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On the Progress of DBD Plasma Actuator in Boundary Layer Control

A Jafarimoghaddam[1] and S Aberoumand[2]

[1]*Department of Aerospace Engineering, K. N. Toosi University of Technology, Tehran, Iran*
[2]*Department of Mechanical Engineering, Islamic Azad University, Takestan, Iran*
a.jafarimoghaddam@gmail.com

ABSTRACT

This study indicates a numerical study on the applicability of DBD plasma actuator in the manipulation of boundary layer. A flat plate has been numerically simulated in this work. Asymmetric electrodes with a dielectric material in the space between, which are comprised of a Dielectric Barrier Discharge (DBD) is considered just at the edge of the flat plate. Lumped Circuit Element Electro-Static Model is applied to simulate the effect of the actuator. The flat plate was considered with no initial flow as the inlet condition. So, the results demonstrate just the impact of the DBD plasma body force on the fluid motion. Finally, as the main result of the present study, the separation of the quiescent flow with the viscous region is determined and also the flow suction by such an actuator is identified. The configuration of the DBD plasma actuator is set to be 10 KHz for the applied voltage frequency, Kapton as the dielectric and various peak voltage amplitudes.

Keywords: Simulation of a flat plate with DBD plasma actuator, Numerical simulation, Lumped Circuit Element Model, DBD plasma actuator

INTRODUCTION

The applications of electro- hydrodynamics have been very vast in the last decades. Electro- magnetic force has been employed for many purposes including the flow and particle control. Two sorts of electro- magnetic force have been conventional so far. First is the Corona plasma wind, which is applied by DC power supply and is usually applicable for the process of mixing the fluid flow, ESP (Electro- Static Precipitator) and etc. the second one is DBD plasma actuator, which is applied by AC power supply and is usually used for the flow control process [1- 4]. Using the electric field for flow control has been reviewed by Cattefesta and Sheplak [5]. Plasma actuator has been tested in variety of applications [6-11] and it has been observed that the actuator causes a body force field which is directed from the exposed electrode to the encapsulated one. So, this last decade has been an exhibition of the variety of applications of DBD plasma body force [7, 8]. Because experimental investigations of DBD plasma actuator are so expensive, CFD tools can be applied for discovering the nature of such an actuator in different applications. Considering that, DBD plasma actuator works in a semi- steady mode, it is inferred that it could be possible to decouple plasma equation with Navier- Stokes equations and then substituting the solution of plasma body force as the source term into the Navier- Stokes equations. The goal of this investigation is to study the behaviour of DBD plasma actuator in the generation of flow suction over a flat plate. So, in the present research, the flow suction for variety of configurations of DBD plasma actuator is identified by using a numerical approach. Moreover, the path line which separates the quiescent air with the viscous region is determined in each case. Furthermore, it is worth to say that we have changed the DBD actuator configuration by changing the peak voltage amplitude. So other parameters of the actuator remained unchanged in the present work.

Plasma Model Description and Simulation Methodology

In general, DBD plasma actuator can be modelled by Electro- Static Model. This model is specified in (2016) [12]. So, in the present work, we have only brought up the main governing equations.
Electrical potential is governed by the following Poisson equation [13]:

$$\nabla(\varepsilon\nabla\varphi) = \frac{1}{\lambda_D^2}\varphi \tag{1}$$

The charge density is obtained from the one- dimensional simulation of the electric charge [13] as:

$$\rho_c = -\frac{\varepsilon_0}{\lambda_D^2}\varphi. \tag{2}$$

By presenting the net charge in a region with the presence of electric field, the induced body force by the DBD plasma actuator can be calculated by:

$$\overrightarrow{f_b} = \rho_C \overrightarrow{E}. \tag{3}$$

Numerical Formulation of Modified Electro-Static Lumped Circuit Element Model

In general, the model for DBD plasma actuator deals with solving Eq. (1) in a mathematical plain, obtaining induced body force due to the presence of the plasma actuator and then mapping the domain into the physical space of the problem. Since Lumped Circuit Element model, is an approach in which considers electrodes, air and dielectric as capacitor elements and each element as finite numbers of attached sectors (subscripted by n), then first, for modifying the Electro- Static model, the modified spatial-time Lumped Circuit Element model, discussed in [13], was used in order to obtain the region of the presence of plasma temporally, $x(t)$, and also dielectric virtual voltage $V_n(t)$ by simultaneously solving of Eq. (4) to (6). Schematic of the model is shown in Fig.1.

