A MODEL FOR PHOTOIONIZATION PRODUCED BY NEGATIVE CORONA PLASMA IN AIR

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Abstract: This paper presents a numerical model for the photoionization produced by the negative corona plasma in the vicinity of cylindrical electrodes based on the general fluid model. Of important is the total photons in the ionization zone responsible for photoionization are considered, which takes advantages of the classic geometric factor for cylindrical electrodes and the wavelength of energetic photons together. The effects of photoionization on the negative corona plasma are investigated for a wide range of conductor radii, relative air densities, and total corona currents. The process of photoionization should be considered for the negative corona plasma in air at low relative air densities.

1 INTRODUCTION

The corona discharge has been extensively used as a source of excited or charged particles [1]. It can be found in electrostatic precipitators, photocopiers, jet printers, etc. New applications also can be found for gas treatment, surface processing, as well as corona enhanced chemical vapor deposition. The corona induced effects also should be limited in some occasions, such as the high voltage transmission lines.

The dc corona discharges in air can produce the energetic electrons in the vicinity of the high stressed electrode or the drifted ions full of almost the whole interelectrode gap. At the threshold, the negative corona discharge is random and irregular in time. With the increase of the applied voltage, a quasi-static negative corona plasma layer can be achieved around a cylindrical electrode [2].

The quasi-static negative corona plasma in air on smooth conductors is always investigated by a general fluid model, which contains the continuity equations of electrons, positive ions and negative ions coupled with Poisson's equation or Guass's equation [2-4]. However, the process of photoionization has never been considered during the secondary electron emission in space for the negative corona plasma in air.

This paper presents a numerical model for photoionization produced by the negative corona plasma in the vicinity of cylindrical electrodes based on the general fluid model. Of important is the total photons in the ionization zone responsible for photoionization are considered, which takes advantages of the classic geometric factor for cylindrical electrodes and the wavelength of energetic photons together. The effects of photoionization are investigated for a wide range of conductor radii, air densities, and total corona currents.

2 NUMERICAL MODEL

A set of governing equations for the negative corona plasma in air, which considers the process of photoionization, is given by:

$$\frac{\mathrm{d}(rn_\mathrm{e}\mu_\mathrm{e}E)}{r\mathrm{d}r} = (\alpha-\eta)n_\mathrm{e}\mu_\mathrm{e}E + S \quad (1)$$

$$\frac{\mathrm{d}(rn_\mathrm{p}\mu_\mathrm{p}E)}{r\mathrm{d}r} = -\alpha n_\mathrm{e}\mu_\mathrm{e}E - S \quad (2)$$

$$\frac{\mathrm{d}(rn_\mathrm{n}\mu_\mathrm{n}E)}{r\mathrm{d}r} = \eta n_\mathrm{e}\mu_\mathrm{e}E \quad (3)$$

$$\frac{\mathrm{d}(rE)}{r\mathrm{d}r} = -\frac{e(n_\mathrm{p}-n_\mathrm{n}-n_\mathrm{e})}{\varepsilon_0} \quad (4)$$

where: r is the radial position; n_e, n_p and n_n are the densities of electrons, positive ions and negative ions, respectively; μ_e, μ_p and μ_n are the mobilities of electrons, positive ions and negative ions, respectively; E is the electric field intensity; α and η are the electron ionization and attachment coefficients, respectively; ε_0 is the permittivity in vacuum; e is the elementary charge; S is the source term due to pnotoionization. Different from the general fluid model, the source term S is considered in (1) and (2).

The wavelength of the radiation produced by corona discharges in air is about between 980-1025 Å [5]. The photoionization term is evaluated by:

$$S(r) = \frac{\xi}{r}\frac{\delta_\mathrm{q}}{\delta+\delta_\mathrm{q}}\int_{r_0}^{r_\mathrm{m}} \alpha n_\mathrm{e}\mu_\mathrm{e}Ef\left(|r'-r|\right)g(r)r'\mathrm{d}r' \quad (5)$$

where: ξ = 0.1 [6], which is a proportionality factor; δ_q = 0.04, corresponding to the quenching pressure 30 Torr; δ is the relative air density; $\delta_\mathrm{q}/(\delta_\mathrm{q}+\delta)$ is the quenching factor; f is the absorption function by

