Numerical investigation of atmospheric pressure plasma jet under nonuniform electric field

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With the advancement in the understanding of plasma discontinuous structures and the progress of related research, numerical methods for simulating plasmas based on continuous medium approach have encountered significant challenges. In this paper, a numerical model is presented to simulate the motion trajectory of an atmospheric pressure plasma jet under an external nonuniform electric field. The method proposes to treat the plasma jet as equivalent particles with permittivity and conductivity, based on its dielectric properties and motion characteristics. The numerical model demonstrates short calculation times and excellent agreement between simulation results and experimental observations, validating its high efficiency and effectiveness. This work contributes to a deeper understanding of the collective effect of the plasma jet and provides an effective and efficient method for predicting the motion trajectory of the plasma jet, along with guidelines for controlling plasma using external nonuniform electric fields.

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I. INTRODUCTION

Plasma jet research has gained significant attention in recent decades [1,2] due to its wide-ranging applications in biomedicine, materials processing, artificial light sources, and the electromagnetic industry [3–16]. Through the manipulation of different parameters, such as explored in the research conducted by Norberg *et al.* [17] concerning the correlation between pulse-repetition frequency and plasma by-products, it is possible to regulate the output effects of plasma. This modulation process serves to enhance the practical utility of plasma. One critical area of exploration in plasma jet applications is the control of plasma jet morphology, particularly in the context of reconfigurable antennas [18–22] and flow separation control [23–26]. Various efforts, including by Liu *et al.*, of deflecting the jet and changing its length by placing a pair of electrode plates around, with one of these plates being supplied DC voltages, have been made in this direction [27–32]. Utilizing an external electric field to modify the motion trajectory of a jet is a low-power and feasible method [33]. However, the mechanism by which an external electric field affects plasma jets is complex and currently under investigation. Therefore, a numerical computational model that can accurately describe the trajectory of plasma jets under the influence of an external electric field is necessary.

Numerical studies on plasma have been challenging due to the complex particle motion of plasma, limitations in plasma diagnostics, and the high requirements but low efficiency of simulation models. Traditional plasma simulation methods based on electromagnetic dynamics, electrochemistry, and fluid dynamics require accurate parameters of the experimental plasma jet, such as pressure, plasma permittivity, and electron density distribution, which are often difficult to obtain accurately. This limitation hinders the implementation of accurate simulations of plasma jet trajectories. Therefore, a computationally efficient plasma jet model is essential for advancing further research and applications in plasma science.

In this study, we present an approach that treats the plasma jet as equivalent particles with specific permittivity and conductivity, taking into consideration its dielectric properties and motion characteristics. We develop a numerical model that simulates the motion trajectory of atmospheric pressure plasma jet (APPJ) under the influence of an external nonuniform electric field. To validate the effectiveness of the proposed model, a series of experiments is conducted and compared with the numerical simulations. The method exhibits large efficiency improvement in computation times and excellent agreement between simulations and experimental observations. This research contributes to a deeper understanding of the collective behavior of plasma jets and provides a practical and efficient method for predicting the motion trajectory of plasma jets, along with guidelines for controlling plasma using external nonuniform electric fields.

II. THEORETICAL CONSIDERATIONS

A. Basic characteristics of atmosphere pressure plasma jet

With the rapid development of intensified charge coupled device (ICCD) technology, the discovery of the discontinuous structure of plasma jets (also known as plasma bullets) was first made by Teschke's research [34]. Subsequently, numerous experimental studies on plasma bullets have been conducted, posing a significant challenge to traditional

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numerical methods based on continuous medium approximations. Numerous research investigations [34–39], among them the in-depth studies conducted by Walsh [40], Naidis [41], and Babaeva [42] focusing on the impact of external electric fields on plasma jet propagation velocity, have consistently revealed, through both experimental observations and simulation studies, that plasma bullets tend to adopt a spherical configuration, with the radius of the plasma bullet closely resembling that of the observed plasma jet. This suggests that the proposed equivalent spherical particles used in numerical simulations may have similar radii to those of the actual plasma jet. Hence, in this paper, we have formulated numerical computation methods rooted in the discontinuous nature of plasma jet.

