NUMERICAL SIMULATIONS OF CATHODE DIRECTED STREAMER PROPAGATION IN ELECTRONEGATIVE GASES

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The numerical simulations are carried out for the cathode directed streamer propagation at the quasi-stationary stage, far from electrodes, and at the stage of going out to cathode, in the gases with the different combinations of three-body and dissociative attachment. The typical features of the process in presence of intensive attachment are revealed.

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INTRODUCTION

At the constant applied voltage, the positive corona at atmospheric pressure usually operates in pulse mode, through the cathode directed streamers. Streamer is ionization wave, which left behind the ionized channel with comparatively small transverse dimension. Positive streamer corona is used for realization of non-equilibrium plasma-chemistry processes. The energy expense per ozone molecule forming in positive corona is usually less than in negative corona. Positive streamer propagation is widely studied [1] and its study is continued [2, 3]. In the present work, the numerical simulations of the cathode directed streamer propagation in the electronegative gases at the constant voltage applied to the discharge gap are carried out. To reveal clearer the peculiarities of the propagation caused by attachment, the numerical simulations of the process are carried out with the artificially overstated values of attachment reaction constants.

1. SIMULATION MODEL

The simulations are carried out in assumption of axial symmetry for the gap between the plane electrodes. The main details of the simulation model are identical to ones in [4]. In particular, there are taken into account drift and diffusion of electrons and ions, positive and negative, and the processes of impact ionization, attachment, electron-ion and ion-ion recombination. In the simulations of the quasi-stationary propagation, the average value of the longitudinal coordinate of electrons in the simulation domain is kept constant, with aid of mesh transposition on some its part at each time step, with corresponding redistribution of particles between cells.

In the atmospheric air the electro-negativity is connected with presence of oxygen, and two different ways of negative ion forming are essential: dissociative attachment, $e + O_2 \rightarrow O + O^-$, and three-body attachment, $e + O_2 + M \rightarrow O_2^- + M$, where M is O_2 or N_2. The simulations are carried out for the case of their ratio corresponding to atmospheric air and for the case of purely three-body attachment, with the overstated values of the reaction constants, in both cases. The large attachment rate leads to the considerable spatial variation of the charged particle densities on the small length of the streamer channel, which helps to reveal the attachment influence in the simulations for the discharge gap of comparatively small length.

The increase of attachment reaction constant for all field strength values by multiplication with the same factor leads to some increase of the strength value corresponding to the equilibrium between ionization and attachment. The dependence of dissociative attachment intensity on the field strength E is approximately characterized by the factor $\exp(-E_0/E)$. The same factor, but with greater value of E_0, is characteristic for the intensity of ionization reaction, $e + O_2 \rightarrow e + e + O_2^+$. Dependence of ionization and attachment constants on the field strength through the factors $\exp(-E_0/E)$ with the different E_0 makes the increase of the equilibrium strength value comparatively small, approximately logarithmic with respect to the multiplication factor mentioned above.

The process of the streamer propagation is based on avalanche multiplication through the impact ionization. The seed electrons for the avalanches appear mainly through ionization by photons radiated from the ionization zone in front of the streamer head. The account of photon transport between the different cells of calculation mesh requires a considerable calculation time. In the numerical simulations of streamers, the photo-ionization is often replaced with the given, very small, initial electron density. Such replacement usually does not lead to the considerable change of the streamer characteristics. But in presence of intensive attachment, the initial electron density quickly decreases, which makes unnatural non-stationary contribution to the simulations. At the present simulations, for the role of seed electron source, a photo-ionization is chosen, but calculations of the photon transport between the cells are not carried out, and the rate of electron appearance is taken homogeneous and proportional to the total photon radiation rate in the simulation domain.

The streamer propagation is realized through the ionization wave, which left behind the high conductive plasma channel. Due to high conductivity of the channel, the comparatively weak external field (that field, which is in discharge gap in absence of space charge in it) through the charge redistribution in the channel causes the field in front of the streamer head, which is sufficiently strong to support intensive ionization there. The length of the well conducting part of streamer channel is bounded with the product of the streamer velocity and the characteristic time of free electron motion before attachment.

