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Time-dependent fluid simulation of negative point-to-plane DC corona discharge: Influence of neutral gas temperature

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Abstract

Negative DC corona discharges are widely used in electrostatic precipitation, ozone generation, and plasma-based surface treatment. In this study, a time-dependent axisymmetric fluid model is developed in COMSOL Multiphysics to investigate the effect of neutral gas temperature on a negative DC point-to-plane corona in dry atmospheric air. The model solves coupled drift-diffusion and Poisson equations under the local field approximation. Results show that increasing gas temperature reduces the densities of electrons, positive ions, and negative ions, while the electric potential and electron temperature remain relatively insensitive. These findings provide useful guidance for the thermal design of atmospheric-pressure corona devices.

Keywords:

DC corona discharge; Drift-diffusion model; COMSOL Multiphysics; Atmospheric-pressure plasma; Neutral gas temperature; Numerical simulation

1. Introduction

Atmospheric-pressure DC corona discharges have attracted considerable interest due to their unique combination of low-temperature operation, intrinsic stability, and broad plasma-based applications [1],[2]. These non-thermal discharges occur in strongly non-uniform electric fields, generally produced by electrode configurations involving pointed, needle-like, or thin-wire shapes [1]. Among various corona configurations, the point-to-plane arrangement is particularly relevant because it

provides a localized high-field region and can operate under low-current conditions. Such configurations have been widely investigated for both fundamental studies and electrohydrodynamic applications because they provide a well-defined ionization region near the high-curvature electrode and a distinct drift region extending toward the grounded electrode [4]–[9]. In these systems, ionization is concentrated near the high-curvature electrode, where electric-field enhancement increases the energy gained by electrons and supports electron-impact ionization. The resulting space-charge distribution modifies the local electric field and influences the temporal evolution and stability of the discharge [9].

In electronegative gases such as air, the behavior of negative corona is strongly influenced by electron attachment and the resulting redistribution of charged species. The electrons generated in the ionization region are rapidly removed from the free-electron population through attachment reactions, leading to the formation of negative ions. The resulting attachment-dominated kinetics, together with the space-charge distribution, contribute to corona stabilization and can inhibit the transition toward streamer formation under typical operating [5], [8], [10]–[13]. As a result, the electric field is strongly distorted near the cathode, whereas charge transport in the drift region is dominated by positive and negative ion drift rather than free electrons [1], [8]. Because of the small spatial scales and steep gradients near the electrode, direct experimental diagnostics of the local plasma structure remain challenging. Therefore, self-consistent numerical modeling has become an effective approach for investigating the physical mechanisms governing corona discharges. Depending on the level of physical detail required, numerical and multiphysics approaches range from simplified charge-transport formulations to multi-species plasma fluid models that account for charged-species continuity equations, plasma chemistry, electron energy conservation, and Poisson’s equation [14][15].

In this context, fluid plasma models based on the drift-diffusion approximation in conjunction with Poisson’s equation have been extensively applied to model DC corona discharges at atmospheric pressure. These models provide a description of charged species transport and space-charge-driven field distortion with reasonable computational efficiency [16]–[19]. In particular, three-species corona models incorporating electrons, positive ions, and negative ions have been successfully employed to describe ionization, attachment, recombination, and space-charge transport in negative corona discharges [20]. Among these approaches, hydrodynamic fluid models have demonstrated good agreement with experimental results and have been widely used to investigate the discharge characteristics of both positive and negative coronas. For example, Ferreira et al. [21] conducted

numerical and experimental investigations into the time-averaged properties of positive and negative corona discharges in a point-plane geometry utilizing a hydrodynamic model. However, their analysis concentrated on time-averaged discharge behavior and did not address the transient effects of neutral gas temperature on the evolution of charged species and space-charge dynamics. More recently, Keshavarzi et al. [7] investigated the spatial distributions of chemical species in a pin-to-plate dry-air corona discharge, providing further insight into the spatially resolved behavior of negative corona plasmas.

Previous numerical studies have examined the effects of applied voltage, electrode geometry, gas composition, and operating conditions on discharge characteristics, including current-voltage behavior, electric-field distribution, humidity effects, and charged-particle densities [7], [11], [21]–[24]. However, under practical operating conditions, the background gas temperature is often not constant. It may increase as a result of discharge-induced heating, energy transfer between charged and neutral species, prolonged discharge operation, or changes in the surrounding thermal environment. Such temperature variations directly alter the neutral particle density and collision frequencies [25]. This subsequently modifies the kinetics of ionization, electron attachment, and recombination in atmospheric-pressure plasmas [5], [8], [10]. More recently, Zhang and Deng [26] performed a microscopic analysis of Trichel pulses within negative corona discharges, showing that variations in gas temperature and air pressure have a direct impact on the development of local charge density and electric field distribution throughout the pulse evolution. These findings further emphasize the importance of incorporating gas temperature into time-dependent numerical models of corona discharges.

Although the majority of temperature-dependent numerical studies have focused on dielectric barrier discharges, they provide valuable physical insight into how neutral-gas temperature governs plasma transport and reaction kinetics. Raising the gas temperature lowers the neutral-particle density, whereas the electron temperature and electric field distribution may exhibit comparatively weaker changes under comparable conditions [27]–[29]. Moreover, variations in gas temperature also modify ion fluxes, secondary electron emission, and the relative importance of different collision processes, thereby impacting discharge stability and plasma transport. Consistent with these findings, Hussain and Lu [30] employed a plasma model in COMSOL Multiphysics to explore how ambient temperature fluctuations can alter plasma densities by multiple orders of magnitude in both positive and negative coronas.

Despite these advances, the specific impact of neutral gas temperature on the transient evolution of negative DC point-to-plane corona discharges is still incompletely understood. DC coronas are frequently modeled under steady-state assumptions, although their time-dependent development governs space-charge formation and discharge stabilization. Previous theoretical and kinetic studies have demonstrated that gas heating and temperature-dependent variations in neutral gas density substantially alter ionization kinetics and charged-particle transport even when the steady-state electric-field distribution remains nearly unchanged [5], [8], [10]. In particular, Chen et al. [31] showed that gas heating plays an important role in the transition from Trichel pulses to a continuous glow. Although recent studies have offered valuable insight into polarity-dependent corona behavior [32] and the effects of gas temperature on discharge characteristics [26], [30], a systematic time-dependent fluid study that quantifies how neutral gas temperature influences the spatiotemporal evolution of charged species, space-charge accumulation, and plasma transport in negative DC point-to-plane corona discharges remains limited. This gap in knowledge forms the primary scientific motivation for the present study.

In this study, we develop a two-dimensional axisymmetric negative DC point-to-plane corona model in atmospheric dry air, using a time-dependent self-consistent drift-diffusion/Poisson framework, to quantify the temperature-dependent changes in charged-particle densities, fluxes, energy transfer, and local electric field. The applied voltage and inter-electrode gap are maintained at -50 kV and 9.5 cm, respectively, while the initial neutral gas temperature is varied from 300 to 600 K. The model enables detailed analysis of the spatiotemporal evolution of electron density, positive- and negative-ion densities, electric potential, and electron temperature under different thermal conditions. Compared with previous studies that emphasized steady-state characteristics or individual discharge parameters, the present work provides a systematic time-dependent analysis. The results improve physical insight into temperature-dependent corona dynamics and offer a useful theoretical basis for the optimization and thermal management of atmospheric-pressure corona plasma devices operating under different environmental conditions.

2. Numerical Model

2.1 Physical Model and Geometry

Among the numerical strategies available for corona-discharge simulation, a self-consistent plasma-fluid formulation is adopted instead of simplified unipolar charge-transport models because it enables the simultaneous prediction of electron, positive-ion, and negative-ion densities together with their mutual coupling through plasma chemistry and the electric field [14], [15]. A two-dimensional axisymmetric point-to-plane configuration is therefore employed to represent a negative DC corona in dry atmospheric-pressure air. The electrode arrangement comprises a sharp metallic point with a tip radius of curvature of 50 μm facing a grounded planar electrode, thereby generating the strongly non-uniform electric field that characterizes corona discharges. The point electrode possesses a parabolic tip and is positioned 9.5 cm above the grounded plane. A high negative DC voltage of -50 kV is applied to the point electrode. The computational domain is a 15 mm $\times$ 110 mm axisymmetric rectangular region. Its lateral dimensions were selected so that boundary effects on the electric-field distribution remain negligible while computational cost stays acceptable. The grounded plate forms the lower boundary, whereas the other external boundaries are treated as electrically insulating. Because the active ionization zone is confined to the vicinity of the needle tip, the computational domain is large enough to eliminate artificial boundary effects on the simulated discharge. Figure 1 shows a schematic of the point-to-plane corona-discharge configuration.

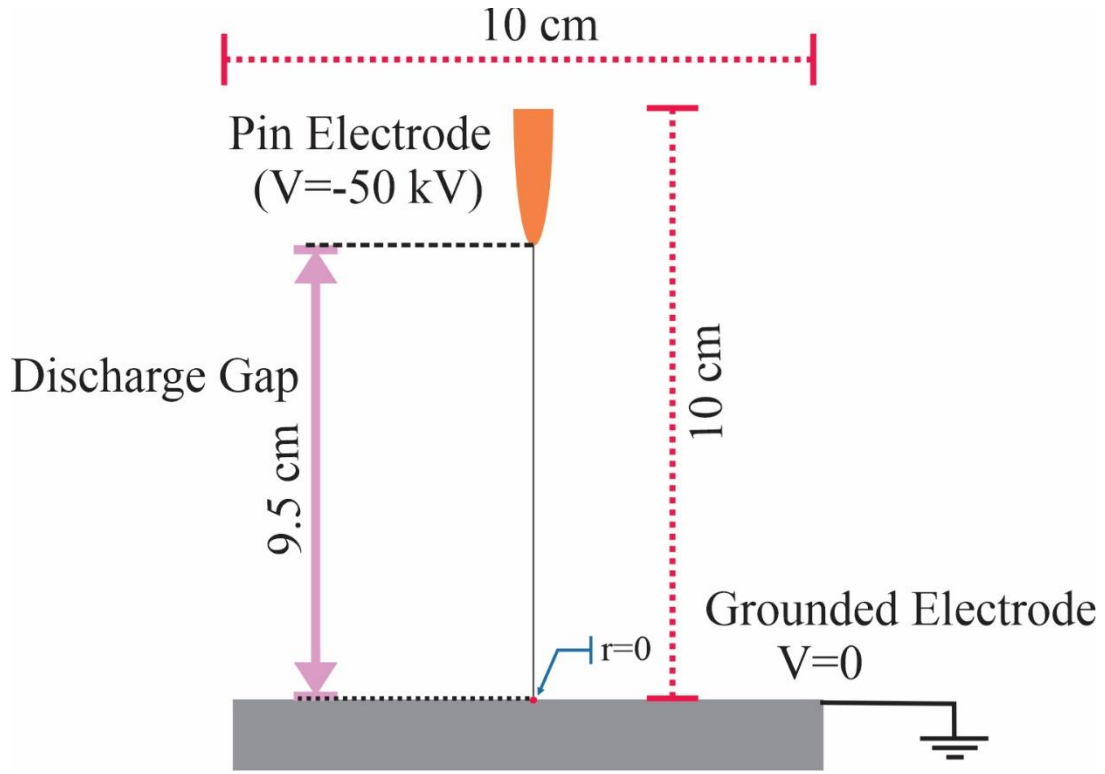


Figure 1. Schematic of the two-dimensional axisymmetric point-to-plane negative DC corona discharge configuration (not to scale).

