Negative Corona Discharge Characteristics in Atmospheric Pressure and the Influence of Detachment on It

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Abstract. Detachment refers to the process in which negative ions react with neutral particles to produce electrons. The theory of negative glow corona is reviewed by probing the influence of detachment. In this paper, a numerical simulation model of fluid dynamics for atmospheric coaxial cylindrical corona discharge is established. We simulate the negative corona discharge in two cases: considering detachment and not considering detachment. By comparing the results, we show the importance of detachment to the corona discharge. The results show that if the influence of detachment is ignored, the generation rate of electrons in the ionization region will be underestimated, resulting in the underestimation of the peak value of positive and negative ions and electron density. And the amplitude of the electric field and current peak value of the wire surface will be smaller. Meanwhile, the consumption rate of negative ions will be underestimated, resulting in a longer pulse period and deviation from the real results. Therefore, it is necessary to consider the detachment in the simulation of atmospheric corona discharge for the accuracy of the simulation.

Keywords: Negative corona discharge · Detachment · The Trichel pulse · Electric field distribution

1 Introduction

Corona discharge is a common form of discharge in industry, which has a broad impact on social production. On the one hand, Corona discharge produces plasma [1], which has good applications in the fields of plasma medicine [2] and environmental governance [3–5] due to its stability and convenience. For example, in the disposal of oil pollution, the active material produced by corona discharge plasma attaches to petroleum hydrocarbons, which will promote their degradation. On the other hand, Corona discharge causes power loss and a series of electromagnetic environmental problems, such as radio interference, audible noise and the surge of reduced electric field [6].

The regular current pulses that occur during negative corona discharge is known as the Trichel pulse, whose periodicity is caused by the generation and disappearance of space charge in discharge. The discharge process can be simulated macroscopically with a fluid model. There are many scholars who have obtained the Trichel pulse by fluid

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model simulation. Zhuang et al. proposed a fluid model simulation of the wire plate electrode for negative discharge to obtain the Trichel pulse. The results were in good agreement with a designed experiment in the laboratory, which provided a reference for analyzing the transient process of corona on transmission lines [7]; He et al. proposed a coaxial cylindrical electrode fluid model and discussed the change of electric field, electron density and negative ion density during the pulse, illustrating the effect of space charge on the synthesized field [8]. However, these traditional fluid models only considered ionization, attachment, and recombination. The effect of detachment was neglected.

Detachment refers to the process in which negative ions react with neutral particles to produce electrons. It will have an effect on the space charge density in the discharge area. Consideration for detachment was first proposed by Morrow. He proposed that the seed electrons required for continuous pulses were mainly provided by detachment of metastable oxygen molecules with negative ions [9]. Then, Liu et al. used a coaxial cylindrical electrode structure and mainly considered the detachment of O2−, extending Morrow's proposed model to two dimensions. It was found that the discharge current suddenly increased by more than two orders of magnitude when streamers with filamentary structures appeared [10]. Furthermore, He et al. proposed a chemical-fluid model and compared it with the model built by Liu Lipeng. The results showed that the model with the averaged kinetic scheme (AKS) underestimated the detachment that played an important role in the positive glow corona discharge.

The above studies are all for the positive glow corona model. However, little research has been done for detachment in the negative corona. Compared to positive corona, negative corona discharge is dominated by negative ions, since positive ions will disappear rapidly from the electrode surface after being generated. Therefore, detachment in a negative corona mainly affects the generation and disappearance of space charges, which differs from its primary role in maintaining discharge in positive corona. In this paper, we proposed a fluid model that considers positive and negative ions and electrons. An infinitely long coaxial cylindrical electrode corona discharge model was developed to simulate separately with and without detachment. The effect of detachment on the negative corona discharge is illustrated by comparing the electric field strength at the wire surface, current, and particle distribution.

2 Model Description

2.1 Circuit Structure and Environment Setting

The corona discharge model is shown in Fig. 1, where the discharge area is an infinitely long coaxial cylindrical electrode with an internal solid wire radius of 0.5 mm. The applied voltage is −24 kV, and the radius of the ground outer electrode is 20 cm. Since it is symmetrical, the one-dimensional model is used to simplify the discharge model. In order to simplify the calculation, we set the artificial boundary at 1 cm [15]. The discharge occurs at ambient temperature and atmospheric pressure. The gas in the gap is air.

