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A Least Squares Regression Formulation for Dielectric Barrier Discharge (DBD) Plasma Actuator Body Force by Scrutinizing the Lumped Circuit Element Electro- Static Model: A Short Report

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ABSTRACT

This study aims to obtain the spatial body force induced by DBD plasma actuators as a function of actuator configuration. Several models have been proposed for simulating the body force of such an actuator so far but all of them deal with solving a system of governing equations including ODEs (Ordinary Differential Equations), PDEs (Partial Differential Equations) or both. Among many attempts to discover the induced body force by DBD plasma actuator, there are some empirical models. Although these empirical models are almost free from ODEs or PDEs but yet they are not closed formulations and require some experimental factors relating to the specific configuration of the DBD plasma actuator. These factors are usually obtained by fitting curves to the experimental data of the specific actuator. So, there is not yet a simple and closed formulation for predicting the DBD plasma body force in the literature. Therefore, the purpose of the present research is to find an explicit and closed formulation for DBD plasma spatial body force by combining the experimental and numerical results. For pursuing this study, we have picked up the Lumped Circuit Element Electro- Static Model (this model is rather simple than other models and also it possesses a suitable precision in simulating the DBD plasma body force) and the empirical formulation proposed in [1]. In this work, it is described how experimental and numerical models can be combined for achieving an explicit formulation for DBD plasma body force.
KEYWORDS: DBD plasma actuator, DBD plasma body force, Lumped Circuit Element Electro- Static Model, Formulating and modeling the DBD plasma body force

A Brief Introduction on the Literature of DBD Plasma Models

DBD plasma actuators were introduced after the former routes for controlling the behavior of the fluid flow were found to be inefficient in many applications [2- 4]. The specific features of this kind of actuator and its applications are comprehensively investigated and discussed by authors in [2- 8]. Considering that the experimental studies on DBD plasma actuators are normally high- cost ones, Computational Fluid Dynamics (CFD) is employed as an alternative approach to understanding the nature of such an actuator. The most important impact of DBD plasma actuator in flow control is its induced body force. And therefore, the manipulation of the flow is mainly reliant on the induced body force caused by the actuator. Regarding that, some models have been proposed so far for simulating DBD plasma body force. Among the earliest models, it is Roth model for predicting the induced body force [9]. This model is an empirical approach in which the term of body force is proportional to the spatial derivative of the second power of the electric field. But the effect of charge density is ignored in this model and also the model first requires the calculation of electric field. Moreover, this model has been criticized by Enloe [9] as the model predicts the existence of body force even in zero charge density condition. In addition, this model is a spatial model and does not contain information about the temporal behavior of the actuator. One of the other well- known and earliest models for simulating the body force of DBD plasma actuator is Shyy model. This model contains the effects of applied voltage frequency, the plasma discharge time, collision efficiency factor and electron charge on the spatial plasma body force. Finally the model proposes a direct formulation for predicting horizontal and vertical body force of the DBD plasma actuator but there is still the need for matching some empirical data to the factors involved in the definition of the body force terms. Moreover, the model suggests a linear decrease in electric field from the edge of the exposed electrode to the end of the encapsulated electrode and this assumption disagrees with the previous reports in [10]. Coming to the numerical models for predicting the DBD plasma body force, Lumped Circuit Element Electro- Static and Suzen Huang stand as the most prominent models for predicting the body force of the DBD plasma actuator [10]. Lumped Circuit Element is an auxiliary model which associates with the Single Potential Model (Electro- Static Model with considering a relation between the charge density and electric potential). This model can simply modify the basic Electro- Static model by considering this that air and

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dielectric are capacitor elements. So each path line from the exposed to the covered dielectric is comprised of a sub- circuit which is set as to be parallel with the others. This model can predict the location of the presence of charge timely. So the Poisson equation for electrical potential is solved in this location rather than to be solved in the whole region over the encapsulated electrode [11]. The other advantage of this model is to consider the effect of applied voltage frequency on DBD plasma body force and also this model allows us to calculate the plasma dissipation. Suzen Huang model is a Dual Potential Model in which assumes that the electro- magnetic behavior of the DBD plasma actuator is due to the effects of electrical potential and charge density simultaneously. So by solving two governing Poisson equations for both electrical potential and charge density, the DBD plasma body force can then be easily achieved. Beside these models, there is Full Electro- Magnetic Model. This model solves the Columbic field coupled with the drift diffusion. So, the model solves the continuity, momentum and energy equation plus to Poisson equations for electric potential and charge density [12].In overall, all of the above- mentioned models (instead of Full Electro- Magnetic Model) have some defects and also some of them are simpler than the others but there is still complexity and even there is not yet a direct explicit formulation for predicting DBD plasma body force. The complexity comes from the engagement of the systems of ODEs and PDEs and there would be more computational complexity when we deal with the Full Electro- Magnetic Model. So, the need for having a direct and simple explicit formulation for calculating the induced body force of DBD plasma actuator is undeniable. Therefore, the goal of the present work is to overcome this issue. In the present study, it has been assumed that the X- Component of the induced Lorantz body force by the DBD plasma actuator as the result of the simulation by Lumped Circuit Element Electro- Static Model can follow a Rayleigh distribution in X- Direction (tangential direction) and an exponential distribution in Y- Direction (normal direction). This form of distribution has been recommended in the literature as the result of PIV data [1]. In addition, the vertical body force has been ignored with respect to the magnitude of horizontal body force [1].Here, by using Least Square optimization methods (2016) [12- 16], it has been tried to fit the horizontal body force of the DBD plasma actuator (achieved from the solution of Lumped Circuit Element Electro- Static Model) to the recommended distribution of the horizontal body force in [1] for many different configurations of DBD plasma actuator. Then by fitting a correlation (with the average R- Square of about 0.95), a direct explicit formulation is derived for X- Component DBD plasma body force as a function of the actuator parameters. Considering this that based on the previous report in [1], the vertical body force is almost negligible in comparison with the horizontal component of the body force, the new proposed formulation can be counted as a new step in the solution of DBD plasma body force. In which the procedure for obtaining the body force is direct, explicit and very fast.

