Numerical simulation transient electron distribution of direct current negative corona discharge in air

Xinghua Liu\textsuperscript{1,**}, Richang Xian\textsuperscript{2}, Peng Yu\textsuperscript{3}, Ying Pei\textsuperscript{4}, Xuebin Lv\textsuperscript{5}, Xuefeng Sun\textsuperscript{1}, Tao Wang\textsuperscript{1}, Shangyuan Ning\textsuperscript{1}, Shikun Wang\textsuperscript{1}

\textsuperscript{1}State Grid Zibo Power Supply Company, Shandong 255000, China
\textsuperscript{2}Shandong University of Science and Technology, Shandong 255000, China
\textsuperscript{3}State Grid Shandong Electric Power Research institute, Shandong 255000, China
\textsuperscript{4}State Grid of China Technology College, Shandong 255000, China
\textsuperscript{5}State Grid Shandong Power Company, Shandong 255000, China

*Corresponding author e-mail: 30280241@qq.com

Abstract. In order to explore the characteristics of electron in DC negative corona discharge, microcosmic process of negative corona discharge in air is simulated in this paper. The numerical computation is established with a bar-plate electrode configuration with an inter-electrode gap of 3.3 mm, the negative DC voltage applied to the bar is 5.0 kV, the pressure in air discharge is fixed at 1.0 atm, and the gas temperature is assumed to be a constant (300 K). By solution the system of electron conservation equation, the electron mean energy conservation, the heavy species multi-component diffusion transport equation, and the Poisson's equation, characteristics of electrons (electron mean energy, electron density, and generation and dissipation performances of electrons) at 6 representative time points during a pulse are obtained and then discussed emphatically.

1. Introduction
Corona discharge is a non-equilibrium low-temperature plasma discharge process and often occurs close to the point electrode with large radius of curvature. With the development of electric power industry in China, high-pressure and ultra-high voltage power transmission lines become the main wire frame and corona loss is assignable. Meanwhile, the audible noise, electromagnetic interference, circuit corrosion, insulation degradation and public in harmony which are brought by corona discharge have attracted high attentions. Various excited particles, ions and free radicals are formed in the microscopic process of corona discharge, which can make complicated physical and chemical reasons. The diversity of plasma species determines the diversity of particle interaction and the law of dynamics is extremely complicated [1]. The impact ionization of electrons and neural electrons is the dominant ionization process in the air discharge process. Additionally, electrons are main carrier of energies between extra electric field and heay ions [2]. Therefore, studying behavioral characteristics of electrons in corona discharge process is of important significance to explain mechanism of corona discharge.

In early numerical studies, scholars often view gas discharge equal to a circuit and simulate arious gas discharge equations by analyzing circuit parameters [3]. With the development of plasma
simulation technology, people’s understanding on gas discharge are not limited in discharge current and discharge voltage of circuit simulation, but goes deep into the distribution law of charged particles produced in the discharge process. Many deeper theoretical discoveries have been achieved. The atmospheric air discharge that considers chemical reaction between particles and non-equilibrium state has become one very important direction of scientific research in future [4]. Nahorny et al. [5] considered 430 chemical reactions when studying the gas discharge process. It is the study that considers the most chemical reactions at present and lays good foundations for follow-up scientific researchers. Pancheshnyi [6] chosen 10 main particles based on Nahorny and proposed a two-dimensional physical model of streamer discharge when the pressure of N2: O2 (9:1) mixed gas is 760Torr. He analyzed discharge parameters (e.g. electric field distribution, charged particle density and reaction coefficient) thoroughly by using this model, which are in high accordance with test data. Liu Xinghua et al. [7] established the fluid-chemical kinetics model of positive corona discharge by Comsol, which was verified by experimental data of Antao [8], achieving high consistency. Key characteristic parameters like current density, electric field/potential distribution and positive/negative ion density distribution in early positive corona discharge were analyzed based on this model. According to existing research fruits, there’s no model that can reflect electron characteristics during the negative corona discharge. Discussions on microscopic characteristics (e.g. electron mean energy, electron density, electro generation and dissipation characteristics) in the corona discharge have important theoretical and actual significance.