2.2 Mesh Generation and Numerical Stabilization

A non-uniform triangular mesh was utilized across the computational domain, as depicted in Figure 2. A locally refined mesh was created around the needle tip to effectively capture the steep gradients of the electric field, densities of charged species, and plasma reaction rates, while a progressively coarser mesh was applied further away from the discharge region to reduce computational cost. The computational domain was divided into two distinct mesh areas. Near the needle electrode, the smallest mesh element size was $37.5\ \mu\text{m}$, with a maximum element growth rate of 1.164. In the other region, the largest element size was 0.045 cm, gradually increasing towards the grounded electrode. The axisymmetric line between the needle and the grounded plate was discretized into 150 elements, maintaining a specified element ratio of 300. A boundary-layer mesh consisting of four layers with a stretching factor of 1.8 was additionally applied at the grounded electrode to improve numerical accuracy in the near-wall region. The final computational mesh consisted of 9852 domain elements and 470 boundary elements. Mesh independence was verified through successive mesh refinement until further refinement produced negligible changes in the predicted electric potential and charged-

species distributions. The adopted mesh, therefore, provided an appropriate balance between numerical accuracy and computational efficiency and was used for all simulations. Similar meshing strategies have been successfully employed in previous numerical studies of atmospheric-pressure corona discharges [12], [13].

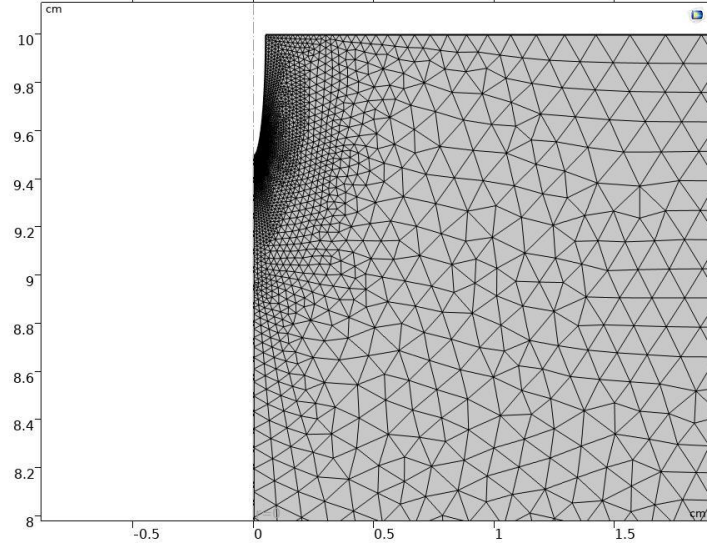


Figure 2. Finite-element computational mesh used for the numerical simulations, showing local mesh refinement near the needle tip to accurately resolve the steep electric-field and charged-species density gradients.

2.3 Governing Equations

The plasma dynamics are described using a fluid-based drift-diffusion model, in which the continuity equations for both electrons and ions are coupled with Poisson's equation related to the electric potential [22], [33]. The electron continuity equation is given by [34]:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma_e = R_e,$$

where n_e is the electron number density, Γ_e is the electron flux, and R_e denotes the net source term resulting from ionization and attachment-recombination processes. The corresponding electron flux is written as

$$\Gamma_e = -\mu_e n_e \mathbf{E} - D_e \nabla n_e,$$

where μ_e and D_e are the electron mobility and diffusion coefficient, respectively, and $\mathbf{E} = -\nabla V$ is the electric field.

For each ion species k , the continuity equation is expressed as

$$\frac{\partial n_k}{\partial t} + \nabla \cdot \Gamma_k = R_k,$$

with the ion flux defined as

$$\Gamma_k = -Z_k \mu_k n_k \mathbf{E} - D_k \nabla n_k,$$

where Z_k , μ_k , and D_k present the charge number, mobility, and diffusion coefficient of species k , respectively. The electric potential V is obtained from Poisson's equation:

$$\nabla \cdot (\epsilon_0 \epsilon_r \nabla V) = -\rho,$$

where ρ denotes the total space-charge density

$$\rho = q(\sum_k Z_k n_k - n_e)$$

with q being the elementary charge. The governing equations are solved simultaneously at each time step using the finite-element method implemented in COMSOL Multiphysics.

2.4 Plasma Chemistry and Boundary Conditions

A reduced air-plasma chemistry is adopted to examine the response of the discharge to variations in neutral gas temperature, while maintaining the computational efficiency required for two-dimensional time-dependent simulations. The model includes electron-impact ionization, two- and three-body electron attachment, as well as electron-ion and ion-ion recombination processes [11], [35], [36]. Electron-impact rate coefficients are obtained from the LXCat database [37] and locally evaluated as a function of the reduced electric field E/N , based on the local field approximation, with N representing the neutral gas number density. The complete set of reactions employed in the simulations is summarized in Table 1. Although recent detailed numerical studies have incorporated dozens of oxygen- and nitrogen-based species to predict the formation of individual reactive species [26] such detailed chemistry is not required for the objectives of the present work. So, the positive- and negative-ion variables are treated as effective lumped ion species rather than individually resolved molecular ions. The positive-ion variable represents the effective positive-ion species formed in atmospheric air, whereas the negative-ion variable represents the effective negative-ion species.

Table 1: plasma-chemical reaction mechanism incorporated into the [35], [36]

Reactions	Formula	Type	$K_f(\text{m}^3/\text{s})$
1	$\text{e} + \text{A} \rightarrow \text{A}^+ + 2\text{e}$	Ionization	$k(\text{E}/N)$
2	$\text{e} + \text{A} \rightarrow \text{A}^-$	Attachment	$k(\text{E}/N)$

3	$e + 2A \rightarrow A^- + A$	Attachment	$k(E/N)$
4	$e + A^+ \rightarrow A$	Recombination	5×10^{-14}
5	$A^- + A^+ \rightarrow 2A$	Recombination	2×10^{-12}

At both electrode surfaces, incident positive and negative ions are assumed to undergo complete neutralization with a sticking coefficient of unity. Secondary electron emission induced by positive-ion bombardment of the cathode is included using a coefficient of $\gamma = 0.004$, following Tran et al. [12]. The corresponding surface reactions are summarized in Table 2. The cathode potential is ramped from 0 to -50 kV during the initial stage of the simulation to improve numerical stability, whereas the planar electrode is maintained at ground potential. The plasma is initially assumed to be quasi-neutral, with a spatially uniform background electron density of 10^8 m^{-3} .

Table 2: Surface reactions applied at the electrode boundaries.

Reaction	Formula	Sticking coefficient
1	$A^+ \rightarrow A$	1
2	$A^- \rightarrow A$	1

2.5 Local Field Approximation and Temperature Dependence

Electron transport properties and reaction rate coefficients are evaluated within the framework of the local field approximation. Under this assumption, both the electron transport coefficients and electron-impact reaction rates are assumed to be determined by the local reduced electric field E/N . The neutral gas number density is subsequently obtained from the ideal gas law as

$$N = \frac{p}{k_B T_g}$$

where p is the atmospheric pressure, k_B is the Boltzmann constant, and T_g is the neutral gas temperature. At constant pressure, an increase in T_g decreases the neutral number density, thereby increasing the reduced electric field for a fixed electric field strength. Consequently, the electron transport coefficients and electron-impact reaction rates are modified indirectly through their dependence on the E/N .

The electron mobility is calculated using [38]:

$$\mu_e = \frac{3.74 \times 10^{22}}{N} \left(\frac{E}{N} \right)^{-0.25} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$$

and the Townsend ionization coefficient in air is given by [39]:

$$\alpha = 1.4 \times 10^{-16} N \exp\left(-\frac{660}{E/N}\right) \text{cm}^{-1}$$

The electron diffusion coefficient is taken as $D_e = 1800 \times 760/p \text{ cm}^2/\text{s}$, where p is the pressure in Torr. Accordingly, the effect of neutral gas temperature on the discharge characteristics is incorporated through its impact on the neutral gas density, which modifies the reduced electric field and, consequently, the electron transport and reaction coefficients within the local field approximation.

2.6 Solution Strategy

A fully time-dependent finite-element solution strategy is employed to investigate the influence of neutral gas temperature on the transient evolution of the negative DC corona discharge. The time-dependent approach enables the simulation of electron avalanche development, ion generation, space-charge formation, and charge transport during discharge evolution, all of which are sensitive to variations in neutral gas temperature [15]. The governing equations are spatially discretized using the finite element method implemented in COMSOL Multiphysics, with a variable-order backward differentiation formula for time integration. An adaptive time-stepping is used to resolve the rapid dynamics near the cathode tip. To improve numerical stability, the applied cathode voltage is gradually ramped to its prescribed value during the initial stage of the simulation. Stationary solutions are used only as reference states and not as the primary basis for temperature-dependent analysis. This approach is in agreement with previous studies, which have shown that gas temperature effects in atmospheric-pressure discharges are more pronounced during discharge development rather than in the final steady-state regime [5], [8], [10], [11].

3. Results and Discussion

3.1 Electron and ion density

Figure 3 shows the spatial distribution of electron density at $t = 1 \text{ s}$ for initial neutral gas temperatures ranging from 300 to 600 K (300, 400, 500, and 600 K), with the applied voltage fixed at -50 kV and the inter-electrode spacing maintained at 9.5 cm. In all cases, the electron density is highly localized within a thin ionization region adjacent to the cathode tip, where the strong geometric enhancement of the electric field promotes electron-impact ionization [1], [13]. The electron cloud

exhibits a bell-shaped distribution extending from the needle tip into the discharge gap, while the highest electron density remains concentrated along the axis of symmetry. At constant pressure, the reduction in neutral density ($N \propto 1/T$) lowers the electron-neutral collision frequency. Therefore, ionization and attachment rates become less efficient, and the generation of charged particles is reduced.

A clear decrease in peak electron density is observed with increasing neutral gas temperature. The maximum electron density decreases from approximately $7.36 \times 10^{11} \text{ cm}^{-3}$ at 300 K to $1.44 \times 10^{11} \text{ cm}^{-3}$ at 600 K, corresponding to an overall reduction of about 80%. The observed behavior can be primarily explained by the decrease in neutral gas density under constant pressure conditions ($N \propto 1/T$), which increases the reduced electric field and consequently modifies the electron transport and reaction rate coefficients. Although a slight local increase in E/N may occur near the cathode as a result of the reduced neutral density; this effect is insufficient to compensate for the lower availability of neutral particles for ionization collisions. Thus, the electron production rate decreases with increasing gas temperature, consistent with previous numerical and experimental investigations of temperature-dependent negative corona discharge behavior [5], [8], [10], [11], [25]. In particular, the strong reduction in charged-particle densities agrees with earlier experimental analyses of negative corona current composition at elevated ambient temperatures [25].

The electron density profiles exhibit similar spatial width and shape across the investigated temperature cases, indicating that the spatial expansion of the ionization zone is weakly sensitive to the neutral gas temperature. This result suggests that, although the magnitude of electron generation is significantly affected by temperature, the fundamental structure of the ionization zone is governed predominantly by the electric field distribution, which exhibits comparatively limited variation with temperature. These findings are consistent with the numerical study of Zhang et al. [27], who reported that increasing the neutral gas temperature mainly reduces plasma density while exerting only a minor effect on the spatial characteristics of atmospheric-pressure discharges.

Away from the ionization region near the cathode tip, electron density decreases rapidly because electrons are efficiently removed through effective attachment reactions included in the reduced air-plasma chemistry, resulting in an attachment-dominated transport regime in the bulk plasma [36], [40]. Our findings suggest that increasing the neutral gas temperature mainly reduces electron generation and space-charge accumulation, whereas the spatial characteristics of the ionization region remain largely unchanged. This behavior is in agreement with the theoretical analyses of Popov [5], [8], [11], which emphasized that gas heating mainly modifies ionization kinetics through temperature-

dependent changes in neutral gas density rather than significant alterations of the electric-field structure.

