Numerical Simulation of the Characteristics of Electrons in Bar-plate DC Negative Corona Discharge Based on a Plasma Chemical Model

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Abstract – In order to explore the characteristics of electrons in DC negative corona discharge, an improved plasma chemical model is presented for the simulation of bar-plate DC corona discharge in dry air. The model is based on plasma hydrodynamics and chemical models in which 12 species are considered. In addition, the photoionization and secondary electron emission effect are also incorporated within the model as well. Based on this model, electron mean energy distribution (EMED), electron density distribution (EDD), generation and dissipation rates of electron at 6 typical time points during a pulse are discussed emphatically. The obtained results show that, the maximum of electron mean energy (EME) appears in field ionization layer which moves towards the anode as time progresses, and its value decreases gradually. Within a pulse process, the electron density (ED) in cathode sheath almost keeps 0, and the maximum of ED appears in the outer layer of the cathode sheath. Among all reactions, R1 and R2 are regarded as the main process of electron proliferation, and R₂₂ plays a dominant role in the dissipation process of electron. The obtained results will provide valuable insights to the physical mechanism of negative corona discharge in air.

Keywords: Corona discharge, Plasma chemical, Numerical simulation

Nomenclature

n_e	electron density
N^+	positive ion density
N^-	negative ion density
N_n	neutral particle density
N_i	particles number of species i ,
$\Delta \varepsilon_k^e$	energy lost per-electron in the reaction k
M_e	electron mobility
M_ε	energy mobility
D_e	electron diffusion coefficient
D_ε	energy diffusion coefficients
Φ	electrostatic potential
ε	electron mean energy
E	unit charge ($1.6021892 \times 10^{-19}$ c)
K	total number of reactions
K_b	boltzmann constant
T	environment temperature
ϵ	air permittivity
P	gas pressure
R	horizontal coordinate
Z	vertical coordinate
P_q	quenching pressure for the photo-ionization states
R_e	rate of electron generation/dissipation
R_k	rate of progress of reaction k with electron

	participation
R_{ion}	rate of ionization
R_{ph}	rate of photoionization
R_{rec}^{ei}	rate of electron-ion
R_{rec}^{ii}	rate of ion-ion recombination
R_{att}	rate of electron adsorption
Γ_e	secondary emission coefficient
Γ_i	surface interaction coefficient
M_i	ion mass of species i
$V_{e,th}$	electron thermal velocity
Γ_e	electron density flux
Γ_ε	electron energy flux
Γ_i	flux density of species i
E	electrical field
N	boundary normal vector

1. Introduction

As a typically non-thermal discharge, corona discharge is usually generated on sharp points, edges or thin wires where the electric field is strongly concentrated [1, 2]. With the rapid development of extra high-voltage (EHV) transmission lines, corona discharge in air has become one of the critical problems associated with high-voltage transmission lines. In many occasion, especially in electric transmission, corona discharge is undesirable. For example, many chemical reactions happen along with corona discharge, and this results in the production of many hazardous substance with great corrosivity and oxidizability, such as ozone and nitrogen oxides. And corona discharge will

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produce high frequency pulse currents which contain higher harmonic. This will bring in interference and affect wireless communications. What's worse, corona discharge can cause energy losses. The higher the voltage grade, the more energy loss [3, 4]. In the meantime, corona discharge has been employed as an effective tool in many industrial applications such as electrostatic precipitators, disinfection, ozone generators, surface treatment, ignition, electrostatic painting, and so on [5-7]. In recent year, the application of corona discharge has been expanded broadly. Kinetic analysis has been developed for pollution control using none thermal plasma by Penetrante [8]. Masuda used surface-induced plasma chemical process for the destruction of gaseous pollutants [9]. Corona discharge is also used for gas separation [10, 11]. What's more, Deli [12] carried out experiments on the cleaning of air using DC streamer discharge. In the past decades, great focuses have been paid on the mechanism of corona discharge in air [13]. As has been reported, the collisions between the high-energy electrons and the neutral molecules are the major ionization processes of air corona discharge. Meanwhile, electrons are the main energy transfer carrier between electric field and heavy particles [14]. Consequently, investigation on characteristics of electrons in corona discharge during a pulse cycle can be of important value to understand the physical mechanism of air discharge, and further provide valuable references to the suppression of corona discharge of transmission lines [15].