In weakly ionized plasma, the movement of charged particles is mainly affected by the collective effects of Coulomb force and particle oscillation, with electrons acting as the primary charge carriers due to their lighter mass than ions. The plasma jet can be viewed as a medium with a particular complex permittivity or conductivity, and its dielectric properties can be estimated based on the Langevin equation of electron motion in weakly ionized plasma. This classical equivalent model, which is commonly used, is given as [12]

$$\sigma_p = \frac{\varepsilon_0\omega_p^2\vartheta_m}{\vartheta_m^2+\omega^2} - j\frac{\varepsilon_0\omega_p^2\omega}{\vartheta_m^2+\omega^2}, \tag{1}$$

$$\varepsilon_p = 1 - \frac{\omega_p^2}{\vartheta_m^2+\omega^2} - j\frac{\omega_p^2\vartheta_m}{\omega\left(\vartheta_m^2+\omega^2\right)}, \tag{2}$$

where σ_p and ε_p are the conductivity and the permittivity of plasma, respectively. ε_0 is the free-space permittivity, ϑ_m is the collision frequency, and ω is the angular frequency of the electric field. ω_p is the oscillation frequency of plasma and given as

$$\omega_p = \sqrt{\frac{n_e q^2}{m_e\varepsilon_0}}, \tag{3}$$

where n_e is the number density of the electron; q and m_e are the electric charge and the mass of an electron, respectively.

B. Response of electrically neutral component of plasma to an external electric field

In practical applications of plasma jets, nonuniform electric-field intensity distributions are commonly encountered, thereby necessitating a comprehensive investigation of the plasma behavior under such conditions. Considering the dielectric properties of plasma, which belong to its electrically neutral component, we have integrated the dielectrophoretic force equation into our simulation of plasma trajectory in order to account for the impact of the nonuniform electric field on the equivalent spherical particles in plasma. The dielectrophoretic force $\boldsymbol{F}_{\mathrm{DEP}}$ on the particles is [43–45]

$$\boldsymbol{F}_{\mathrm{DEP}} = 2\pi\varepsilon_r\varepsilon_0 R^3 \mathrm{CM}(\nabla E^2), \tag{4}$$

where ε_r is the relative permittivity of the surrounding medium. In the context of the present study, the value of 1 is assigned to this parameter, as the medium under investigation is a gas mixture of air and argon. R is the particle radius; E is the amplitude of the external electric field; and CM is the Clausius-Mossotti factor related to the effective polarizability of the particle [46,47], given as

$$\mathrm{CM} = \left(\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*}\right), \tag{5}$$

where ε_p^* and ε_m^* are the complex absolute permittivity of the particle and the surrounding medium, respectively. When the frequency of the external electric field is below 50 kHz, CM is reduced to [48,49]

$$\mathrm{CM} = \left(\frac{\sigma_p - \sigma_m}{\sigma_p + 2\sigma_m}\right). \tag{6}$$

The conductivity of the surrounding medium, denoted as σ_m, approaches zero and is much lower than the conductivity of the plasma, σ_p, in our study due to the mixed gas medium. As a result, CM, the complex permittivity of the medium, remains equal to 1, and Eq. (4) is reduced to

$$\boldsymbol{F}_{DEP} = 2\pi\varepsilon_0 R^3(\nabla E^2). \tag{7}$$

To facilitate simulation, this study focuses on modeling the plasma jet under the influence of an external electrostatic