Lumped Circuit Element Electro- Static Model in Brief

DBD plasma actuator can be modeled by Single Potential Model (Electro- Static Model with considering a relation between the charge density and electric potential). This model is specified in [11]. So, in the present work, we have only brought up the procedure of simulating by this model.

Electrical potential is governed by the following Poisson equation [11]:

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

The charge density is obtained from the one- dimensional estimation of electric charge [11] as:

$$\rho_c = -\frac{\varepsilon_0}{\lambda_D^2}\varphi. \quad (2)$$

The presence of the net charge in a region with the presence of electric field, results in the induced body force by the following equation:

$$\overrightarrow{f_b} = \rho_C \overrightarrow{E}. \quad (3)$$

In general, the model deals with solving Eq. 1 in a mathematical plain, obtaining the induced body force due to the presence of plasma and then mapping the domain into the physical space of the problem. Lumped Circuit Element model is an axillary approach which considers electrodes, air and dielectric as capacitor elements. Finite numbers of electrical sub- circuits(subscripted by "n" for the modified form of Lumped Circuit Element [11]), are considered for any possible path from the exposed electrode to the covered one.Since Single Potential Model is not a complete model (the impact of applied voltage frequency is neglected and then it is assumed that plasma occurs in the whole region over the covered electrode), it requires some modifications. So Lumped Circuit Element Electro- Static Model is used as an auxiliary model for timely predicting the plasma extent and also to include the effect of applied voltage frequency. This auxiliary model consists of governing equations as follow:

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

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

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

$V_{app}(t)$, represents the applied voltage amplitude, $V_n(t)$ is the voltage at the virtual electrode in each element of encapsulated electrode which is assumed to be on the surface of dielectric material (virtual electrode), $I_{pn}(t)$ is the current through the plasma resistance for each element. R_n, is the air resistance in each section. vv, is a coefficient which indicates the increase in the sweep velocity by the increase of applied voltage amplitude. According to [17] vv can be assumed to be $10\frac{m/s}{kV}$. C_{an}, and C_{dn} are capacitor elements of air and dielectric material for each element respectively. k_n, is a constant representing the zener diode in each element which is assumed to be 0 or 1 depending on the presence of plasma. A specified description for Eq. 4 to 6 can be found in the previous work by authors [8].
For illustrating the model, a schematic is shown in Fig.1.

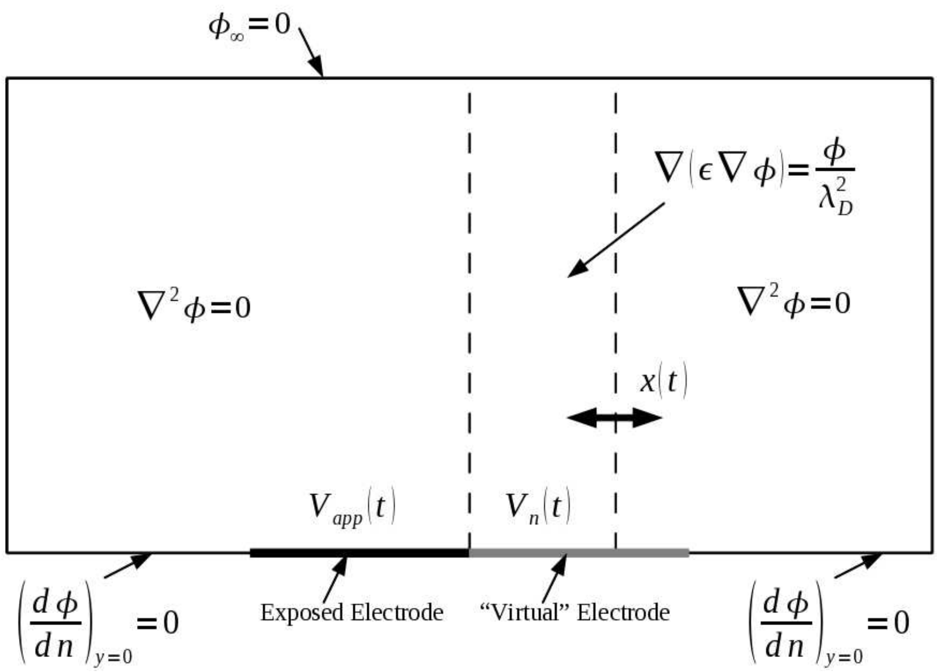

Fig.1 Lumped Circuit Element Electro- Static model [11]

Validation

For a two dimensional incompressible flow, Vorticity- Stream Function algorithm can be employed for solving the flow field. By considering the x- component of the spatial body force as a function of x and y (f(x, y)), Vorticity- Stream Function equations can be written as:

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

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

The above equations are discretized using implicit FDM scheme. In the present work, guidelines presented in [19] were applied.

A comparison between experimental results reported by Debiasi *et al* [18] at the threshold voltage of 12 KV, 25000Hz for the applied voltage frequency, Kapton as the dielectric material and the specific plasma geometry used in the experiment, and the present numerical simulation is shown in Fig.2. This comparison was also used in the previous work by authors [8] as a validation for the developed codes; in which indicates that the simulated plasma is in a good agreement with the experiment. In this case, Debye length was selected to be 0.00001 based on the previous work by Ibrahim et al [20].