A variety particles such as excited-state species, ions, free radicals, are generated during the microcosmic process of corona discharge, which would lead to complex physical and chemical reactions. In addition, it will also determine the multifariousness of interaction between them. The preferable approach to carry out in-depth investigations within the microcosmic process of corona discharge should be numerical modeling because of the lack of effective measurement methods in plasma discharge process [16]. Chemical reactions and non-equilibrium can better reflect the microcosmic process of gas discharge, which should be incorporated within the discharge simulation, and it will provide more important information to gas discharge investigation. Nahomy et al. [17] presented a comparatively comprehensive fusion of 430 chemistry reactions in air discharge with the demerit of large-scale computation. A two-dimensional physical model proposed by Pancheshnyi et al. [18] for discharge in N_2 - O_2 (9:1) mixed gas under 760 Torr was improved based on the selection of 10 kinds of primary particles from Nahomy's model, which was further employed to analyze electric field distribution, densities of charged particles, reaction rates and other discharge parameters, and the obtained results fairly correspond to the experimental data. Liu et al. [19, 20] established a fluid-chemical mixed kinetic model for corona discharge under atmospheric pressure and the computed V-I curve and electron temperature curve accorded well with the experiment values carried by

Antao [21]. Based on this model, current density, electron density, and positive/negative ion densities distribution are discussed. Furthermore, collision reactions were added into fluid dynamics model, and an improved model for negative corona discharge was obtained to acquire the information of electric field distribution, rates of collision reaction, development tendency of space charge, electron density distribution and other characteristics in the microcosmic process of Trichel pulse [22]. To sum up, characteristics of electrons were roughly analyzed by the presented simulation models, and until now no specific models are proposed for analysis of characteristics of electrons during the microcosmic process of corona discharge.

This paper presents a new plasma hybrid model for the simulation of DC negative corona discharge under atmospheric air. Using the proposed novel simulation model, this work aims at discussing some microcosmic characteristics such as electron mean energy distribution, electron density distribution, generation and dissipation performances of electrons along the axis during a pulse cycle in order to understand the main physical mechanisms. The rest of the present paper is organized as follows. The detailed descriptions are presented for the negative corona discharge model in Sec. 2. Sec. 3 presents the corresponding results and discussions. Finally, the conclusions are summarized in Sec. 4.

2. Mathematical Model

In substance, the solution of the microcosmic mechanism for corona discharge is to convert the electron conservation equation, the electron energy conservation, the heavy species multi-component diffusion transport equation, governing equations for heavy particles, and the Poisson's equation into the appropriate system of partial differential equations which are then normalized and solved by means of discrete numerical difference equations.

2.1 Governing equations

The balance governing equation for electron density is [23]:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma_e = R_e \quad (1)$$

R_e is related to ionization or recombination, photoionization processes and secondary emission processes on the cathode and Γ_e is expressed as:

$$\Gamma_e = -\nabla(D_e n_e) + \mu_e n_e \nabla \varphi \quad (2)$$

The electron mean energy density equation is given as [24]:

$$\frac{\partial}{\partial t}(n_e \epsilon) + \nabla \cdot \Gamma_\epsilon = -e \Gamma_e \cdot \nabla \varphi + e \sum_{k=1}^K \Delta \epsilon_k^e R_k \quad (3)$$

Γ_ϵ is described by the following equation:

$$\Gamma_\epsilon = n_e \mu_\epsilon \nabla \varphi - D_\epsilon \nabla n_e \epsilon \quad (4)$$

