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RESEARCH ARTICLE

Analysis of Temperature Sensitivity Parameters in Hydrodynamic Model of Streamer

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ABSTRACT Temperature is an important environmental factor affecting streamer discharge. However, the mechanism and regularity of the influence are still unclear. This paper analyzes the mechanism of how the parameters in the hydrodynamic model are affected by temperature and the finite element method is used to solve three particle continuity equations along with Poisson's equation simultaneously. The results show that the increase in temperature inhibits the ionization and the attachment process, and the reduction rate of the ionization coefficient is 40 times the attachment coefficient numerically, which means that the streamer is easier to initiate at low temperatures. The increase in temperature accelerates the diffusion and drift of electrons. This effect increases the average velocity of the streamer, and the average velocity increases by about 4.89m/(s·K) with temperature, which means that the fast-moving charged particles at high temperature may affect the discharge signals. The essence of the influence of temperature on the physical quntities in the streamer discharge is its influence on ionization, attachment, diffusion, and drift effects. The results in this paper can comprehensively consider the effects and obtain the effect mechanism of temperature on the micro-process of the streamer, contributing to the research on the insulation design of power equipment and the influence of temperature on the discharge signals.

INDEX TERMS Streamer, influence of temperature, parameters, hydrodynamic model, simulation.

I. INTRODUCTION

The streamer discharge is one of the main forms of gas discharge in the field of high voltage, which is also a key issue in the study of gap discharge. The streamer is closely related to the insulation problems of power equipment of various voltage levels, with complex nonlinear dynamic processes included. For the safe and stable operation of power system, clarifying the mechanism of streamer discharge is of great importance [1], [2].

Currently, the numerical simulation is a common method for the theoretical research of the streamer discharge. The simulation results are almost consistent with the experiment by setting reasonable discharge models and parameters. The existing streamer discharge simulation models are mainly divided into two types, the particle model and the hydrodynamic model. Most particle simulations of streamers are solved with the PIC/MCC (particle-in-cell/Monte Carlo Collision) model. The PIC/MCC model describes complex particle changes accurately through the collision reaction equations between particles, but it requires much calculation cost [3], [4]. The hydrodynamic model is computationally much more efficient because of the approximation of the continuous electron densities. By using better modeling techniques and effective coupling of photoionization terms in the hydrodynamic model, the calculation results can be more accurate. Most streamer discharge simulations are based on the hydrodynamic model [5], [6], [7], [8]. In addition, Ebert proposed a hybrid model simulation method that integrates the particle model and hydrodynamic model. According to the value of the electric field in the calculation, the models are applied in different calculation area, considering both the efficiency and accuracy of the calculation [9], [10].

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The key to the streamer simulation is to solve the partial differential equations. In the existing related research, Morrow [11] used the finite difference (FD) and the flux-corrected transport (FCT) methods to solve the coupling of the particle transport equations and Poisson's equation. Hussain et al. [12] used the regular perturbation method to transform the partial differential equations into non-linear ordinary differential equations for the solution. Satari et al. [13] combined the finite element method (FEM) and FCT to solve the two-dimensional axisymmetric single-species model of positive corona discharge.

With the popularization of high-voltage equipment and the development of UHV construction, environmental factors have become a non-negligible part that affects the insulation performance of equipment and interferes with the judgment of insulation status. Temperature is an important environmental factor during the operation of power equipment. The load current, sunlight, and environmental temperature will change the temperature of the power equipment, which affects the insulation and condition assessment of the equipment. However, the mechanism and regularity of temperature affecting discharge is still unclear. There is also a lack of methods about how to change temperature in simulations. Therefore, it is necessary to explore the microscopic mechanism of temperature influence on streamer discharge.

This paper studies the effect of temperature on streamer discharge from the perspective of microscopic simulation and parameter control. Given the calculation efficiency and the model accuracy comprehensively, this paper uses the hydrodynamics model to simulate the streamer discharge. A method that simulates the change of temperature by modifying the temperature sensitivity parameters in the hydrodynamic model is innovatively proposed. By studying the temperature-sensitive parameters, the exact results and microscopic mechanism of the influence of temperature on the streamer discharge process can be obtained. Furthermore, at the application level, it can be used as a basis to optimize the insulation design of power equipment in cold and high-temperature regions and improve the accuracy of the evaluation of the power equipment insulation status based on discharge signals.

