielectric surface where an electron avalanche is caused by the electrons reaching the dielectric surface, along the yet undistorted field lines.



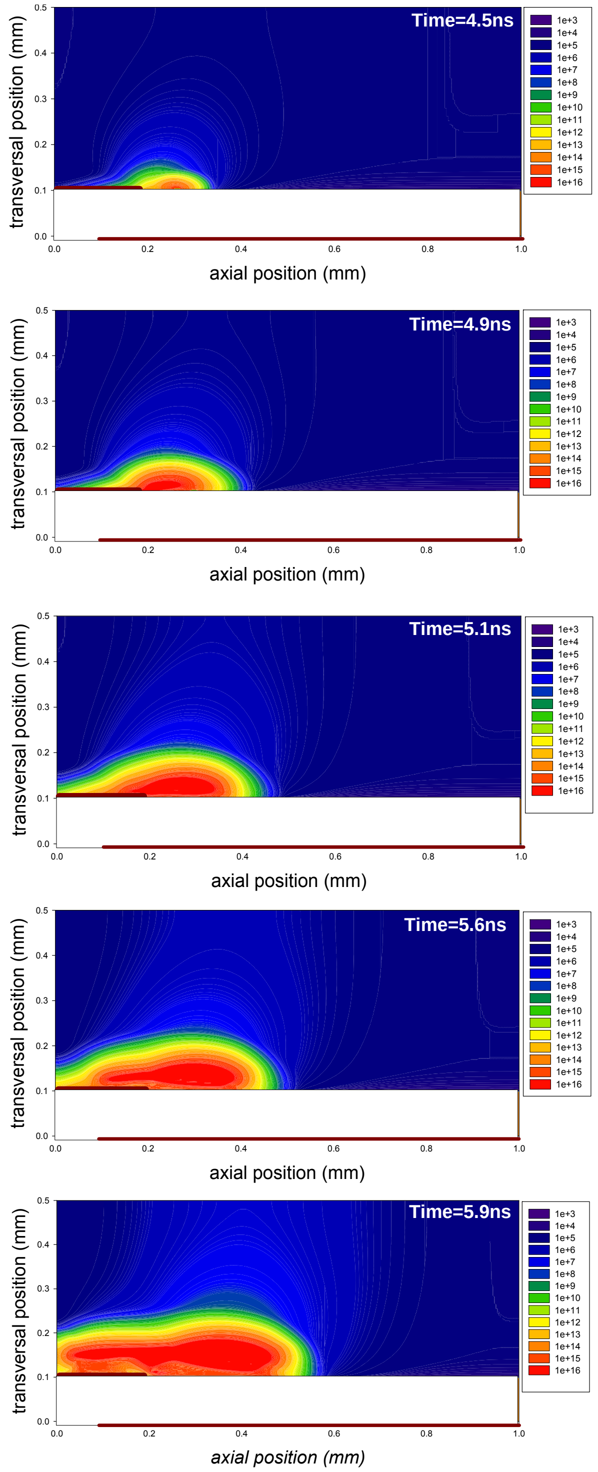
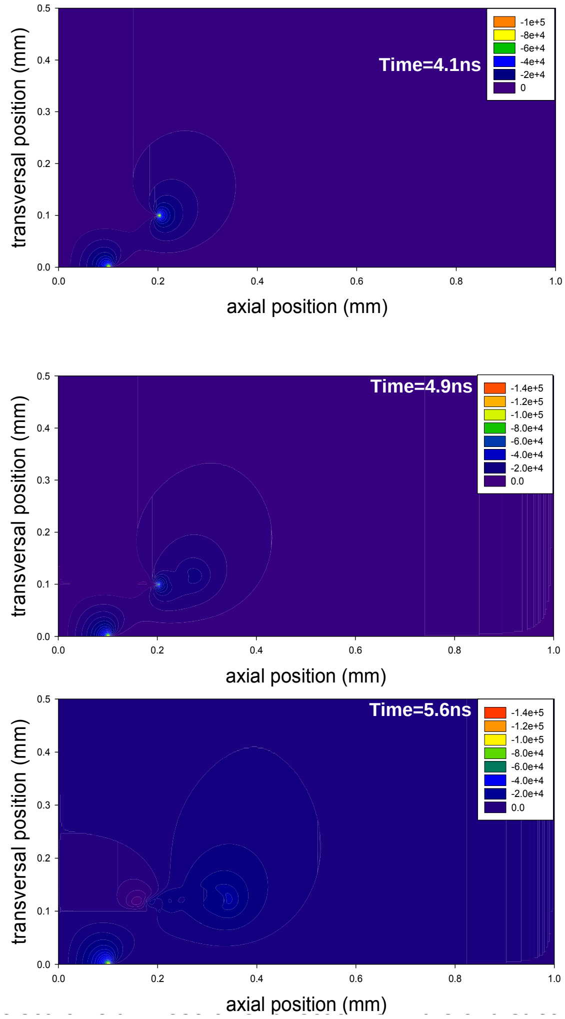


Fig. 4: Positive ion density of a discharge during the application of a negative pulse ($\log_{10}(n_p)$ cm^{-3}).