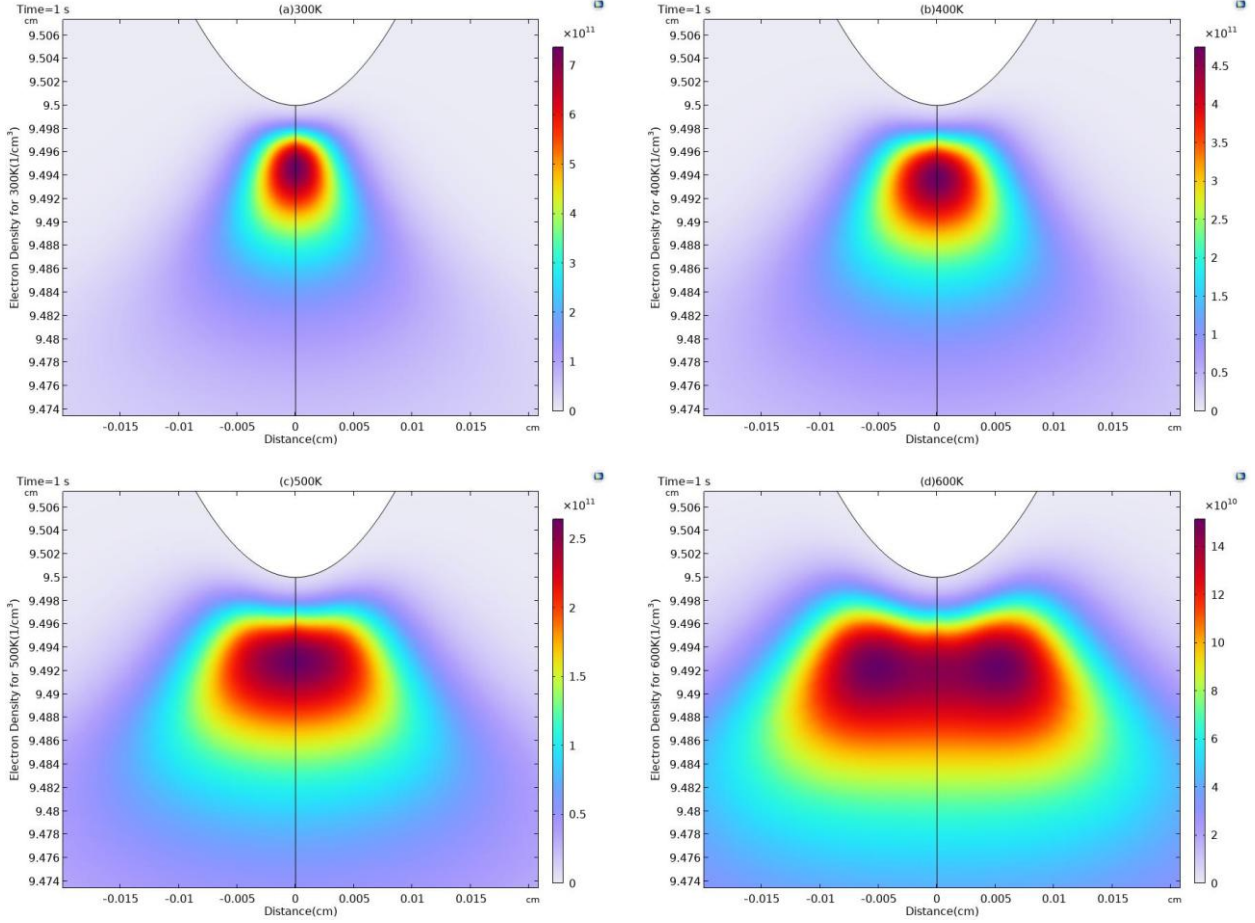


Figure 3. Electron number density distributions at $t = 1$ s for initial neutral gas temperatures of (a) 300 K, (b) 400 K, (c) 500 K, and (d) 600 K. Simulations were performed for a -50 kV applied voltage and a 9.5 cm point-to-plane electrode gap. The color scale shows the electron number density in cm^{-3} .

The electric potential distributions obtained at different initial neutral gas temperatures are nearly identical. Because no discernible differences are observed among the four cases, only the distribution at 300 K is shown in Figure 4(a). In all simulations, the potential gradient is confined near the cathode tip, where the non-uniform electrode geometry produces a strong localized electric field. Moving away from the cathode, the potential varies gradually toward the grounded electrode, while the overall equipotential pattern remains largely unchanged throughout the discharge gap.

The negligible influence of neutral gas temperature on the electric potential indicates that the global electric-field structure is controlled mainly by the electrode geometry and the self-consistent solution

of Poisson's equation. Although increasing the gas temperature reduces the charged-particle densities and weakens the space-charge density, these changes are insufficient to produce noticeable modifications in the potential distribution under the present operating conditions. Our results corroborate previous numerical studies of corona discharges, which likewise reported that thermal effects have a much stronger influence on charged-particle densities than on the electric potential distribution [13], [31].

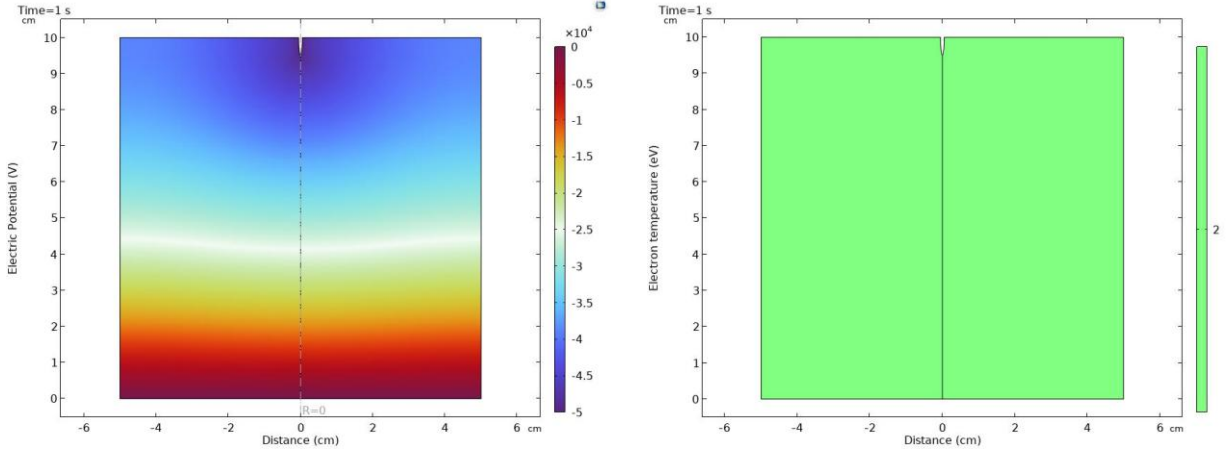


Figure 4. Spatial distributions of (a) electric potential (equipotential lines) and (b) electron temperature for an initial neutral gas temperature of 300 K. The applied voltage is -50 kV, and the inter-electrode gap is 9.5 cm.

The equipotential lines in (a) are plotted at 5 kV intervals. Simulations performed at 400, 500, and 600 K exhibited nearly identical spatial distributions for both quantities; therefore, only the 300 K results are presented for clarity.

The corresponding electron temperature distributions also exhibit only minor variations over the investigated temperature range. Because the spatial distributions at 400, 500, and 600 K are nearly identical to that at 300 K, only the 300 K result is presented in Figure 4(b) for clarity. In all cases, the highest electron temperature is confined to the thin ionization region adjacent to the cathode tip, where electrons gain energy from the locally enhanced electric field, reaching values of approximately 8-12 eV. Outside this region, the electron temperature decreases rapidly as energetic electrons lose energy through frequent collisions with neutral molecules during their transport into the bulk plasma, falling below 2 eV within 1-2 mm from the tip. Across the temperature range from 300 K to 600 K, the maximum electron temperature increases only slightly (by about 10%), while the spatial distribution remains essentially unchanged.

The weak dependence of electron temperature on neutral gas temperature can be explained by the local field approximation adopted in the present model. Under this approximation, electron transport

coefficients and electron energy are governed primarily by the reduced electric field, E/N [5], [8], [11]. Despite the reduction in neutral gas density with increasing gas temperature, the resulting variation in E/N remains relatively small under the present discharge conditions. Although the absolute electric field E decreases with rising temperature, the reduction is smaller than that of the neutral density, so E/N increases over the investigated temperature range. Consequently, the electron energy distribution and the corresponding electron temperature are only weakly affected by thermal variations. Overall, these results indicate that increasing the neutral gas temperature primarily influences the generation and transport of charged particles, whereas the electric potential and electron temperature remain largely unchanged. This interpretation agrees well with previous numerical studies of atmospheric-pressure plasmas, which reported that gas heating significantly modifies plasma density while exerting only a limited influence on electron temperature and the overall electric field [27], [41].

The two-dimensional spatial distributions of positive- and negative-ion densities for initial neutral gas temperatures of 300-600 K are presented in Figures 5 and 6. In all cases, positive ions are generated within the ionization zone adjacent to the cathode tip, where electron-impact ionization is most intense [8][11]. Their highest concentration is located approximately 50-100 μm from the cathode along the symmetry axis and decreases rapidly with increasing distance because of ion drift and recombination [35]. In contrast, negative ions are formed mainly through electron attachment to oxygen molecules and therefore become dominant farther from the cathode, extending into the drift region, where charge transport is dominated by ion motion rather than electron conduction [36].

Increasing the neutral gas temperature from 300 to 600 K results in a pronounced reduction in the densities of both positive and negative ions. The peak positive-ion density falls from approximately $1.87 \times 10^{13} \text{ cm}^{-3}$ to $6.31 \times 10^{12} \text{ cm}^{-3}$ corresponding to a reduction of about 66%, whereas the peak negative-ion density decreases from $1.62 \times 10^{12} \text{ cm}^{-3}$ to $4.05 \times 10^{11} \text{ cm}^{-3}$ by approximately 75%.

As noted earlier, the lower neutral-gas density under constant-pressure conditions suppresses both ionization and attachment, thereby reducing the overall plasma density throughout the discharge region [13], [31]. Although the magnitudes of both ion densities decrease considerably, their spatial distributions remain qualitatively similar across the investigated temperature range. Positive ions remain concentrated within the ionization region close to the cathode, whereas negative ions extend farther into the drift region owing to electron attachment and ion transport. The axial evolution of both ion species is discussed in greater detail using the profiles presented in Figure 6.