$$\frac{dV_n(t)}{dt} = \frac{dV_{app}(t)}{dt}\left(\frac{C_{an}(t)}{C_{an}(t)+C_{dn}(t)}\right) + k_n \frac{I_{pn}(t)}{C_{an}(t)+C_{dn}(t)} \tag{4}$$

$$I_{pn}(t) = \frac{1}{R_n}[V_{app}(t) - V_n(t)] \tag{5}$$

$$\frac{dx(t)}{dt} = vv\left|V_{app}(t) - V_n(t)\right| \tag{6}$$

In which vv , is a coefficient representing the increase in the sweep velocity by the increase of applied voltage amplitude. According to [13], vv is assumed to be $10\frac{m/s}{kV}$. $V_{app}(t)$, represents the applied voltage amplitude, $V_n(t)$ is the voltage at the virtual electrode in each sector of the encapsulated electrode which is assumed to be on the surface of dielectric material, $I_{pn}(t)$ is the current through the plasma resistance for each sector, R_n is the air resistance in each section, C_{an} and C_{dn} are capacitor elements of air and dielectric respectively, and k_n is a constant which is assumed to be 0 or 1 depending on the presence of plasma in the each sector. These factors are well discussed in [13]. Equations of 4 to 6 were solved by using second order Range-Kutta. Then, Eq. 1 was solved for spatial-time re-corrected conditions. Finally, the obtained spatial steady body force was substituted into the Navier-Stokes equations as the source term. Length of the exposed and encapsulated electrodes was assumed to be 0.5inch for both and also in the present work, vertical and horizontal distances between the electrodes were assumed to be 0.003 inch [13]. Based on the results of the present simulation by Electro- Static Model, plasma is formed just on a region over the encapsulated electrode. This happens because there would be no assumption of the presence of charge density in other regions in this model. Moreover, it is noticeable that vertical body force is almost negligible in comparison with the horizontal body force. So, according to the results of the present simulation, the vertical term of the body force contains less than 10% of the horizontal body force for each case. As the result of this simulation by Lumped Circuit Element Electro- Static Model, the plasma body force for the case of having the applied voltage frequency of 10 KHz and peak voltage amplitude of 6KV is shown in Fig. 2. Other cases possess a similar body force distribution shape (this is maybe because of changing only the peak voltage amplitude in each case) and the difference is only the range of the distribution. So, the result of other cases is provided in Table 1. This Table shows the maximum induced body force for each case.

Table -1 Maximum Induced Body Force in Different Peak Voltage Amplitudes

Peak Voltage Amplitude (V)	Maximum Induced Body Force (N/ m^3)
2000	15.283
3000	34.403
4000	61.173
5000	95.595
6000	137.71
7000	187.393
8000	244.769
9000	309.795
10000	382.474

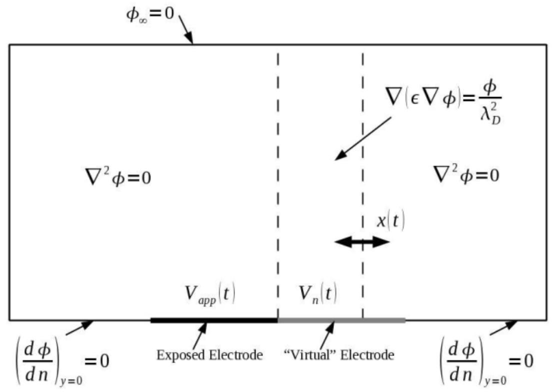

Fig.1 Plasma model [13]

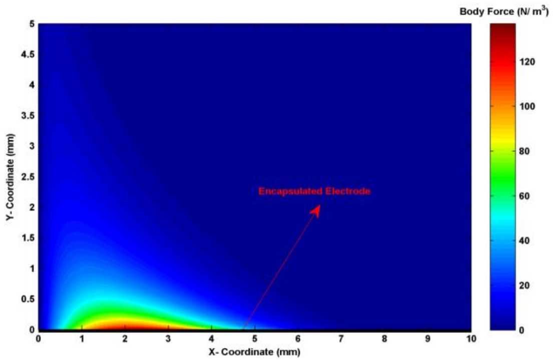

Fig. 2 DBD Plasma body force

FLUID FLOW EQUATIONS

Coming to this point that fluid flow has been considered to be two dimensional and incompressible, in this work Vorticity- Stream Function algorithm is used for solving the fluid flow equations. By eliminating the pressure term from the momentum equations, the transport equation for Vorticity is obtained and also there will be one more Poisson equation left for the Stream Function variable from the continuity equation. If the steady spatial body force induced by the DBD plasma actuators is considered as a function of x and y (f(x, y)), the manipulated Transport and Poisson equations can be re- written as:

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}=-\xi \tag{7}$$

$$\rho(\frac{\partial\xi}{\partial t}+u\,\frac{\partial\xi}{\partial x}+v\,\frac{\partial\xi}{\partial y})=\mu(\frac{\partial^2\xi}{\partial x^2}+\frac{\partial^2\xi}{\partial y^2})+\frac{\partial f\,(x,y)}{\partial y}-\frac{\partial f\,(x,y)}{\partial x} \tag{8}$$

The above equations were discretized and solved by using implicit FDM scheme (2016) [12].

PLASMA VALIDATION

A comparison between experimental measurements reported by Debiasi *et al* [14] at threshold voltage of 12 KV, 25000Hz for the voltage frequency and Kapton as the dielectric in the conditions and specific plasma configuration used in the experiment, and the present numerical simulation is shown in Fig.3. It is illustrated that the simulated plasma is in a good agreement with the experiment. In this case, Debye length was chosen to be 0.00001 based on the previous works in [15- 19]

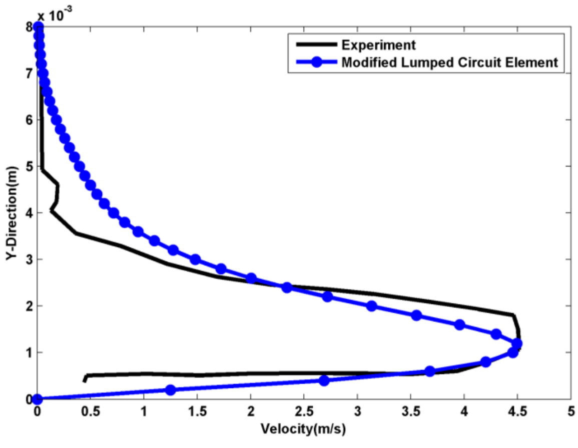

Fig.3 A comparison between experimental results reported in [14] and the numerical simulation in this study

SCHEMATIC OF THE PROBLEM AND MESH INDEPENDENCY

In this section, we have provided a schematic of the problem in Fig. 4. Moreover, the written CFD code has been applied for the most challenging case (peak voltage amplitude of 10KV) for different grid numbers. As a result of this, the maximum induced velocity is shown as a function of numbers of grids in Fig. 5. It is simply illustrated that the mesh independency is obtained by using 40,000 Numbers of grids.