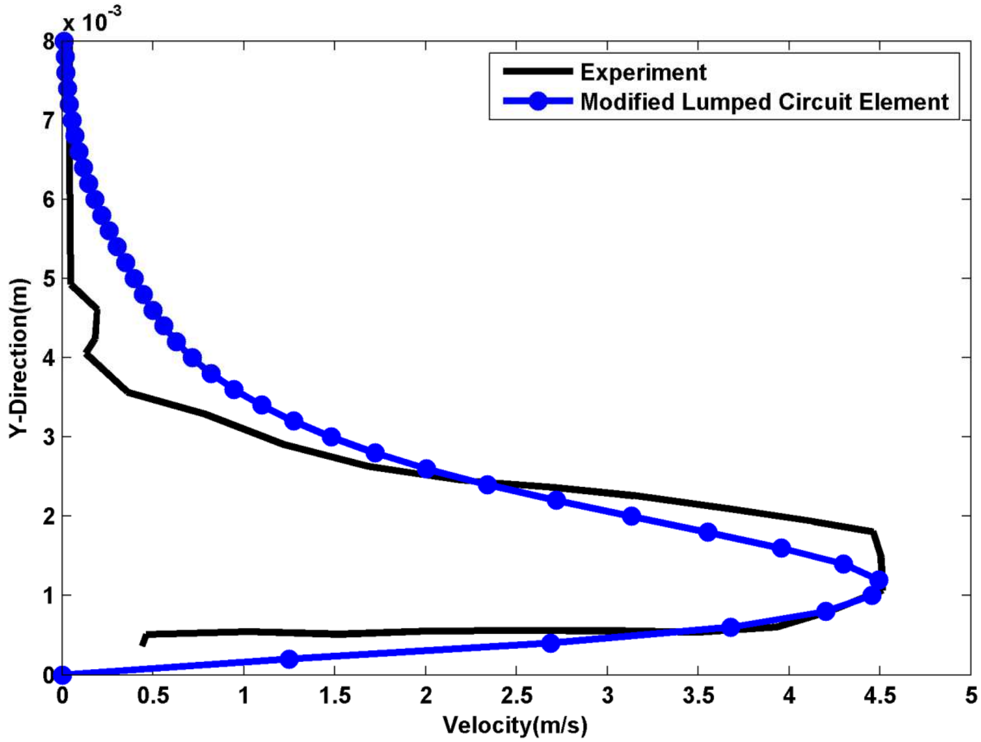

Fig.2A comparison between experimental results reported in [18] and the present numerical simulation

Implementation of Lumped Circuit Element Electro- Static Model

In this section, we have continued the simulation of the body force for many configurations of DBD plasma actuator by using Lumped Circuit Element Electro- Static Model. The configurations of DBD plasma actuator were changed by applying different peak voltage amplitudes, applied voltage frequencies, dielectric coefficients and Debye lengths. Although modeling the DBD plasma actuator by Lumped Circuit Element is rather simple but the model still cannot be generalized for any different configuration of DBD plasma unless the critical voltage for forming the plasma in any configuration is available. Having this that the critical voltage required for the formation of plasma is highly depended on the geometry of electrodes (it also depends on voltage frequency and Debye length), we have limited the present work to the minimum voltage amplitude (required for formation of plasma) of 1KV in all the cases (this can be considered as a simplification used in the present work). Moreover, we have also kept the geometry of electrodes unchanged in which the length for the exposed and encapsulated electrodes was assumed to be 0.5inch and in addition, vertical and horizontal distances between the electrodes were assumed to be 0.003 inch [11].

Proposing the Explicit Formulation

Based on the previous work in [1], the vertical (normal) component of the DBD plasma body force is almost negligible in the comparison with the horizontal (tangential) component of the body force. And also the horizontal body force follows the general form of:

$$F_x(x,y) = ax \times e^{bx^2+cy} \quad (9)$$

In which a, b and c are constant factors relating to the configuration of the applied DBD plasma actuator.

We have assumed that each result of the simulation by Lumped Circuit Element represents a certain a, b and c. Using the Least Square Methods (2016) [12- 16] the fittest factors of a, b and c for each case (each specific

DBD plasma configuration) were found. So, each result of simulation of the specific configuration of DBD plasma actuator represented certain values of a, b and c; corresponded to the general form of Eq. 9.Based on the results of the present simulation by Lumped Circuit Element Electro- Static model, the distribution of body force is not exactly corresponded to the Eq. 9. Therefore, there are deviations in distribution of body force in both x any y directions. This is certainly because of the inherent behavior of the governing equations of the model. By applying the simulation procedure for variety of cases and using Least Square technique, the general explicit formulation for predicting the body force of the DBD plasma actuator was achieved:

$$
\begin{aligned}
F_x(x,y) &= ax \times e^{bx^2+cy} \\
a &= 3.1054 f^{0.5} e^{0.01411} D^{-0.5}\left[(-9.405\times10^{-11})V_0^{\,3} + (5.918\times10^{-6})V_0^{\,2} + (-0.008657)V_0 + 17.9\right] \\
b &= (0.0069\times10^{-3})(V_0 - 30\times10^{3}) - 0.1 \\
c &= (0.069\times10^{-3})(V_0 - 30\times10^{3}) - 1.5
\end{aligned}
\qquad (8)
$$

This new formulation falls within about 5% error with the results of the Lumped Circuit Element Model (average R- Square for each case is about 0.95).

In the above formulation, the coordinates of x and y are in the scale of mm, while other parameters of DBD plasma actuator are in SI scale. Moreover, f represents the applied voltage frequency, e stands as dielectric coefficient, D is for the Debye length and V_0 is the peak voltage amplitude.

Although the above formulation is so simple and explicit to apply but there are still some limitations in applying the proposed formulation. Based on the previous discussions and also the bands of the changes in different parameters, the formulation is valid for the maximum peak voltage amplitude to 30KV, applied voltage frequency to 30 KHz, dielectric coefficient to 280 and Debye length of 0.00001m to 0.0001m. Moreover, the formulation is only applicable for the specific geometry of electrodes with 0.5 inch for both of the exposed and covered electrodes. And also the vertical and horizontal distances between the two electrodes must be 0.003 inch. Although there are still some limitations, but this model has shown a good agreement with the results of Lumped Circuit Element Electro- Static Model. Because the study is focused on the X- Component (tangential) body force of the DBD plasma actuator, Fig. 3 to 15 (the main results of the present work) show the different distributions of tangential body force by the new proposed formulation and it is also compared with the results by Lumped Circuit Element model. In which Fig. 3 represents the distribution of x- component of the spatial body force acquired from the results of Lumped Circuit Element Electro- Static model in contour form for peak voltage amplitude of 30 KV, 10 KHz for the voltage frequency, 0.00001m for the Debye length and Kapton as the dielectric material. The contour of body force as a result of Eq. 8 is shown in Fig. 4 for the same configuration of Fig. 3. Fig. 5 indicates the distribution of plasma body force by the correlation for the peak voltage amplitude of 1KV, 10KHz for the voltage frequency, 0.00001m for the Debye length and Kapton as the dielectric material. Fig. 6 to 9 show a comparison between the results of Lumped Circuit Element Electro- Static model and the proposed correlation for different conditions of plasma configuration. Fig. 10 to 15 indicate a comparison between the two models in predicting the distribution of the plasma body force in both x and y directions.