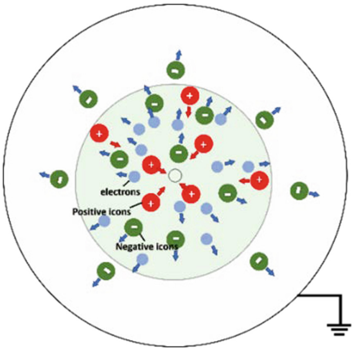


Fig. 1. Schematic diagram of circuit structure

2.2 Governing Equations

In this study, a fluid model was constructed with the consideration of detachment. The Poisson equation is solved to describe the effect of space charge on the electric field intensity. The continuity equation is solved to describe the generation, disappearance and transport of positive ions, negative ions and electrons. By coupling the Poisson equation with the continuity equation, the discharge process of coaxial cylindrical electrode can be numerically simulated [10].

$$\nabla^2\varphi = -e(N_p - N_n - N_e)/\varepsilon \tag{1}$$

$$\nabla\varphi = -E \tag{2}$$

The Poisson equation is shown above. Where ε is the permittivity of air. *e* is the charge of an electron. φ is the electric potential. E is the electric field vector. The potential distribution can be calculated from the charge distribution. Then, the electric field strength distribution can be obtained from the potential distribution.

The continuity equation of each particle is solved according to the reaction source term and transport in the discharge process. It involves the ionization and attachment of electrons and neutral particles, the combination of electrons and positive ions, and the detachment of negative ions and neutral particles. For positive ions, ionization and recombination are considered. For negative ions, attachment, recombination, and detachment are considered.

$$\partial N_\mathrm{e}/\partial t = (\alpha - \eta)N_\mathrm{e}|W_\mathrm{e}| - \beta N_\mathrm{e}W_\mathrm{e} + K_dN_n - \nabla(N_\mathrm{e}W_e) \tag{3}$$

$$\partial N_n/\partial t = \eta N_\mathrm{e}|W_\mathrm{e}| - \beta N_\mathrm{n}W_\mathrm{p} - K_dN_n - \nabla(N_\mathrm{n}W_n) \tag{4}$$

$$\partial N_\mathrm{p}/\partial t = \alpha N_\mathrm{e}|W_\mathrm{e}|| - \beta(N_\mathrm{n} + N_\mathrm{e})N_p - \nabla(N_\mathrm{p}W_\mathrm{p}) \tag{5}$$

Ne, *Np*, and *Nn* are the densities of electrons, positive ions, and negative ions, respectively. α is the ionization coefficient and η is the attachment coefficient. They are used to describe the intensity of ionization and attachment under different electric field strengths. β is the recombination coefficient, which is independent of the electric field strength. *Kd* is the detachment rate coefficient. Since negative ions mostly react with stable background gas to generate electrons, the detachment rate coefficient characterizes the ability of negative ions to detach electrons. *Wi* is the velocity vector of the corresponding substance, determined by the mobility and the electric field strength of the spatial location. The specific calculation of the relevant parameters is shown below [13].

$$W_i = E\mu_i \tag{6}$$

$$\beta = 2.2 \times 10^{-12} \tag{7}$$

$$\eta = 9.865 \times 10^2 - 5.41 \times 10^{-4}|E| + 1.145 \times 10^{-10}|E|^2 \tag{8}$$

$$\alpha = \begin{cases} 3.632 \times 10^5 \times e^{-1.68\times10^7/E} & |E| \le 4.56 \times 10^6 V/m \\ 7.356 \times 10^5 \times e^{-2.01\times10^7/E} & |E| \ge 4.56 \times 10^6 V/m \end{cases} \tag{9}$$

According to values for the detachment rate coefficient taken by previous scholars, we take the *Kd* value as 1×10^5 orders of magnitude [14, 15]. The finite element method is applied to solve the fluid model. The simulation stops after obtaining the regular pulse.