These energy transport coefficients are given by [19]:

$$\mu_\epsilon = \frac{5\mu_e}{3}, \quad D_\epsilon = \frac{5D_e}{3} \quad (5)$$

These transport coefficients of electrons are obtained from solving the Boltzmann equation [25]. The streamer discharge in air in highly overstressed gap is very fast (several nanoseconds). On the several nanoseconds time scale, the diffusion and mobility phenomenon of heavy species (ions and neutral particles) have almost no influence on the discharge propagation. So the diffusion and mobility coefficients of heavy species can be ignored [18]. The governing equations for ions and neutral particles are given by

$$\begin{cases} \frac{\partial n_i^+}{\partial t} = R_{ion} + R_{ph} - R_{rec}^{ei} - R_{rec}^{ii} \\ \frac{\partial n_i^-}{\partial t} = R_{att} - R_{rec}^{ii} \\ \frac{\partial n_n}{\partial t} = R_{rec}^{ei} + R_{rec}^{ii} - R_{ion} - R_{ph} - R_{att} \end{cases} \quad (6)$$

Here, subscript i indicates species of ion (O_2^+ , O_4^+ , O_2^- , O^- , N_2^+ , N_4^+ , and $N_2O_2^+$).

The electric field in the discharge gap is calculated using Poisson's equation [18]:

$$\epsilon \nabla^2 \varphi = -e (\sum n_i^+ - \sum n_i^- - n_e) \quad (7)$$

2.2 Air chemistry and transport

The essence of air discharge is regarded as collision between charged particles and neutral air molecules (atoms), molecules (atoms) clusters and other basic particles, as well as results of the collision between these particles and electrode surfaces [19]. The reaction pathways are adopted primarily from the mechanism of Pancheshnyi [18]. Table 1 lists the reaction processes that are taken into account in the model [26, 27].

The charged ions are quenched to the neutral species due to the surface reactions:

Table 1. Kinetic processes considered in the model

No.	Reaction	Rate coefficient	
R ₁	$N_2 + e \rightarrow 2e + N_2^+$	$f(\epsilon)$	15.6
R ₂	$O_2 + e \rightarrow 2e + O_2^+$	$F(\epsilon)$	12.06
R ₃	$N_2^+ + 2N_2 \rightarrow N_4^+ + N_2$	5.0×10^{-41}	
R ₄	$N_2^+ + N_2 + O_2 \rightarrow N_4^+ + O_2$	5.0×10^{-41}	
R ₅	$N_4^+ + O_2 \rightarrow O_2^+ + 2N_2$	2.5×10^{-16}	
R ₆	$N_2^+ + O_2 \rightarrow O_2^+ + N_2$	$1.04 \times 10^{-15} T^{-0.5}$	
R ₇	$2N_2 + O_2^+ \rightarrow N_2O_2^+ + N_2$	$8.1 \times 10^{-38} T^{-2}$	
R ₈	$N_2O_2^+ + N_2 \rightarrow O_2^+ + 2N_2$	$14.6 T^{-5.3} \exp(-2357/T)$	
R ₉	$N_2O_2^+ + O_2 \rightarrow O_4^+ + N_2$	1.0×10^{-15}	
R ₁₀	$O_2^+ + O_2 + N_2 \rightarrow O_4^+ + N_2$	$2.04 \times 10^{-34} T^{-3.2}$	
R ₁₁	$O_2^+ + 2O_2 \rightarrow O_4^+ + O_2$	$2.04 \times 10^{-34} T^{-3.2}$	
R ₁₂	$O_4^+ + e \rightarrow 2O_2$	$1.4 \times 10^{-12} (300/T_e)^{0.5}$	
R ₁₃	$O_2^+ + e \rightarrow 2O$	$2.42 \times 10^{-13} (300/T_e)$	
R ₁₄	$2O_2 + e \rightarrow O_2 + O_2^-$	$2.0 \times 10^{-41} (300/T_e)$	
R ₁₅	$O_4^+ + O_2^- \rightarrow 3O_2$	1.0×10^{-13}	
R ₁₆	$O_4^+ + O_2^- + N_2 \rightarrow 3O_2 + N_2$	2.0×10^{-37}	
R ₁₇	$O_4^+ + O_2^- + O_2 \rightarrow 3O_2 + O_2$	2.0×10^{-37}	
R ₁₈	$O_2^+ + O_2^- + N_2 \rightarrow 2O_2 + N_2$	2.0×10^{-37}	
R ₁₉	$O_2^+ + O_2^- + O_2 \rightarrow 3O_2$	2.0×10^{-37}	
R ₂₀	$O + O_2 + N_2 \rightarrow O_3 + N_2$	2.5×10^{-46}	
R ₂₁	$O + 2O_2 \rightarrow O_3 + O_2$	2.5×10^{-46}	
R ₂₂	$e + N_2^+ + N_2 \rightarrow 2N_2$	$6.07 \times 10^{-34} T_e^{-2.5}$	
R ₂₃	$2e + N_2^+ \rightarrow N_2 + e$	$5.651 \times 10^{-27} T_e^{-0.8}$	
R ₂₄	$O_2^+ + O^- \rightarrow O + O_2$	$3.46 \times 10^{-12} T_e^{-0.5}$	
R ₂₅	$N_2 + e \rightarrow e + N_2$	$f(\epsilon)$	1.0
R ₂₆	$O_2 + e \rightarrow e + O_2$	$F(\epsilon)$	1.0
R ₂₇	$O_2 + e \rightarrow O + O^-$	$f(\epsilon)$	3.6