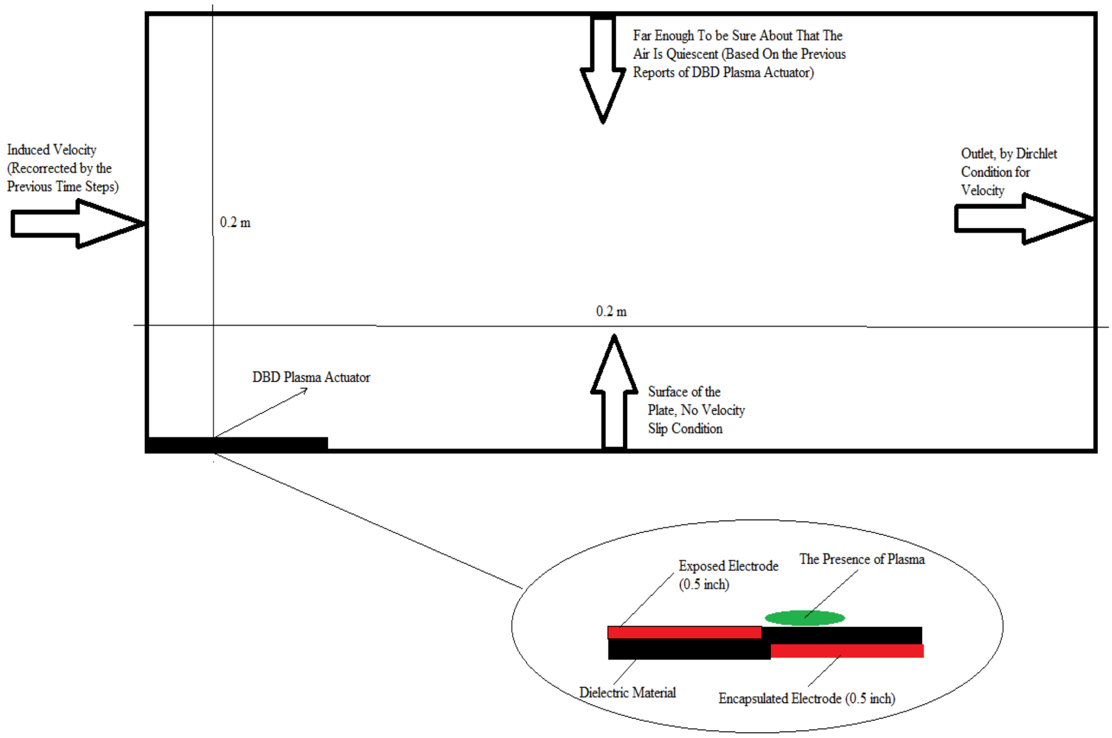

Fig. 4 The schematic of the problem

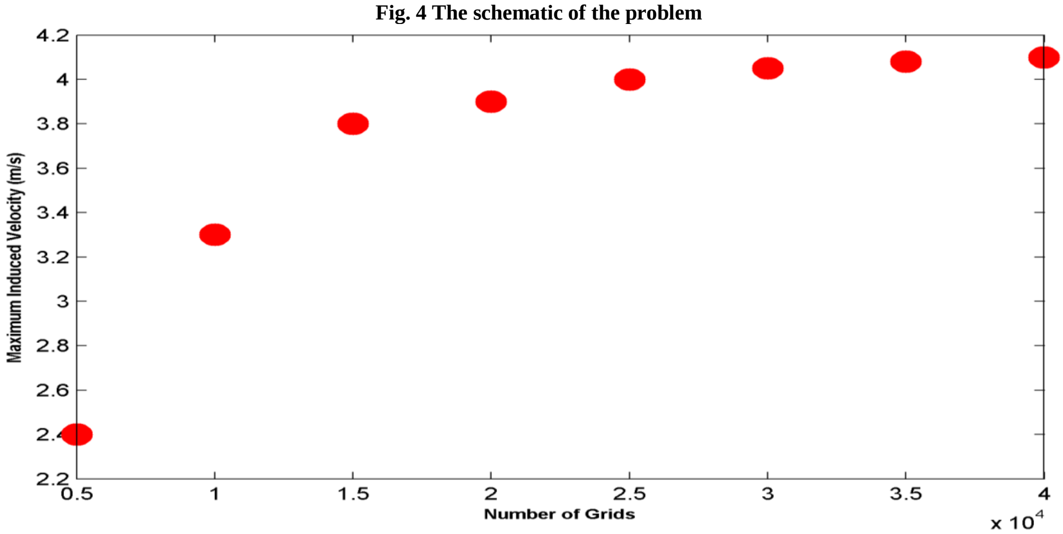

Fig. 5 Mesh independency

RESULTS AND DISCUSSION

This study was continued by simulating the variety of DBD plasma actuator configuration in a flat plate problem. The variety of actuators configuration were made by changing just the peak voltage amplitude (from 2KV to 10KV). Note that the minimum peak voltage amplitude was chosen to be 2KV and not 1KV, because the value of 1KV for the peak voltage amplitude was already set as the minimum voltage required for the formation of plasma in Lumped Circuit Element Electro- Static Model. As it is well- discussed in [13]. The value of zener diodes (K_n) in the Lumped Element Model depends on the minimum value of peak voltage amplitude which is assumed as the required voltage for the formation of plasma. So, based on this model (Lumped Circuit Element), if the value of voltage amplitude exceeds the critical voltage for the formation of plasma, the value of these diodes are set to be 1, otherwise they are assumed to be 0. Therefore, by setting 1KV for this critical voltage, there would be no plasma formation in this value of peak voltage amplitude. So, it is worth to start the simulation with a peak voltage amplitude which is greater than 1KV. Then, in the present numerical simulation, this start point (for starting the simulation) has been chosen to be 2KV. As it was mentioned earlier, the DBD plasma actuator causes a body force which is directed to the covered electrode. This body force simply accelerates the fluid (air) through its direction. As the result of this acceleration, a kind of flow suction can be identified at the inlet of the flat plate. This suction is not certainly in a uniform shape. So in the present numerical simulation we have reported the average induced velocity (since x- component body force is the governing parameter in this study, subsequently it is worth to deal with the x- component of the induced velocity. Then the results stand for this term of the induced velocity). The results of these suctions are provided in Table 2. As it is shown in Table 2, average induced velocity at the inlet of the flat plate increases with the increase of peak voltage amplitude. Based on the acquired results of simulation, a correlation is presented in Fig. 6, which predicts the behavior of this increment as a function of peak voltage amplitude. The other result of the DBD plasma body force could be found in the creation of a boundary which separates the quiescent air with the