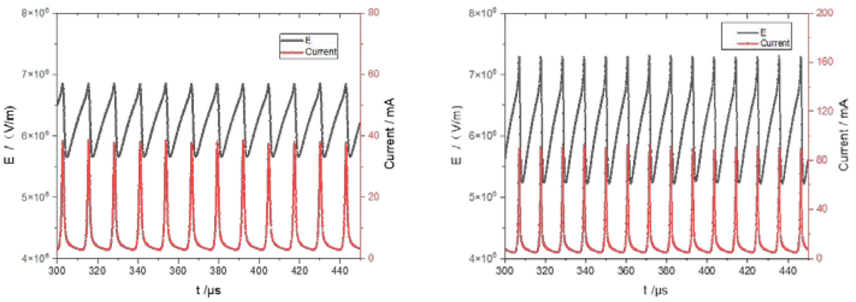
3 Simulation Results and Analysis

3.1 Characteristics of Trichel Pulse

Figure 2 shows the variation of simulated current and simulated electric field on the wire surface. The results show that the current pulse has a relatively short rising edge and duration, and it occurs again after a long dead time. The amplitude of each current pulse is almost the same, which seems relatively regular, exhibiting the typical characteristics of Trichel pulse. Analyzing the features of the current pulse, we can observe that the simulation results conform to the characteristics of negative corona discharge. The pulse period of the electric field on the wire surface is consistent with the current pulse period. The value of electric field accumulates continuously during the dead time of the current pulse, and then drops sharply in the meantime when the current falling edge occurs. Since the discharge near the wire surface is intense, the variation of the electric field on the wire surface can basically represent the overall electric field in the ionization region. Therefore, the pulse discharge can be represented by the electric field on the wire surface.

The pulse discharge period studied in this paper starts when the electric field on the wire surface reaches the trough. In a period, the electric field on the wire surface rises slowly and then drops sharply before the next period begins. The electric field on the wire surface is affected by the space charge. After the collision ionization and attachment in the ionization zone, a large number of positive and negative ions are generated, which will distort the electric field near the cathode. Whereas the positive ions are closer to the cathode surface and have higher density, they tend to have a stronger impact on the electric field distortion on the cathode surface, which leads to a sharp increase on the electric field; When the positive ions collide with the cathode surface and disappear, the electric field on the conductor surface will also drop sharply. However, when the reactions of the ionization zone become weak, the influence of positive ions on the surface field strength of the conductor becomes little. The electric field strength of the wire surface is mainly affected by the inhibition of the negative ions that are gradually away and run out. As negative ions lose inhibition gradually, the electric field strength presents a slowly rising trend.

The detachment mainly affects the distribution of negative ions. When the detachment is considered in the simulation, the current amplitude will increase and the period will be shortened, corresponding to the increase in the amplitude and decrease of the period length of the electric field on the wire surface.



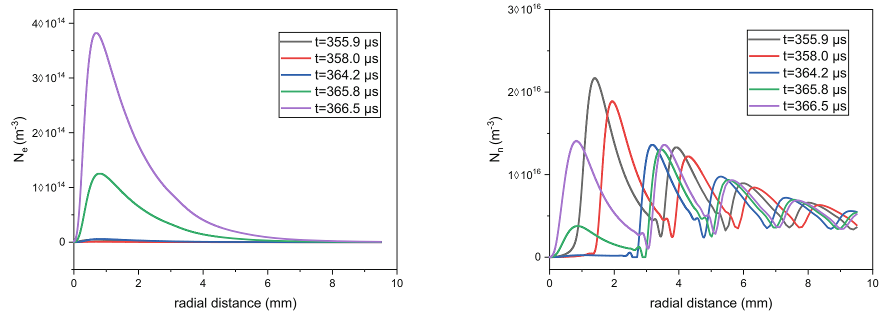
(a) Model without detachment (b) Model with detachment

Fig. 2. Trichel pulse characteristics

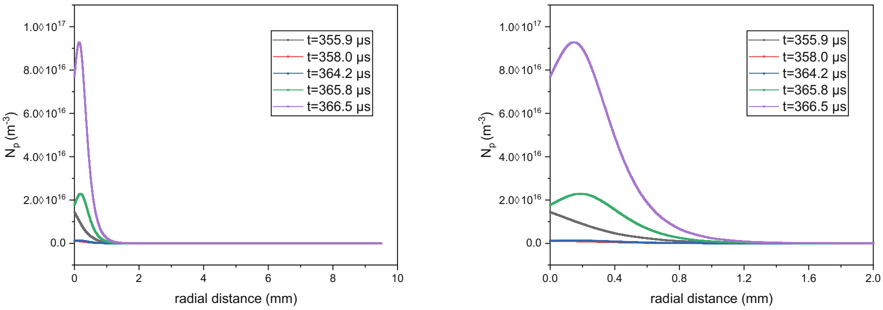
3.2 The Distribution of Particles in a Single Period and the Effect of Detachment

The period of the discharge model without detachment starts at 355.9 μs and ends at 368.7 μs. While the period of the model with detachment starts at 362.3 μs and ends at 373.1 μs. Select five moments with typical characteristics to describe the changes of positive and negative ions and electrons in a period discharge process. These moments will be further illustrated in the next section.