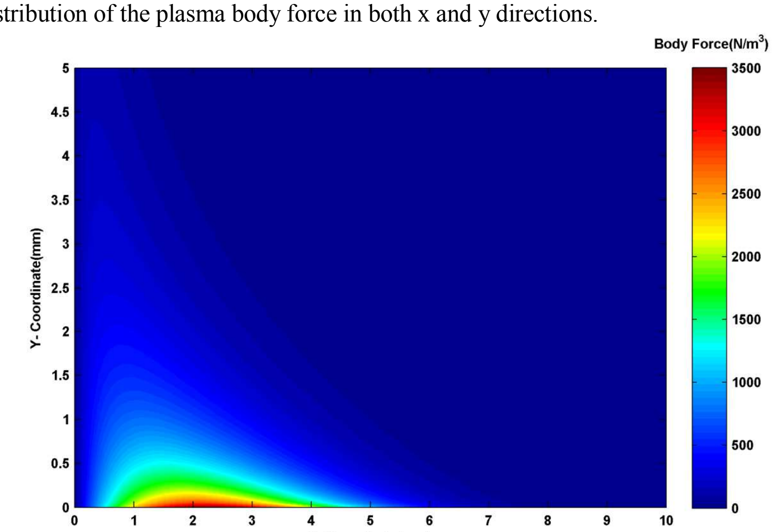

Fig.3Tangential body force by Lumped Circuit Element for 30KV of peak voltage amplitude, 10KHz for voltage frequency, 0.00001 m for Debye length and Kapton as the dielectric (dielectric coefficient of 2.8): Note that zero x- coordinate represents the edge of covered electrode

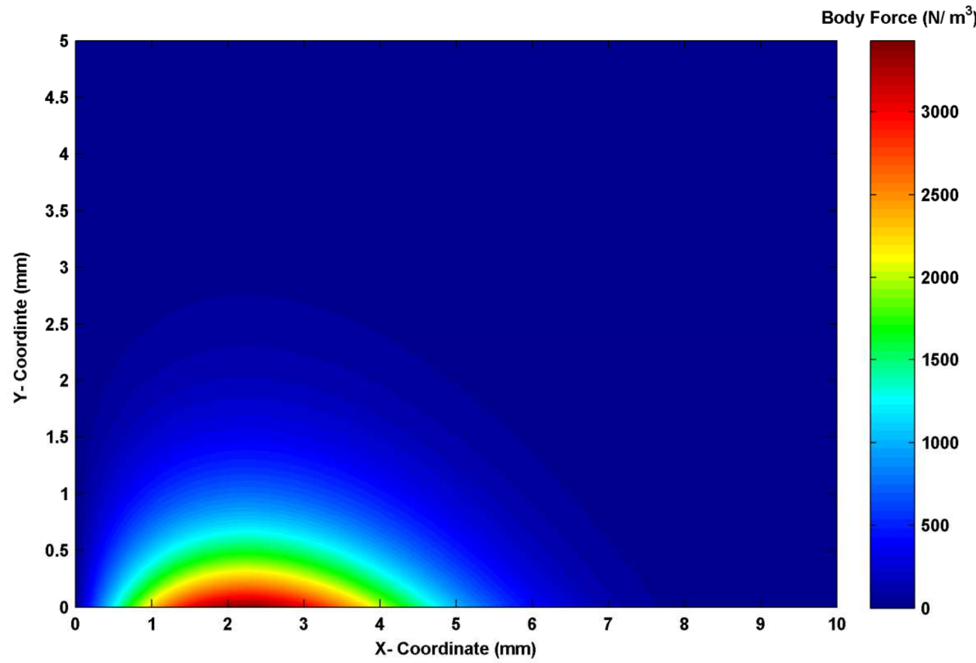

Fig.4 Tangential body force by Proposed Formulation for 30KV of peak voltage amplitude, 10 KHz for voltage frequency, 0.00001 m for Debye length and Kapton as the dielectric (dielectric coefficient of 2.8): Note that zero x- coordinate represents the edge of covered electrode

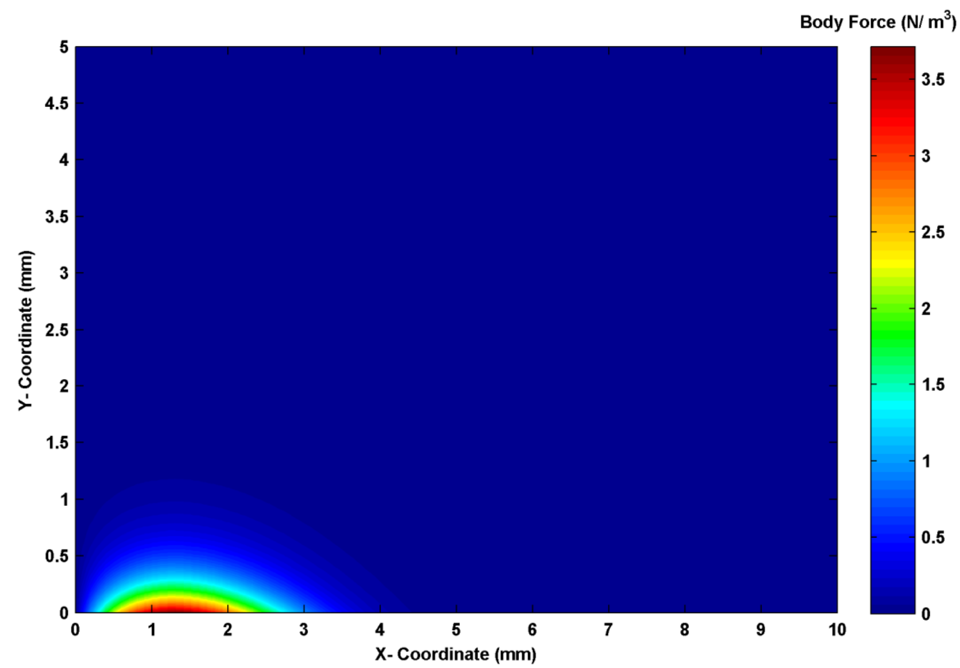

Fig.5 Tangential body force by Proposed Formulation for 1KV of peak voltage amplitude, 10 KHz for voltage frequency, 0.00001 m for Debye length and Kapton as the dielectric (dielectric coefficient of 2.8): Note that zero x- coordinate represents the edge of covered electrode