II. SIMULATION MODEL

A. GOVERNING EQUATIONS

The governing equations in the hydrodynamic model include particle continuity equations (Equations 1-3) and electric field Poisson equation (Equation 4) [17].

$$\partial N_\mathrm{e}/\partial t + \nabla\cdot(-N_\mathrm{e}\mu_\mathrm{e}\boldsymbol{E} - D_\mathrm{e}\nabla N_\mathrm{e}) = S_\mathrm{ph} + \alpha N_\mathrm{e}\left|\mu_\mathrm{e}\boldsymbol{E}\right| - \eta N_\mathrm{e}\left|\mu_\mathrm{e}\boldsymbol{E}\right| \tag{1}$$

$$\partial N_\mathrm{p}/\partial t + \nabla\cdot(N_\mathrm{p}\mu_\mathrm{p}\boldsymbol{E} - D_\mathrm{p}\nabla N_\mathrm{p}) = S_\mathrm{ph} + \alpha N_\mathrm{e}\left|\mu_\mathrm{e}\boldsymbol{E}\right| \tag{2}$$

$$\partial N_\mathrm{n}/\partial t + \nabla\cdot(-N_\mathrm{n}\mu_n\boldsymbol{E} - D_\mathrm{n}\nabla N_\mathrm{n}) = \eta N_\mathrm{e}\left|\mu_\mathrm{e}\boldsymbol{E}\right| \tag{3}$$

$$-\nabla\cdot(\varepsilon_0\varepsilon_\mathrm{r}\boldsymbol{E}) = -q(N_\mathrm{p} - N_\mathrm{e} - N_\mathrm{n}) \tag{4}$$

where the subscript e, p, and n represent variables about electron, positive-ion, and negative-ion respectively; t is the time; N the numerical density; μ the mobility in $\mathrm{m}^2/(\mathrm{V}\cdot\mathrm{s})$; E the vector representation of electric field; $\mu\boldsymbol{E}$ represents drift velocity of particles. The symbols α, η, and D denote the ionization, attachment, and electron diffusion coefficients respectively. S_ph denotes the source term due to photoionization.

Equations 1-3 are a set of convection-dominated time-varying equations with source terms on the right side of the equal sign, describing the transport processes of electrons, positive ions, and negative ions. On the left side of the equations, the transport processes of the three particles are described by partial differential equations with the same form. The reaction source terms on the right side of the equations represent the types of reactions related to the generation and consumption of this particle. In gas discharge, the reactions that affect the density of charged particles mainly include ionization, attachment, recombination, and photoionization. The recombination includes the reaction between positive ions and both the negative ions and the electrons. Compared with other reactions, the rates of the recombination reactions are very small, for which reason the recombination is ignored in the simulation of this paper. As can be seen in Equations 1-3, the effects of ionization, attachment, and photoionization on particle concentration are considered. Equation 4 calculates the effect of space charge on the electric field distribution, coupled to the particle continuity equations in the simulation.

Local field approximation assumption is an important condition for the establishment of particle continuity equations. This assumption holds that the coefficient of the gas property is a function only related to E/N, where E is the electric field and N the number density of the neutral particles, which means that the electron distribution function and the neutral plasma are in a local equilibrium state. This assumption is valid as long as the relaxation time to reach a steady-state electron energy distribution function is shorter than the characteristic time of discharge development. Vitello et al. [18] calculated the relaxation time of the electron energy distribution by solving the Boltzmann equation and confirmed the feasibility of the local field approximation method.

B. GEOMETRIC MODEL AND BOUNDARY CONDITIONS

This paper uses a two-dimensional axisymmetric needle-plate discharge model for simulation. The needle electrode potential is set to 9kV to generate streamer across the poles. The plate electrode is grounded, and the distance between the poles is 3mm. The tip of the needle electrode is elliptical and the initial distribution of charged particles satisfies the Gaussian distribution [19], which has the distribution equation,

$$N_\mathrm{p} = N_\mathrm{e} = N_0 \times \exp(-(x/s_0)^2 - ((y-y_0)/s_0)^2) \tag{5}$$

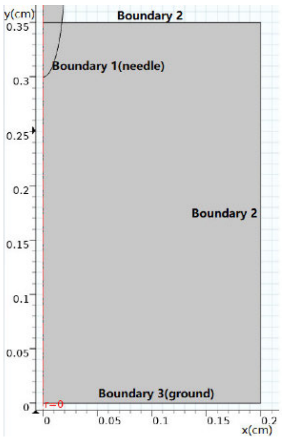

FIGURE 1. Geometric model.

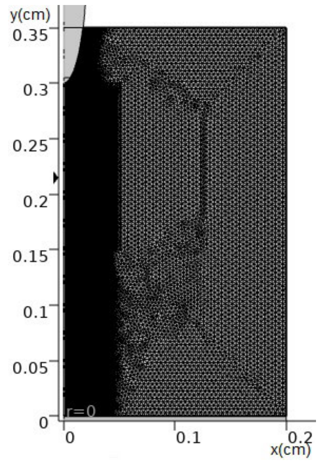

FIGURE 2. The meshing of the model.

where N_p and N_e represent the positive ion and the electron concentration respectively. $N_0 = 10^{20}/\mathrm{m}^3$, $s_0 = 2.5\times10^{-5}\mathrm{m}$, $y_0 = 0.3\mathrm{cm}$. Selecting the Gaussian distribution for the initial distribution of electrons can accelerate the development of the initial stage of the streamer, not affecting the essential process of the discharge. The initial value of negative ion concentration is 0. The geometric model in the simulation is shown in Figure 1.