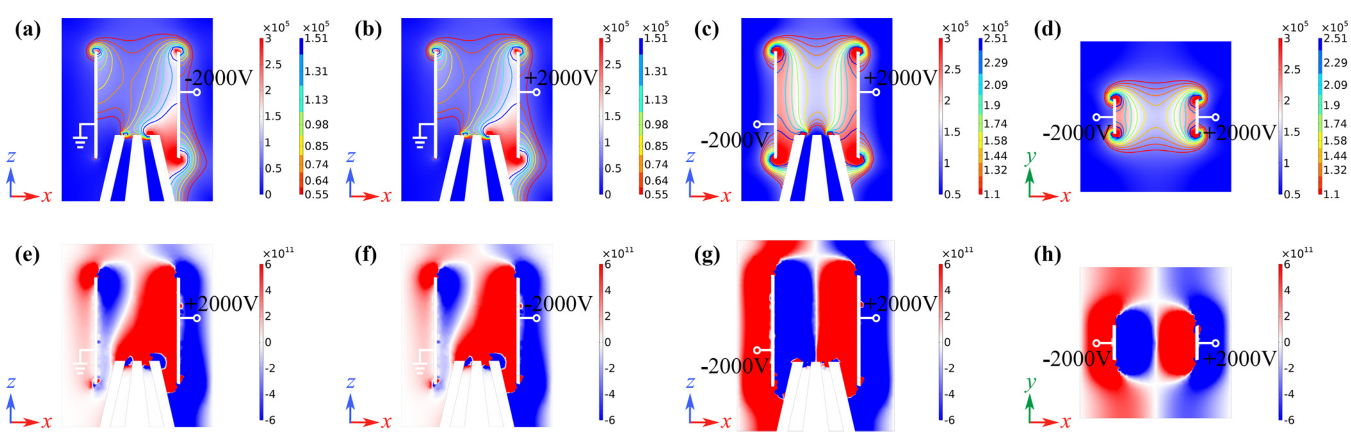

FIG. 1. Simulations of distributions of E and ∇E^2. White area in color cross-section drawing represents electrode plates and plasma jet generator. Contour lines are denoted by lines of varying color. (a)–(d) Distributions of E (V/m). (e)–(h) Distributions of ∇E^2 (V^2/m).

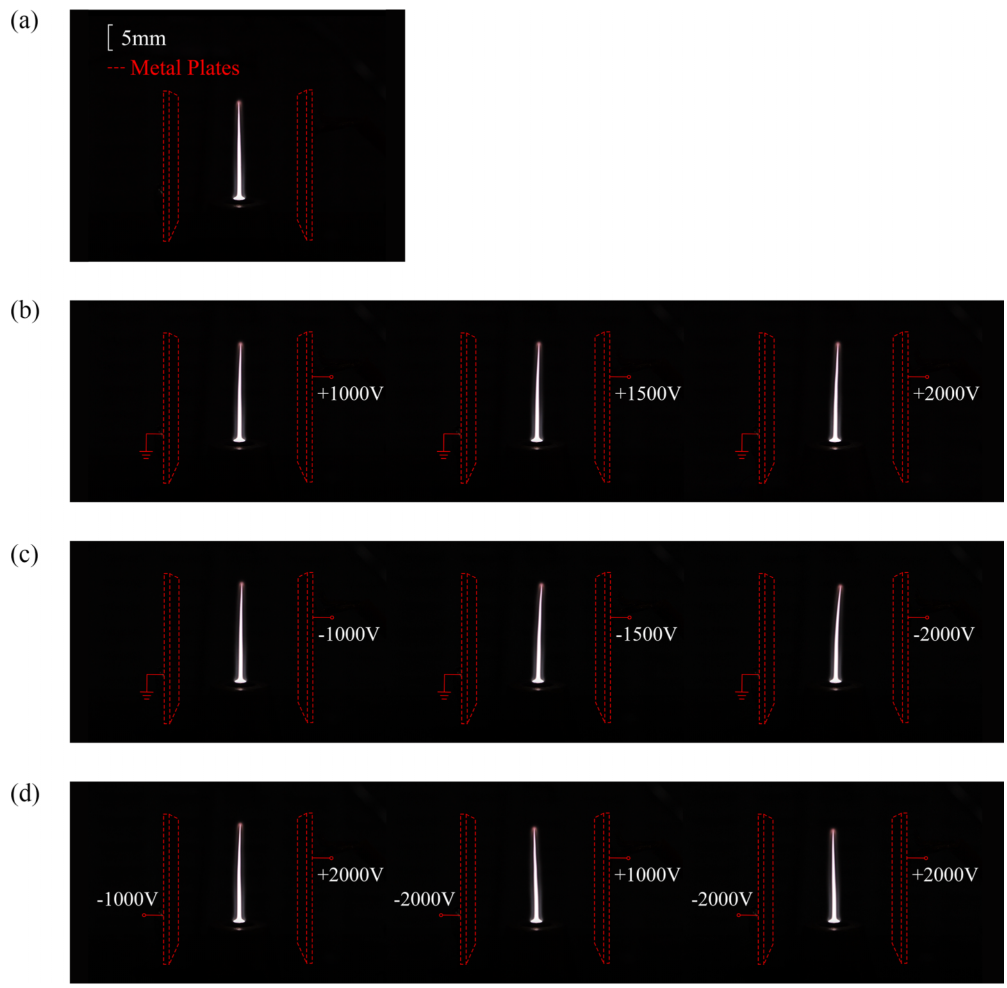

FIG. 2. Optical imagery of influence of nearby electrode plates supplied different DC voltages on 2.45-GHz microwave-induced APPJ. (a) Without external DC voltage. (b) With external DC positive voltages. (c) With external DC negative voltages. (d) With external DC negative and positive voltages.