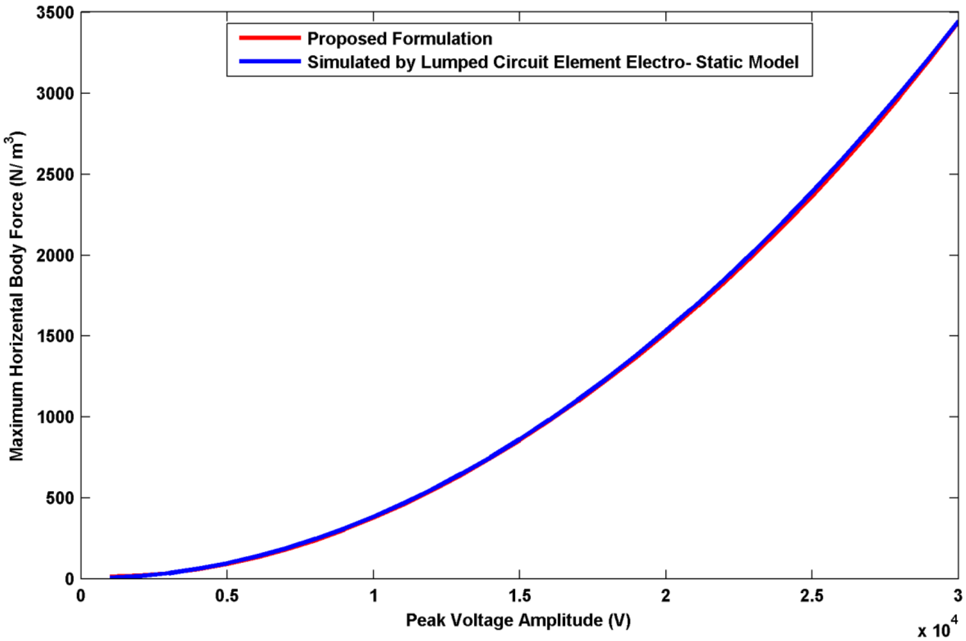

Fig.6Maximum tangential body force by the Proposed Formulation compared with the Lumped Circuit Element Model for 10 KHz of voltage frequency, 0.00001 m for Debye length and Kapton as the dielectric (dielectric coefficient of 2.8)

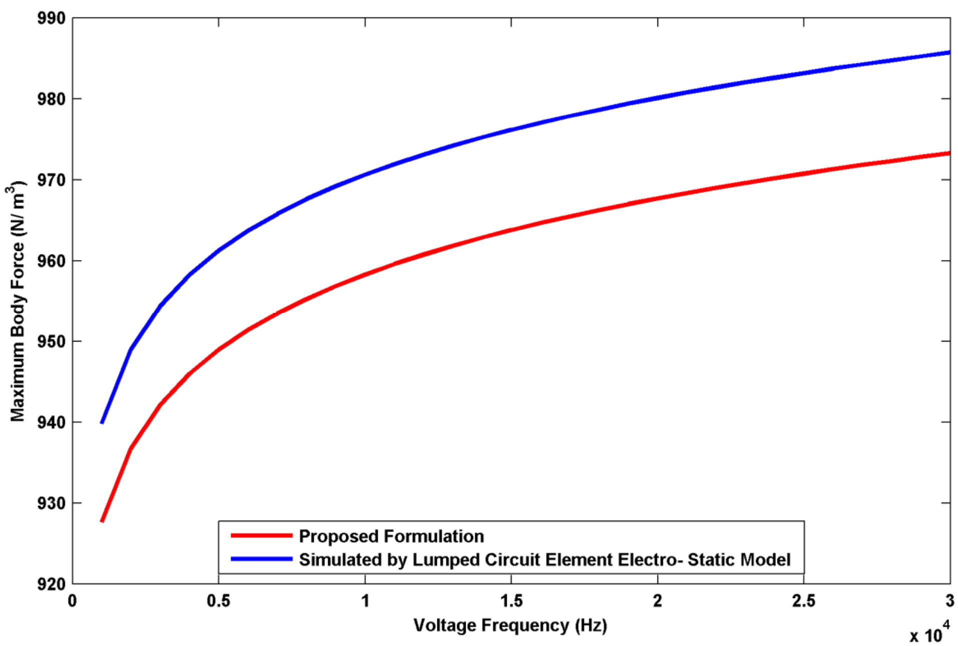

Fig.7Maximum tangential body force by the Proposed Formulation compared with the Lumped Circuit Element Model for 15KVofpeak voltage amplitude, 0.00001 m for Debye length and Kapton as the dielectric (dielectric coefficient of 2.8)