In this paper, the electron mean energy transport equation was considered based on the two-dimensional fluid kinetics model of corona discharge and some important processes like photoionization, secondary emission and chemical reactions between particles were discussed. An improved numerical model of negative corona discharge was constructed. Corona discharge under 3.3mm bar-plane distance and -5.0kV applied voltage was calculated based on this model, getting the single-discharge pulse current waveform of negative corona discharge. The electron mean energy distribution, electron density distribution, electron generation and dissipation characteristics in the negative corona pulse process were analyzed by choosing 6 typical time points in one discharge pulse period.

2. Model

The solving of this model is actually to convert the electron continuity equation, heavy particle transport equation, electron energy equation and Poisson’s equation to appropriate system of partial differential equations. Then, the model was solved by discrete numerical difference form after normalization of these equations.

2.1. Control equations

The electron continuity control equations [9] is:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \vec{\Gamma}_e = R_e$$

(1)

where \(n_e\) is the electron number density, \(R_e\) is the electron generation and dissipation rate, and \(\vec{\Gamma}_e\) is electron flux.

$$\vec{\Gamma}_e = - \nabla (D_e n_e) + \mu_e n_e \nabla \phi$$

(2)

where \(\mu_e\) is the electron mobility, \(D_e\) is the electron diffusion coefficient and \(\phi\) is potentials.

The electron mean energy can be described as [10]
\[ \frac{\partial}{\partial t} (n_\varepsilon \hat{\varepsilon}) + \nabla \cdot \vec{\Gamma}_\varepsilon = -e \vec{\Gamma}_\varepsilon \cdot \nabla \varphi + e \sum_{i=1}^{f} \Delta \varepsilon_i R_i \]  

where \( \hat{\varepsilon} \) is the electron mean energy, \( e \) is the elementary charge (1.602x10^{-19} \text{ C}) , \( \Delta \varepsilon_i \) is energy loss of single electron in one impact during the impact reaction process, \( R_i \) is the reaction rate of the chemical reaction \( i \) and \( \vec{\Gamma}_\varepsilon \) is the electron mean energy flux[10].

\[ R_i = \int_{0}^{\hat{\varepsilon}} \frac{(\hat{\varepsilon})^{1/2}}{(\hat{\varepsilon})} f(\hat{\varepsilon}) \sigma(\varepsilon)d\varepsilon \]  

\[ \vec{\Gamma}_\varepsilon = n_\varepsilon \hat{\varepsilon} \mu_\varepsilon \nabla \varphi - D_\varepsilon \nabla n_\varepsilon \hat{\varepsilon} \]  

where \( \hat{\varepsilon} \) is the electron mean energy, \( f(\hat{\varepsilon}) \) is the electron energy distribution function (EEDF). In this paper, EEDF was gained from solving the Boltzmann equation by constructing a one-dimensional model based on Comsol Multiphysics[11]. \( \sigma(\varepsilon) \) is the impact section area of the reaction and is determined according to Reference [12] in this paper. \( \mu_\varepsilon \) and \( D_\varepsilon \) are electron mean energy migration rate and the electron mean energy diffusion coefficient[10]:

\[ \mu_\varepsilon = \frac{5}{3} \mu_\varepsilon, \quad D_\varepsilon = \frac{5}{3} D_\varepsilon \]  

The single discharge is very short (generally within hundreds of seconds), during which the influences of particle interaction on particle transport almost could be neglected. Therefore, existing researches on corona discharge simplify the heavy particle transport process. The evolution equation of heavy particles in the discharge process after simplification is:

\[
\begin{align*}
\frac{\partial n_{k+}}{\partial t} &= R_{\text{ion}} + R_{\text{ph}} - R_{\text{rec}}^+ - R_{\text{rec}}^- \\
\frac{\partial n_{k-}}{\partial t} &= R_{\text{rec}}^+ - R_{\text{rec}}^- \\
\frac{\partial n_n}{\partial t} &= R_{\text{rec}}^+ + R_{\text{rec}}^- - R_{\text{ion}} - R_{\text{ph}} - R_{\text{att}} \\
\end{align*}
\]  

where \( n_{k+}, n_{k-} \) and \( n_n \) are positive ions, negative ions and neural particles. \( R_{\text{ion}}, R_{\text{ph}}, R_{\text{rec}}^+, R_{\text{rec}}^- \) and \( R_{\text{att}} \) are reaction rates related with impact ionization, photo ionization, electron-ion, ion-ion and electron adsorptions.