A positive streamer tendency to be transversely localized is connected with opposition of the directions of the electron flow and the streamer propagation. Avalanche multiplication begins far from the streamer front, electron density there is small, and to increase it from the initial value $10^5…10^6\ \mathrm{cm}^{-3}$ given with photo-ionization to the final value $10^{14}…10^{15}\ \mathrm{cm}^{-3}$ natural for streamer it is necessary approximately 30 successive acts of electron number doubling. The difference between the values of ionization coefficient α for the points ahead of streamer at the symmetry axis and at the nonzero distance from it is small, but the proportionality of the obtained electron density to the quantity $\exp(\int \alpha dl)$ (where integral is taken over the electron drift path) leads to the considerable preference of one direction of avalanche development over other, with relevant consequences for successive ionization results at the different distance from the symmetry axis.

But for the preference of longitudinal propagation with respect to radial one, the ratio of the radial and longitudinal components of the field strength should be small in all space of intensive ionization. If the attachment frequency is very large then the length of the high conductive channel part behind the streamer head is not much more than the transverse streamer dimension. The charge redistribution in such channel cannot make the mentioned ratio of the strength components small at the streamer head side, where ionization is intensive, and so, it cannot prevent the considerable tendency to the radial propagation of the ionization wave. At such circumstances the streamer may be realized in narrow voltage range. At the lower limit of the range the field in front of streamer head (even with taking into account of field enhancement due to polarization of charge on the channel) is not strong enough to support intensive ionization, whereas at the upper limit of the range the field in the considerable part of discharge gap is sufficiently strong to support intensive ionization even without aid of the charge in channel, and the ionization wave in simulations becomes similar to plane one. The range is narrow because the conductive channel is short and the field enhancement in front of streamer with aid of charge polarization in such channel is comparatively weak. That is, the strong attachment is not favorable for the transverse localization of ionization wave. On the other hand, the streamer tendency to be transversely localized is stronger for more sharp dependence of ionization coefficient on the electric field strength. It may be obtained with replacing of the factor $\exp(-E_0/E)$ on the factor $\exp[-(E_0/E)^p]$ with $p>1$. The use of such replacing helps to reveal some features of the considered process in the simulations for the comparatively small simulation domain. The simulations are carried out for the simulation domain width 1 mm.

2. SIMULATION RESULTS

In the Fig. 1, for the quasi-stationary streamer propagation the electron density distributions typical for the cases of strong attachment with the ratio of dissociative and three-body attachment typical for atmospheric air (above) and with purely three-body attachment (below) are shown. The scale (from blue to red, at the top) is logarithmic, $(10^9…10^{15})\ \mathrm{cm}^{-3}$, the values out of the range are replaced with limits.

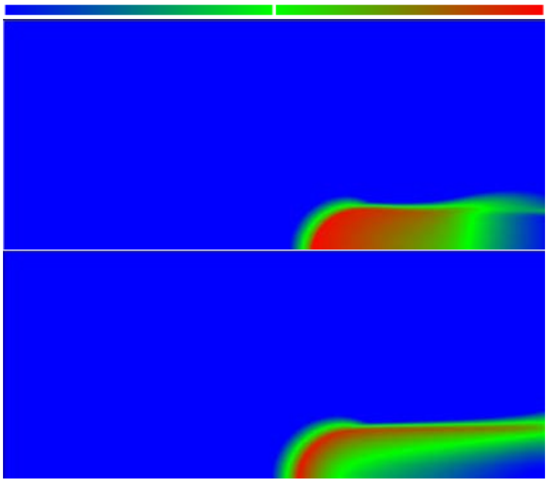

Fig. 1. Electron density distributions typical for the cases of strong attachment with the ratio of dissociative and three-body attachment typical for atmospheric air (above) and with purely three-body attachment (below)

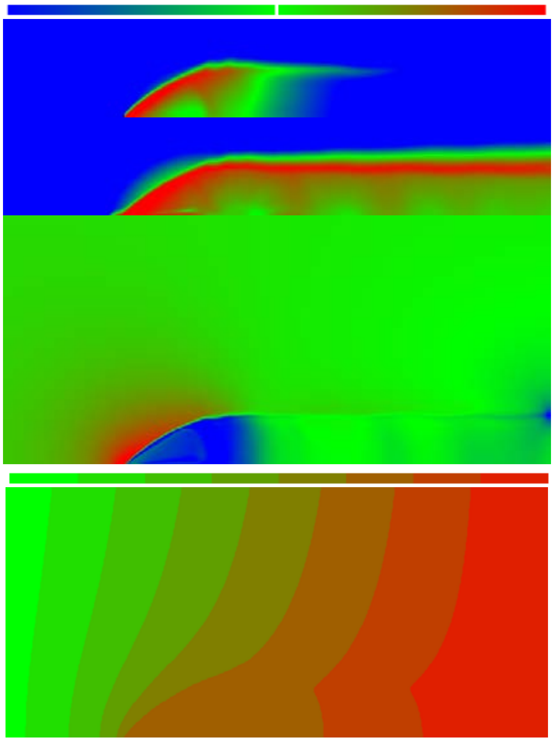

Fig. 2. Distributions of electron and positive ion densities, electric field strength, and potential in the right half of the simulation domain at the voltage near the cut-off