On the needle, the negative ion concentration of the plate is zero, and the electrons and positive ions satisfies $-\vec{n}\cdot D_i\nabla n_i = 0$. On boundary 2, three types of particles are set as open boundaries [20], which means:

$$\begin{cases} -\vec{n}\cdot D_{\mathrm{i}}\nabla n_{\mathrm{i}} = 0; \quad \vec{n}\cdot(-\mu_{\mathrm{i}}\boldsymbol{E}) \geq 0 \\ n_{\mathrm{i}} = 0; \quad \vec{n}\cdot(\mu_{\mathrm{i}}\boldsymbol{E}) < 0 \end{cases} \tag{6}$$

C. NUMERICAL METHOD IN THE SIMULATION

The finite element method can eliminate artificial oscillations in the calculation results and deal with three-dimensional problems better. Therefore, the finite element simulation software COMSOL Multiphysics 6.0 is used in this paper for the streamer simulation. It can couple multi-physics and realize more convenient solutions to multi-dimensional complex geometric problems. Furthermore, powerful functions in meshing and post-processing of results are provided.

The FEM is the key theory for solving the partial differential equations (1)-(3), and the successive over-relaxation iterative method is applied to solve the Poisson equation. Linear and quadratic discretization are performed on the particle continuity equations and Poisson equation respectively, and the backward differentiation method is used on the temporal part when solving. The Galerkin discrete finite element method is the core of the solver, but when the value of the convection term is dominant or the grid resolution is insufficient, the solution of the equation is prone to instability.

Therefore, although the FEM has been widely used in the simulation of streamer discharge, some strategies are needed to achieve convergence, efficiency, and accuracy of the calculation. This paper adopts mesh refinement and the artificial diffusion method to avoid the divergence of the calculation results while maintaining computational efficiency and accuracy.

The gradient of the electric field and the charged particle density are both large in the area near the tip electrode and the streamer's head, which may lead to the divergence of the numerical calculation. Therefore, the meshes of these parts need to be refined. In the simulation model, a non-uniform triangular mesh is applied to the computational domain, and the mesh size reaches 1 μm near the tip electrode and about 5 μm on the streamer development path. In other parts of the computational domain, the maximum mesh size reaches 1 mm to reduce the complexity. The total model degrees of freedom is 1.28 million. The meshing of the model is shown in Figure 2.

In this paper, the artificial diffusion method based on streamline diffusion (SD) is used to improve the stability of the calculation. This diffusion method is a kind of non-isotropic diffusion, which only increases the diffusion in the direction of the electric field. As the approximate solution of the convective-diffusion problem approaches the exact solution, the added stability term gradually approaches zero. As a result, this method does not interfere much with the solution to the original problem. Researches show that as the solution error decreases, the stability term gradually disappears [21]. Compared with the commonly used artificial isotropic diffusion method, the calculation error introduced by SD is smaller. Another anisotropic diffusion method is crosswind diffusion (CWD), which is more time-consuming compared with SD. CWD is more suitable for higher electric fields.

About the verification part of the calculation method in this paper, see the first section of Chapter V.

III. ANALYSIS OF THE INFLUENCE OF TEMPERATURE ON THE PARAMETERS

A. OVERVIEW OF THE INFLUENCE

This paper simulates the temperature change based on parameter control. The parameters with a greater influence on the discharge that need to be controlled in the equations are the ionization coefficient α, the attachment coefficient η, the electron mobility μ_e, and the electron diffusion coefficient D_e. Changes in these parameters lead to changes in the discharge micro-process.

The ionization coefficient α represents the number of electrons generated by collisions per unit length along the direction of the electric field during the discharge. It reflects the intensity of the ionization. The increase in both the free path of the electron and the number of collisions increase the ionization coefficient. In a constant pressure environment, when the temperature increases, the distance between particles increases, which extend the free path of the electron but reduce the number of collisions. Therefore, the specific influence of temperature on its value needs to be determined by specific expressions.

The attachment coefficient η reflects the strength of the process that free electrons absorbed by the electronegative gas, which inhibits the discharge. When the electrons move at a slower speed, they stay in the vicinity of gas molecules for longer, leading to a greater chance of attachment. Therefore, the attachment coefficient should be inversely proportional to the speed of electron movement.

The mobility and diffusion coefficient of electrons are the key parameters in the transport equations. The two coefficients of electrons have much more influence on the discharge than positive and negative ions, and they are also the key parameters discussed in this paper. Mobility represents the velocity coefficient of charged particles moving under the action of the electric field. When the temperature rises, the free path of electron movement increases and the number of charged particle collisions decreases. The increase in the free path magnifies the energy accumulated of the electrons in the electric field. The fewer collisions mean that the electron speed decays fewer times. Therefore, the temperature increases the electron mobility theoretically. The diffusion coefficient characterizes the degree to which particles are diffused by chaotic thermal motion due to the concentration gradient. The temperature rise intensifies the thermal motion, thereby enhancing the diffusion effect.