Finally, the Poisson’s equation is:

\[ \varepsilon \nabla^2 \varphi = -e \left( \sum_k n_{k+}^+ - \sum_k n_{k-}^- - n_e \right) \]  

where \( \varepsilon \) is the vacuum dielectric constant.
2.2. Chemical reactions of particles

Tremendous types of particles will be formed in the corona discharge process and the reaction equation is relatively complicated. It is difficult and unnecessary to analyze the reaction between electrons and all particles. Based on our previous researches [7, 13], the micro mechanism of corona discharge is described by particle reactions in Table 1.

| No. | Reaction equation | Reaction rate$^{[11,13]}$ |
|-----|-------------------|--------------------------|
| R1  | $N_2 + e \rightarrow 2e + N_2^+$ | $f(e)$ |
| R2  | $O_2 + e \rightarrow 2e + O_2^+$ | $f(e)$ |
| R3  | $N_2^+ + 2N_2 \rightarrow N_4^+ + N_2$ | $5.0 \times 10^{-41}$ |
| R4  | $N_2^+ + N_2 + O_2 \rightarrow N_4^+ + O_2$ | $5.0 \times 10^{-41}$ |
| R5  | $N_4^+ + O_2 \rightarrow O_2^+ + 2N_2$ | $2.5 \times 10^{-16}$ |
| R6  | $N_4^+ + O_2 \rightarrow O_2^+ + N_2$ | $1.04 \times 10^{-15}T^{0.5}$ |
| R7  | $2N_2 + O_2^+ \rightarrow N_2O_2^+ + N_2$ | $8.1 \times 10^{-38}T^2$ |
| R8  | $N_2O_2^+ + N_2 \rightarrow O_2^+ + 2N_2$ | $14.6T^{5.3}\exp(-2357/T)$ |
| R9  | $N_2O_2^+ + O_2 \rightarrow O_4^+ + N_2$ | $1.0 \times 10^{-15}$ |
| R10 | $O_2^+ + O_2 + N_2 \rightarrow O_4^+ + N_2$ | $2.04 \times 10^{-34}T^{3.2}$ |
| R11 | $O_2^+ + 2O_2 \rightarrow O_4^+ + O_2$ | $2.04 \times 10^{-34}T^{3.2}$ |
| R12 | $O_4^+ + e \rightarrow 2O_2$ | $1.4 \times 10^{-12}(300/T_0)^{0.5}$ |
| R13 | $O_2^+ + e \rightarrow 2O$ | $2.42 \times 10^{-17}(300/T_0)$ |
| R14 | $2O_2 + e \rightarrow O_2 + O_2^+$ | $2.0 \times 10^{-41}(300/T_0)$ |
| R15 | $O_4^+ + O_2^- \rightarrow 3O_2$ | $1.0 \times 10^{-13}$ |
| R16 | $O_4^+ + O_2^- + O_2 \rightarrow 3O_2 + N_2$ | $2.0 \times 10^{-37}$ |
| R17 | $O_4^+ + O_2^- + O_2 \rightarrow 3O_2 + O_2$ | $2.0 \times 10^{-37}$ |
| R18 | $O_2^+ + O_2^- + O_2 \rightarrow 2O_2 + N_2$ | $2.0 \times 10^{-37}$ |
| R19 | $O_2^+ + O_2^- + O_2 \rightarrow 3O_2$ | $2.0 \times 10^{-37}$ |
| R20 | $O + O_2 + N_2 \rightarrow O_3 + N_2$ | $2.5 \times 10^{-46}$ |
| R21 | $O + 2O_2 + O_3 \rightarrow O_3 + O_2$ | $2.5 \times 10^{-46}$ |
| R22 | $e + N_2^+ + N_2 \rightarrow 2N_2$ | $6.07 \times 10^{-34}T_e^{2.5}$ |
| R23 | $2e + N_2^+ \rightarrow N_2 + e$ | $5.65 \times 10^{-27}T_e^{-0.8}$ |
| R24 | $O_2^+ + O^- \rightarrow O + O_2$ | $3.46 \times 10^{-12}T_e^{-0.5}$ |
| R25 | $N_2 + e \rightarrow e + N_2$ | $f(e)$ |
| R26 | $O_2 + e \rightarrow e + O_2$ | $f(e)$ |
| R27 | $O_2 + e \rightarrow O + O^+$ | $f(e)$ |