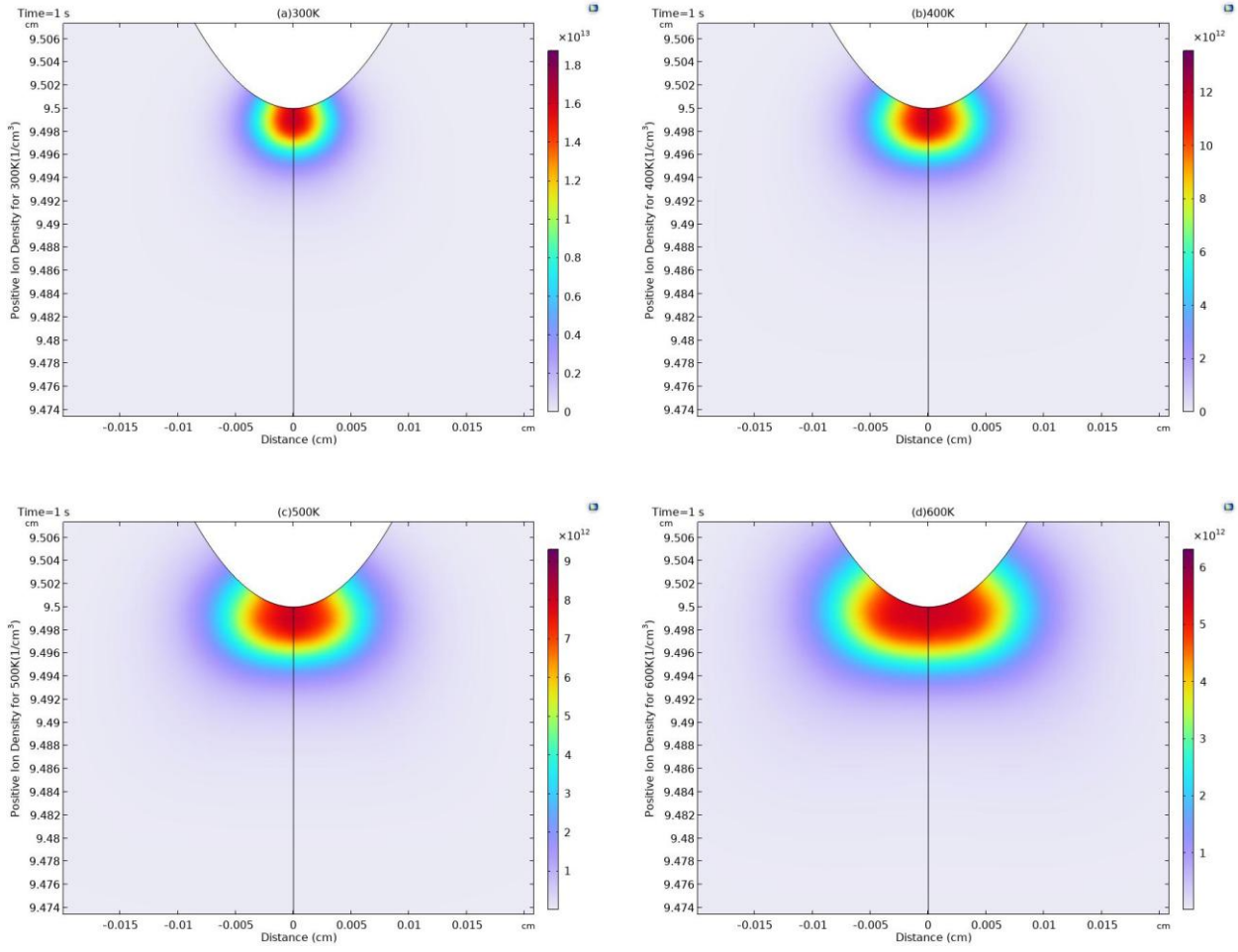
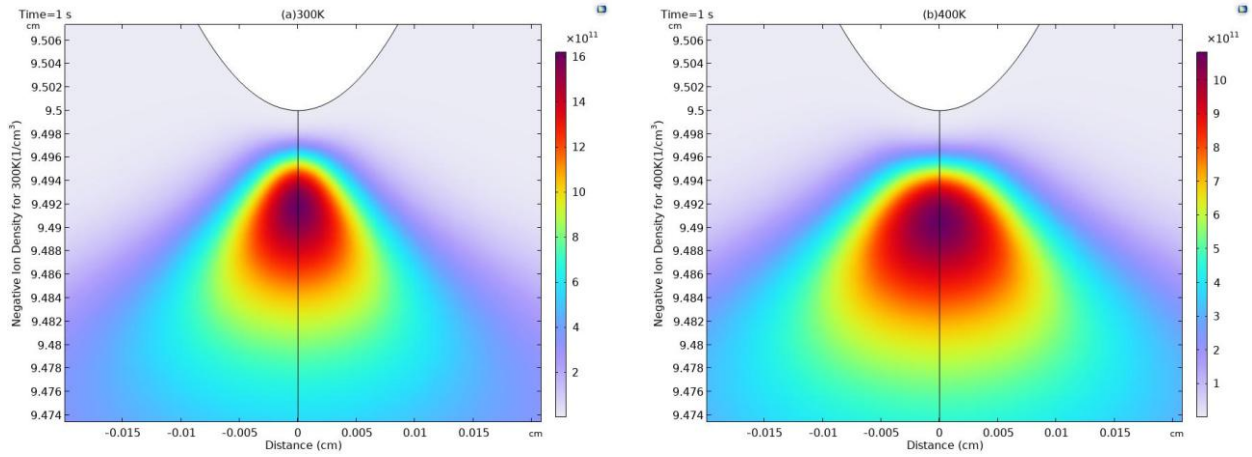


Figure 5. Spatial distribution of positive ion density at $t = 1$ s for different initial neutral gas temperatures: (a) 300 K, (b) 400 K, (c) 500 K, (d) 600 K. The applied voltage is -50 kV. The color scale shows positive ion density in cm^{-3} .



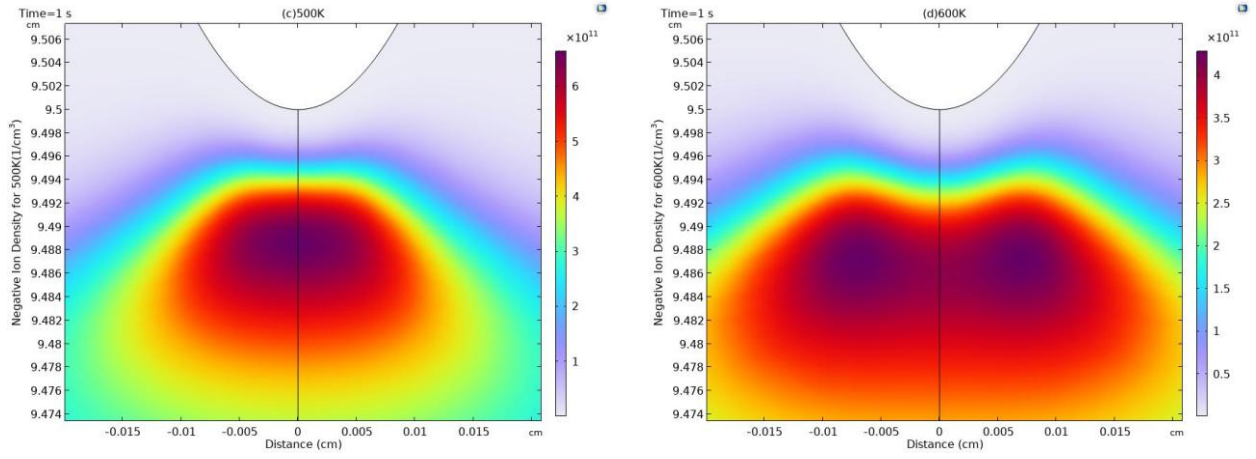


Figure 6. Spatial distribution of negative ion density at $t = 1$ s for different initial neutral gas temperatures: (a) 300 K, (b) 400 K, (c) 500 K, (d) 600 K. The applied voltage is -50 kV. The color scale shows negative ion density in cm^{-3} .

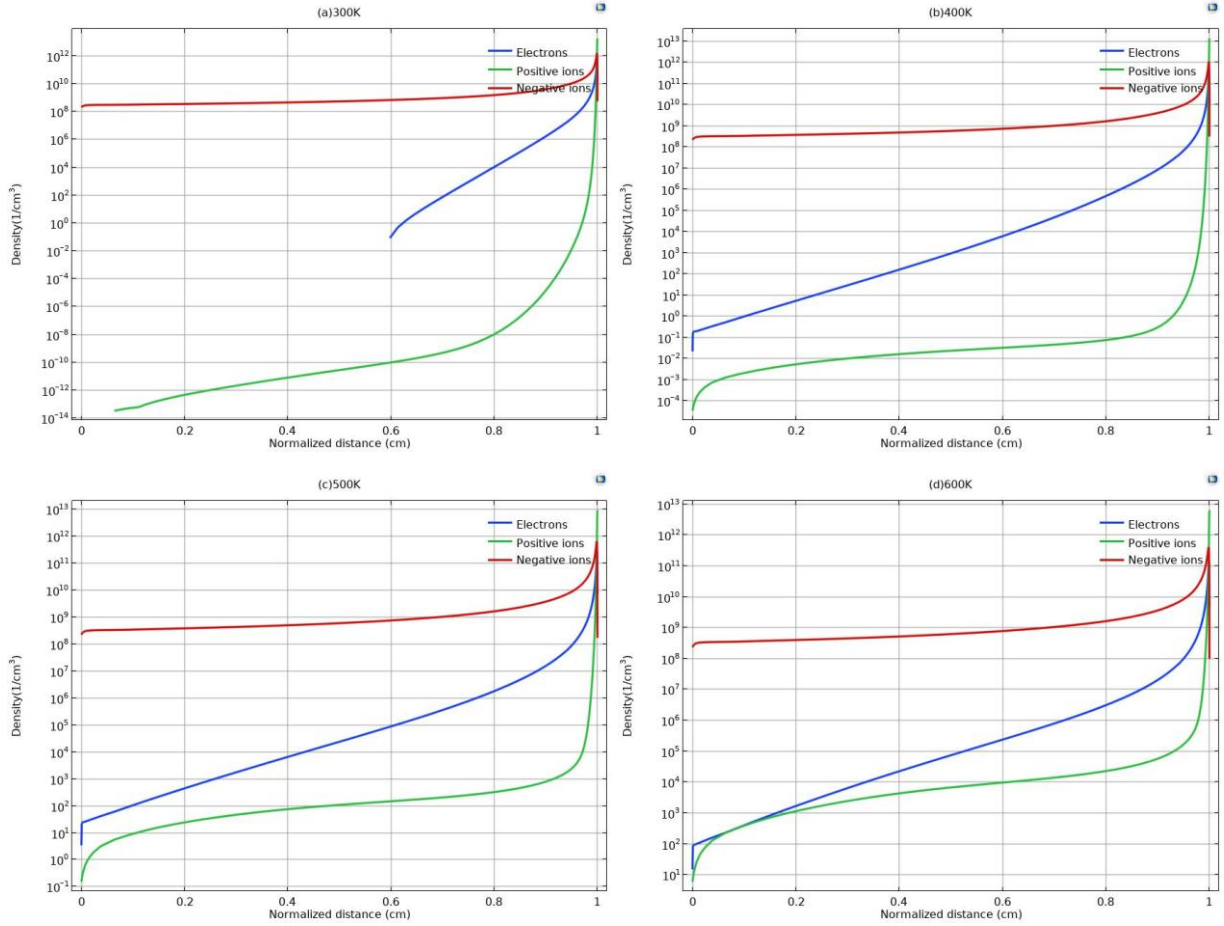


Figure 7. Variation of (a) electron density, (b) positive ion density, and (c) negative ion density along the axis of symmetry as a function of distance from the cathode tip for initial neutral gas temperatures of 300, 400, 500, and 600 K at $t = 1$ s.

To further quantify these observations, Figure 7 compares the axial distributions of (a) electron density, (b) positive-ion density, and (c) negative-ion density for the four initial gas temperatures. The electron and positive-ion densities attain their maximum values within the ionization layer, located approximately 50-100 μm from the cathode tip [8][11]. In contrast, the negative-ion density peaks farther downstream, at approximately 200-500 μm , as electron attachment occurs after electrons drift away from the ionization layer [35]. For all three species, increasing the neutral gas temperature lowers the peak density while leaving the positions of the density maxima almost unchanged [5][8]. These profiles further illustrate that neutral-gas heating primarily suppresses charged-particle production without appreciably altering the spatial organization of the discharge [36]. Our results are in good agreement with previous fluid simulations of atmospheric-pressure negative corona discharges [11] and with Popov's analyses of the influence of neutral density on ionization kinetics [5][8][40].

3.2 Particle fluxes

Figure 8 shows the spatial distribution of the absolute electron flux at $t = 1$ s for initial neutral gas temperatures ranging from 300 to 600 K and the applied voltage of -50 kV. The electron flux is concentrated within the ionization region surrounding the needle tip, where the strong electric-field enhancement accelerates electrons and promotes rapid charge transport. Outside this region, the electron flux decreases rapidly because both the electric field and electron density become significantly lower. This distribution follows directly from the drift-diffusion transport model, in which the electron flux depends on both the local electric field and the electron density ($\Gamma_e = -\mu_e n_e E - D_e \nabla n_e$).