Photoionization is one of the main factors promoting discharge propagation in air [18, 28-31]. Recently, the detailed studies on photoionization were given through the comparison of experiments and simulations by Nijdam and Wormeester [30]. Photoionization of corona discharge in air is caused by the radiation in the wavelength range 980-1025 tenthmeter resulting from the radiative transitions from the three single states of N_2 ($b^1 \Pi_u$, $b^1 \Sigma_u^+$ and $c_4^1 \Sigma_u^+$) to the ground state $N_2(x^1 \Sigma_g^+)$ [32]. Based on the above assumptions, Zheleznyak [31] proposes the rate R_{ph} of a non-local photoionization, as expressed in the following equations:

$$N_2(b^1 \Pi_u, b^1 \Sigma_u^+, c_4^1 \Sigma_u^+) \rightarrow N_2(x^1 \Sigma_g^+) + h\nu \quad (9)$$

$$O_2 + h\nu \rightarrow O_2^+ + e \quad (10)$$

Here the Eddington approximation method [33] is used to calculate R_{ph} :

$$R_{ph} = \frac{1}{4\pi} \cdot \frac{p_q}{p + p_q} \int_V d^3 r_1 \frac{R_{ion}(r_1)}{|r - r_1|^2} h(|r - r_1| \cdot p) \quad (11)$$

where $1/4\pi$ is the normalizing constant, r is the observation point, r_1 is the source point, and $h(|r - r_1| \cdot p)$ is the coefficient of absorption of the ionizing radiation in the

medium.

2.3 Boundary conditions and computational implementation

Fig. 1(a) gives the description of the schematic diagram of bar-plate DC negative corona discharge in air at atmospheric environment. A copper bar, with a tip radius curvature R (0.4 mm) and length L (2 mm), is perpendicular to an infinitely large plate which is made of copper and has a radius of 1 cm at a distance D (3.3 mm). Negative potential is applied to the bar, the plane electrode is grounded as zero potential, and the zero charge boundary conditions [34] ($\mathbf{n} \cdot (\epsilon \nabla \phi) = 0$) are used at the open boundary. The ambient gas is air ($O_2: N_2=1:4$) at room temperature (300 K) and atmospheric pressure (1.0 atm). Within numerical model, the bar-plate electrode system model is simplified into a two-dimensional representation using the rotational symmetry. The computational domain is highlighted with green in Fig. 1(a). Some important boundary conditions are given as follows.

The electron flux at the electrode is expressed as [35]

$$\Gamma_e \cdot \mathbf{n} = \frac{1-\gamma_e}{1+\gamma_e} \left[-(2\alpha_e - 1)\mu_e \mathbf{E} \cdot \mathbf{n} n_e + \frac{1}{2} v_{e,th} n_e \right] \quad (12)$$

a_e is 1 when the electron flux is directed toward the electrode, and zero otherwise. The electron energy flux at the cathode and the anode is:

$$\Gamma_e \cdot \mathbf{n} = \frac{1}{3} v_{e,th} \epsilon n_e \quad (13)$$

$v_{e,th} = \sqrt{8k_B T / \pi m_e}$ is the electron thermal velocity. At the electrode surfaces, the ions and unstable neutral particles are quenched to stable neutral particles due to surface reactions (Eq. (8)).