Due to the neutralization reaction on electrode surface, positive and negative ions are changed into neutral particles on electrode surface through following reactions

$$\begin{align*}
N_2^+ &\rightarrow N_2, \quad N_4^+ \rightarrow 2N_2, \\
O_2^+ &\rightarrow O_2, \quad O_4^+ \rightarrow 2O_2, \\
N_2O_2^+ &\rightarrow O_2+N_2, \quad O_2^+ \rightarrow O_2, \quad O^- \rightarrow 0.5O2
\end{align*}$$

Generally, the electrons generated by photo ionization are far less than those generated by impact ionization. However, the photo ionization can trigger new electron avalanche at the electron avalanche head and facilitate the discharge develop forward. Photo ionization under atmosphere pressure plays an important role in air discharge. Zheleznyak et al. believed that photo ionization in air discharge is the process that photos released when the excited nitrogen molecules ($b^1\Pi$, $b^1\Sigma_u^+$ and $c^1\Sigma_u^+$) attenuate into steady $N_2(x^1\Sigma_g^+)$ are absorbed by oxygen molecules and form oxygen ions.
\[ \text{Equation (9) represents the process that excited nitrogen molecules release photons and hv means releasing photons. Equation (10) represents the photo ionization of oxygen molecules. In this paper, the photo ionization coefficient } S_{ph} \text{ was calculated by Eddington method [15] in this paper:} \]

\[ S_{ph} = \frac{1}{4\pi p + p_g} \int d^3 \hat{r}_i \frac{S_{se}(\hat{r}_i)}{|\hat{r} - \hat{r}_i|} h(|\hat{r} - \hat{r}_i| \cdot p) \]

(11)

where \( \hat{r} \) is the distance between photo radiation and absorption; \( \hat{r}_i \) is the photo ionization source point, \( p_g \) is the attenuation pressure of N2 molecules, \( p \) is gas pressure, and \( h(|\hat{r} - \hat{r}_i| \cdot p) \) is the photo ionization absorption coefficient.

2.3. Boundary conditions

The external circuit and computational domain of negative corona discharge are shown in Fig.1, where radius of curvature of bar electrode is 0.4mm, the radius of plane electrode is 5.0cm, and the bar-plane distance is 3.3mm. The external circuit is composed of DC power supply, capacitance C and protection resistance R. In this model, DC voltage, C and R are -5.0kV, 1.0pF and 5.0kΩ, respectively. The environmental conditions are set \( T=300K \) and \( p=1.0\text{atm} \). The model is solved by the plasma module based on Comsol Multiphysics software. The physical computational domain of corona discharge is simplified into a two-dimensional bar-plane structure through axial symmetric rotation (the dotted frame in Fig.1). The computational domain is divided into 244,884 solving units. The boundary conditions of this model mainly include:

Voltage at the bar end is 5.0kV and the plane electrode has zero potential because of the ground connection. The voltage boundary condition of open boundary is [16]:

\[ \vec{n} \cdot (\vec{E} \nabla \phi) = 0 \]

(12)

Boundaries of electron flux on electrodes are: [16]

\[ \vec{g} \cdot \vec{n} = \frac{1 - \gamma_e}{1 + \gamma_e} \left[ -(2\alpha_e - 1) \mu_e \vec{E} \cdot \vec{n}_e + \frac{1}{2} V_{e,th} \vec{n}_e \right] \]

(13)

The boundary condition of electron mean energy flux that the electron mean energy equation meets at electrode surface is:

\[ \vec{g} \cdot \vec{n} = \frac{1}{3} V_{e,th} \vec{n}_e \]

(14)

where \( \vec{n} \) is normal vector on electrode surface, \( \gamma_e \) is the secondary electron yield coefficient, and \( V_{e,th} = \sqrt{\frac{8kT_e}{m_e}} \) is the electron thermodynamics speed. When the electron flux orients to electrode, \( a_e = 1 \); otherwise, \( a_e = 0 \).