field. The dielectrophoretic force is independent of the permittivity and conductivity of the plasma, which eliminates measurement errors associated with plasma diagnosis. The right side of Eq. (7), except for the gradient term, consists of constants, making calculations significantly more convenient. Only two parameters, the velocity in the direction of emission and the average electron density of the plasma bullet, are required to simulate the jet trajectory. These parameters can be obtained through ICCD camera imaging and spectral methods. The average velocity of atmospheric pressure low-power microwave plasma bullet at 2.45 GHz has been measured to be around 250 m/s, which differs from plasma jets ignited by lower-frequency sources [36,38,39,50]. The average electron density of the plasma has been diagnosed using spectroscopy in our previous work [51].

C. Response of electrically non-neutral component of plasma to an external electric field

The dielectrophoretic force arises from the influence of the electric field on the electrically neutral component of the plasma. However, the nonelectrically neutral part of the plasma should not be overlooked. Our previous research findings reveal that the plasma jet has a certain range of nonelectrical neutrality, with an electrostatic potential distribution surrounding it [32]. This nonelectrically neutral part of the plasma can be regarded as an equivalent net charge in the plasma. Hence, when calculating the dielectrophoretic force, it is imperative to consider the impact of the external electric field on this net charge. Our previous work involved the measurement of the electrostatic potential distribution surrounding the jet and the determination of the equivalent static charge and its influence on the external electrostatic field using the Poisson equation:

$$\nabla^2\varphi = -\nabla E = -\frac{\rho}{\varepsilon_0}, \tag{8}$$

$$F = qE, \tag{9}$$

where φ is the electrostatic potential, ρ is the charge density, $\boldsymbol{F}$ is the Coulomb force, and q is the charge. Once the forces acting upon plasma particles have been determined, the plasma's trajectory can be easily calculated by applying Newton's second law:

$$\boldsymbol{F}_t = \frac{d(m_p\boldsymbol{v})}{dt}. \tag{10}$$

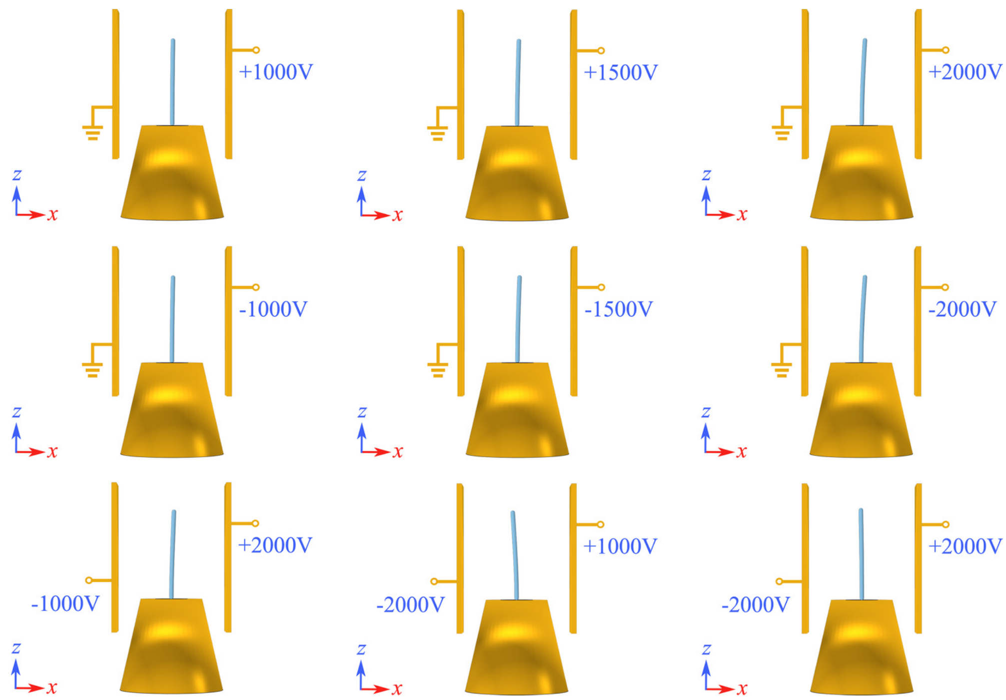

FIG. 3. Simulated results of motion trajectory of APPJ near electrode plates supplied different DC voltages.