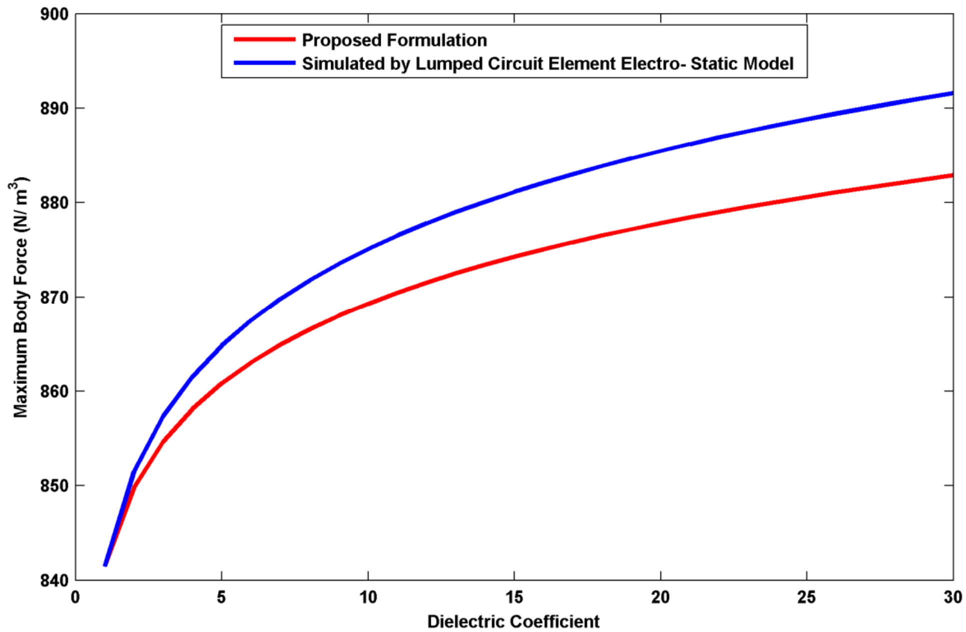

Fig.8Maximum tangential body force by the Proposed Formulation compared with the Lumped Circuit Element Model for 15KVofpeak voltage amplitude, 0.00001 m for Debye length and 10KHz for the voltage frequency

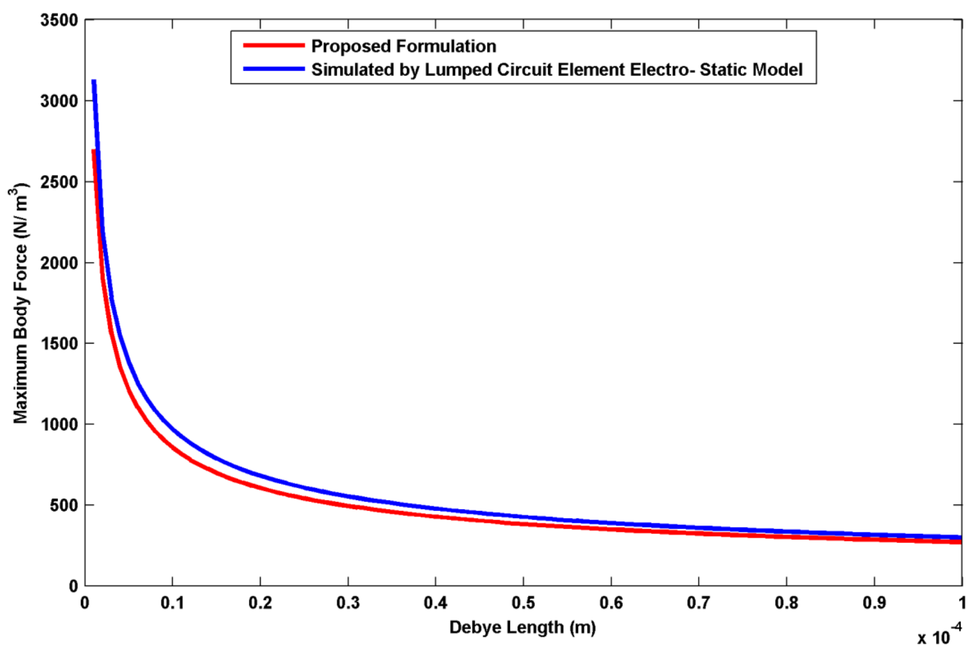

Fig.9 Maximum tangential body force by the Proposed Formulation compared with the Lumped Circuit Element Model for 15KVofpeak voltage amplitude, 10 KHz for the voltage frequency and Kapton as the dielectric (dielectric coefficient of 2.8)

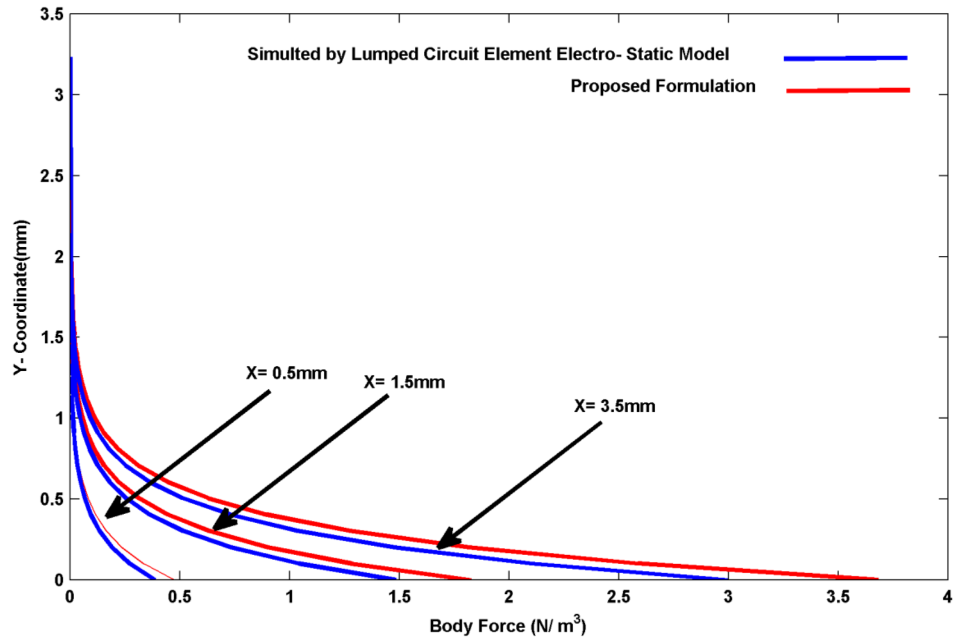

Fig.10 Tangential body force distribution at three x- coordinate compared with the Lumped Circuit Element Model for peak voltage amplitude of 1KV, voltage frequency of 10 KHz, 2.8 for dielectric coefficient and 0.00001 m for Debye length