viscous region. Considering this that the plate is dominated by the no- slip velocity condition, and the upper region is assumed to be quiescent air, so there would be a point in between in which the velocity profile reaches to its peak. But it is observed that after the peak point, the velocity rapidly decreases to the quiescent region. So, by having a more powerful DBD plasma actuator (greater peak voltage amplitude), this peak point would be closer to the wall, subsequently, the induced velocity is obscured in a smaller distance from the plate. Fig. 7 shows a schematic of plasma suction. Velocity contours are shown in Fig. 8 to 10 for three cases of 2KV, 6KV and 10KV as the peak voltage amplitude. Moreover, the difference between the separation region (quiescent air from the viscous region) for three cases of 2KV, 6KV and 10KV as the peak voltage amplitude is shown in Fig. 11. This figure basically shows estimations of the separation line in different peak voltage amplitudes. This estimation was achieved by using Least Square Technics [20- 28]. And finally, based on this poweral form of estimation, a correlation has been derived to stand for the estimation of the separation line (which separates viscous region from the quiescent air) in different peak voltage amplitude (note that the effect of other parameters of DBD plasma actuator is not identified in the present correlation. So the correlation is just valid for the specific conditions of the DBD plasma configuration which was previously described in this work). This correlation falls within about 1% error with the simulation results:

$$\begin{aligned} \delta(x) &= a\sqrt{x} + b \\ a &= 10.97V_0^{-.526} \\ b &= \text{-3.125e-007}V_0 + 0.004642 \end{aligned} \quad (9)$$

In the above formulation, all the parameters are in the scale of SI. And V_0 indicates the peak voltage amplitude. This correlation is valid for the specific geometry used in the present study, applied voltage frequency of 10 KHz, Kapton as the dielectric and the peak voltage amplitude in the band of 2KV to 10KV. Based on the numerical results, we hypothesis that there is a similarity parameter according to the DBD plasma parameters. So, further researches are required to define a similarity parameter for presenting a full analytical solution of DBD plasma actuator in a flat plate problem.

Table- 2 Average Induced Velocity at the Inlet in Different Peak Voltage Amplitudes

Peak Voltage Amplitude (V)	Average Induced velocity at The Inlet (m/ s)
2000	1.5
3000	1.6
4000	1.8
5000	1.9
6000	2.3
7000	2.6
8000	2.8
9000	3.1
10000	3.3