The boundary condition of ion is [16]:
where $\vec{\Gamma}_i$ and $n_i$ are density flux and number density of the particle $i$, $\gamma_i$ is the surface neural reaction coefficient of the particle $i$, and $m_i$ is the weight of the $i^{th}$ type of particles.

At bar tip, suppose the particles before the air discharge are in Gaussian distribution with maximum value of $10^{16} m^{-3}$[17].

$$N_{e,i} = N_{\text{max}} \times \exp\left(-\frac{(r-r_0)^2}{2s_0^2} - \frac{(z-z_0)^2}{2s_0^2}\right)$$

where $N_{\text{max}}=10^{16} m^{-3}, r_0=0\mu m, z_0$ is position of the bar tip, and $s_0=25\mu m$.

![Figure 1 Schematic diagram of the negative corona discharge](image)

3. Results and discussion

3.1. Current waveform of single discharge

The negative corona pulse waveform is shown in Fig.2. It is dark current (uA) at the initial discharge period, which is caused by few space charges in the electrode gap and very high equivalent resistance in the migration area. Current increases to 0.195A quickly during $t_1$-$t_2$. This is mainly because electric field concentrated region is mainly close to the bar electrode during this period. The field-induced ionization generates abundant electrons and positive ions close to the bar electrode, and positive ions make neural reaction (Equation (9)) quickly after gained electrons at the cathode. Subsequently, current begins to decrease during $t_2$-$t_4$. Since abundant charged ions will be produced by adsorption when the electron avalanche moves toward the anode, the internal field formed by ion cloud and
electrons causes distortion of electric field in the electrode gap, thus weakening the field-induced ionization. Only few electrons have to enter into the anode surface in order to keep equilibrium of electric field. Therefore, the current during $t_4 - t_6$ is maintained at about 1mA. In this paper, electronic properties in the negative corona discharge were analyzed by 6 time points ($t_1 - t_6$) in single pulse process.

![Figure. 2 The discharge current waveform in the electrode gap](image)

3.2. Electron mean energy distribution

The electron mean energy determines the reaction rate and energy transfer rate at impact diffusion of electrons and other particles. Studying electron mean energy in corona discharge is conducive to understanding the impact diffusion (ionization and excitation) between electrons and other particles during the corona discharge process and has important significance to reveal the microscopic physical mechanism of streamer discharge. Electron mean energy distribution curves along axis at different discharge moments are shown in Fig.3. “0mm” in the x-axis is the position of ground electrode (anode) and “3.3mm” is the position of bar tip (cathode). The electron mean energy distribution trend in Fig.4 is similar with the electric field distribution trend in negative corona pulse process in the Reference [18]. Obviously, the energy acquisition of electron is accelerated through the electric field. As the discharge process continuous, the distortion of space electric field in the electrode gap caused by space charges is the main cause of changes of electron mean energy. This can explain following phenomena.
in Fig.3: in the initial pulse stage ($t_1$), the electron mean energy mainly concentrated close to the bar electrode, which is determined by the electrode gap structure. As the discharge continues ($t_2$-$t_6$), the maximum of electron mean energy occurs in the field-induced ionization region and the energy decreases, accompanied with the field-induced ionization zone moving toward the anode. This because impact and adsorption reactions will generate plenty of charged ions when the electron avalanche moves toward the anode and the internal field formed by ion cloud and electrons causes electric field distortion in the electrode gap. The electron mean energy close to the anode (0-1mm) increases gradually during $t_1$-$t_6$. This is because electrons arriving at the anode increase continuously and the internal field between the anode and electron avalanche enhances the electric field close to the anode.