To facilitate the resolution of the implicated differential equations, we engaged COMSOL MULTIPHYSICS software, grounded in the finite-element method, for our numerical analyses. Both spatial and temporal parameters within the solution domain were subject to mesh discretization, with iterative algorithms deployed to secure accurate approximate solutions. Throughout the computational phase, an array of techniques, including Newton-Raphson method, was invoked to obtain solutions to nonlinear equations effectively. We also instituted a minimal tolerance threshold to validate the fidelity of our computational results. The inherent risk of test functions converging to local optima during iterative procedures warrants mention, as it poses a potential threat to the accuracy of the results. To mitigate this risk, we undertook a comparative analysis of numerical solutions, derived from a multiplicity of initial conditions, against established experimental data.

III. RESULTS AND DISCUSSION

Based on Eqs. (7)–(9), it is evident that the trajectory of the plasma jet can be influenced by an external nonuniform electrostatic field. In our experiments, we utilized a pair of parallel electrode plates subjected to different DC voltages, which is a common setup for generating an electrostatic field.

Prior to describing the series of numerical simulations and experiments that were conducted, it is noteworthy that in our experiments, observable jet deflection was achieved when the DC voltage across the electrode plates exceeded the kilovolt (KV) level. However, we observed that the plasma jet was interfered with by ionic wind, particularly when the DC voltage was positive or higher than 2000 V. Conversely, when a dielectric medium was introduced to disrupt the ion wind, the jet deflection decreased or disappeared due to charge accumulation on the dielectric wall. Therefore, it was challenging to completely eliminate the interference of ionic wind while maintaining the desired distribution of the external electric field. As a result, to minimize the interference from ionic wind, we compared the experimental and simulated results under the condition of a DC positive voltage of 1000 V and a DC negative voltage ranging from −1000 to −2000 V.

A. Three-dimensional simulations of nonuniform distributions

Figure 1 depicts the simulations of the distributions of electric field E and its gradient squared ∇E^2. The distribution of E exhibits nonuniformity consistently [Figs. 1(a)–1(d)], which can be attributed to the presence of the metal plasma generator. Figures 1(e) and 1(f) demonstrate the distributions of ∇E^2, leading to the generation of dielectrophoretic forces acting on the plasma.

B. Theoretical elucidation of experimental phenomena

In order to validate the numerical model, a series of experiments and simulations was conducted. Surprisingly, in our experiments, we observed that the plasma jet consistently deflected towards the plate with an electrostatic potential, irrespective of whether the potential was positive or negative, as shown in Fig. 2. Intriguingly, when the absolute values of the potentials supplied to the plates were the same, the jet deflected more significantly under negative potential compared to positive potential. These phenomena [29,33] can be clearly explained through the theoretical framework presented above. According to the simulations, when the polarity of the DC voltage applied to the right electrode plates is reversed, the distributions of ∇E^2 are almost identical, regardless of whether the DC voltage is positive or negative [Figs. 1(e) and 1(f)]. Combining this observation with Eq. (7), it can