B. DETERMINATION OF THE PARAMETER VALUES

In order to introduce the temperature in the parameter values, this paper mainly uses the conclusion in the local field approximation assumption, that is, each parameter is considered to be a function of E/N. About the neutral gas number density N, it can be derived from the Ideal Gas Law that the relationship between the number density N of neutral particles and the pressure and temperature is:

$$p = NkT \tag{7}$$

where k is the Boltzmann constant. Therefore, under the condition of constant pressure, each parameter is actually a function related to temperature, and the synchronous control of the parameters can reflect the change in the temperature in the simulation model. The parameters in the current research are usually the fitted values of the experimental results. This paper mainly refers to the parameters of Morrow [22], a recognized scholar in the field. The formula (7) is used to replace the parameter N with a value related to pressure and temperature, and then the pressure is substituted into a constant value of atmospheric pressure to obtain the temperature-related value of each parameter in the simulation. The specific parameters used in this paper are shown in Table 1.

TABLE 1. Parameter values of the simulation model.

Parameter	Value	Unit
α	$\begin{cases} \frac{4.858\times10^5}{T}\exp\left(-4.105\times10^7/(\lvert E\rvert\times T)\right), \lvert E\rvert\times T\le 1.101\times10^7 \\ \frac{1.468\times10^6}{T}\exp\left(-5.32\times10^7/(\lvert E\rvert\times T)\right), \lvert E\rvert\times T> 1.101\times10^7 \end{cases}$	1/cm
η	$\begin{cases} 8.889\times10^{-5}\lvert E\rvert+1884.18/T, \lvert E\rvert\times T>7.707\times10^6 \\ 6.089\times10^{-4}\lvert E\rvert+2123.46/T, \lvert E\rvert\times T\le 7.707\times10^6 \end{cases}$	1/cm
μ_e	$\begin{cases} -(1.008T+7.1\times10^6/\lvert E\rvert), \lvert E\rvert\times T>1.469\times10^7 \\ -(1.403T+1.3\times10^6/\lvert E\rvert), 7.34\times10^5\le\lvert E\rvert\times T\le 1.469\times10^7 \\ -(0.9942T+1.63\times10^6/\lvert E\rvert), 1.908\times10^5\le\lvert E\rvert\times T\le 7.34\times10^5 \\ -(9.63T+3.38\times10^4/\lvert E\rvert), \lvert E\rvert\times T\le 1.908\times10^5 \end{cases}$	$cm^2/(Vs)$
μ_p	2.43	$cm^2/(Vs)$
μ_n	-2.70	$cm^2/(Vs)$
D_e	$5.027\times10^{-4}\times(\lvert E\rvert\cdot T)^{0.54069}\times\lvert u_e\rvert$	cm^2/s
D_p	0.046	cm^2/s
D_n	0.11	cm^2/s
β_{ep}	2×10^{-7}	cm^3/s
β_{np}	2×10^{-7}	cm^3/s

C. THE INFLUENCE OF TEMPERATURE ON THE PARAMETERS

According to the relationship between various parameters and temperature shown in Table 1, in the temperature range of 273K-353K, the changes in ionization coefficient, attachment coefficient, electron mobility, and electron diffusion coefficient with temperature are shown in Figure 3. The temperature range is chosen because most discharges in electric equipment occur in this range. Since some parameter values are related to the electric field strength, the field strength needs to be taken as a fixed value when analyzing the influence of temperature on the parameter values. The magnitude of the electric field strength of the streamer head is about 10^7V/m [17]. Figure 3 shows the change of four key parameters with temperature when the electric field strength is 2×10^7V/m, which is the typical value of electric field strength in the streamer head. For other electric field values, the parameters also show the same change law with temperature.

Figure 3 can approximately show the variation of various parameters with temperature in the streamer head. The particles react most violently in the streamer head, where the changes in parameters have a greater influence on the discharge. It can be seen in Figure 3a that the ionization

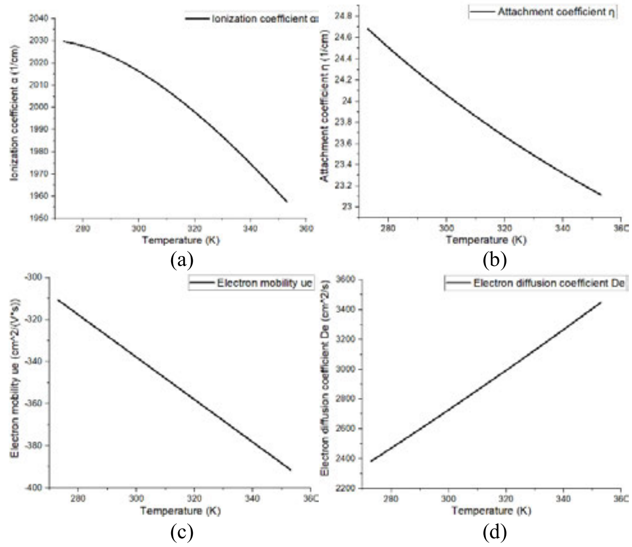

FIGURE 3. **Changes of key transport parameters with temperature ($E=2\times10^7$V/m). (a) ionization coefficient α; (b) attachment coefficient η; (c) electron mobility μe; (d) electron diffusion coefficient De.**

coefficient shows a downward trend with the increase in temperature, which means that the reduction of the number of collisions has a greater impact on the ionization process than the increase in the free path of electron motion. The changes in the attachment coefficient, mobility, and diffusion coefficient of electrons are consistent with the results analyzed in Section III-A. The increase in temperature weakens the attachment effect and makes the diffusion and drifting of electrons uniformly accelerate.