The contribution of the dissociative attachment to the process kinetics is relatively large in the interval of field strength values, where the dissociative attachment intensity is large and the ionization intensity is small. Such strength values are characteristic for the outlying part of ionization zone and for the side part of streamer channel beginning. But if the streamer propagates in gas with intensive purely three-body attachment then the attachment rate is larger nearer to the symmetry axis of the streamer channel, whereas in the side part of the streamer channel beginning, where the field strength is larger, three-body attachment rate is comparatively small. So, the decrease of the ratio of dissociative and three-body attachment constants leads to the decrease of relative contribution of the near-axis part of streamer channel to the total channel conductivity.

Both cases in the Fig. 1 illustrate the possibility of the stationary streamer propagation in the unbounded space with an attaching gas and uniform external field, which detailed substantiation is in [5]. In the case of intensive attachment, the electron density distribution corresponds to the streamer model described in [6].

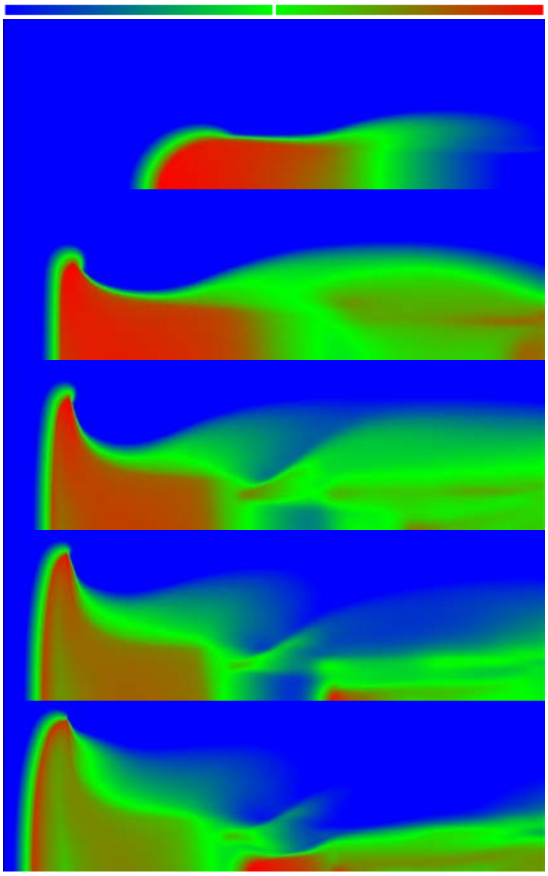

Fig. 3. Change of electron density distribution during streamer approach to cathode in the gas with the enhanced dissociative and three-body attachment (time interval 0.6 ns)

The distributions in the Fig. 1 are related to the case when the applied voltage is not too near to one minimum sufficient for the possibility of streamer propagation. For the voltage values near the cut-off of streamer mode, the distributions are somewhat different. In the Fig. 2, for such voltage in the gas with the attachment constant enhanced by the factor 100 with respect to one in atmospheric air, the distributions of electron and positive ion densities, electric field strength, and potential in the right half of simulation domain are shown. The scale is logarithmic for densities, $(10^9\ldots10^{15})$ cm^{-3}, and strength, $(10^4\ldots10^6)$ V/cm, and linear for potential (with the reduced set of colors). The corresponding form of the streamer head is connected with the considerable decrease of the streamer propagation velocity for the voltage value approaching to the cut-off, and it is observed not only for the electronegative gases. This velocity decrease leads to increase of the time, during which the relevant portion of gas motionless in the laboratory frame of reference is subjected to intensive impact ionization. At forepart of streamer head near the axis, the comparatively small space with large positive charge density is formed. This charge causes the strong field in the near space, and positive ions in such field have velocities not much less than the streamer propagation velocity.