3.3. Electron density distribution

![Electron density distribution](image)

**Figure. 4** Electron density distribution along the axis

The electron density distribution along the axis at 6 time points in one corona pulse process is shown in Fig.4. The electron density close to the cathode sheath is approximately 0, because electrons are kept off from the cathode. The maximum electron density at outer layer of the cathode sheath, which is related with the strongest field emission effect close to the bar electrode where has the most concentrated electric fields. In one discharge pulse period, electron density distribution develops toward the anode and the electron density in the electrode gap increases gradually during $t_1$-$t_6$. This is caused by continuous occurrences of impact and ionization reactions as electrons move toward the anode, construction of basic electron avalanche towards the anode, and continuous excitation reactions and ionization reactions.

3.4. Generation and dissipation characteristics of electrons

| Time | The key reactions at different instants |
|------|----------------------------------------|
| $t_1$ | R₁, R₂, R₃, R₇ R₁₀ R₂₂, R₈... |
| $t_2$ | R₁, R₂₂, R₂, R₇, R₁₀, R₃, R₈... |
| $t₃$ | R₁, R₂, R₂₂, R₇, R₃, R₁₀, R₈... |
| $t₄$ | R₂, R₁, R₂₂, R₇, R₈, R₁₀, R₁... |
| $t₅$ | R₂, R₁, R₂₂, R₇, R₈, R₁₀, R₁... |
| $t₆$ | R₁, R₂₂, R₂, R₇, R₈, R₁₀, R₃... |
Fig. 5 Chemical reaction rates of main particles at different time points: (a) $t_1$, (b) $t_2$, (c) $t_3$, (d) $t_4$, (e) $t_5$, (f) $t_6$ ("+" is production process of electrons and "-" is the diffusion process of electrons. The unit of monomer reaction rate constant is $s^{-1}$, the unit of disome impact rate constant is $m^3s^{-1}$, and the unit of trisomy impact rate constant is $m^6s^{-1}$.)

It can be known from Table 1 that $R_1$, $R_2$ and $R_{17}$ are the three key reactions in the whole pulse discharge process. The first two represents impact ionization reactions related with $N_2$ and $O_2$ and are the main process of electron reproduction. The reaction rates of $R_1$ and $R_2$ are almost constant throughout the discharge process (Fig.5). $R_{17}$ is the composite reaction involving $N_2$, $N_2^+$ and electrons and occupies absolute advantages in electron diffusions. This is because the ionization threshold energy (12.06 eV) of $O_2$ is lower than that (15.6 eV) of $N_2$, thus inhibiting the impact ionization of $N_2$. In addition, $R_6$ and $R_7$ are charge transfer reaction containing position $N$ ions and have relatively higher reaction rate. This is why positive ions containing $O$ have far higher content than position ions containing $N$ in the electrode gap throughout the negative corona discharge process[17]. Electron production and diffusion rate at different time points are shown in Fig.5.

Development trend of electric field intensity under same bar-plane electrodes with time was computed in Reference [16], finding that electron production and diffusion mainly concentrated in field-induced ionization region, because electric field attenuation also concentrated in this region. In the early pulse stage, particle reaction increases to the maximum during $t_1$-$t_2$. In this period, abundant electrons and ions will be produced, bringing a sharp rising edge of discharge current. Subsequently, the electric field amplitude of field-induced ionization region reduces during $t_2$-$t_5$ and the particle reaction rate decreases gradually. At the end of single pulse period ($t_6$), aerial drainage will occur in the bar-plane gap, thus making the electrode gap recover to neutral quickly. This causes serious distortion of field intensity in the electrode gap, manifested by an abnormal growth trend of particle reactions in the whole gap.

4. Conclusion

1) In the early pulse period, electron mean energy mainly concentrate at places close to the bar electrode. The maximum electron mean energy occurs at the field-induced ionization region and
moves toward the anode as the discharge continues, accompanied with reduction of energy. In addition, the electron mean energy close to the anode increases gradually.

2) The electron density in cathode sheath is approximately 0 and achieves the maximum at outer layer of the cathode sheath. In one discharge pulse period, electron density distribution develops toward the anode as the discharge continues and the electron density in the electrode gap increases gradually.