Zheleznyak *et al*. [5]; g is the geometric factor; r' is a dummy integration variable; r_0 is the conductor radius; r_m is the outer boundary of the corona plasma region. In this paper, r_m is a moveable boundary, which is decided when its value has insignificant effect on the results. The relative air density is given by:

$$\delta = (P/P_0)/(T/T_0) \tag{6}$$

where: P is the air pressure; T is the temperature in K; P_0 = 760 Torr; T_0 = 293 K. The absorption function is given by [5]:

$$f(\rho) = \frac{\exp(-\kappa_1\delta\rho) - \exp(-\kappa_2\delta\rho)}{\rho\ln(\kappa_2/\kappa_1)} \tag{7}$$

where: κ_1 = 5.6 cm^{-1}; κ_2 = 320 cm^{-1}; ρ is the distance from the emission point. The geometric factor g is the product of the radial geometric factor g_{rad} and the axial geometric factor g_{ax} by [7]:

$$g(r) = g_{\mathrm{rad}}(r) g_{\mathrm{ax}}(r) \tag{8}$$

where:

$$g_{\mathrm{rad}}(r) = \begin{cases} \displaystyle\int_0^{\pi - \sin^{-1}(\frac{r_0}{r'})} \frac{f\left(\left|r'\cos\theta - \sqrt{r^2 - r'^2\sin^2\theta}\right|\right)}{\pi f(|r'-r|)} \mathrm{d}\theta \\ \text{for} \quad r_0 < r < r' \\ \displaystyle\int_0^{\sin^{-1}(\frac{r}{r'})} \frac{f\left(\left|r'\cos\theta - \sqrt{r^2 - r'^2\sin^2\theta}\right|\right)}{\pi f(|r'-r|)} \mathrm{d}\theta \\ \text{for} \quad r < r' < r_{\mathrm{m}} \end{cases} \tag{9}$$

$$g_{\mathrm{ax}}(r) = \int_0^{\frac{\pi}{2}} \frac{2f(|r'-r|/\cos\varphi)}{\pi f(|r'-r|)} \mathrm{d}\varphi \tag{10}$$

Here, θ and φ are radial and axial angles, respectively. The relationship between all the parameters in (9) and (10) is shown in Figure 1. The configuration of the electrode is considered by the geometric factor.

The boundary conditions for (1)-(4) are similar as those for the general fluid model. Accordingly, the boundary conditions for charges particles are:

$$n_{\mathrm{e}}(r_0) = \frac{I - 2\pi r_0 e n_{\mathrm{p}}(r_0)\mu_{\mathrm{p}}(r_0)E(r_0)}{2\pi r_0 e \mu_{\mathrm{e}}(r_0)E(r_0)} \tag{11}$$

$$n_{\mathrm{p}}(r_{\mathrm{m}}) = 0 \tag{12}$$

$$n_{\mathrm{n}}(r_0) = 0 \tag{13}$$

where: I is the total corona current without photoionization. Based on Kaptzov's assumption [2], the boundary condition for (4) is resulting from

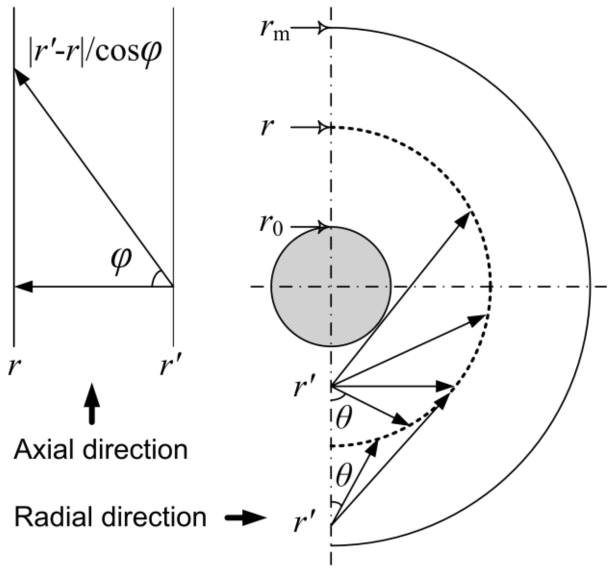

Figure 1: Diagram for the propagation of photons in the radial and axial directions from an arbitrary avalanche in a negative corona plasma on the smooth conductor

Peek's formula for coaxial cylinders by [8]:

$$E(r_0) = 31.0(\delta_0 + 0.308/\sqrt{\delta_0 r_0}) \tag{14}$$

where: δ_0 is the relative air density with a reference temperature T_0 of 298 K.

