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NUMERICAL SIMULATION OF REPRODUCTION OF THE DEVELOPMENT CONDITIONS OF THE NEXT TRICHEL PULSE IN NEGATIVE CORONA

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Numerical simulations of the negative corona at a constant applied voltage in the Trichel pulse mode are carried out for different contents of an electronegative gas component. The dependences of the total current peak value and the time interval between pulses on the values of the applied voltage and the content of electronegative components are obtained. The results are somewhat explained using simplified models.

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INTRODUCTION

Negative corona in the Trichel pulse mode is used in plasma chemical devices (in particular, in ozone sources). At a constant voltage, a quasi-periodic process occurs, each cycle of which consists of the formation of a plasma space not far from the cathode tip, the propagation of this space to cathode, almost simultaneously, with some delay, the formation of a negative ion cluster somewhat further from the cathode, and the subsequent attenuation of ionization processes, with the creation of conditions for the development of a new pulse. Experimental research and numerical modeling of Trichel pulses in various electronegative gases were carried out in many works (in particular, in [1 - 7]). In this work based on numerical simulations, the effect of the electronegative gas component content on the process of reproducing the conditions for the development of the next Trichel pulse is studied. The time interval between Trichel pulses is six to seven orders of magnitude greater than the time interval between successive (performed by one electron) ionization acts, which determines the time step required for the stability of the calculations. Calculations are carried out for a certain axially symmetric electrode system, using a non-homogeneous, not very dense mesh, which make it possible to carry out a significant number of calculations and find out some trends in the process characteristics change under the influence of the process parameters change.

Below, it is considered the stationary mode, then the pulse mode, and the transition from the pulse mode to the stationary mode, when the voltage is increased.

1. STATIONARY MODE

If the sufficiently large voltage is applied to the gap between the anode and needle cathode then an independent discharge, a negative corona, which does not need an external electron source, is realized in the gap. In the case when the multiplication of electrons occurs due to ion-electron emission and impact ionization, for the independence of the discharge it is sufficient to hold the inequality $F > 1$, where F is the average number of electrons knocked out of the cathode by positive ions formed during the ionization multiplication of electrons in an avalanche initiated by one electron, knocked out of the cathode earlier (hereinafter referred to as the "discharge independence factor").

Approximately, if diffusion is neglected, for an electropositive gas one has $F \approx \gamma \max(\int dl\ \alpha)$, where the integrals are taken along the field lines, α is the ionization coefficient, γ is the ion-electron emission coefficient. In the presence of electronegative components in the gas, the difference between the coefficients related to ionization and attachment should be substituted for α in the given approximate equality.

If the conditions are sufficient for the development of an independent discharge, and if there is at least a small number of electrons in the gap, the ionization processes near the tip are initially strengthened. Then, due to the movement of charges in the corresponding directions and the redistribution of the field, the process can reach a stable stationary mode, in which a random change in the characteristics of the process will cause a tendency for them to return to the stationary values. The Fig. 1 shows a sample of the distribution of ionization intensity (below) and field strength (above) in the stationary mode near the cathode with a tip radius of 50 μm. The range of colors (above) corresponds to intensity $(10^{14}...10^{20})$ cm^{-3}·s^{-1}, and strength $(10^{4.5}...10^{5.7})$ V / cm; larger and smaller values are shown in extreme colors, the scale is logarithmic.

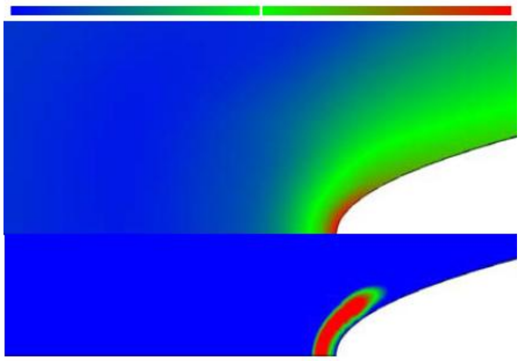


Fig. 1. Ionization intensity and field strength (in text)

At low pressure, such a stationary mode corresponds to a glow discharge with a cathode layer, which can also occur in a flat gap. In the stationary mode of the negative corona, the cathode layer is located near the tip. In it, in a strong field, there is an avalanche multiplication of electrons with the formation of positive ions, which, coming to the cathode, cause the emission of electrons, which, in turn, start the mentioned multiplication.

In a low-pressure glow discharge, behind the cathode layer, further from the cathode, there is a positive column, a plasma space, in which the field is weak and the difference between the densities of particles of different signs is relatively small. And near the anode there is an anode layer, in which, in a slightly stronger field compared to the field in the positive column, ionization occurs, with the formation of positive ions, the drift of which to the positive column supports the existence of the latter.