The ion fluxes at the electrode are expressed as follows [34]:

$$\Gamma_i \cdot \mathbf{n} = \frac{\gamma_i}{4} \sqrt{\frac{8k_B T}{\pi m_i}} n_i \quad (14)$$

γ_i specifies the probability that species i will react at the surface, and The normal gradient of the density of all species is zero [$\mathbf{n} \cdot (\nabla n_i) = 0$] at the open boundaries.

A Gaussian distribution of seed electrons and positive ions with a maximum value of 1016 m^{-3} and width of $25 \text{ } \mu\text{m}$ is set at the needle tip according to the following equation [25]:

$$\sum_i n_i^+(r, z) \Big|_{t=0} = n_e \Big|_{t=0} = N_{\max} \times \exp \left[-\frac{(r-r_0)^2}{2s_0^2} - \frac{(z-z_0)^2}{2s_0^2} \right] \quad (15)$$

Fig. 1. Schematic of the computational model: (a) schematic diagram of the negative corona discharge; (b) mesh figure; (c) triangle of six-node second order

Fig. 2. Flowchart of computer program

where $N_{max} = 10^{16} \text{ m}^{-3}$, $r_0 = 0 \text{ } \mu\text{m}$, z_0 is the needle tip, $s_0 = 25 \text{ } \mu\text{m}$. $\sum_i n_i^+(r, z) \Big|_{t=0}$ (The subscript i denoting O_2^+ , O_4^+ , N_2^+ , N_4^+ , and N_2O_2^+), and $n_e|_{t=0}$ are positive ion and electron density at $t=0$. The initial condition has been confirmed to only speed up the pulse formation and not to change the discharge characteristics [25, 36].

The model in this work is implemented in COMSOL Multiphysic package based on finite element method. Fully implicit time stepping method is used for the Eqs. (1), (3), (6) and (7). It has been proved that the corona discharge propagates along the axial direction, therefore, due to the high electric field and charge densities [37], a very fine ‘unstructured mesh (Fig. 1(b))’ need to be used along the axial symmetry line [38]. Triangle of six-node second order (Fig.1 (c)) is used in the mesh, and the mesh parameters are shown in Table 2. Finally, the flowchart of the computer program is shown in Fig. 2.

Table 2. Mesh statistics

Mesh Parameter	
Triangular elements	22218
Edge elements	608
Minimum element quality	0.7527
Average element quality	0.9785
Element area ratio	0.03552
Mesh area	$7.469 \times 10^{-6} \text{ m}^2$
Elements nodal points	6

3. Results and Discussion

3.1 Individual pulse waveform

In this paper, 6 typical time points (t_1 - t_6) is used to describe microcosmic characteristics of electrons during a pulse cycle in bar-plate DC negative corona discharge. Fig. 3 shows the pulse current waveform in the electrode gap where the negative DC voltage applied to the bar is 5.0 kV. The pulse of the discharge current is characterized by a fast rising front (as short as 1.6 ns) and a slow decaying (about 60 ns), which has been confirmed by Zentner [39] and Soria [40]’s experiment. The maximum discharge current rapidly increases to 0.195 A from t_1 - t_2 . Then, it starts to

Fig. 3. The discharge current waveform in the electrode gap

Fig. 4. Electron mean energy distribution along the axis

Fig. 5. Electric field distribution along the axis

decrease slowly from t_2 - t_4 . The first peak is generated due to the field ionization. During t_1 and t_2 , the electric field keeps at a high level as shown in Fig. 5. A large electrons are produced in the cathode for the impact of positive ion in the cathode and field ionization. Electrons are accelerating in the electric field, and the number of electron and positive ion are growing exponentially because of ionization. The strong electric field guarantees the fast movement of electron. As a results, corona current increase rapidly in a short time from t_1 to t_2 . The electric field decreases fast with the distance away from bar plate. Ionization caused by electron weakens. On the contrary, the attachment of electron is enhanced.