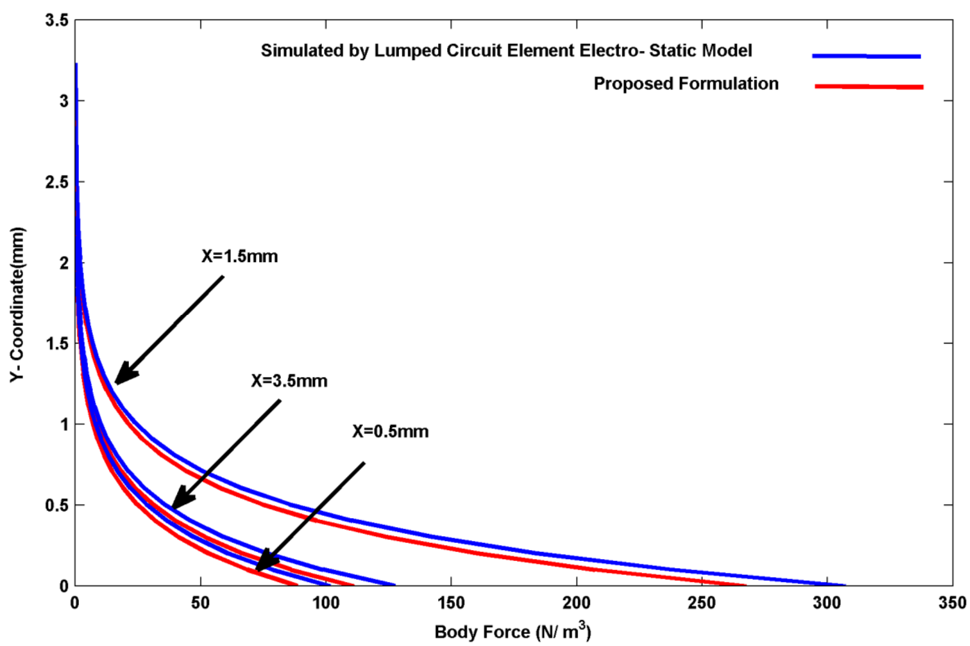

Fig.11 Tangential body force distribution at three x- coordinate compared with the Lumped Circuit Element Model for peak voltage amplitude of 15KV, voltage frequency of 10 KHz, 2.8 for dielectric coefficient and 0.00001 m for Debye length

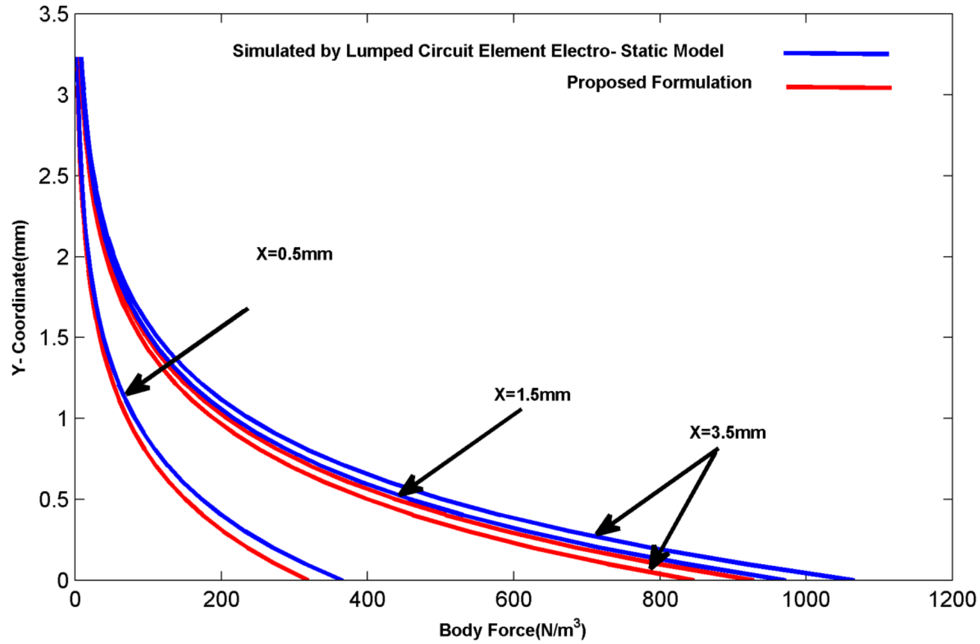

Fig.12Tangential body force distribution at three x- coordinate compared with the Lumped Circuit Element Model for peak voltage amplitude of 30KV, voltage frequency of 10 KHz, 2.8 for dielectric coefficient and 0.00001 m for Debye length

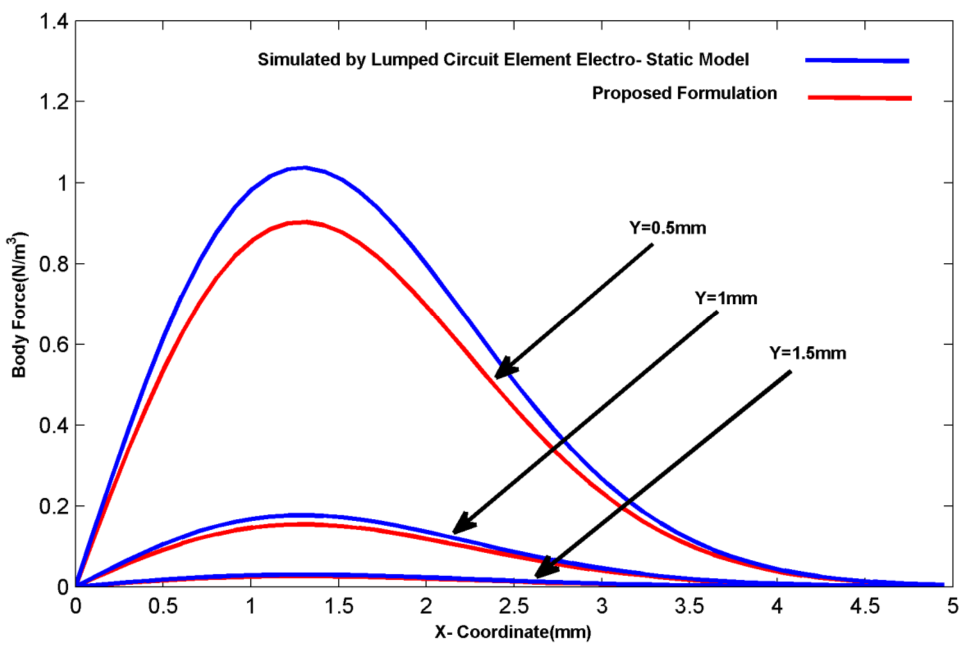

Fig.13Tangential body force distribution at three y- coordinate compared with the Lumped Circuit Element Model for peak voltage amplitude of 1KV, voltage frequency of 10 KHz, 2.8 for dielectric coefficient and 0.00001 m for Debye length