The transport properties in air should be associated with the relative air density. The electron ionization and attachment coefficients are given by [3]:

$$\frac{\alpha}{\delta} = \begin{cases} 3632\exp(-168.0\dfrac{\delta}{E}) & \text{for} \quad \dfrac{E}{\delta} \le 45.6 \\ 7358\exp(-200.8\dfrac{\delta}{E}) & \text{for} \quad \dfrac{E}{\delta} > 45.6 \end{cases} \tag{15}$$

$$\frac{\eta}{\delta} = 9.865 - 0.541\frac{E}{\delta} + 1.145\times10^{-2}(\frac{E}{\delta})^2 \tag{16}$$

where: α and η are in cm^{-1}; E is in kV/cm. μ_e, μ_p and μ_n are 500/δ, 1.5/δ and 1.8/δ cm^2/(Vs), respectively [4].

3 RESULTS

3.1 The role of photoionization

The distributions of the electron density without photoionization and that with photoionization are compared in Figure 2. The electron densities at cathode are the same. It can be found that the electron density in space is slightly increased when the process of photoionization is considered. The maximum electron density without photoionization is about 2.277×10^{11} m^{-3}, while the maximum electron density with photoionization is about 2.333×10^{11} m^{-3}.

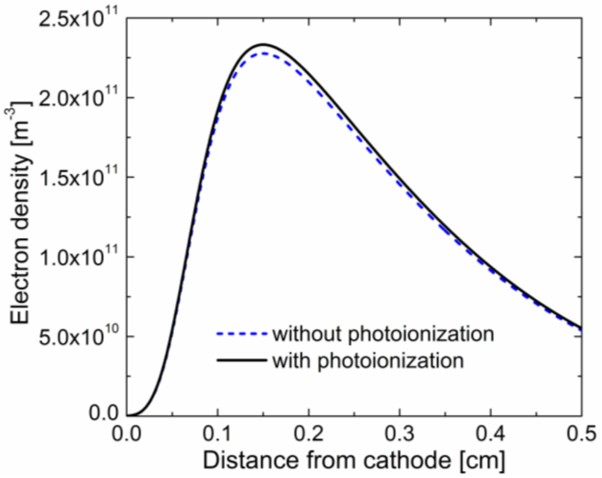

Figure 2: Comparison of the electron density distribution without photoionization and that with photoionization at r_0 = 0.1 cm, δ = 1, and I = 1 μA/cm

The amplification factor is defined by:

$$F = I_{\mathrm{ph}} / I \tag{17}$$

where: I_{ph} is the total corona current with photoionization. At the same conditions as shown in Figure 1, F is about 1.024. Compared with the total corona current without photoionzaition, the total corona current due to photoionization is more than 2%. Therefore, F can be used to reflect the role of photoionization.

3.2 The effect of conductor radius

The relationship between the amplification factor and the conductor radius is shown in Figure 3. It can be found that the values of F are all larger than 1.02. When the conductor radius is 0.01 cm or 1 cm, the values of F are both close to 1.04. The effect of photoionization is strengthened when the conductor radius is relatively small or large.

3.3 The effect of air density

The relationship between the amplification factor and the relative air density is shown in Figure 4. It can be found that the value of F is significantly increased with the decrease of the relative air density. When δ is 0.2, the value of F is about 1.15. Therefore, the photoionization plays an important role in the development of the negative corona plasma in air.

3.4 The effect of corona current

The relationship between the amplification factor and the total corona current without photoionization is shown in Figure 5. It can be found that the value of F is decreased with the increase of the corona current. However, the effect of the corona current is insignificant. It is because that the distribution of the electric field in the ionization region is almost not affected by space charges.

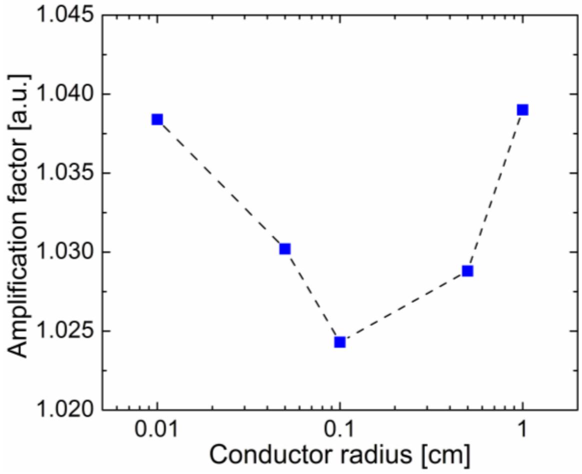

Figure 3: The relationship between the amplification factor and the conductor radius at δ = 1 and I = 1 μA/cm