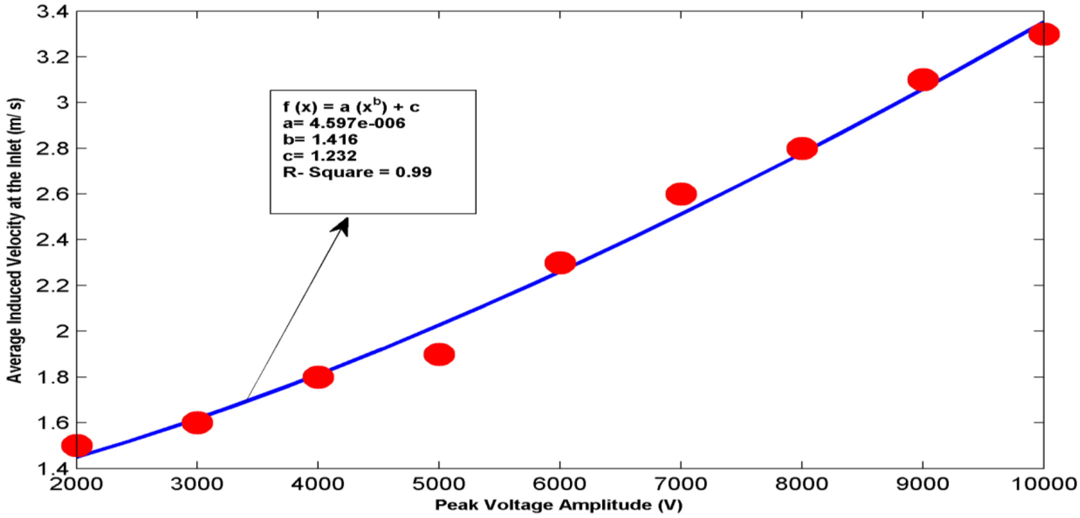

Fig. 6 Average induced velocity at the inlet as a function of the peak voltage amplitude

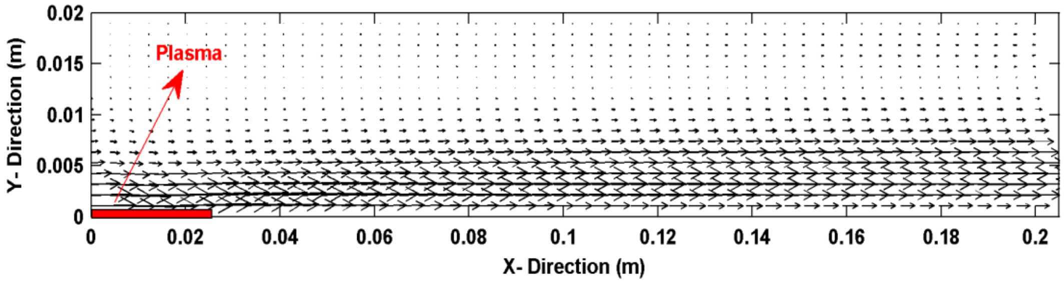

Fig. 7 A schematic of plasma suction (a zoomed in view)

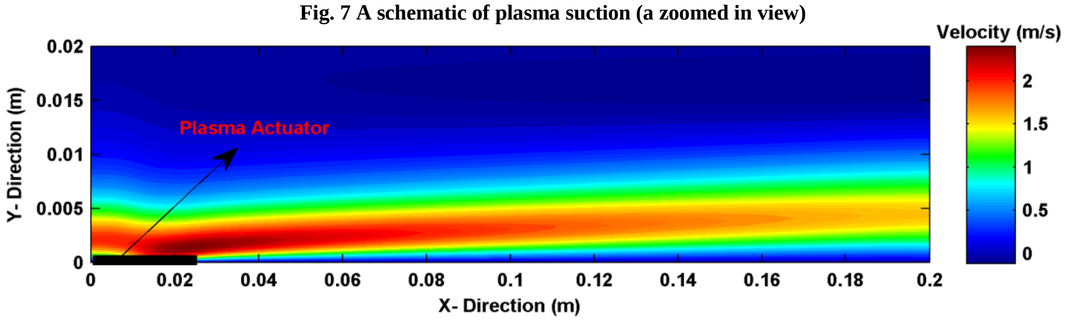

Fig. 8 Contour of velocity for the case of 2KV as the peak voltage amplitude (a zoomed in view)

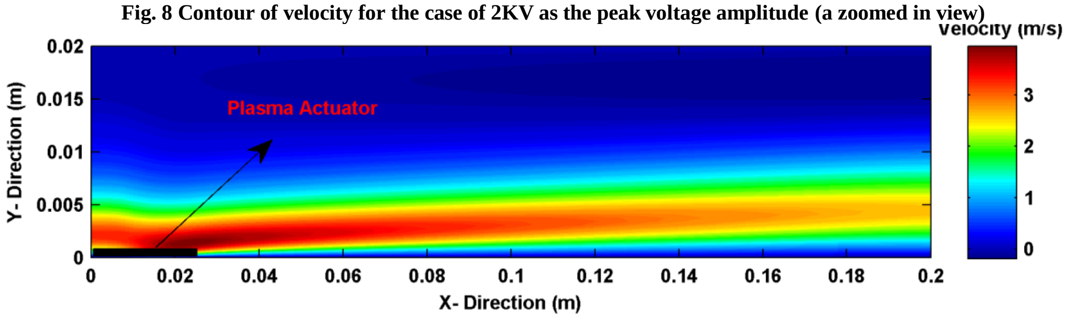

Fig. 9 Contour of velocity for the case of 6KV as the peak voltage amplitude (a zoomed in view)