IV. SIMULATION RESULTS

This paper simulates the discharge process from the development of the primary streamer to the initial stage of the secondary streamer at four different temperatures from 0 to 4ns. The temperature- controlled parameters in Table 1 are used to change environment temperature. By comparing the physical quantities such as streamer velocity, electron concentration, and photoionization, the influence of temperature changes on the discharge micro-process is analyzed.

A. THE INFLUENCE OF TEMPERATURE ON THE PROPAGATION VELOCITY OF STREAMER

Figure 4 shows the average streamer propagation velocity between the current location and the previous position when the streamer head reaches a specific position at different temperatures. The variation trend of the average speed with temperature in the whole process of streamer development is shown clearly.

From the curve in Figure 4, the streamer propagation process can be roughly divided into the slow streamer and the fast streamer stage. When the distance between the head of the streamer and the cathode is greater than 0.15cm, the streamer

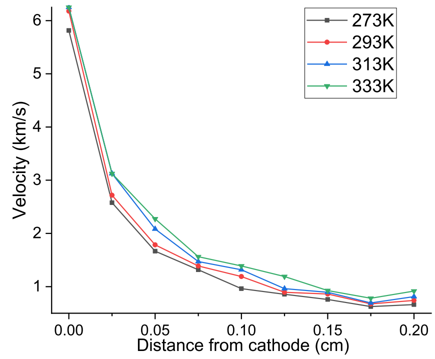

FIGURE 4. **Variation of streamer propagation velocity at specific locations.**

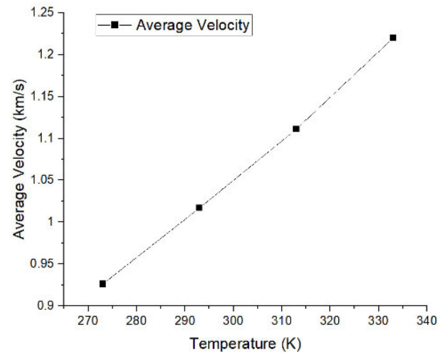

FIGURE 5. **The average velocity of streamer varies with temperature.**

develops slowly, and the temperature has a significant effect on the streamer's speed. With every 20K increase in temperature, the streamer propagation speed in the slow streamer stage increases by about 12 %. As the distance between the streamer head and the cathode turns smaller, the streamer velocity continues to increase, and the rapidly developing discharge enters the fast streamer stage (d<0.15cm). At this time, the temperature rise also accelerates streamer propagation. When the streamer is close to the cathode, the velocity increases significantly. At this time, the relative influence of temperature on the streamer development speed is small. It can be seen from Figure 5 that the average velocity of streamer increases uniformly with the temperature rise of about 4.89m/(s·K).

B. THE INFLUENCE OF TEMPERATURE ON THE ELECTRON CONCENTRATION AND ELECTRIC FIELD

The movement of electrons is one of the most critical elements in the discharge process. It not only affects the space charge and electric field distribution but also largely determines the changes in discharge current and other physical quantities. Figure 6 shows the change process of electron concentration during the development of the streamer when T=273K. It can be seen that when the streamer starts near the anode, it develops slowly toward the cathode in a wide region. Then as the streamer propagates, the streamer channel

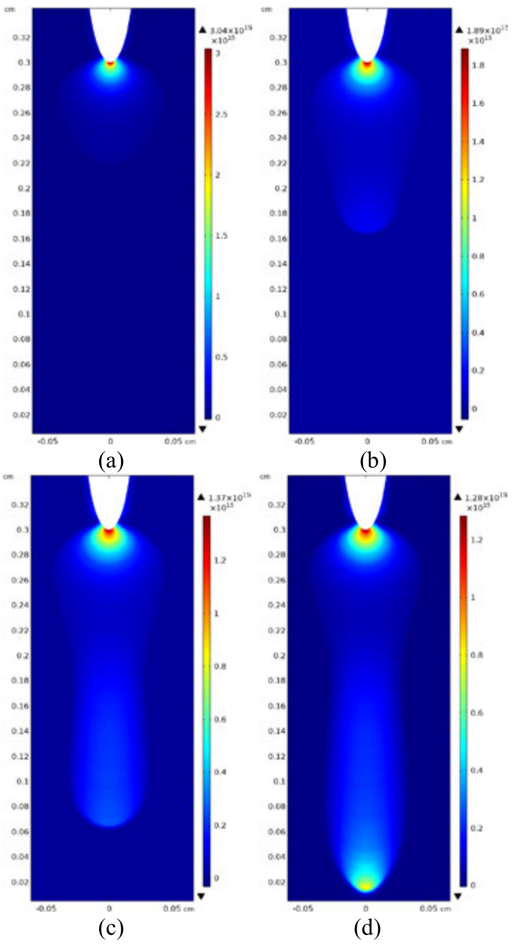

FIGURE 6. **The change process of electron concentration during the development of streamer at 20°.(a) t=1ns; (b) t=2ns; (c) t=3ns; (d) t=3.24ns.**