The decreasing of current right after the peak of the main pulse is due to the electric field reduction in the electrode gap caused by the existence of negative ion cloud and electron clusters which move towards the anode directionally [41]. In order to maintain the balance field by requiring fewer electrons into the anode surface, so from t_4 - t_6 , only a small DC current ($I=1\text{mA}$) will remain in the circuit.

3.2 Electron mean energy distribution (EMED)

Electron-impact reactions (e.g., ionization and excitation)

significantly affect the corona discharge. The rate of collision between a molecule/atom and an electron and the transport coefficient of an electron (e.g., electron diffusion coefficient and mobility) are functions of the electron mean energy (EME) [42]. Therefore, research on the electron mean energy distribution (EMED) during a corona discharge pulse cycle is extremely important for a comprehensive understanding of its physical mechanism [42]. Fig. 4 demonstrates the EMED along the axis at 6 typical time point during a pulse cycle, in which “0 mm” represents the position of the plate electrode (anode) while “3.3 mm” indicates the position of the bar electrode (cathode). After comparing with literature [42], it is interesting to note that EMED has the same development tendency with the electric field distribution (EFD) during a pulse cycle (Fig. 5), because field accelerating is the main way for electrons to gain energy [43]. So, the electric field distortion caused by the directional movement of charged particles in external field plays a key role in EMED, which can explain the phenomena of Fig. 4 as follow. At the beginning of pulse cycle (t_1), the maximum of EME occurs near the cathode, and declines to its minimum near the anode in a form of exponential decay, this is owing to the space shape of bar-plate electrode. As time goes on (t_2 - t_6), the maximum of EME appears in the field ionization layer, and moves with the field ionization layer from cathode to anode, with its value reduces gradually. In the process of electron avalanche moving to the anode, collision ionization and adsorption reaction create a large number of charged particles. The internal electric field caused by electrode, ion cloud, and electron clusters which directionally move in the external electric field, distorts the electric field between bar and plane electrode. Furthermore, EME has a slightly increase near the anode region (0- 1mm) with time progresses (t_1 - t_6). It's for that more and more electrons reach the anode during this period, electric field is strengthened by the internal electric field between anode and electrons near the anode.

3.3 Electron density distribution (EDD)

As reported [14, 44], collision ionization between high-energy electrons and neutral molecules are seen as the major chemi-ionization process in the micro-process of corona discharge, and electrons are the main energy transfer carrier between electric field and heavy particles, consequently. Investigation on the EDD can be of

Table 3. The key reactions at different instants

Time	The key reactions at different instants
t_1	$R_1, R_2, R_3, R_7, R_{10}, R_{22}, R_8 \dots$
t_2	$R_1, R_{22}, R_2, R_7, R_{10}, R_3, R_8 \dots$
t_3	$R_1, R_2, R_{22}, R_7, R_3, R_{10}, R_8 \dots$
t_4	$R_2, R_1, R_{22}, R_7, R_8, R_{10}, R_3 \dots$
t_5	$R_2, R_1, R_{22}, R_7, R_8, R_{10}, R_3 \dots$
t_6	$R_1, R_{22}, R_2, R_7, R_8, R_{10}, R_3 \dots$

Fig. 6. EDD along the axis: (a) EDD along the whole axis; (b) EDD near the cathode

Fig. 7. 2D-EDD at 6 typical time

important value to understand the physical mechanism of air discharge. Fig. 6(b) shows the thickness of cathode sheath is about 30 μm , and the electron density (ED) keeps almost 0 in the cathode sheath in the whole discharge process, because of the exclusion which prevents electrons to enter into the cathode. The maximum of ED appears in the outer layer of cathode sheath where the field ionization effect is strongest due to the concentrated electric field. As time increases (t_1 - t_3), the ED in the outer layer of cathode sheath rapidly increase to the maximum. Then the ED begin to decrease to a stable point until the time point t_5 . Fig. 6(a) shows the EDD along the whole axis at 6 typical time during a pulse cycle. As time increases