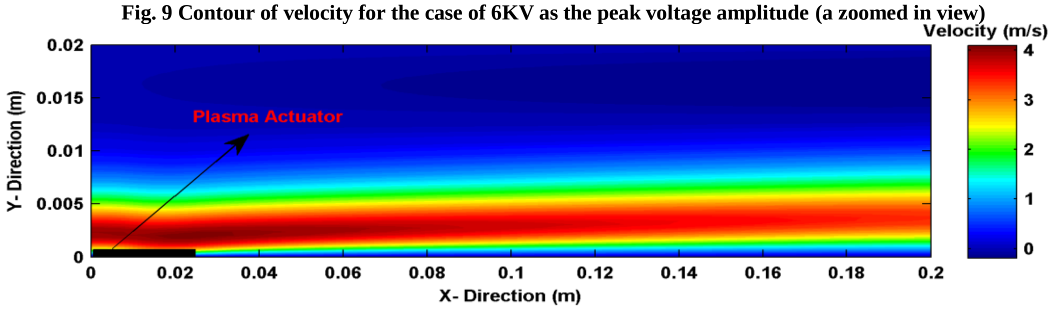

Fig. 10 Contour of velocity for the case of 10KV as the peak voltage amplitude (a zoomed in view)

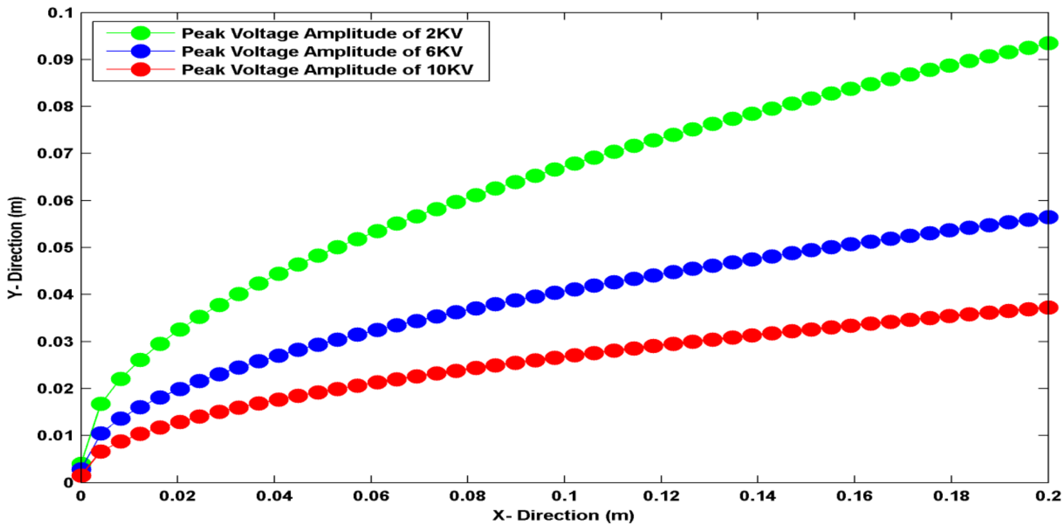

Fig. 11 Path lines which separates the quiescent air from the viscous region

CONCLUSION

The impact of different configurations of DBD plasma actuator on a flat plate is numerically studied. The configurations of actuators were changed by changing the peak voltage amplitude and so the other parameters of actuator including applied voltage frequency, dielectric material, and the geometry of the electrodes were assumed to be in a fixed condition. In which we set 10 KHz for the voltage frequency and Kapton as the dielectric material (with the dielectric coefficient of 2.8) and also the actuator geometry used in this simulation was corresponded to the previous work by authors in 2016 [12]. Peak voltage amplitudes were considered to be 2KV to 10 KV with the change step of 1KV. Two aims were followed during the present work. First was to determine the flow suction for each case. And the second was to identify the boundary between the quiescent air and the viscous region. As a result of the present simulation, the maximum flow suction was calculated to be about 0.015 Kg/m^3 for the case of 10KV for the peak voltage amplitude. In the further researches we seek for the effect of changing the other parameters of actuator on the flow suction and the separation boundary. Moreover, based on the results of the numerical simulation, the similarity parameter for DBD plasma actuator will be defined and studied in the future work.

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