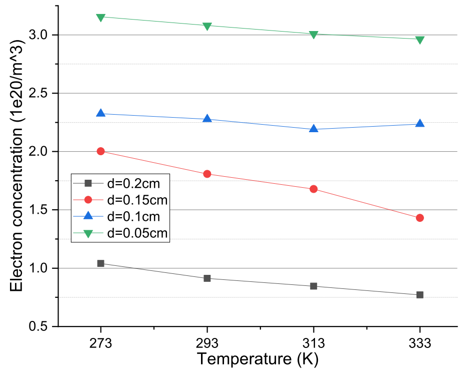

FIGURE 7. **The electron concentration in the streamer head at specific positions versus temperature.**

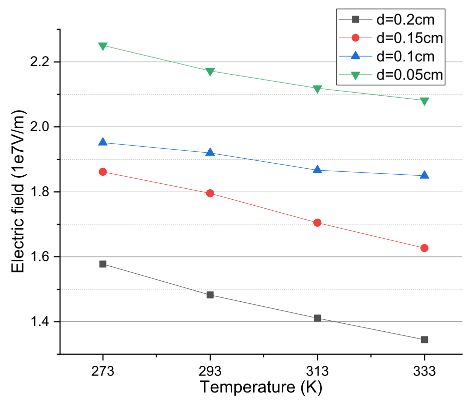

FIGURE 8. **The electric field in the streamer head at specific positions versus temperature.**

narrows and penetrates rapidly downward. The maximum electron concentration is located at the root of the streamer. When the streamer reaches the cathode, the electron concentration at the head of the streamer is equivalent to that at the root.

In order to compare the influence of temperature, this paper chooses to compare the electron concentration and electric field strength at the streamer head when the streamer propagates to the same position at each temperature.

The electron concentration and electric field intensity at the streamer head when the streamer propagates to the same position at each temperature are chosen to be compared to illustrate the influence of temperature, which are shown in Figure 7 and Figure 8. In these two figures, "d" means the distance between the streamer head and the cathode.

It can be seen that during the development of the streamer towards the cathode, the electron concentration and electric field in the streamer head continue to increase. As the temperature increases, the values of electron concentration and electric field strength of the streamer head decrease slightly, but the reduction is small. The change rules of the two quantities are almost the same because the distribution of the space charge determines the electric field. Therefore, it can be considered that the increase in temperature reduces the electron concentration and electric field strength in the streamer channel, but the influence is small.

C. THE INFLUENCE OF TEMPERATURE ON THE PHOTOIONIZATION

Photoionization is an important feature that distinguishes streamer discharge from other forms. The secondary electron avalanche produced by photoionization can continuously flow into the discharge channel to make the streamer self-sustained. It is an important micro-process in the streamer discharge. The photoionization term in the simulation is a function related to position and time, which can reflect the intensity of photoionization in the discharge space [23], [24]:

$$S_{\mathrm{ph}}(\vec{r},t)=\int_{V_1}\frac{I(\vec{r},t)g(R)}{4\pi R^2}\mathrm{d}V_1,$$
$$I(\vec{r},t)=\frac{p_q}{p+p_q}\xi\cdot\alpha\mu_e n_e(\vec{r},t) \tag{8}$$

where $R=\left|\vec{r}-\vec{r_1}\right|$ represents the distance between the radiation and absorption of ultraviolet photon. $g(R)$ is the absorption function, and $I(\vec{r},t)$ is the number of photons

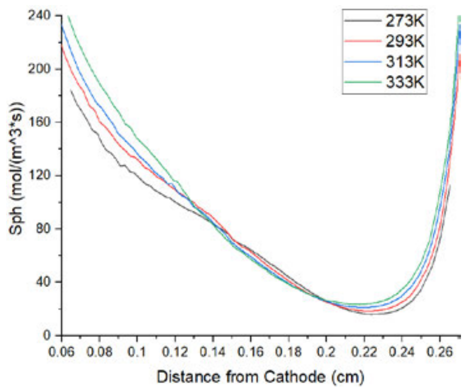

FIGURE 9. The value of the photoionization term in the streamer head at different positions and temperatures.

released per unit of time by dV_1. ξ is a proportionality factor that weakly depends on the local reduced electric field which is commonly assumed to be constant. And the ratio $p_q/(p+p_q)$ is a quenching factor generally taken as constant.