(t_1 - t_6), the EDD moves towards the anode, and the density of electrons increases gradually. Fig. 7 shows the development tendency of EDD clearly. We also noticed that ED has an abnormal increase near the anode at the end of pulse cycle (t_6). The reasons are as follows. Firstly, the secondary electron emission caused by the collision between negative ions and anode. Secondly, more and more positive ions gain electrons from the anode in order to restore electrical neutrality. Lots of light radiation phenomena usually are accompanied with air discharge process, whose intensity generally depends on the energy transfer intensity caused by collision between electrons and other particles, therefore, the EDD is often related to

Fig. 8. Top 3 reaction rate at 6 typical time, (a) t_1 , (b) t_2 , (c) t_3 , (d) t_4 , (e) t_5 , (f) t_6 (Note: two-body reaction coefficient unit is $\text{m}^3 \text{s}^{-1}$; three-body reaction coefficient unit of $\text{m}^6 \text{s}^{-1}$.)

corona imaging. This is why the 2D-EDD at t_6 has a very similar distribution with the images of corona discharge in literature [45].

3.4 Generation and dissipation performances of electron

The rate of collision reaction can reflect the strength of that reaction process in air discharge. According to the existing literature, simplified chemical model which contains limited charged particles and collision reactions is considered into corona discharge process. Consequently, behavior of charged particles and chemical reactions in micro-process of corona discharge are still unclear. In this paper, 7 reactions whose maximum rate along the axis ranked top 7 at 6 representative time points are listed in Tab. 3. From Tab. 3 we note that, R_1 , R_2 and R_{22} play the main role in the whole discharge process. R_1 and R_2 are collision reactions of electrons collision reactions associated with N_2 and O_2 respectively. Meanwhile, they are the main process of electron proliferation. Besides, reaction rates of R_1 and R_2 almost show the same curve (Fig. 8). R_{22} is a recombination reaction of N_2 , N_2^+ and e , which play a dominant role in the dissipation process of electron. Fig. 8 indicates that generation and dissipation reactions of electron are mainly concentrated in field ionization layer because of the high electric field. With the increase of time (t_1 - t_2), the rates of R_1 , R_2 and R_{22} rapidly increase from a

very limited value to the maximum. A large number of electrons and ions are produced in this process which would lead to a fast rising front in the discharge current. Sequentially, from t_2 - t_5 , the rates of R_1 , R_2 and R_{22} begin to fall slowly due to the declining electric field in field ionization layer. At the end of pulse cycle (t_6), the rates of R_1 , R_2 and R_{22} increase with an exception state, because at this time, the electrode gap restores to electrical neutrality, so ions and electrons are widely distributed in the whole gap, so the electric field is extremely distorted.

4. Conclusions

In this paper, a plasma chemical model for simulation of bar-plate DC negative corona discharge under atmospheric air is presented. Under the condition of applied voltage of -5.0 kV, microcosmic characteristics at 6 typical time points during a pulse period are used to describe the characteristics of electrons of negative corona discharge in air. The important conclusions based on the current investigations are as follows:

- 1) At the beginning of the pulse cycle, the maximum of electron mean energy (EME) occurs near the cathode, and declines to its minimum near the anode in a form of exponential decay. As time goes on, the maximum of EME appears in the field ionization layer, and moves along the field ionization layer from cathode to anode,

meanwhile its value reduces gradually.

- 2) Within a pulse process, the electron density (ED) in cathode sheath almost keeps almost 0, and the maximum of ED appears in the outer layer of the cathode sheath. The electron density distribution (EDD) moves towards the anode, and the density of space gap increases gradually.
- 3) R_1 , R_2 and R_{22} play the main role in the whole discharge process. R_1 and R_2 which are the collision reaction of electrons associated respectively with N_2 and O_2 regarded as the main process of electron proliferation, besides, reaction rates of R_1 and R_2 almost keep the same curve. R_{22} is the recombination reaction of N_2 , N_2^+ and e , which plays a dominant role in the dissipation process of electrons.

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