The peak electron flux drops sharply as the neutral gas temperature increases from 300 to 600 K. The maximum electron flux decreases from approximately $1.35 \times 10^{19} \text{ cm}^{-2}\text{s}^{-1}$ at 300 K to about $2.94 \times 10^{18} \text{ cm}^{-2}\text{s}^{-1}$ at 600 K, corresponding to a reduction of nearly 78%. Intermediate temperatures (400 K and 500 K) exhibit the same trend, with progressively lower peak values as the gas temperature increases. The strong sensitivity of electron flux to neutral gas temperature highlights the controlling role of gas heating in charge transport. The reduction in electron flux is closely associated with the decrease in electron density discussed in Section 3.1. Consistent with the mechanism outlined earlier, the lower neutral-gas density under constant-pressure conditions reduces the frequency of electron-neutral collisions and thereby limits electron production. As a result, fewer

charge carriers are available for drift. Since the electric potential distribution changes only marginally with temperature (Figure 4), the observed drop in electron flux is governed mainly by the lower electron density rather than by significant modifications of the electric-field structure. The pronounced sensitivity of the electron flux to neutral-gas temperature underscores the controlling role of gas heating in charge transport. Comparable observations have been reported in numerical simulations of atmospheric-pressure plasmas, where increasing the gas temperature reduced plasma density and electron transport while producing only minor changes in the electric-field distribution [27].

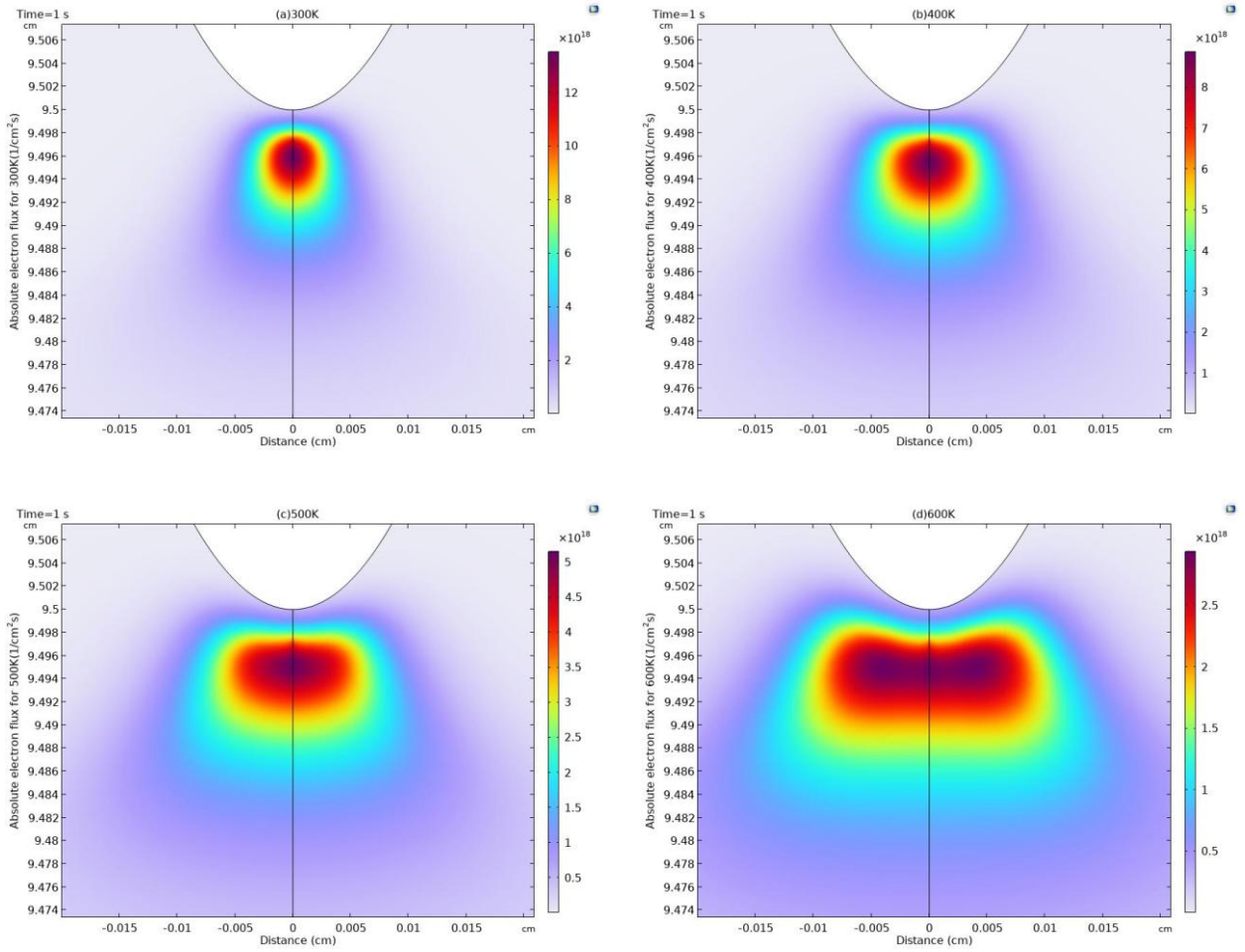


Figure 8: Spatial distribution of the absolute electron flux at $t = 1$ s for initial neutral gas temperatures of (a) 300 K, (b) 400 K, (c) 500 K, and (d) 600 K. The applied voltage is -50 kV, and the inter-electrode gap is 9.5 cm. The electron flux reaches its maximum in the ionization region adjacent to the needle tip and decreases progressively with increasing neutral gas temperature.

Figures 9 and 10 present the spatial distributions of the negative- and positive-ion fluxes, respectively, for initial neutral gas temperatures of 300-600 K at $t = 1$ s. The negative-ion flux (Figure 9) is directed from the cathode toward the grounded electrode and reaches its maximum approximately 200-500 μm from the needle tip, coinciding with the region of maximum negative-ion density shown in Figure 6. The peak of the negative-ion flux is displaced farther from the cathode than that of the electron flux because electron attachment occurs after electrons have traveled beyond the primary ionization region. In this region, ion transport is governed predominantly by drift under the applied electric field ($Z_k \mu_k n_k \mathbf{E}$), while diffusion provides a secondary contribution.

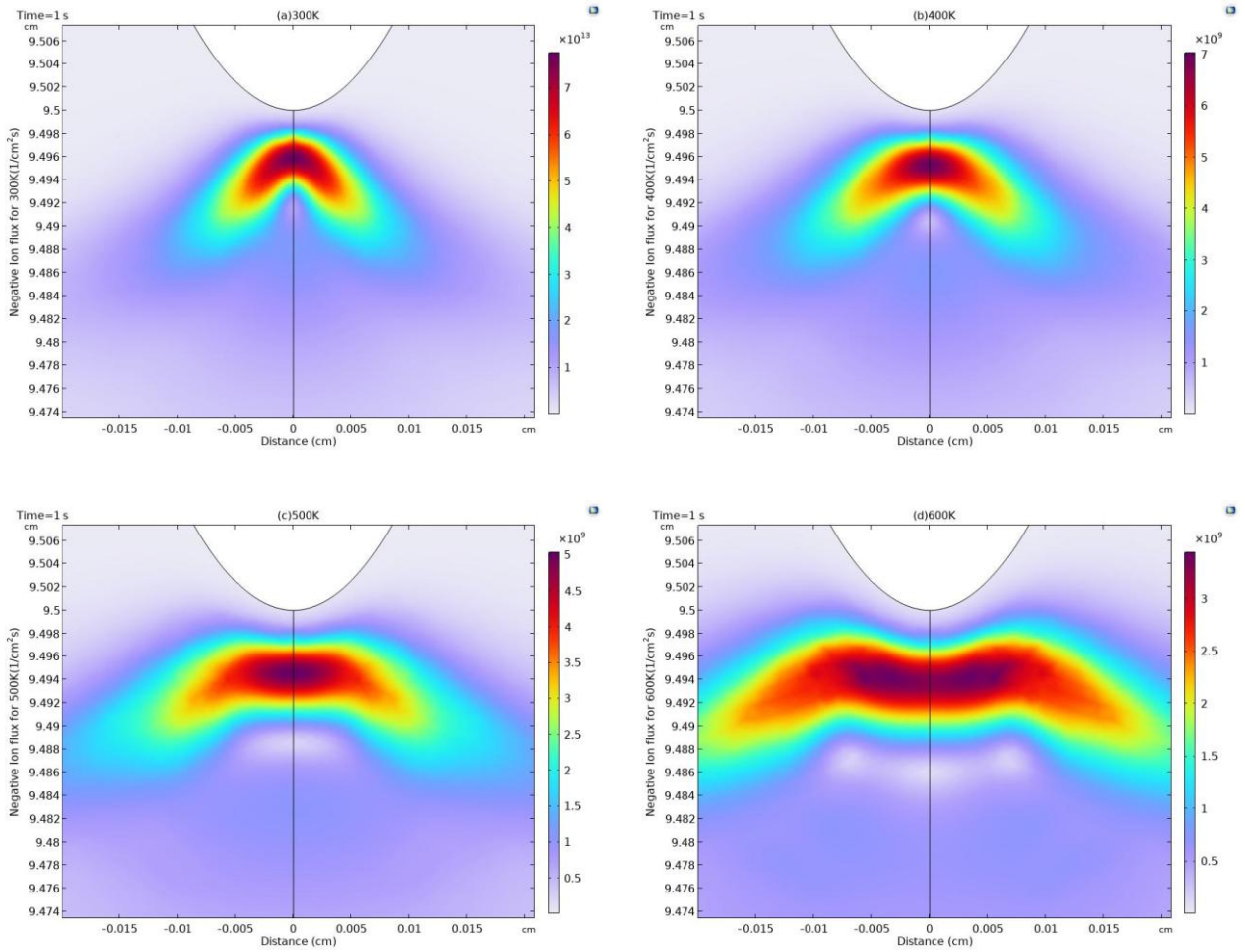


Figure 9: Spatial distribution of the negative-ion flux at $t = 1$ s for initial neutral gas temperatures of (a) 300 K, (b) 400 K, (c) 500 K, and (d) 600 K. The applied voltage is -50 kV, and the inter-electrode gap is 9.5 cm.

The color scale represents the negative-ion flux ($\text{cm}^{-2} \text{s}^{-1}$).

As the neutral gas temperature increases, the magnitude of the negative-ion flux decreases throughout the discharge domain. The peak value drops monotonically from $7.75 \times 10^{13} \text{ cm}^{-2} \text{s}^{-1}$ at 300 K to

$3.29 \times 10^{13} \text{ cm}^{-2}\text{s}^{-1}$ at 600 K, a reduction of approximately 58%. This decline follows directly from the lower electron and neutral-particle densities at elevated temperatures, which reduce the electron-attachment rate and consequently limit negative-ion production. Although the flux magnitude decreases substantially, its spatial distribution changes very little, indicating that neutral gas temperature mainly affects the amount of transported charge rather than the transport pathway. These findings align with the work of Sakiyama et al. [35] and Sohbatzadeh & Soltani [36], who showed that the negative-ion flux in atmospheric-pressure discharges is dependent on the gas density and the electron attachment kinetics. The observed temperature dependence highlights the importance of considering gas heating effects when predicting ion transport in corona devices.

