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Electrostatic Analysis of Electric Field Distribution in AC, Nanosecond Pulsed, and Hybrid DBD Plasma Actuators Using COMSOL Multiphysics.

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ABSTRACT

Dielectric barrier discharge (DBD) plasma actuators are widely used for active flow control due to their ability to generate plasma without moving parts. In this study, a two-dimensional electrostatic model of an asymmetric DBD plasma actuator is developed using COMSOL Multiphysics to investigate the effect of different excitation conditions on electric field distribution. Three excitation cases, namely AC, nanosecond pulsed (NS), and hybrid AC+NS, are considered using simplified voltage approximations.

The results show that the electric field is strongly concentrated near the edge of the exposed electrode for all cases. While the spatial distribution of the electric field remains similar, its magnitude increases with the applied voltage. The hybrid case produces the highest electric field intensity, indicating improved potential for plasma generation. The study demonstrates that a simplified electrostatic approach can provide a qualitative understanding of DBD actuator behavior and serve as a basis for more advanced plasma modeling.

INTRODUCTION

Plasma actuators have emerged as a promising technology for active flow control due to their ability to manipulate airflow without any moving mechanical components [1], [2]. These actuators operate by applying a high-voltage electric field across two asymmetric electrodes separated by a dielectric material, resulting in the formation of non-thermal plasma near the surface [3]. The interaction between charged particles and neutral air produces an electrohydrodynamic (EHD) body force, which can effectively modify boundary layer characteristics and delay flow separation [4].

Alternating current (AC) driven DBD actuators are widely used due to their stable and continuous plasma generation [5]. However, nanosecond pulsed (NS) DBD actuators have recently gained attention because they can generate significantly higher peak electric fields within very short time scales, leading to stronger localized ionization and improved actuation efficiency [6], [7]. To further enhance actuator performance, combining the advantages of both continuous and pulsed operation, resulting in improved control authority and energy efficiency [8].

Despite these advantages, accurate modeling of plasma actuators remains computationally challenging due to the need for COMSOL Multi-physics coupling involving plasma chemistry, charge transport, and fluid dynamics [9]. As a result, simplified electrostatic models are often employed to capture the fundamental behavior of the actuator, particularly the spatial distribution of the electric field, which plays a crucial role in plasma formation and actuator effectiveness [10].

Recent numerical studies, including the work you provided, have demonstrated that the electric field is highly concentrated near the edge of the exposed electrode due to geometric discontinuities, making this region critical for plasma generation and actuator efficiency [11]. These studies also highlight that dielectric material properties and electrode configuration significantly influence the electric field distribution and overall actuator performance.

In this study, a two-dimensional electrostatic model of an asymmetric DBD plasma actuator is developed using COMSOL Multiphysics. The actuator consists of an exposed electrode and a buried electrode separated by a dielectric layer. Three excitation conditions AC, nanosecond pulsed (NS), and hybrid (combination of AC DBD and NS DBD) are approximated using equivalent voltage levels to investigate their influence on electric field distribution. The results are analyzed in terms of electric field intensity along the dielectric surface, providing a qualitative understanding of plasma actuator behavior under different operating conditions.

METHODOLOGY

Model Description

A two-dimensional (2D) numerical model of a dielectric barrier discharge (DBD) plasma actuator was developed using COMSOL Multiphysics. The actuator consists of two asymmetric electrodes separated by a dielectric layer. The upper electrode is exposed to the surrounding air domain, while the lower electrode is embedded within the dielectric material. This asymmetric configuration is essential for generating a non-uniform electric field distribution, which plays a key role in plasma actuation.

Geometry Configuration

The computational domain was constructed in a 2D Cartesian framework. The dielectric layer was positioned at the bottom of the domain, with the air region extending above it. The exposed electrode was placed on the upper surface of the dielectric layer, while the buried electrode was embedded within the dielectric at an offset location to ensure asymmetry.