Figure 3 shows the changes of the radial number density distribution of each particle in a period in the model without detachment. After the field strength trough arrives, each reaction stagnates. Since a large number of electrons come from the ionization zone, the electron density reaches a peak near the ionization zone, but the value of density is diminutive; Positive ions collide with the cathode and they gradually run out; Negative ions mainly accumulate outside the ionization zone. There are almost no negative ions in the ionization zone. Then, the negative ions gradually move away from the cathode, decreasing with the progress of recombination. When the electric field strength in the ionization zone reaches a certain value, the electron ionization rate increases sharply. Due to the different migration directions of positive ions and electrons, the peak of positive ion density appears near the cathode in the ionization zone. These positive ions distort the electric field near the cathode, resulting in a sharp increase on the surface field strength of the cathode; Whereas the peak of electron density appears in the outer region of the ionization zone, a large number of negative ions are generated by attachment at the same position. At this stage, the density of positive and negative ions and electrons and the surface field strength of the wire reach their peak value almost simultaneously. As the positive ions begin to collide with the cathode, the field strength in the ionization zone drops rapidly, and all reactions come to a standstill. Due to the large specific charge, the electrons rapidly migrated away from the ionization region under the effect of the electric field force. Due to the concentration of the positive ions, they quickly collide with the cathode and run out. There are almost only negative ions left in the space. They slowly move away from the cathode, and gradually depleted.



(a) Electron distribution (b) Negative ion distribution

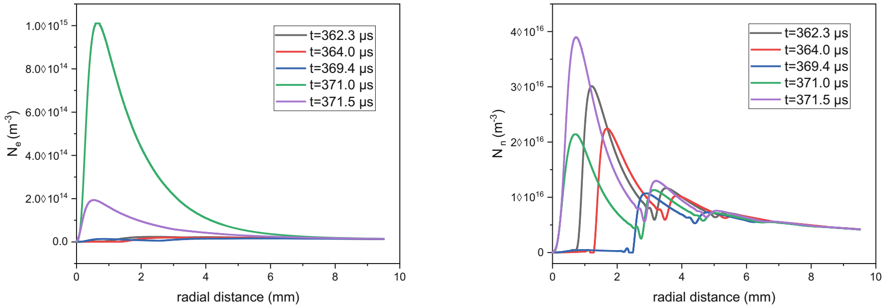


(c) Positive ion distribution(complete) (d) Positive ion distribution(detailed)

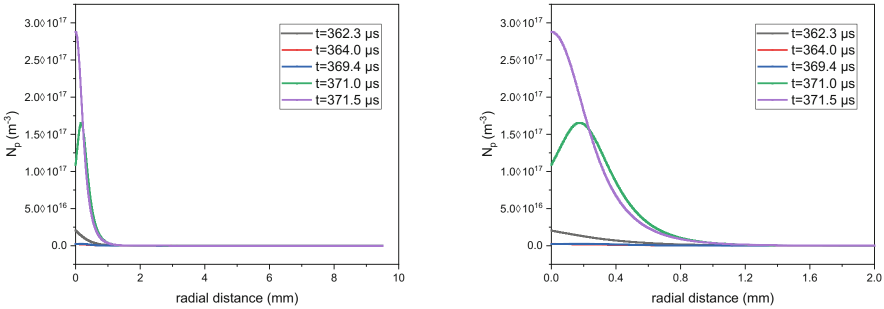
Fig. 3. Spatial distribution of positive and negative ions and electron densities (the model without detachment)

Figure 4 shows how positive and negative ions and electrons change in a period in the model with detachment. After the field strength trough arrives, each reaction stagnates. Since the detachment greatly accelerates the loss of negative ions, the negative ions rapidly come to a lower level not far from the ionization zone. Compared with the model without detachment, the electric field intensity in the ionization zone reaches a higher level in advance, shortening the period length. When the ionization zone gets into the active state, the electrons generated by the detachment are positive feedback to the collision ionization to generate a large number of electrons. More positive ions are generated at the same time, which will make the electric field strength near the cathode greater. As a result of great electric field strength, the generation of positive and negative ions is more intense, thus accelerating the reaction rate, which makes the peaks of positive and negative ions and electrons higher.