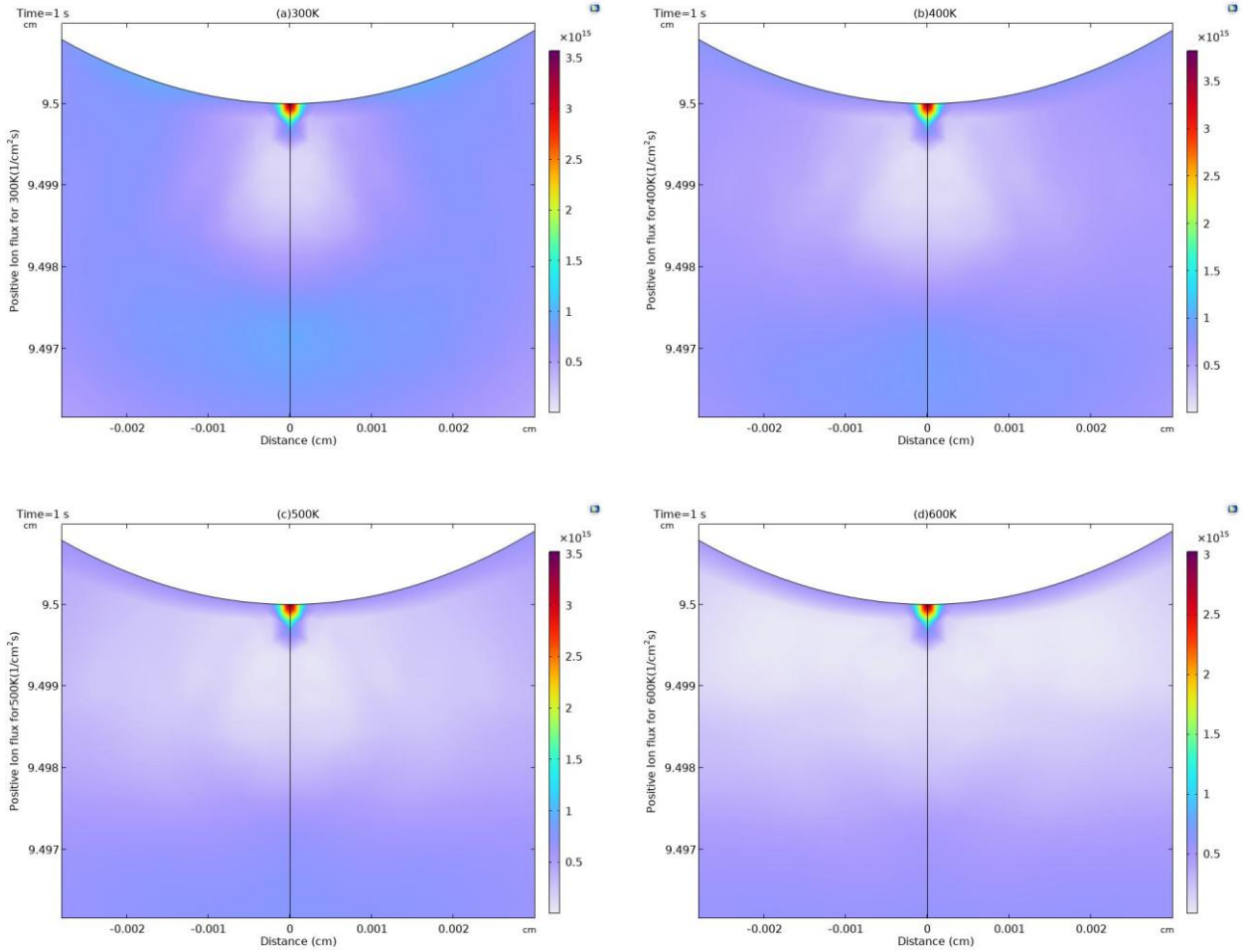


Figure 10: Spatial distribution of the positive ion flux at $t = 1 \text{ s}$ for initial neutral gas temperatures of 300 K, 400 K, 500 K, and 600 K. The ion flux is expressed in units of $\text{cm}^{-2}\text{s}^{-1}$.

The corresponding positive-ion flux is concentrated much closer to the cathode tip, with its maximum located within 50-100 μm of the electrode where electron-impact ionization is strongest [8], [10]. Because positive ions are generated in the ionization region, they are driven predominantly toward the negatively biased cathode by the electric field [11][12]. Raising the neutral gas temperature lowers the positive-ion flux across the discharge domain. The peak value decreases from approximately $3.39 \times 10^{15} \text{ cm}^{-2}\text{s}^{-1}$ at 300 K to $2.84 \times 10^{15} \text{ cm}^{-2}\text{s}^{-1}$ at 600 K, a reduction of about 16%. The decrease reflects the lower positive-ion density (Figure 5) and the reduced ionization rate resulting from the lower neutral-gas density under constant-pressure conditions [5][8]. Since positive ions are responsible for cathode bombardment and the subsequent emission of secondary electrons, a lower positive-ion flux weakens this feedback process and reduces the ability of the discharge to sustain itself [11][12]. This interpretation agrees with previous numerical studies of negative DC corona discharges, which identified positive-ion transport as one of the key mechanisms controlling cathode processes and discharge stability [10], [11].

3.3 Energy transfer

The effect of the initial neutral gas temperature on the spatial distribution of capacitive power deposition is illustrated in Figure 11 for an applied voltage of -50 kV at $t = 1 \text{ s}$. The deposited power is strongly localized within the ionization region surrounding the needle tip, where electrons acquire energy most efficiently from the electric field through the power absorption term $P_a = -e\Gamma_e \cdot \mathbf{E}$ in the electron energy balance equation. Outside this narrow high-field region, the power deposition decreases rapidly as both the electron density and electron flux become significantly smaller. A continuous reduction in power deposition is observed as the neutral gas temperature increases. The maximum power density decreases from approximately $1.47 \times 10^5 \text{ Wcm}^{-3}$ at 300 K to $2.27 \times 10^4 \text{ Wcm}^{-3}$ at 600 K, corresponding to a reduction of nearly 85%. The results obtained at 400 K and 500 K follow the same trend, showing that the transfer of electrical energy from the applied field to the plasma becomes less efficient as the gas temperature increases.

The decrease in deposited power follows naturally from the reductions in electron density and electron flux discussed in Section 3.1. Because capacitive power absorption depends on both the number of electrons and their transport in the high-field region, the smaller electron population at elevated temperatures absorbs less energy from the applied electric field. Consequently, less energy is available to sustain electronic energy excitation and ionization. A comparable temperature dependence is obtained for the total capacitive power deposited to electrons, confirming that the

reduction in energy absorption is a robust feature of the discharge. These results are consistent with previous numerical studies of atmospheric-pressure plasmas, which likewise reported that gas heating reduces power deposition while only weakly affecting the overall electric-field structure [27], [41]. Increasing the neutral-gas temperature, therefore, weakens not only charged-particle production but also the efficiency of energy transfer from the electric field to the plasma.

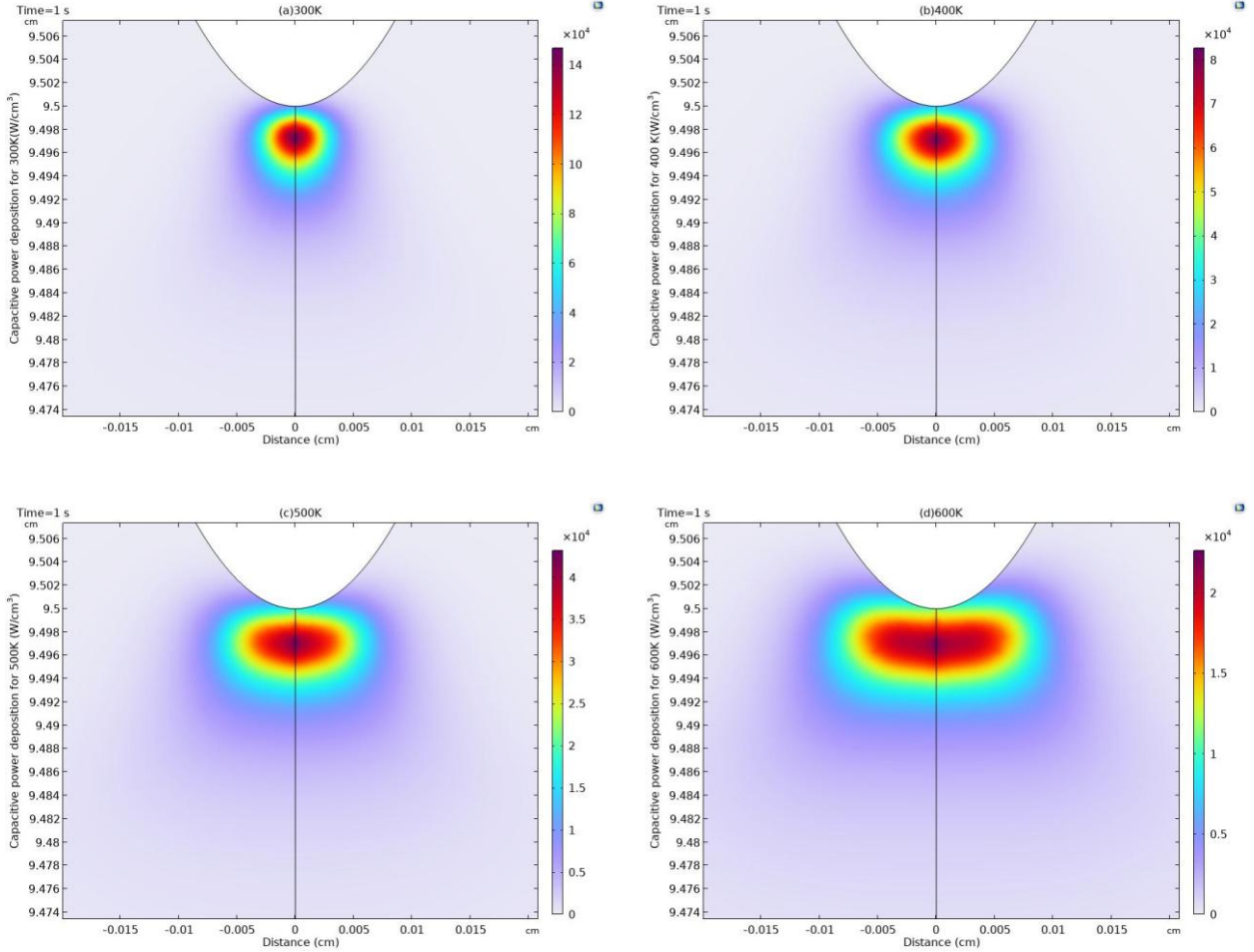
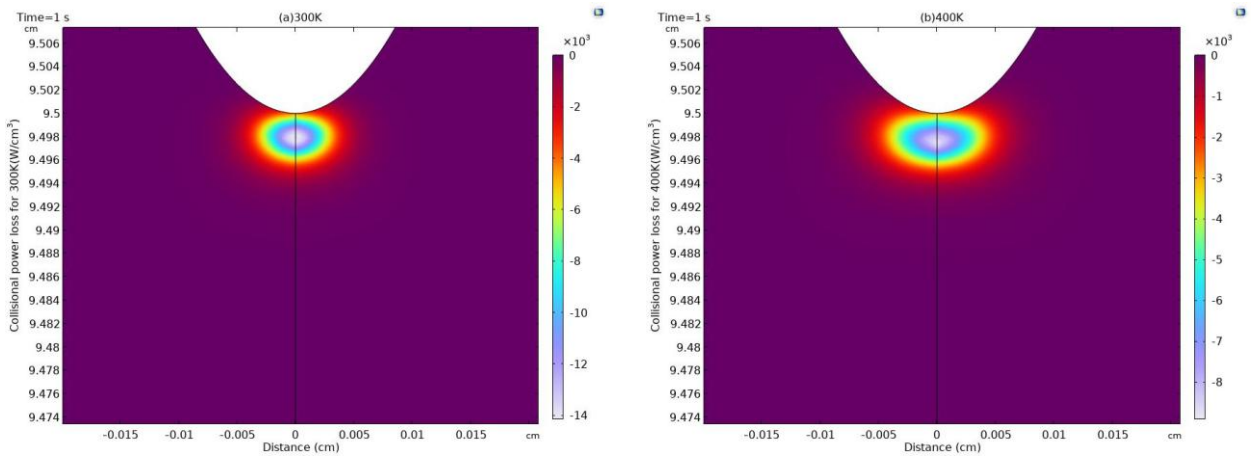


Figure 11: Spatial distribution of capacitive power deposition at $t = 1$ s for initial neutral gas temperatures of (a) 300 K, (b) 400 K, (c) 500 K, and (d) 600 K. The applied voltage is -50 kV and the inter-electrode gap is 9.5 cm. The color scale represents the capacitive power deposition in W/cm^3 .