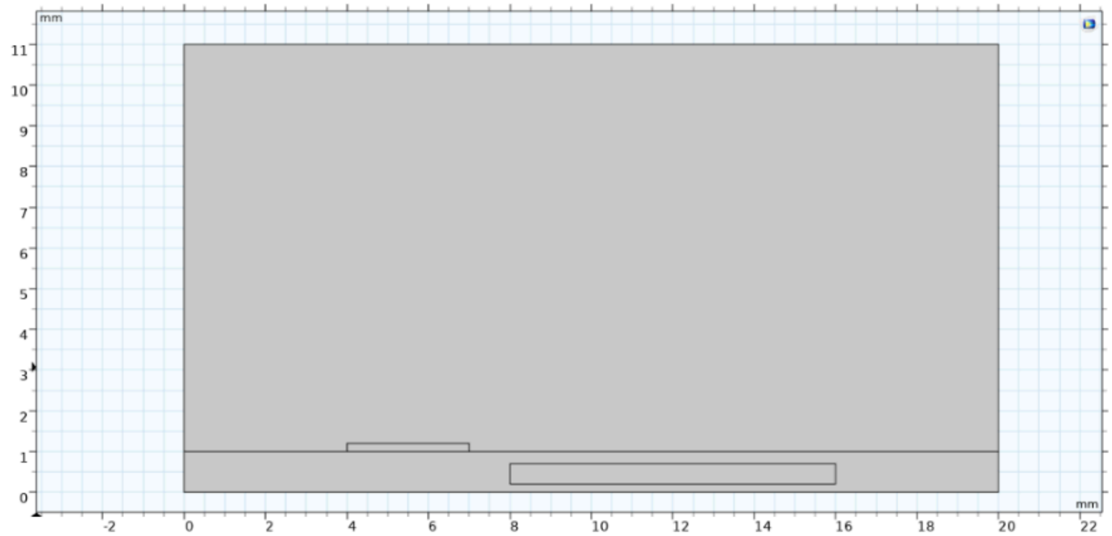

Figure 1: Schematic diagram of the 2D DBD plasma actuator geometry showing the asymmetric electrode configuration.

The dimensions of the geometry were selected to represent a simplified actuator configuration while maintaining the essential physical characteristics. The dielectric layer was modeled as a thin region, and the air domain was extended sufficiently in the vertical direction to capture the spatial decay of the electric field.

Material Properties

Two materials were considered in the model. Air was assigned to the upper domain to represent the surrounding medium, while mica was used as the dielectric material due to its stable electrical properties and relatively high permittivity. The electrodes were treated as conductive regions, where appropriate electrical boundary conditions were applied.

Governing Physics

The Electrostatics interface from the AC/DC module was employed to simulate the electric field distribution. A simplified electrostatic approach was adopted to reduce computational complexity by neglecting detailed plasma chemistry and charge transport mechanisms. The governing equations are based on Gauss's law for electrostatics, where the electric potential distribution is obtained by solving the Poisson equation, and the electric field is subsequently derived as the negative gradient of the electric potential.

Boundary Conditions

The boundary conditions were applied directly to the electrode regions. The buried electrode was assigned a ground potential (0 V), while the exposed electrode was subjected to a specified electric potential. All other external boundaries were treated as electrically insulated. These conditions were implemented within the Electrostatics interface to simulate the electric field distribution across the domain.

Simulation Cases

Three different excitation conditions were investigated to analyze their effect on the electric field distribution. The AC case was represented by an applied potential of 5000 V, while the NS case was modeled using a higher potential of 15000 V to capture the effect of high-voltage pulsed excitation. The hybrid AC+NS case was approximated by applying a combined potential of 20000 V. These voltage levels were selected as simplified representations to qualitatively examine the influence of different excitation mechanisms on the electric field behavior within the actuator.

Mesh Generation

The computational domain was discretized using a free triangular mesh to ensure numerical stability and solution accuracy. A non-uniform meshing strategy was adopted, where finer mesh elements were generated near the electrode edges and the dielectric interface. This localized refinement is essential for accurately capturing the strong electric field gradients and sharp variations that occur in these regions due to geometric discontinuities.

In contrast, a comparatively coarser mesh was applied in regions farther away from the electrodes, where the electric field variation is relatively smooth. This approach helps in reducing computational cost while maintaining sufficient accuracy in critical regions.