Compared with the model without detachment, the peak of positive ion density increased to 3.10 times, the peak of negative ion density increased to 2.78 times, and that of electron density increased to 2.65 times.



(a) Electron distribution (b) Negative ion distribution



(c) Positive ion distribution(complete) (d) Positive ion distribution(detailed)

Fig. 4. Spatial distribution of positive and negative ions and electron densities (the model with detachment)

3.3 Cathode Surface Field Strength Change in a Single Period and the Effect of Detachment

Given the discharge process is closely related to the wire surface field strength, the following analysis of the discharge process will be based on the fluctuation period of the wire surface field strength as a complete stage to explore the relationship between the positive, negative ions and the electron density and the cathode surface field strength, so as to illustrate the impact of the detachment.

Figure 5 shows the change of the electric field intensity on the cathode surface in a period in the discharge model without detachment. At 355.9 μs, the electric field intensity reaches the valley, and only a small number of positive ions remain in the ionization zone, which hasn't collided with the cathode. The negative ions gradually move away from the cathode and the electric field strength begins to rise. Since the electric field intensity is too low, all reactions will stagnate. Almost no new particles are produced in the ionization zone. At 358.0 μs, the positive ions in the ionization zone run out. Since then, the negative ions gradually move away from the cathode and slowly recombine with a small number of positive ions. The electric field strength gradually increases. At 364.2 μs, the electric field strength reaches a certain level, and the collision ionization rate of electrons begins to increase sharply, producing a large number of electrons and positive ions. At the same time, due to the increase in electron density, the attachment rate of electrons and neutral particles increases, A large number of negative ions begin to be generated outside the ionization zone. In contrast, the reaction rate of electron collision ionization is higher than the level of negative ion density, which makes the positive ion density rise faster. At the same time, due to the closer distance to the ionization region, the distortion of the electric field in the ionization region is greater. At 365.8 μs, the electron density is relatively high. The gain of positive ions on the electric field strength in the ionization region also reaches a higher level. The collision ionization reaction is further accelerated and continues to promote the attachment, producing more positive and negative ions and electrons. The electric field strength shows a trend of sharp increase. At 366.5 μs, some positive ions collide with the cathode surface and emit electrons. Due to the violent and short-lived collision process of high-density positive ions, the electric field intensity in the ionization region begins to drop rapidly. At 368.7 μs, only a small number of positive ions haven't collided with the cathode, which makes the electric field intensity reaches the trough again.

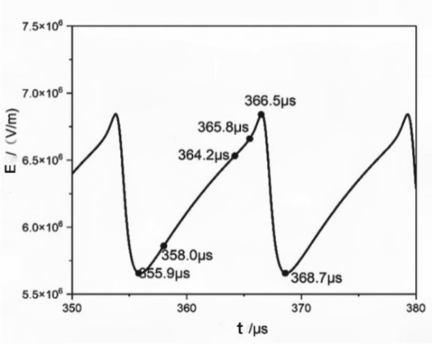


Fig. 5. Cathode surface electric field strength (the model without detachment)

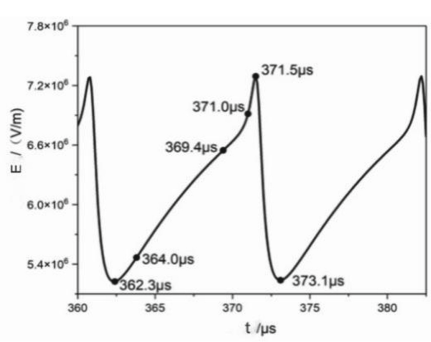


Fig. 6. Cathode surface electric field strength(the model with detachment)