Unlike the capacitive power deposition discussed in the previous section, which represents the energy transferred from the electric field to electrons, the collisional power loss characterizes the subsequent transfer of electron energy to heavy particles through elastic and inelastic collisions. The corresponding distributions obtained for initial neutral gas temperatures of 300, 400, 500, and 600 K

are presented in Figure 12. The collisional power loss is concentrated within the ionization region surrounding the cathode tip, where energetic electrons undergo frequent collisions with neutral molecules. In the present model, this energy-loss term is expressed by $P_t = P_{ex} + P_i + P_{si} + P_{sc}$, which accounts for the energy transferred from electrons to heavy particles through excitation, ionization, and other electron-neutral collision processes. The negative values, therefore, reflect the continuous transfer of energy from electrons to heavy particles during discharge development. The largest energy dissipation occurs near the cathode tip, whereas its magnitude decreases rapidly outside the ionization region as both the electron density and the electron energy decline.

The magnitude of the collisional power loss decreases steadily as the neutral gas temperature increases. At 300 K, the most negative value reaches approximately $-1.44 \times 10^4 \text{ Wcm}^{-3}$, whereas at 600 K, the minimum is only about $-2.67 \times 10^3 \text{ Wcm}^{-3}$. The curves corresponding to 400 K and 500 K exhibit intermediate losses. The lower collisional power loss originates from the reduced transfer of electron energy to neutral molecules at elevated temperatures. In line with the earlier discussion, the decrease in neutral-gas density reduces the frequency of electron-neutral collisions, thereby limiting excitation and ionization events and lowering the energy dissipated through collisional processes. This interpretation is supported by the concurrent reductions in electron density (Figure 3), electron flux (Figure 8), and capacitive power deposition (Figure 11), which together indicate weaker energy coupling between the applied electric field and the plasma. The resulting decrease in collisional energy transfer also limits the formation of ions and excited species, reinforcing the reduction in plasma density. Similar temperature-dependent changes in electron energy transfer have been reported previously [5], [8], [11].



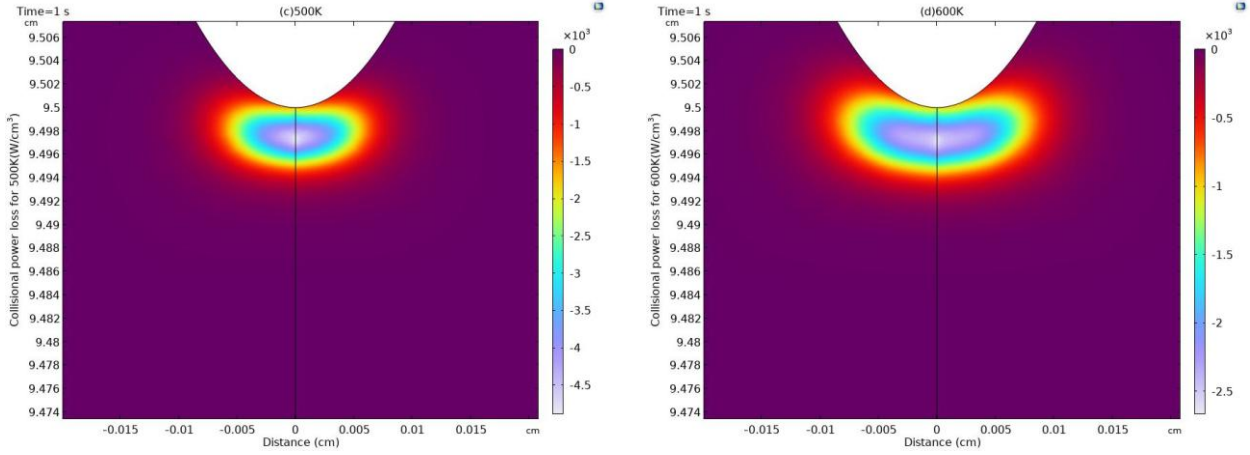


Figure 12: Spatial distribution of collisional power loss at $t = 1$ s for initial neutral gas temperatures of 300 K, 400 K, 500 K, and 600 K. The collisional power loss is expressed in units of Wcm^{-3} .

3.4 Ionization Rate

Whereas the previous sections demonstrated that increasing the neutral-gas temperature weakens charged-particle transport and energy deposition, the ionization behavior requires a clear distinction between the ionization rate coefficient and the actual ionization production rate. As illustrated in Figure 13, the ionization rate decreases with increasing gas temperature. The peak value falls from approximately $6.0 \times 10^{21} cm^{-3}s^{-1}$ at 300 K to $1.11 \times 10^{21} cm^{-3}s^{-1}$ at 600 K, corresponding to a reduction of about 81 %. This reduction occurs even though the reduced electric field E/N increases under constant-pressure conditions.

The ionization rate itself is controlled by the electron energy distribution and therefore rises with E/N [11]. However, the ionization source term also depends on the local electron density and the neutral gas density. Because both densities decrease markedly with increasing temperature (Section 3.1), the total number of ionization events declines despite the higher per-collision rate coefficient [8][27]. In other words, individual electrons become more effective at ionizing, yet the smaller electron population and the lower availability of target molecules more than offset this gain. As a result, the net ionization rate decreases, which is consistent with the observed reductions in plasma density, charged-particle fluxes, and power deposition [5][8]. Neutral-gas heating, therefore, acts through two competing effects: it enhances the ionization capability of individual electrons by increasing E/N , while simultaneously reducing the electron and neutral populations available for ionization. Under

the conditions examined here, the second effect dominates. Similar behavior has been reported in kinetic and fluid models of atmospheric-pressure discharges [5][27].

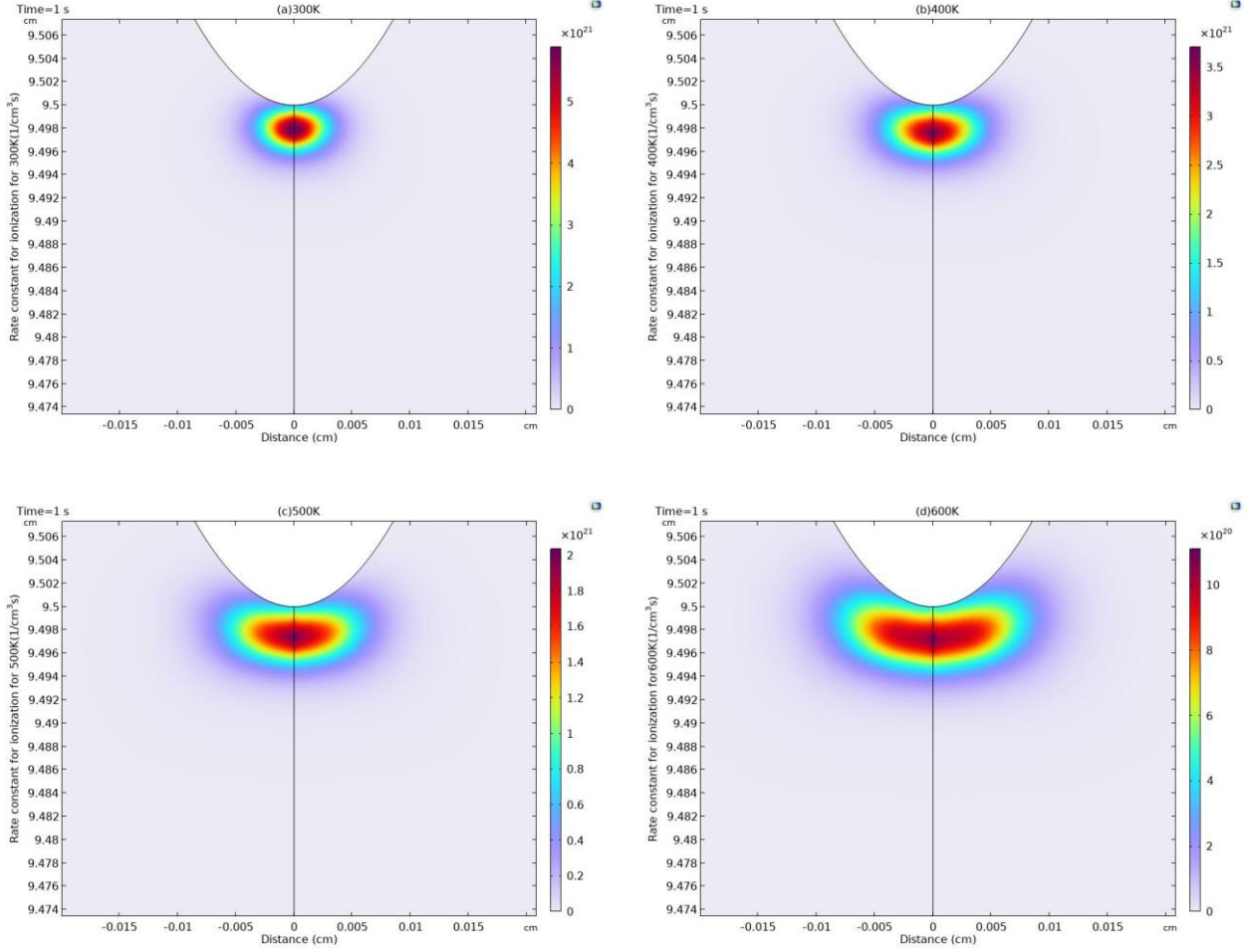


Figure 13: Spatial distribution of the ionization rate at $t = 1$ s for initial neutral gas temperatures of (a) 300 K, (b) 400 K, (c) 500 K, and (d) 600 K. The ionization rate is expressed in units of $\text{cm}^{-3}\text{s}^{-1}$.