Some variation of positive ion density observed in the Fig. 2 is connected with the artificial oscillations, which arise in the simulations of quasi-stationary propagation and dump very slowly for the voltage near cut-off. They consist of the longitudinal propagation of comparatively small space with large positive charge density at forepart of streamer head near the axis and the propagation of annular ionization wave along the front of streamer head, by turn. The conditions for the next cycle are recovered, in particular, due to mesh transposition with somewhat artificial keeping of the potential difference on simulation domain length constant, which is used in the simulations of the quasi-stationary propagation. And if one begins the simulations of the streamer approach to cathode in the laboratory frame of reference (with cancellation of mesh transposition) from the distributions obtained in the simulations of the quasi-stationary propagation then the time derivatives of the different quantities are nonzero at the beginning. In particular, the propagation of the cathode directed streamer with the positively charged channel in the bounded gap is accompanied with the increase of positive charge in the gap, leading to the field enhancement near the streamer head and to the enhancement of ionization there. In the simulations of quasi-stationary propagation such increase is absent, through the simulation domain displacement. Relative effect of ionization enhancement most of all reveals in space, where excess of ionization over attachment is small, in particular, in the side of streamer head, where the angle between the perpendicular to the constant electron density surface and the symmetry axis direction is near to right angle. And from the side part of streamer head the annular ionization wave is developed. The field strength in front of this wave is determined, mainly, by the charge on the length approximately equal to transverse streamer dimension. The next similar wave may be formed due to the charge accumulation in the neighboring space during the longitudinal streamer propagation. But if this propagation is accompanied with the sufficiently quick increase of transverse streamer dimension then the field strength near the side part of streamer head quickly becomes insufficient for the next transverse ionization wave development. In the simulations, two consecutive annular ionization waves are obtained.

The streamer going out to cathode in gas without very large attachment is described in [7] with some details. When the streamer head approaches to the cathode, the considerable decrease of the streamer propagation velocity takes place, which is followed by the drift of positive ions to the cathode and the propagation of ionization wave in the approximately radial direction. The going out of the considerable amount of positive ions to cathode is accompanied with the considerable potential redistribution in the conductive part of streamer channel, stopping of the ionization wave propagation, and decay of the intensive ionization process. In the case of large attachment reaction constants, the phenomena based on the electron movement away from the cathode are suppressed. But in the case of purely three-body attachment the free electrons obtained in the radial ionization wave can move far from cathode at such distance from the axis, which exceeds the channel radius.

In the non-conductive part of streamer channel (if three-body attachment is strong), the new ionization waves can propagate already during the propagation of the main streamer. The main source of seed electrons for them is photo-ionization. These waves start from the spaces with the enlarged field strength near the non-uniformities of charge distribution. Such ionization wave development is observed in the Fig. 3, where the electron density distribution with time intervals 0.6 ns during streamer approach to cathode in gas with the enhanced dissociative and three-body attachment is shown.

CONCLUSIONS

The large attachment rate leads to the considerable spatial variation of the charged particle densities on the small length of the streamer channel. The length of the well conducting part of streamer channel is bounded with the product of the streamer velocity and the characteristic time of free electron motion before attachment. In presence of intensive attachment, the cathode directed streamer may be realized in narrow voltage range. The decrease of the ratio of dissociative and three-body attachment constants leads to the decrease of relative contribution of the near-axis part of streamer channel to the total channel conductivity. The form of streamer head for the voltage values approaching to the cut-off of streamer mode is connected with the considerable decrease of the streamer propagation velocity. Already during the propagation of the main streamer, the new ionization waves can be developed.

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ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ РАСПРОСТРАНЕНИЯ КАТОДОНАПРАВЛЕННОГО СТРИМЕРА В ЭЛЕКТРОНЕГАТИВНЫХ ГАЗАХ

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Выполнено численное моделирование распространения катодонаправленного стримера на квазистационарной стадии, вдали от электродов и на стадии выхода на катод в газах с разным сочетанием трехтельного и диссоциативного прилипания. Выявлены типичные черты процесса при наличии интенсивного прилипания.

ЧИСЛОВЕ МОДЕЛЮВАННЯ ПОШИРЕННЯ КАТОДОСПРЯМОВАНОГО СТРИМЕРА В ЕЛЕКТРОНЕГАТИВНИХ ГАЗАХ

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Виконано числове моделювання поширення катодоспрямованого стримера на квазістаціонарній стадії, далеко від електродів, та на стадії виходу на катод у газах з різним поєднанням трьохтільного та дисоціативного приставання. Виявлено типові риси процесу за наявності інтенсивного приставання.