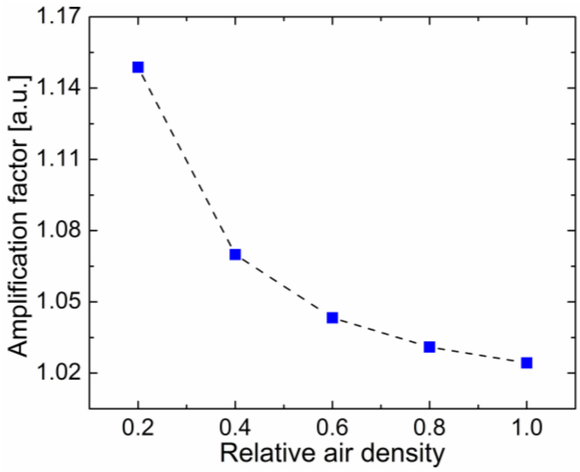

Figure 4: The relationship between the amplification factor and the relative air density at r_0 = 0.1 cm and I = 1 μA/cm

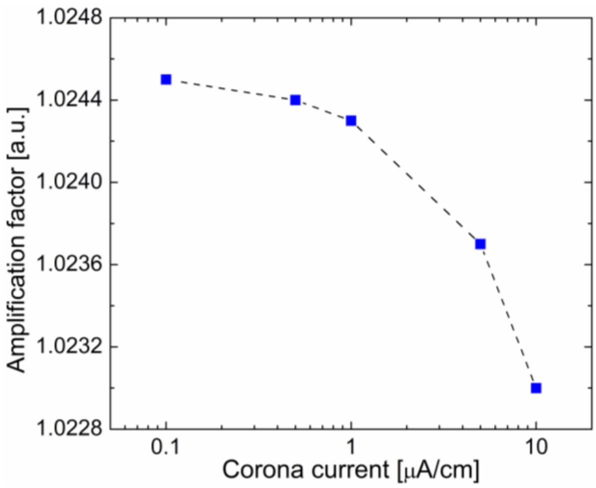

Figure 5: The relationship between the amplification factor and the corona current at r_0 = 0.1 cm and δ = 1

4 DISCUSSION

The photoionization model, which considers the wavelength of energetic photons, is widely used for the non-thermal discharges. The photoionization plays an important role in the development of positive streamers in air for producing seed electrons. What is more, the positive corona onset in air is sustained by photoionization. However, the process of photoionization is always not considered for the negative streamers in air. The general photoionization model is reformed for the negative corona plasma in air. It can be found that the effect of photoionization is significant at low air densities. It is because the effect of the quenching factor $\delta_q/(\delta_q+\delta)$. The effect of photoionization is strengthened with the increase of the quenching factor at low air densities, corresponding to conditions with low pressure or high temperature.

The proportionality factor ξ is selected be 0.1 in this paper, which is the same used by Nikonov *et al*. [1]. Under the uniform electric fields, the values of ξ are 0.12, 0.08 and 0.06, corresponding to the electric field E/p 50, 100 and 200 V/(cm·Torr), respectively. A fitting formula proposed by Naidis [9] is:

$$\xi = 0.03 + 3.78 / E \qquad (18)$$

where: E is in kV/cm. Different from the streamer discharges in air, the intensity of the electric field in the ionization region of corona discharges in air is always not much high. Therefore, the value of 0.1 is used. When the electric field intensity is relatively high, the value of 0.03 may be more suitable. In deed, the value of ξ is difficult to decide under the non-uniform electric field, because it is related to the local electric field and the electric field at the photon emission point.

The mechanism of secondary electron emission for negative corona discharges in air is still not clearly. It may be caused by ion impact or photoemission at the cathode surface. If the secondary electron emission is dominated by ion impact, the numbers of positive ions due to photoionization should be considered, especially at low air densities. If the secondary electron emission is dominated by photoemission, a new photoemission model can be built up, which considers the wavelength of energetic photons similar to the absorption function in (7). So the photoionization also has an effect on the secondary electron emission. Without considering the mechanism of secondary electron emission, Kaptzov's assumption is used as a boundary condition for Gauss's equation in (4). Compared with Townsend's second coefficients, the onset corona fields are easy to measure accurately.

5 CONCLUSION

This paper presents a numerical model for the photoionization produced by the negative corona plasma in the vicinity of cylindrical electrodes based on the general fluid model. Compared with the total corona current without photoionzaition, the total corona current due to photoionization is more than 2% for a wide range of conductor radii, relative air densities, and total corona currents. The process of photoionization should be considered at low relative air densities, which has a significant effect on the negative corona plasma in air.

6 ACKNOWLEDGMENTS

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