3.5 Space-charge and electric field

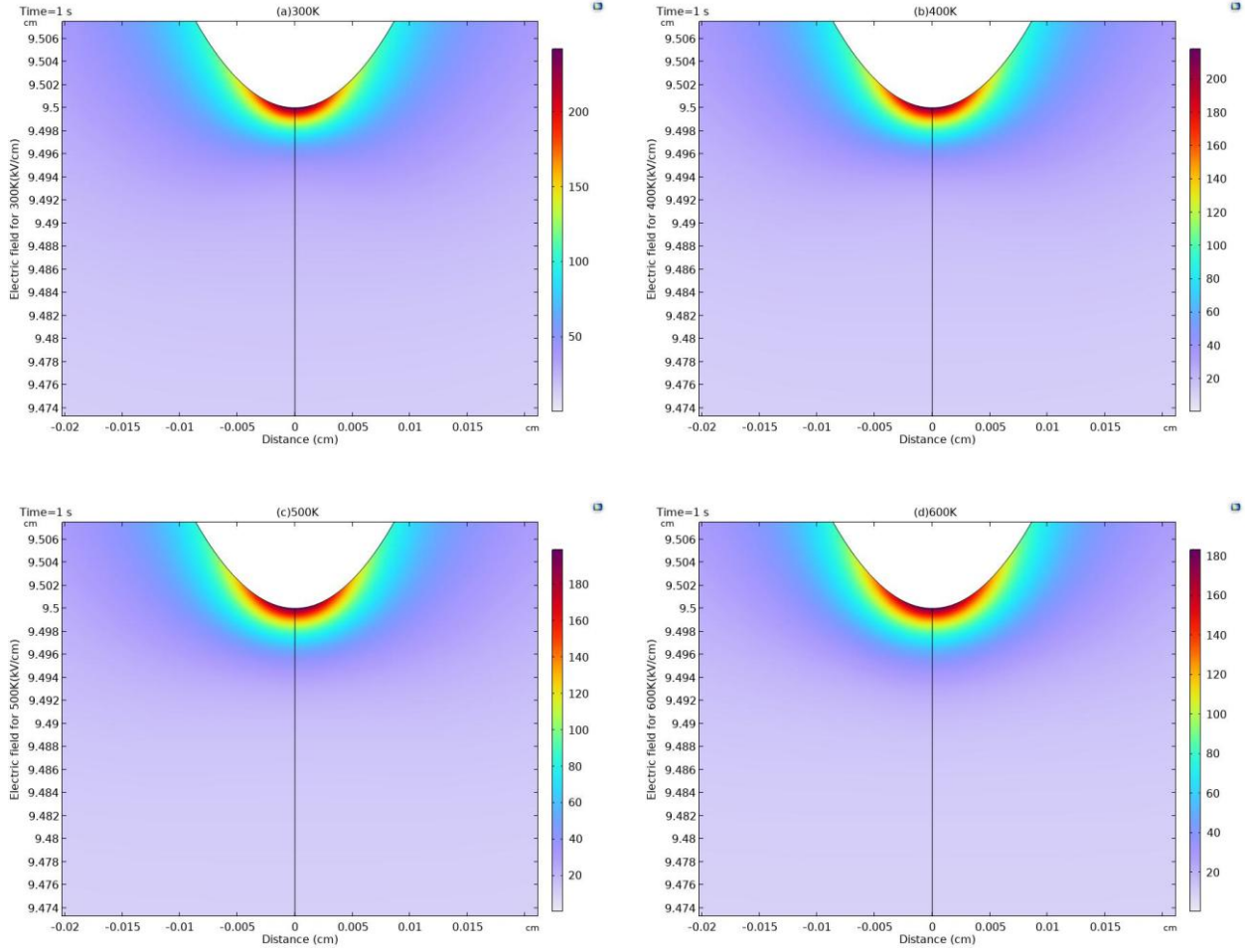


Figure 14: Spatial distribution of the electric field magnitude at $t = 1$ s along the symmetry axis for initial neutral gas temperatures of 300 K, 400 K, 500 K, and 600 K. The electric field is expressed in units of kV cm^{-1} .

The influence of neutral-gas temperature on the electric-field distribution is presented in Figure 14. In all cases, the electric field is highly localized near the cathode tip because of the strong geometric field enhancement associated with the needle electrode. Away from the cathode, the field decreases rapidly, and the applied voltage together with the electrode geometry becomes the primary factor governing the potential distribution. Although increasing the neutral-gas temperature produces substantial reductions in the electron and ion densities (Section 3.1), its effect on the electric field distribution is comparatively weaker [5]. The peak electric field decreases from 232 kV cm^{-1} at 300 K to about 176 kV cm^{-1} at 600 K, corresponding to a reduction of nearly 24%. Such moderate variation indicates that space charge primarily modifies the electric field within the ionization region, whereas the overall spatial profile of the electric field remains largely determined by the applied

voltage and electrode geometry [10][27]. This behavior is consistent with previous numerical observations of space-charge-driven flow patterns in negative point-plane coronas [9].

The weaker electric field near the cathode reflects the lower space-charge density at elevated temperatures. As the densities of electrons and ions decrease, the accumulated charge responsible for local field enhancement also diminishes. Even so, the electric-field profile retains nearly the same shape throughout the investigated temperature range, showing that gas heating alters the field magnitude rather than its spatial characteristics [8]. The modest reduction in the absolute electric field is consistent with the decrease in the net ionization rate [10], as discussed in Section 3.4. Under constant-pressure conditions, the neutral-gas density decreases more rapidly than the electric-field magnitude, leading to an increase in the reduced electric field E/N . Although the higher E/N increases the ionization rate, the simultaneous drop in electron and neutral densities causes the net ionization rate to decline. This interpretation is fully consistent with the local-field approximation and agrees with previous kinetic and fluid simulations of atmospheric-pressure air discharges [5][27], [41].

3.6 Quantitative summary

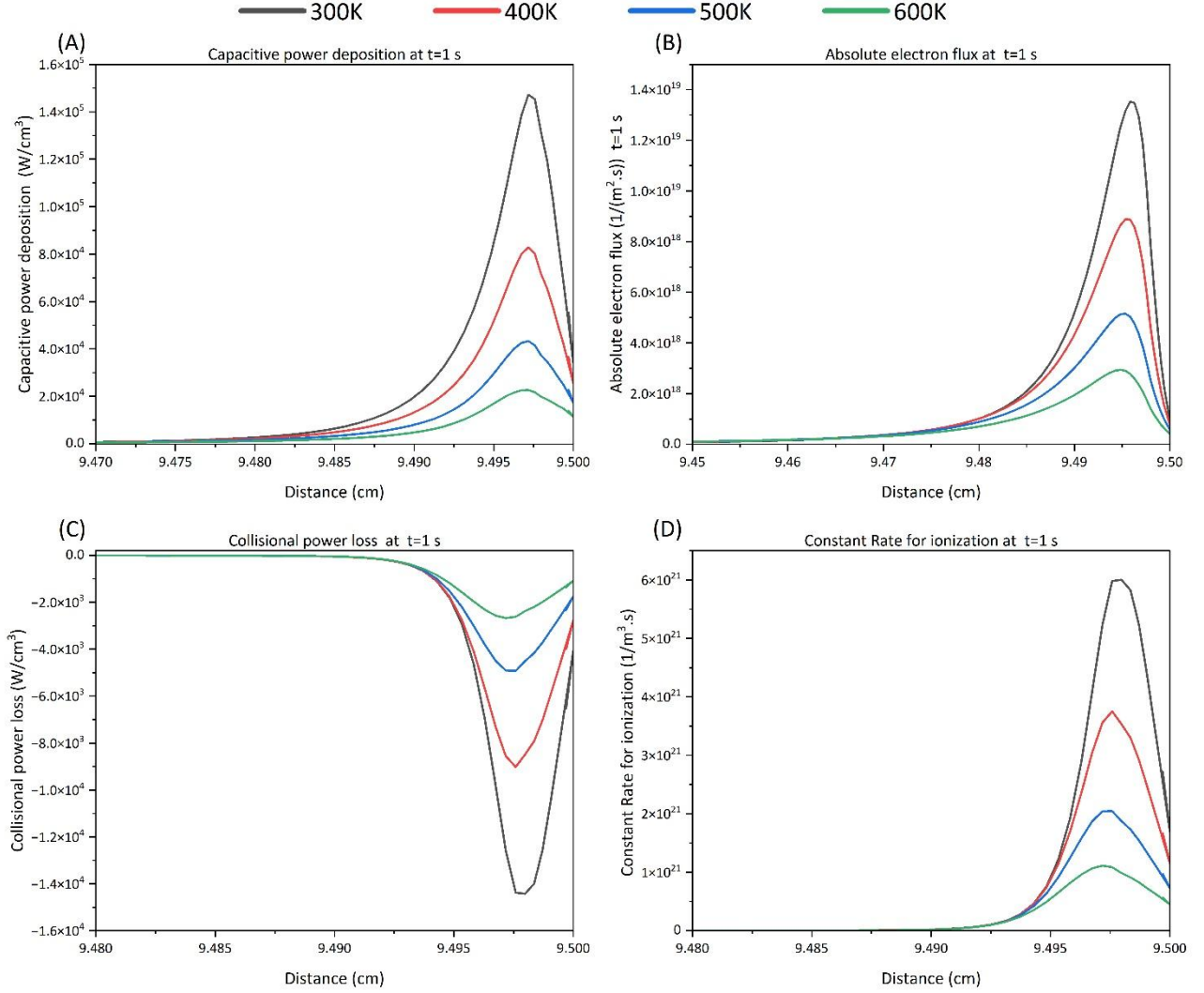


Figure 15: Effect of neutral gas temperature on the spatial distributions of (A) capacitive power deposition, (B) absolute electron flux, (C) collisional power loss, and (D) electron-impact ionization rate at $t = 1$ s in a negative DC point-to-plane corona discharge. Results are shown for initial neutral gas temperatures of 300, 400, 500, and 600 K, while the applied voltage (-50 kV) and electrode gap (9.5 cm) remain unchanged.

Figure 15 provides an integrated comparison of the principal transport and energy-transfer parameters governing the negative DC corona discharge: (A) capacitive power deposition, (B) absolute electron flux, (C) collisional power loss, and (D) the electron-impact ionization rate. Although these quantities respond differently to temperature, together they offer a coherent picture of the discharge behavior. The electron flux, capacitive power deposition, and collisional power loss all decrease with rising neutral-gas temperature. These reductions originate from the lower neutral density under constant-pressure conditions, which limits electron-impact ionization and reduces the number of electrons available for transport and energy exchange. Consequently, both the energy delivered to the plasma

and the energy transferred to heavy particles decline, confirming that gas heating weakens charge transport and energy coupling within the discharge. In contrast, the ionization rate increases with temperature because the reduced electric field E/N increases. This rise reflects a higher ionization probability per collision rather than an increase in the total ionization rate. Because the ionization source also depends on local electron and neutral densities, the marked drop in these populations outweighs the higher rate coefficient, leading to a net decrease in ionization. Taken together, the results in Figure 15 show that neutral-gas heating acts through two competing effects: it reduces the availability of charged particles and weakens energy transfer, while the simultaneous increase in E/N enhances the ionization capability of individual electrons. Under the present conditions, the first effect dominates, resulting in lower plasma density and weaker discharge development.

Overall, neutral-gas temperature influences the kinetics of this attachment-dominated negative corona primarily through its effect on neutral density and collision frequencies, rather than through direct modification of the electric-field structure. The spatial organization of the discharge remains largely unchanged, while its intensity decreases. The weak sensitivity of the electric potential and electron temperature is consistent with the local-field approximation, in which electron properties are governed by E/N . These findings align with previous kinetic analyses by Popov [5][8][11] and with fluid simulations of high-pressure plasmas [26][40], which likewise identify neutral-density modulation as the dominant temperature-dependent mechanism. Similar temperature-driven changes in corona current and the increasing role of free electrons at high ambient temperatures have also been reported experimentally [25].

4. Conclusions

A two-dimensional axisymmetric time-dependent fluid model has been developed in COMSOL Multiphysics to investigate the effect of neutral-gas temperature on a negative DC point-to-plane corona discharge in atmospheric-pressure dry air. With the applied voltage and electrode gap held fixed at -50 kV and 9.5 cm, the initial gas temperature varied from 300 K to 600 K. Raising the neutral gas temperature produced a notable decrease in the peak densities of electrons ($\approx 80\%$), positive ions ($\approx 66\%$), and negative ions ($\approx 75\%$). The corresponding electron, positive-ion, and negative-ion fluxes, as well as the capacitive power deposition and collisional power loss, decrease by comparable factors. These reductions originate from the decrease in neutral density under constant-pressure conditions, which lowers the electron-neutral collision frequency and thereby suppresses both

ionization and attachment. In contrast, the electric-potential distribution and the electron temperature show only minor sensitivity to the temperature change; the peak electron temperature rises by at most $\approx 10\%$, and the overall shape of the potential profile is essentially unchanged. This behavior is in agreement with the local-field approximation, in which electron energy is governed by the reduced electric field E/N . Although the ionization rate itself increases with temperature because of the rise in E/N , the net ionization rate still declines. The simultaneous drop in electron and neutral densities more than compensates for the higher rate coefficient, resulting in lower plasma density, weaker charged-particle fluxes, and reduced power deposition. Consequently, increasing fixed neutral gas temperature primarily affects the discharge intensity through the associated reduction in neutral-particle density, while the fundamental spatial structure of the ionization and drift regions remains largely preserved. The present results underscore the necessity of time-dependent modeling if the transient development of space charge and ionization fronts is to be captured. They also provide practical guidance for the thermal design and operation of atmospheric-pressure corona devices, such as electrostatic precipitators, ozone generators, and plasma-assisted combustion systems, that operate under elevated ambient temperatures.

Acknowledgment

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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