3) $R_1$, $R_2$ and $R_{17}$ are the three key reactions in the whole pulse discharge process. The first two represents impact ionization reactions related with $N_2$ and $O_2$ and are the main process of electron reproduction. The reaction rates of $R_1$ and $R_2$ are almost constant throughout the discharge process. $R_{17}$ is the composite reaction involving $N_2$, $N_2^+$ and electrons and occupies the absolute advantages in electron diffusions.

References

[1] Du Hongliang, He Liming, Ding Wei, at el. Calculation of non-equilibrium plasma under air discharges [J]. High Power Laser and Particle Beams, 2011, 23(4): 1077-1081(in Chinese).

[2] Fofana I, Beroual A. A model for long air gap discharge using an equivalent electrical network [J] IEEE Transactions on Dielectrics Electrical and Insulation, 1996, 3(2): 273-282.

[3] d’Agostino R, Favia P, Oehr C, at el. Low-temperature plasma processing of materials: Past, present, and future [J]. Plasma Processes and Polymers, 2005, 2(1): 7-15.

[4] Nahorny J, Ferreira C M, Gordiets B, at el. Experimental and theoretical investigation of a N2-O2 DC flowing glow discharge [J]. Journal of Physics D: Applied Physics, 1995, 28(4): 738-747.

[5] Pancheshnyi S V, Starikovskii A Y. Two-dimensional numerical modelling of the cathode-directed streamer development in a long gap at high voltage [J] Journal of Physics D: Applied Physics, 2003, 36(21): 2683-2691.

[6] Liu X H, He W, Yang F, Wang H Y, et al. Numerical simulation and experimental validation of direct current air corona discharge under atmospheric pressure [J]. Chinese Physics B. 2012, 21(7): 075201.

[7] Antao D S, Staack D A, Fridman A, et al. Atmospheric pressure dc corona discharges: operating regimes and potential applications [J]. Plasma Sources Science and Technology, 2009, 18: 035016.

[8] Georghiou G E, Papadakis A P, Morrow R, et al. Numerical modelling of atmospheric pressure gas discharges leading to plasma production[J] Journal of Physics D: Applied Physics, 2005, 38(20): R303-R328.

[9] Li C, Ebert U, Hundsdoerfer W. 3D hybrid computations for streamer discharges and production of runaway electrons [J]. Journal of Physics D: Applied Physics, 2009, 42(20): 202003.

[10] Liu Xinghua, He Wei, Yang Fan, et al. Simulation and analysis of electron transport parameters in air discharge [J]. High Voltage Engineering, 2011, 37(7): 1614-1619.

[11] Y. Itikawa. Cross sections for electron collisions with oxygen molecules [J]. J. Phys. Chem. Ref. Data, 2009, 38: 3025886.

[12] Zheleznyak M B, Filimonova E A, Simulation of a gas-Phase chemical reactor for removal of toxic impurities, based on the use of a pulsed streamer discharge [J]. High Temperature, 1998, 20 (4): 533-540.

[13] Segur P, Bourdon A, Marode E, et al. The use of an improved Eddington approximation to facilitate the calculation of photoionization in streamer discharges [J]. Plasma Sources Science and Technology, 2006, 15(4): 648-660.

[14] Simulation of dc atmospheric pressure argon micro glow-discharge [J]. Plasma Sources Science and Technology, 2006, 15(4): 676-688.

[15] Tran T, Golosnoy I O, Lewin P L, et al. Numerical Modelling of Negative Discharges in Air with Experimental Validation [J]. Journal of Physics D: Applied Physics, 2011, 44(1): 015203.
[16] Liao R J, Wu F F, Yang L J, et al. Investigation on Microcosmic Characteristics of Trichel Pulse in Bar-plate DC Negative Corona Discharge based on a Novel Simulation Model [J]. International Review of Electrical Engineering, 2013, 8(1): 504-413.

[17] Sima W X, Peng Q J, Yang Q, et al. Study of the characteristics of a streamer discharge in air based on a plasma chemical model [J]. IEEE Transactions on Dielectrics Electrical and Insulation, 2012, 19(2): 660-670.