Figure 6 shows the change of the electric field intensity on the cathode surface in a period in the discharge model with detachment. At 362.3 μs, the electric field strength reaches the valley value. Since more negative ions were generated in the previous period, the electric field strength will be lower than that without the detachment. At 364.0 μs, the positive ions run out. After that, in addition to gradually moving away from the cathode and slowly recombining with a small number of positive ions, the electrons will also detach from the negative ions. It greatly increases the loss rate of the negative ion density while improving the electron density. Therefore, the electric field strength will increase at a higher rate, which will advance the stage of violent reaction. At 369.4 μs, positive and negative ions and electrons begin to generate in large quantities. At 371.0 μs, the electric field strength begins to rise sharply. At this time, the electric field intensity has been high. The collision ionization rate of electrons has reached a high level, producing a large number of electrons and positive ions. As the electron density increases, the attachment rate of electrons and neutral particles increases. A large number of negative ions are generated in the area with high electron density. The generated large number of negative ions will have a violent detachment with the neutral ions, which will consume part of the negative ion density and continuously increase the electron density. This process will positively feedback on the collisional ionization of electrons, significantly increasing the electron density and positive ion density. Due to the further increase of electron density, the attachment between electrons and neutral particles is intensified, resulting in a large number of negative ions. On the other hand, due to the higher density of positive ions, the distortion effect on electric field intensity is also stronger, and greater electric field intensity is generated in the ionization region. The great electric field intensity also helps to improve the rate of various reactions and increase the density of positive, negative ions and electrons. Therefore, in the ionization region with large field strength, the gain of negative ion density brought by the detachment will be greater than the loss of negative ion density in the detachment. After considering the detachment, the reaction rates will be improved, the positive and negative ions and electron densities will be higher, and a higher maximum density will be generated at the same time. At 371.5 μs, a large number of positive ions collided with the cathode, and the electric field strength began to decline. The electric field intensity has a higher peak due to the higher density of positive ions after detachment. At 373.1 μs, only a small number of positive ions have not yet collided with the cathode, and the electric field strength quickly reaches the valley. Since the negative ion density is higher after considering the detachment, the valley value of the electric field strength is also lower.

After considering the detachment, the discharge period is reduced from 12.8 μs to 10.8 μs. The period is only 84.4% of the previous one.

3.4 The Current Change in a Single Period and the Effect of Detachment

Figure 7 shows the changes of current in the two models. The pulse period of the electric field on the wire surface is consistent with the current pulse period. Considering detachment, the period of the current is shortened. In addition, the peak value of the current will increase significantly. Since the directional movement of positive and negative ions and electrons generates the current, the significant increase in their peak density will cause a significant increase in the peak current.

Compared to the model that does not consider detachment, the peak current in this model is 2.4 times higher. Additionally, the gain factor of the current peak is close to the density gain of each particle, which justifies the model.

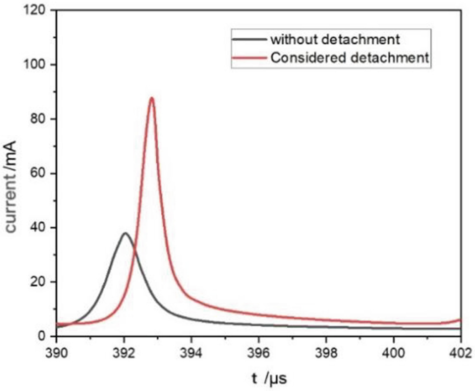


Fig. 7. Comparison of currents in a single period between the two models

4 Conclusion

For negative corona discharge with coaxial cylindrical electrode structure, a fluid model was constructed to analyze the discharge process and the influence of detachment. Compared with the traditional fluid model without the detachment, the model considering the detachment shows differences in the spatial distribution of particles, the electric field intensity waveform on the wire surface and the current waveform.

In the process of negative Trichel pulse discharge, the negative ions mainly have an inhibitory effect on the electric field. The consideration of detachment makes the negative ions not only move away from the cathode surface under the action of the electric field, but also makes their density continuously depleted in the process of migration. Some of the negative ions are detached into neutral particles and electrons. As a result, the density of negative ions outside the ionization region is lower in the model with detachment. Therefore, compared with the traditional model, when negative ions leave, the inhibition on the electric field intensity strengthens, the pulse period shortens. Apart from this, due to the addition of the electron source, the particle activity in the ionization region becomes more intense. During this period, the positive and negative ions together with electron production are higher than that in the traditional model. As a consequence, the peak value of the field intensity on the wire surface is increased, while the peak value of the current within the period is also greater. Compared with the traditional model, more residual negative ions also make the trough of the electric field on the wire surface lower, which makes the electric field peak on the wire surface larger.

It can be seen that if the influence of detachment is ignored, the generation rate of electrons in the ionization region during the period of high field intensity will be underestimated. This could lead to our underestimation of the peak number of particles. Additionally, the amplitude of the field intensity as well as the peak current of the wire surface will be smaller. As a result, the consumption rate of negative ions will be underestimated, and the pulse period will be longer. All of this will deviate from the real results.

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