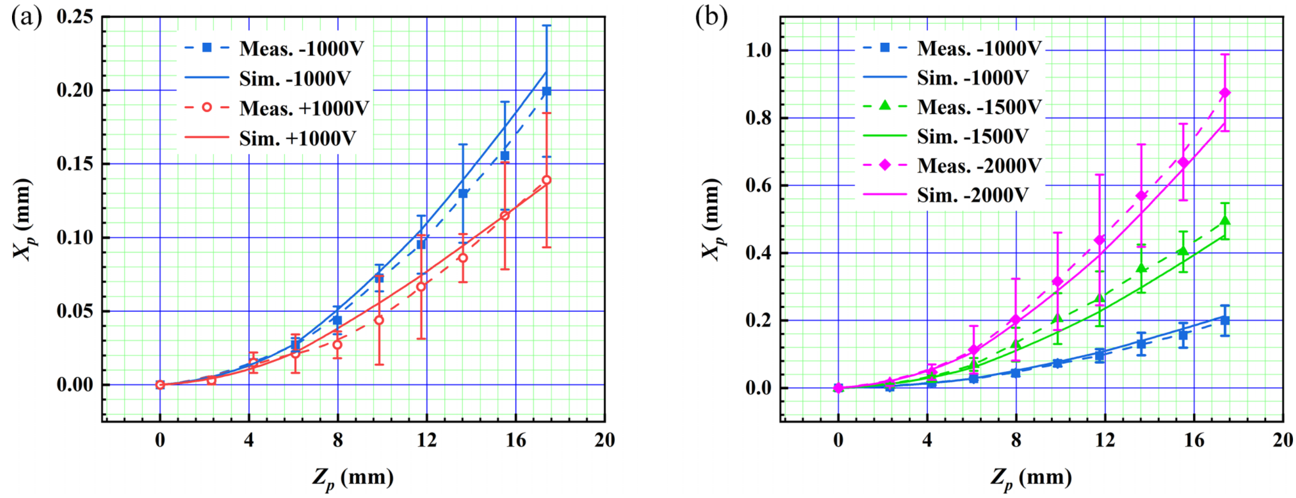

FIG. 4. Comparison of simulated results and experimental data of motion coordinate of plasma. Left electrode plate was maintained at ground potential, while right electrode plate was connected to DC voltage source. X_p and Z_p are X coordinate and Z coordinate of plasma, respectively. (a) Comparison of different voltage polarities at same amplitude. (b) Comparison of different voltages at same polarity. Data are connected by Bezier curves. Error bars represent standard deviation of measurements.

be inferred that the polarity of the DC voltage across the electrode plates has minimal impact on the dielectrophoretic force $\boldsymbol{F}_{\mathrm{DEP}}$, leading to a lack of correlation between the directions of jet deflection and the electrostatic field. Furthermore, in our previous study, the plasma was found to have a net positive charge as measured by the positive electric potential [32]. Consequently, the Coulomb force [Eq. (9)] has a greater impact on the deflection of the plasma jet under negative voltage [see Fig. 4(a)].

C. Assessing the accuracy and efficiency of the numerical model

As previously stated, a set of experiments and simulations was carried out to verify the accuracy of the numerical model.

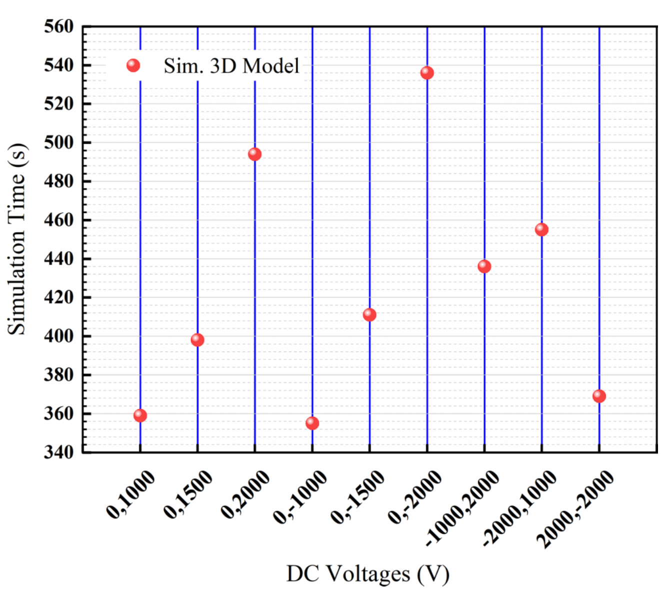

FIG. 5. Simulation time at different DC voltages on parallel electrode plates. Two numbers of horizontal coordinate represent voltages on two plates, respectively.

Optical imagery captured the trajectories of the plasma jet affected by electrode plates with varying DC voltages, and the simulation outcomes are depicted in Fig. 2, while Fig. 3 presents the corresponding simulated results. A visual comparison between the simulated and experimental results is provided in Fig. 4, showing excellent agreement between the two, which proves the validity of the numerical model.

The simulation time was recorded and presented in Fig. 5 to demonstrate the practicality of the employed simulation method. The 3D simulations were completed in a relatively short timeframe of 359 to 536 s on a computer with 1TB RAM and an ADM EPYC 7H12 processor (64-Core, 2.60 Hz). It is noteworthy that if a 2D model is used instead of the 3D model, the computational time would be significantly reduced, enabling real-time simulation of the plasma motion trajectory.

IV. SUMMARY AND CONCLUSIONS

In this study, an approach is presented that treats the plasma jet as equivalent particles with specific permittivity and conductivity, considering its dielectric properties and motion characteristics. A numerical model is developed to simulate the motion trajectory of the plasma jet under the influence of an external nonuniform electric field. The proposed model is validated through a series of experiments and shows efficient computation times and excellent agreement with experimental observations. This research enhances our understanding of the collective behavior of plasma jets and provides a practical and efficient method for predicting their motion trajectory, as well as guidelines for controlling plasma using external nonuniform electric fields.

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