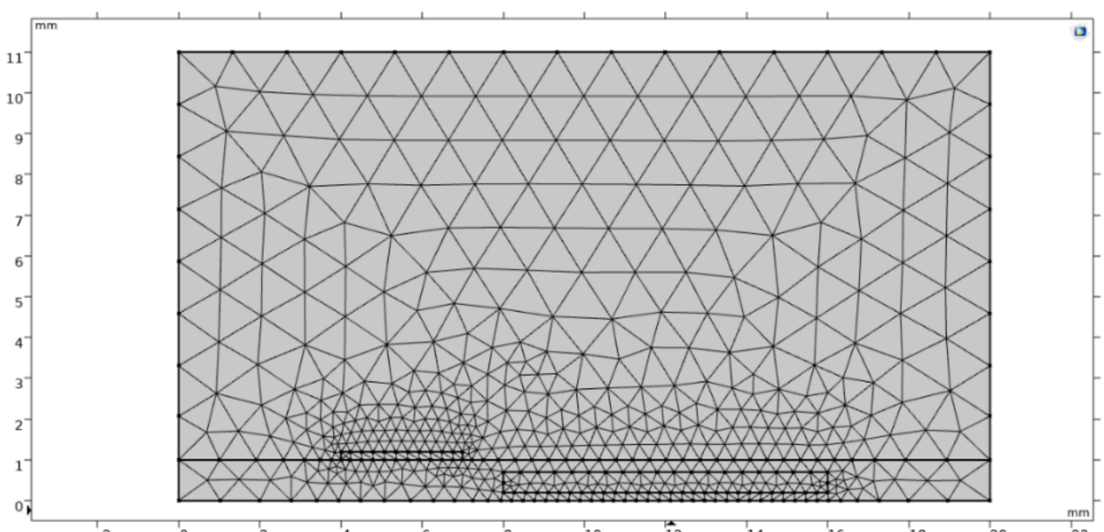

Figure 2: Computational mesh used in the simulation with refinement near electrode edges.

Figure 2 illustrates the generated mesh for the computational domain. It can be observed that the mesh density is significantly higher near the exposed and buried electrode regions, indicating targeted refinement. The gradual transition from fine to coarse elements ensures numerical efficiency without compromising the quality of the solution. Such adaptive meshing is particularly important in electrostatic simulations, where field intensification near sharp edges plays a dominant role in determining actuator performance.

Solution Procedure

A stationary study was performed to solve the electrostatic problem. The simulations were carried out separately for each excitation case by modifying the applied voltage at the exposed electrode. The resulting electric potential and electric field distributions were obtained for further analysis.

Post-Processing

The simulation results were analyzed using both contour plots and line graphs. The electric field magnitude (V/m) was visualized through surface plots to illustrate its spatial distribution across the domain. In addition, a cut line was defined along the dielectric surface to extract the variation of the electric field with distance. Line graphs were then generated to compare the electric field distribution for the AC, NS, and hybrid excitation cases.

RESULTS AND DISCUSSION

The electric field distribution of the DBD plasma actuator was analyzed under three different excitation conditions: AC, nanosecond pulsed (NS), and hybrid AC+NS. Both contour plots and line graphs were used to investigate the spatial variation and magnitude of the electric field.

Electric Field Distribution

The contour plots of the electric field magnitude reveal a highly non-uniform distribution across the computational domain.

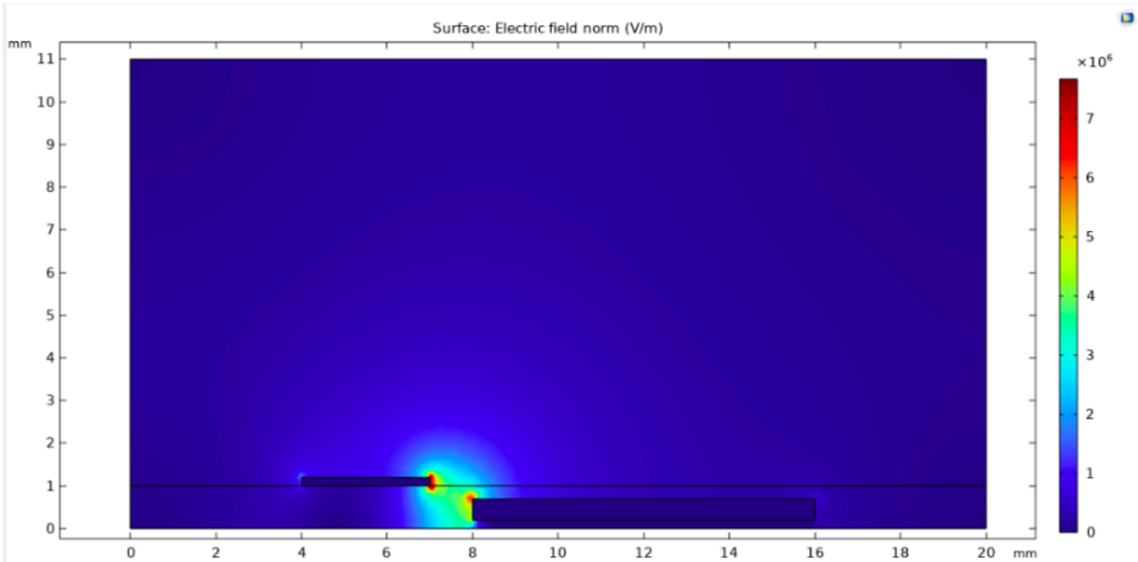

Figure 3: Electric field distribution for AC case (5000 V).