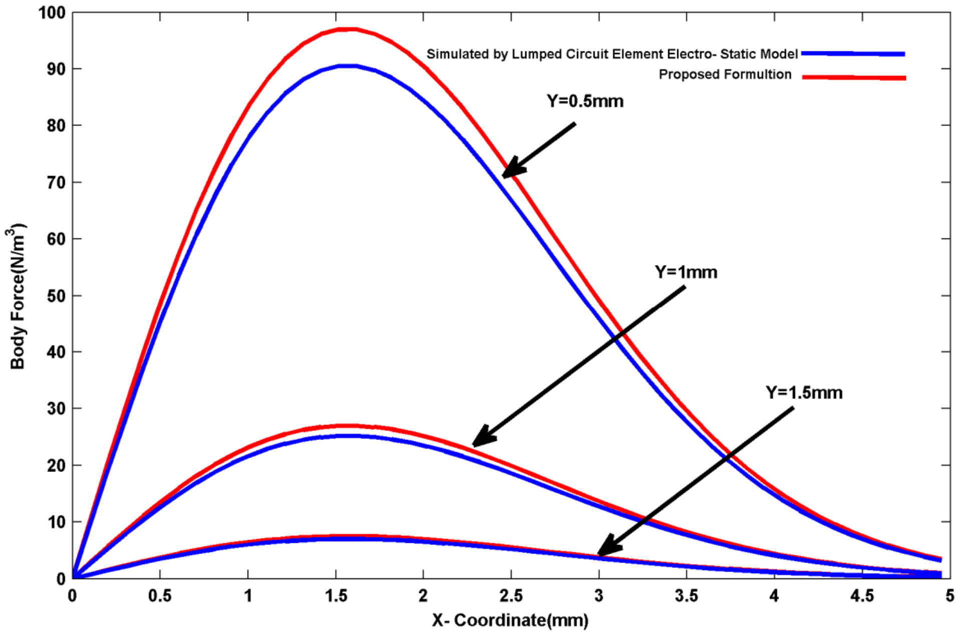

Fig. 14 Tangential body force distribution at three y- coordinate compared with the Lumped Circuit Element Model for peak voltage amplitude of 15KV, voltage frequency of 10 KHz, 2.8 for dielectric coefficient and 0.00001 m for Debye length

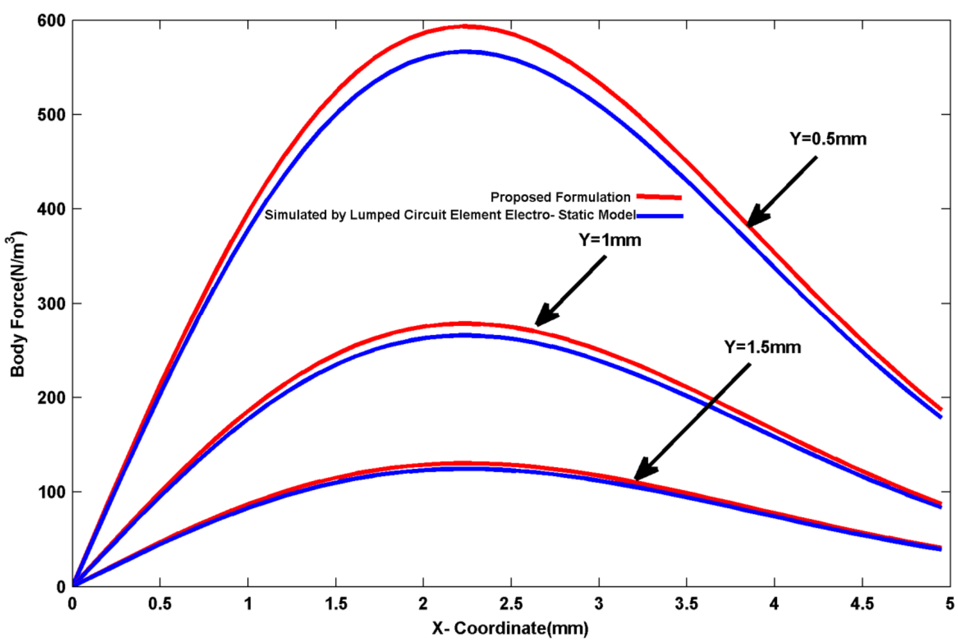

Fig. 15Tangential body force distribution at three y- coordinate compared with the Lumped Circuit Element Model for peak voltage amplitude of 30KV, voltage frequency of 10 KHz, 2.8 for dielectric coefficient and 0.00001 m for Debye length

Conclusion

In this work, a novel formulation for predicting the tangential body force of DBD plasma actuator (the most important term of the body force) is proposed by correlating the results of Lumped Circuit Element Electro- Static model to a general form of the body force which has been previously derived from the PIV data.

Although this formulation is direct, explicit and simple to apply, but there are still some limitations in applying this formulation. First is that the length of the electrodes are set to be 0.5 inch for both. Second is that the vertical and horizontal length between the electrodes must be 0.003 inch. Moreover, the new proposed formulation cannot predict the effect of different critical voltages (required for the plasma formation) on the body force of the DBD plasma actuator. In spite of having this incompleteness, the new formulation can stand as an applicable model for simulating the main term of the body force of the DBD plasma actuator. Coming to this point that this new model comes from a combination of the results from PIV data and Lumped Circuit Element Electro- Static Model, it almost contains all the different phenomena engaged with the formation of DBD plasma body force. In further researches, we will deal with removing these limitations from the present model.

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