This is followed by a cathode directed streamer seen at 5 nanoseconds. After the streamer strikes the exposed electrode, the plasma begins to propagate on the dielectric surface, as a discharge directed towards the buried grounded electrode which is now positively prejudiced with respect to the exposed electrode. The head of the discharge consists of a net negative charge, populated by electrons. The variation of the electric field of axial direction at different times is illustrated in figure 5.



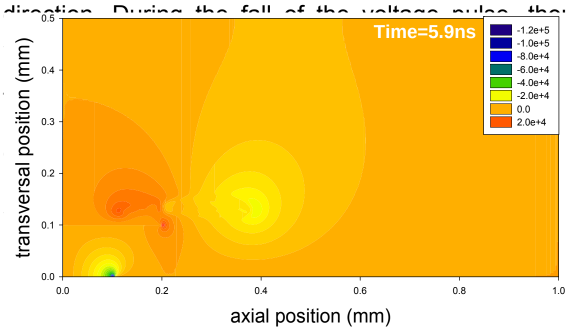
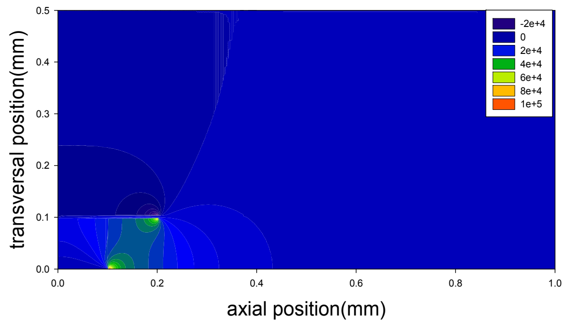


Fig. 5: The variation of the electric field for axial direction at different times (Kv/cm)

From the potential plot show in figure 7, we can see that the surface of the dielectric is at the same potential as the exposed electrode [10].



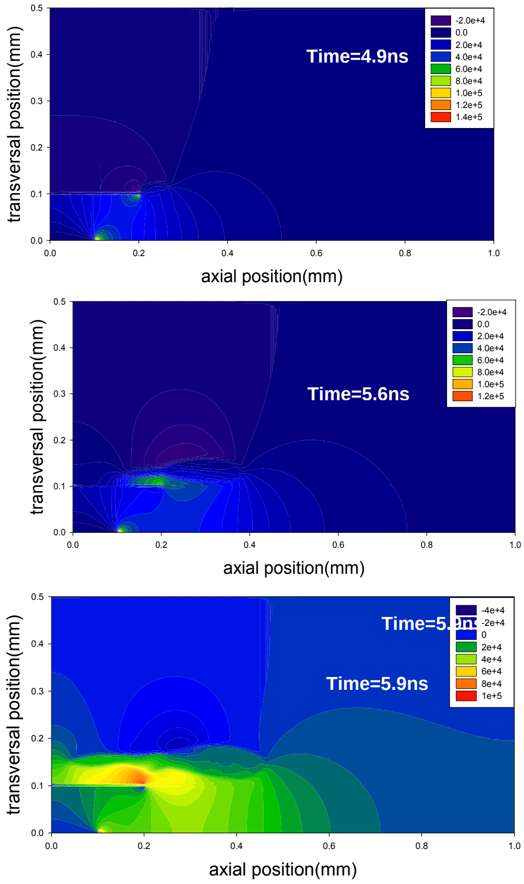


Fig. 6: The variation of the electric field for transversal direction at different times (Kv/cm)