The three-exponential Helmholtz model developed by Bourdon [17] is used to calculate the photoionization term, which approximates the computationally expensive model proposed by Zhelezniak [25]. In this method, the photoionization term Sph is approximated as:

$$S_{ph}(\vec{r},t) = \sum_{k=1}^{3} S_{phk} \tag{9}$$

where S_{phk} is obtained by solving the Helmholtz equation in Equation (10):

$$\nabla^2 S_{phk} - (\lambda_k p_{O_2})^2 S_{phk} = -A_k p_{O_2}^2 \xi \cdot \alpha \mu_e n_e(\vec{r},t) \tag{10}$$

where the values of constants λ_i and A_i is referred from the reference [26]. From the form of Equation 10, it can be known that the intensity of photoionization depends on the temperature-affected variables α, μ_e, and n_e.

The streamer head is the area where the photoionization is the most intense, and the maximum value of the photoionization term also appears in the streamer head. Figure 9 shows the change of the photoionization term value at the streamer head with the position of the streamer head at different temperatures. As can be seen, the photoionization term has experienced a process of falling first and then rising during the streamer propagation process, which is consistent with the change rule of the variables α, μ_e, and n_e during the streamer propagation process.

In the early stage of the streamer development, when the streamer head is more than 0.2cm away from the cathode, the photoionization increases slightly with temperature. In the range of 0.13cm-0.2cm, the influence of temperature on photoionization is not obvious. After the head of the streamer is less than 0.13cm from the cathode, the photoionization shows a law of increasing with the increase of temperature, and the rising amplitude at this time is more obvious than in the early stage of the streamer.

V. RESULT ANALYSIS

A. VERIFICATION OF THE SIMULATION RESULTS

The reasonableness of the simulation model is the basis for the analysis of the results. Since there are few relevant studies on the effect of temperature on the streamer discharge, it is difficult to directly compare the simulation results with the existing experiments. This paper chooses to compare the simulation results with existing research in terms of propagation velocity and theoretical calculation results to verify the accuracy of the simulation.

The streamer velocity is one of the important physical quantities in the process of streamer discharge. Since the experimental environment has a great influence on the streamer propagation, it is necessary to unify the velocity under different environmental conditions to facilitate theoretical comparison and analysis. According to the analysis method in references [27], and [28], the average value of E/p or the peak value of E/N at the streamer head can be taken as a reference for comparative analysis of the streamer velocity. References [27], and [28] pointed out that when the average value of E/p is 12V/(cm·torr), the streamer average velocity v is about 1×10^6m/s. And when the average value of E/p is 26-34V/(cm·torr) [29], v is about 1.7×10^6-3.6×10^6m/s. In the simulation results of this paper, the average value of E/p in the streamer development channel at each temperature is maintained at 20.26-25.53V/(cm·torr), and the average speed of the streamer from the anode to the cathode is 1.02×10^6-1.22×10^6m/s, roughly consistent with the range in the existing studies.

In terms of theoretical calculation, by combining the space charge-induced current in the streamer's head with the conduction current equation of the charged particles, the empirical formula for calculating the electron number density in the streamer head can be obtained, [30], [31]

$$N_{eh} = \frac{4v\varepsilon}{r_h e \mu_e} \tag{11}$$

where v is the velocity of the streamer and r_h is the effective radius of the space charge distribution at the streamer head. The electron density at the streamer head is defined by the streamer velocity and the electron mobility, both of which are affected by temperature. If the simulation value of the electron density in the streamer head can be consistent with the simulated value, the rationality of the temperature-controlled parameters can be verified. The comparison between the theoretical and simulated values of the electron density of the streamer head at different positions at different temperatures is shown in Figure 10. The error percentage between the simulation results and theoretical values is shown in Table 2. It can be noticed that the theoretical value is larger than the simulation results, but the differences fluctuate within an acceptable range of about 10%, which verifies the rationality of the simulation model from the perspective of theoretical calculation.

TABLE 2. Error percentage between simulation results and theoretical values.

Distance from cathode(cm)	The error percentage at different distance 273K	293K	313K	333K
0.20	8.07%	7.34%	12.35%	11.69%
0.15	2.08%	2.40%	6.40%	9.34%
0.10	4.54%	5.37%	2.25%	10.47%
0.05	3.00%	3.84%	6.14%	6.74%

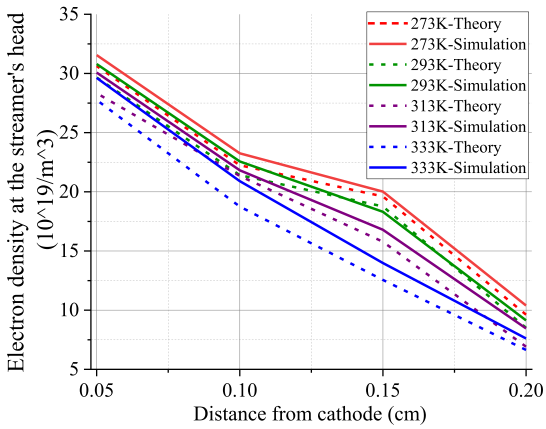

FIGURE 10. Comparison between the theoretical values and the simulation results of electron density at the streamer's head.