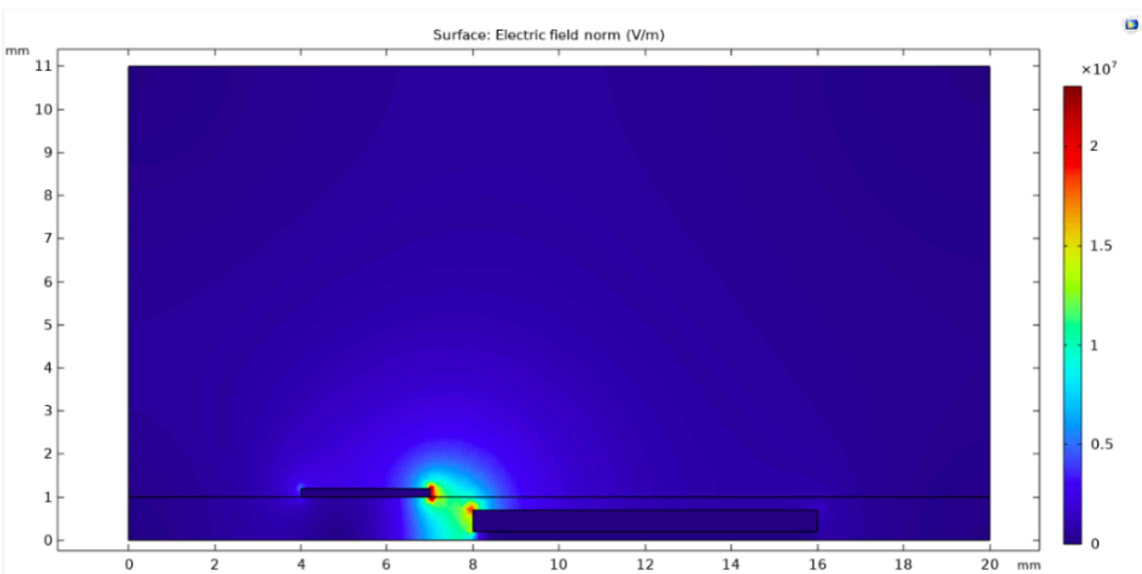

Figure 4: Electric field distribution for NS case (15000 V).

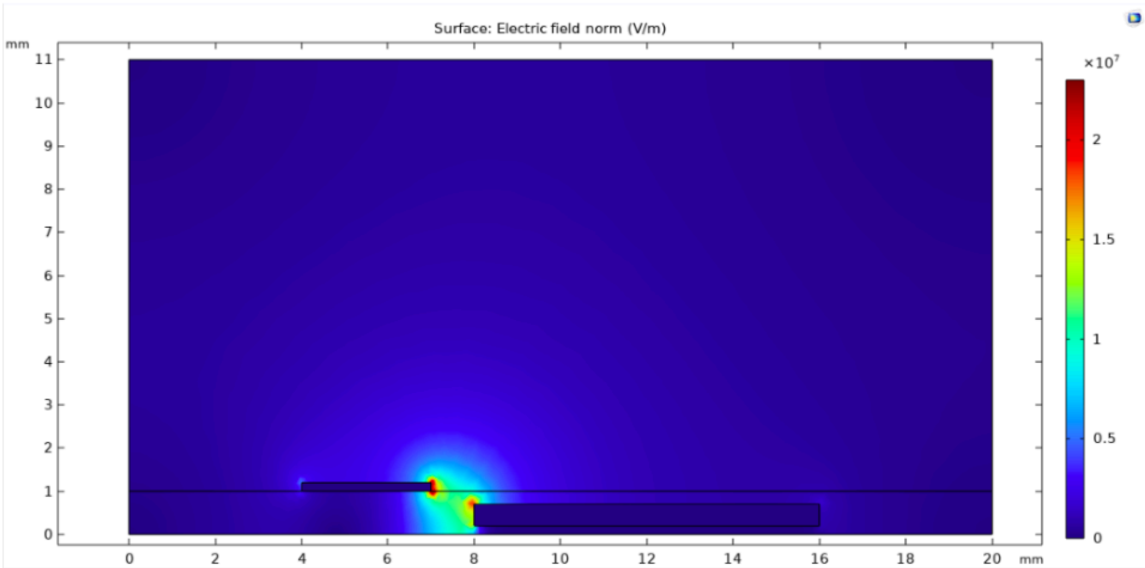

Figure 5: Electric field distribution for hybrid case (20000 V).