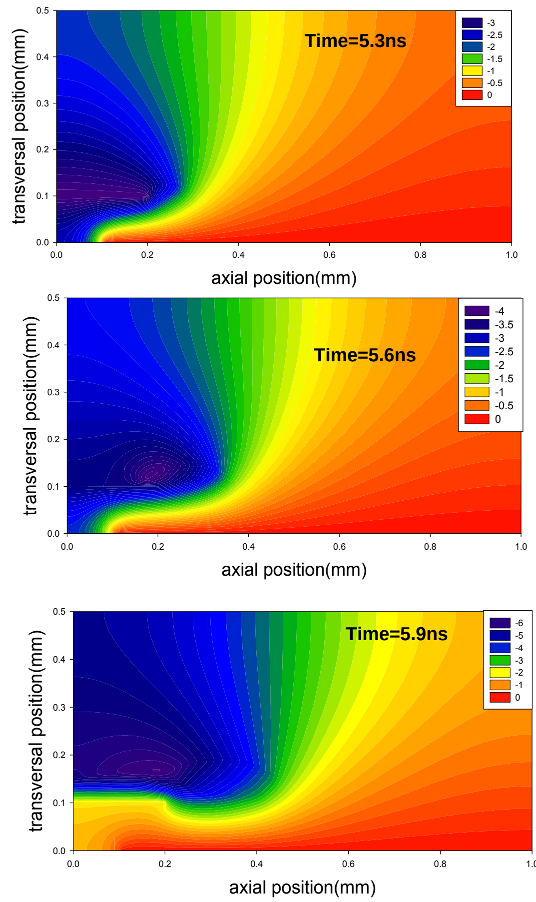


Fig. 7: The variation of the potential at different times (Kv)

The Parallel component of body force is directed towards the cathode, with large values in a small region localized around the tip of this electrode. This is because the Electro Hydro-Dynamic (EHD) force [17] [18] in that case is significant only in the cathode sheath region. This force has small positive values away from the electrode tip because the contribution of electrons is slightly larger than the contribution of positive ions in that region. The force perpendicular to the surface (not represented) [18] has a space distribution and order of magnitude similar to the parallel force shown in figure 8.

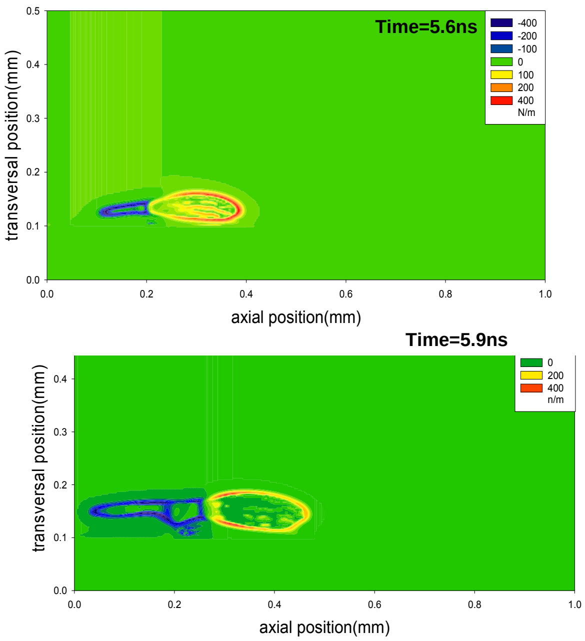


Fig. 8: The variation of the body force parallel at different times (N/m)

Conclusion

A two dimensional fluid simulation was performed to understand the working of a DBD plasma actuator. The model consists of the continuity equations for electrons and positive ions coupled to Poisson's equation for the electric field. We use Scharfetter and Gummel schemes SG and SG0 schemes coupling at time splitting method to resolve the transport equations system. The Poisson's equation is resolved by the tri-diagonal method coupled with the over-relaxation method to calculate the electrical field. This technique is a good approach for the two-dimensional simulation of plasma actuator.

A negative voltage was seen to create a thin diffuse discharge propagating on the dielectric surface; the discharge at the edge of the exposed electrode imparted an anti-streamwise force, while the discharge propagating on the dielectric imparted a weak streamwise force. A normal force directed to the actuator surface was seen. The thrust creation by actuator was thus explained at the level of the smallest timescale processes.

Nomenclature

n_e, n_p, n_n - Electron, positive and negative ions
Φ_e, Φ_+ - Electron and Ion flux
S_e, S_p, S_n - Source term for Electron, positive and negative ions
V - Electric potential
E - Electric field
ε_r - Relative permittivity
D_e, D_+ - Electron and ion diffusion
γ Coefficient for secondary electron emission
N - Neutral species density
e- Elementary charge
ε_0 - Free space permittivity
Δx - Axial spatial step
Δy - Transversal spatial step
Δt - Temporal step
σ - Surface charge density
δs - Expressed by the Dirac function

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