B. FURTHER ANALYSIS OF SIMULATION RESULTS

Based on the key parameter system of temperature, this paper gets the law how the key parameters are affected by the temperature and simulates the temperature change. Through the analysis of temperature sensitivity parameters in Figure 3, it can be seen that the increase in temperature under constant pressure aggravates the diffusion and drift process of the electrons and weakens the process of ionization and attachment. Numerically, the decreasing slope of the ionization coefficient curve is about 40 times that of the attachment coefficient, thus the overall ionization process weakens as the temperature increases. The absolute values of both the diffusion and the drift coefficient increase with temperature, which reflects the changes in the intensity of the diffusion and drift process. The diffusion process is significantly enhanced with the increase in temperature with a growth rate of the diffusion coefficient of about 13cm^2/(s·K).

Figures 4 and 5 show the effect of temperature on streamer propagation velocity, It can be found in the simulation results that the increase of temperature uniformly increases the average speed of streamer. At the same position in the streamer channel, the streamer has a greater speed when the temperature is higher. The microscopic physical reasons for this effect can be explained from the perspective of transport parameters.

When the electron diffusion and drift effects are stronger with other factors unchanged, the electrons will move forward for a longer distance under the action of the high electric field, which means that the high-density electron cluster at the head of the streamer moves further forward. Therefore, it can be regarded that the velocity of the streamer is mainly affected by the coefficients of electron mobility and electron diffusion. As the temperature rises, the greater mobility and diffusion coefficients mean that the electrons have a faster movement speed, which causes the streamer to develop faster. It can be seen from Figure 4 that the speed of the streamer is increasing during the propagation process mainly due to the enhancement of the ionization effect. During the development of the streamer, the electron concentration at the streamer head increases continuously, which increases the concentration gradient of charged particles, in turn increasing the electric field strength and making the ionization process more intense. Overall, the streamer travels forward faster and faster with increasingly stronger ionization.

As shown in Figure 7 and Figure 8, the electron concentration and electric field strength at the streamer head tend to decrease slightly with the increase in temperature. From the perspective of microscopic mechanism, this is caused by the decrease of the intensity of ionization with the increase of temperature. The weakening of the ionization intensity reduces the increase of electrons in the streamer head, thereby reducing the electron concentration gradient and the electric field intensity.

The relationship between the photoionization term and temperature shown in Figure 9 is more complex because the value of the photoionization term increases with the rise of the product of the three variables: α, μ_e, and n_e. Figure 3 shows as the temperature rises, the value of α decreases, and the absolute value of μ_e increases. In Figure 7, it can be seen that the electron concentration in the streamer head slightly reduces. Thus, the product of the three variables does not show strong regularity. From the changing trend of the photoionization term in Figure 9, it can be seen that in the early and late stages of the streamer, the law of the photoionization term affected by temperature is more obvious. The increase in temperature promotes the photoionization of the streamer discharge in these stages, but this effect of promotion is small. In the middle of the streamer, the photoionization term is not affected by the temperature obviously. From the overall trend of change, as the temperature rises, the increase in electron mobility has a more significant impact on photoionization. Although ionization is weakening, photoionization still shows a tendency to increase with temperature.

Furthermore, it can be deduced from the numerical changes of ionization and attachment coefficients with temperature that a streamer is more likely to occur in lower temperature environment. Therefore, more adequate insulation measures may be required in cold regions during the design of power equipment and transmission lines. In addition, the simulation results show that the movement speed of charged particles is faster, which means that the streamer at high temperature can produce a more violent high-frequency current. The change of current may affect the shape of the discharge signals during on-site detection. The discharge signal is an important factor for evaluating the insulation state of power equipment. Based on the research in this paper, the relationship between the discharge signal and temperature can be explored in the future.

VI. CONCLUSION

By analyzing the influence of temperature on the key parameters and the streamer development process, the influence of temperature on the microscopic change trend of the streamer development process is obtained. The conclusions are as follows:

1) The increase in temperature makes the ionization and the attachment coefficient uniformly drop, and the mobility and diffusion coefficients of electron rise. The greater decrease in the ionization coefficient than the attachment coefficient indicates that the ionization process weakens as the temperature rises. The increase in diffusion and drift coefficients indicates that the diffusion and drift motions of particles continuously strengthen when the temperature is high.

2) The increase in temperature increases the propagation velocity of the streamer evidently, which makes the time for the streamer to penetrate the electrode largely shorten. For every degree of temperature increase, the streamer development speed increases by about 4.89 m/s. This is mainly because of the increase in the mobility and diffusion coefficient of the electron. The electron concentration and electric field in the streamer head decrease slightly with the increase in temperature mainly due to the reduction of the ionization, but the influence is small.

3) In the early and late stages of the streamer, the increase in temperature promotes photoionization. In the middle of streamer development, the law of temperature on photoionization is not obvious. This is the result of the interaction of the ionization coefficient and electron mobility. The photoionization intensity is related to the three temperature-affected variables α, μ_e, and n_e in theoretical calculations. From the overall trend, the combined effect of the three variables makes the photoionization slightly increase with the rise of temperature.

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