In all cases, the maximum electric field is observed near the edge of the exposed electrode. This strong localization is primarily due to the geometric discontinuity at the electrode edge, which enhances the electric field intensity.

A secondary region of elevated electric field is also observed near the buried electrode; however, its magnitude is comparatively lower. Away from the electrode region, the electric field rapidly decreases within the air domain, indicating strong spatial confinement of the field near the actuator surface.

Effect of Excitation Conditions

The influence of different excitation conditions on the electric field distribution was evaluated using line plots extracted along the dielectric surface.

In the AC case (5000 V), the electric field distribution shows a relatively lower magnitude with a sharp but narrow peak near the exposed electrode edge. The field remains confined to a small region, indicating weaker actuation potential.

For the NS case (15000 V), the electric field intensity increases significantly compared to the AC case. The peak becomes more pronounced, and the region of influence slightly expands, indicating stronger field concentration due to higher applied voltage.

In the hybrid AC+NS case (20000 V), the electric field exhibits the highest overall intensity and a broader region of influence. The combination of continuous and high-voltage excitation results in enhanced field strength, which is expected to improve plasma generation and actuator effectiveness.

Line Graph Analysis

The variation of electric field magnitude along the dielectric surface was analyzed using line graphs for the AC, NS, and hybrid excitation cases. The comparison is illustrated in Figure 6.

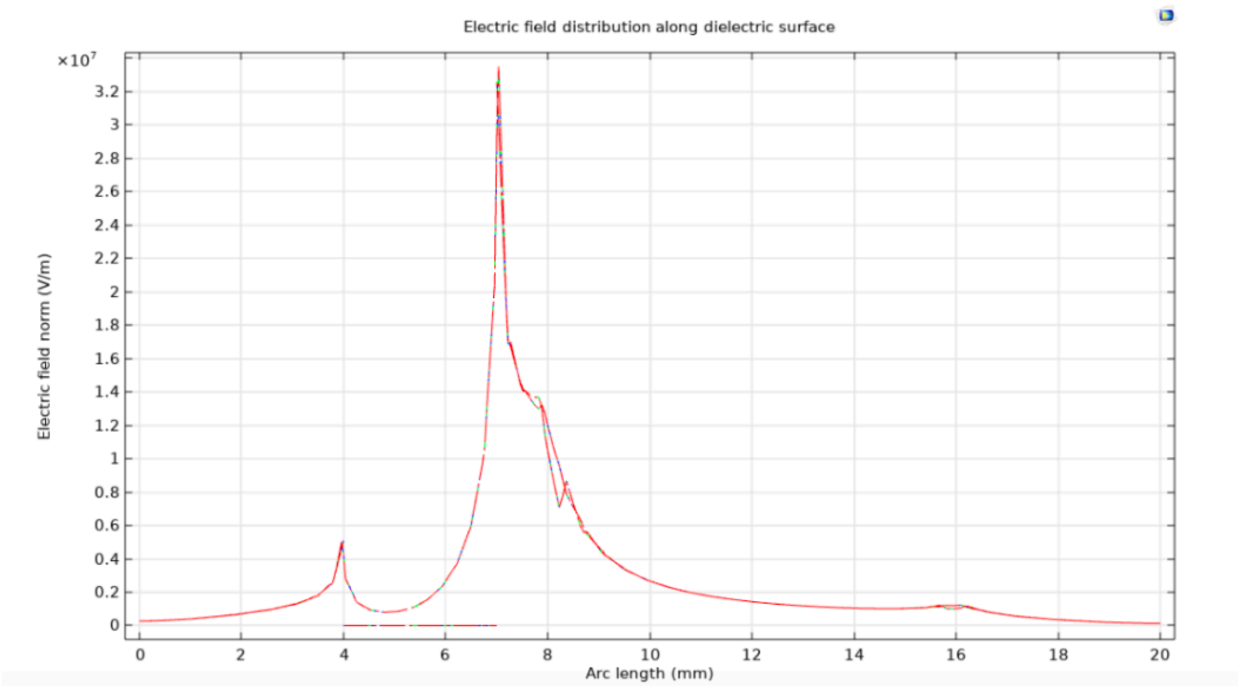

Figure 6: Comparison of electric field distribution along the dielectric surface for AC, NS, and hybrid excitation cases.

The results show that all three excitation cases exhibit a similar spatial distribution of the electric field, with a sharp peak occurring near the edge of the exposed electrode (approximately at x≈6–7mm). This indicates that the location of the maximum electric field is primarily governed by the electrode geometry rather than the type of excitation.

In the AC case, the electric field magnitude is relatively lower, with a peak value in the order of 10^7V/m. The field gradually decreases away from the electrode region, indicating limited spatial influence.

For the NS DBD case, the overall electric field magnitude increases compared to the AC DBD case, while maintaining the same spatial pattern. The peak becomes slightly higher, demonstrating the effect of increased applied voltage.

In the hybrid AC+NS DBD case, the electric field reaches its maximum value among all cases. Although the shape of the curve remains nearly identical to the AC and NS cases, the magnitude of the peak is significantly enhanced, indicating stronger electric field intensity due to combined excitation.

Furthermore, the overlap of the curves suggests that the electric field distribution is linearly dependent on the applied voltage under the electrostatic approximation. This confirms that while the excitation type influences the strength of the electric field, it does not significantly alter its spatial characteristics.

Physical Interpretation

The observed electric field distribution can be explained based on the asymmetric electrode configuration of the dielectric barrier discharge (DBD) plasma actuator. The strong concentration of the electric field near the edge of the exposed electrode is primarily due to the geometric discontinuity, which leads to local field enhancement. This high electric field region is crucial for initiating plasma discharge in practical applications.

The dielectric layer plays an important role in shaping the electric field distribution by limiting current flow and redistributing surface charges. As a result, the electric field remains confined near the actuator surface, preventing excessive field penetration into the surrounding air domain.

The similarity in the spatial profiles of the electric field for AC, NS, and hybrid cases indicates that the overall distribution is mainly governed by the geometry of the actuator rather than the excitation type. However, the increase in electric field magnitude with higher applied voltage demonstrates that the excitation condition significantly influences the strength of the electric field.

In particular, the hybrid excitation case produces the highest electric field intensity, which suggests a greater ability for ionization and plasma generation. This implies that hybrid excitation can enhance the effectiveness of plasma actuators in flow control applications.

Summary of Findings

The present study demonstrates that the electric field distribution in the DBD plasma actuator is highly non-uniform for all excitation conditions. In each case, a strong concentration of electric field is observed near the edge of the exposed electrode, indicating that this region plays a dominant role in plasma formation.

It is also observed that the location of the peak electric field remains unchanged across all cases. This suggests that the spatial distribution of the electric field is primarily governed by the geometry of the actuator rather than the type of excitation applied.

Furthermore, an increase in the applied voltage results in a proportional increase in the electric field magnitude, while maintaining a similar distribution pattern. The NS and hybrid excitation cases exhibit higher electric field intensities compared to the AC case, demonstrating the effect of increased voltage levels.

Among the three cases, the hybrid AC+NS excitation produces the highest electric field magnitude. This indicates a greater potential for plasma generation and improved actuator performance under combined excitation conditions.

Finally, the electric field is found to decay rapidly away from the electrode region, confirming that the actuator effect is strongly localized near the dielectric surface.

CONCLUSION

In this study, a two-dimensional electrostatic model of a dielectric barrier discharge (DBD) plasma actuator was developed using COMSOL Multiphysics to investigate the electric field distribution under different excitation conditions. The results demonstrate that the electric field is highly concentrated near the edge of the exposed electrode, confirming the critical role of geometric asymmetry in plasma actuator operation.

A comparative analysis of AC, nanosecond pulsed (NS), and hybrid AC+NS excitation cases reveals that the spatial distribution of the electric field remains largely unchanged across all conditions, while the magnitude of the field increases with the applied voltage. Among the three cases, the hybrid excitation produces the highest electric field intensity, indicating its potential for enhanced plasma generation and improved actuator performance.

The findings highlight that a simplified electrostatic approach can effectively capture the fundamental behavior of DBD plasma actuators, providing valuable insights into electric field characteristics without the need for complex plasma modeling. This study serves as a useful foundation for future work involving coupled plasma-fluid simulations and advanced actuator designs.

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