In the stationary mode of the negative atmospheric pressure corona, there is no plasma space (as it is evident from the distribution of the field strength in Fig. 1), and behind the cathode layer, further from the cathode, there is a drift space, in which, practically in absence of ionization, the drift of electrons and negative ions to the anode occurs, and which usually contains the rest of the discharge gap (although near those areas of the surface of the real anode, where the field is somewhat enhanced due to the shape of the anode, enhanced ionization, with a sufficiently large gap voltage, can significantly increase the supply of positive ions to the drift space and somewhat change process characteristics [7]). In any case, the drift space makes up most of the interelectrode gap. Electrons and negative ions present in the drift space slightly weaken the field between themselves and the cathode (in particular, in the ionization zones).

2. PULSE MODE

If the value of the voltage applied to the gap with an electronegative gas exceeds the threshold for the development of an independent discharge, but it is insufficient for the realization of a stationary mode, then the discharge occurs in the Trichel pulse mode.

Near the needle-cathode, an electron multiplication happens, mainly, through impact ionization, carried out by electrons knocked out of the cathode by positive ions, which, in turn, are formed through impact ionization. In absence of diffusion, photoemission, photoionization, and changes in the spatial distribution of the electric field strength over time, the multiplication of electrons due to ion-electron emission and impact ionization would happen on the different field strength lines separately. Then, even a small difference in the multiplication factor on close strength lines would lead, over time, to a large difference in electron densities, as a result of which, on a certain transversely limited beam of trajectories, the electron density would much earlier reach a level, at which the field weakening time due to the polarization drift of electrons (time of viscoelastic relaxation, Maxwell relaxation), $t_M = \varepsilon_0 / (e_0 \mu n)$ (where ε_0 is the electric constant, e_0 is the elementary charge, μ and n are the electron mobility and density), approaches time between successive ionizations carried out by one electron in a strong field (and the next act of ionization no longer occurs, through the field weakening). At the beam end far from the cathode, a well-conducting plasma space would be formed, transversely limited by the beam size, and the polarization of charges in this space would significantly strengthen the field near its cathode side, enhancing ionization there.

If the ionization coefficient α had near values at different points between the plasma space and the cathode and did not change over time, then the avalanche multiplication of electrons knocked out of the cathode would give a dependence of the positive ion density on the distance z from the cathode, close to $\exp(\alpha z)$, and such ion distribution, moving towards the cathode (with ion velocity, υ_p, much less than the electron velocity), would arrive at the cathode, causing an increase (over time t) in the electron flux from the cathode and the total current, according to the dependence near to $\exp(\alpha \upsilon_p t)$.

But an increase in the ionization coefficient in the gap between the plasma space and the cathode leads to an acceleration of the plasma space propagation in cathode direction, with a further field and the ionization intensity strengthening, in the mentioned gap. Such propagation is similar to the cathode directed streamer propagation, and the plasma space corresponds to the streamer channel, but, unlike the case of streamer propagation in a uniform external field, here the transverse process localization is enhanced, to some extent, due to the field inhomogeneity caused by the cathode shape.

The formation and propagation of the ionization wave is an important component of the ionization flash, which determines the pulse nature of the process. An increase in voltage, up to a certain level, leads to the transition to a stationary mode, due to the impossibility of the formation of an ionization wave. During an ionization flash, a negative ion cluster forms behind the plasma space, further from the cathode, and it weakens the field between itself and the cathode, contributing to the attenuation of ionization processes there. The next ionization flash near the cathode can occur after the field there is strengthened, due to the movement of negative ions further from the cathode. The negative ion cluster located around the symmetry axis (in the axially symmetric electrode system considered here), weakens the field in the gap between itself and the cathode more just on the axis, whereas further from the axis the field weakens less, which leads to the decrease of the difference between electron multiplication intensities on the near field strength lines, and, as a result, to the increase of the transverse size of the beam of trajectories, in which the level of electron density sufficient for the formation of a plasma space would be reached approximately simultaneously. The larger transverse size of the plasma space at the beginning of the development of the second ionization flash, compared to the size at the beginning of the development of the first flash, at approximately the same potential difference between the plasma space and the cathode, gives a lower field strength near the cathode side of plasma space, in connection with which, during the second flash, the ionization wave is weaker. In particular, the peak value of the total current and the total number of ionization acts are smaller.

When the voltage on the discharge gap increases, the pulse frequency increases, contributing to an increase in the number of negative ions in the discharge gap and a further decrease in the difference between the intensities of electron multiplication on the field lines located at different distances from the axis. Ultimately, the transverse size of the beam of trajectories, in which the level of electron density sufficient for the plasma space formation would be reached at about the same time, increases so much that, despite the increase in voltage, the maximum value of the field strength near the cathode side of the plasma space becomes insufficient for the formation of an ionization wave, and the plasma space propagates to the cathode with a velocity of the order of the positive ions velocity (corresponding to the local field strength values). And then the formation of negative ions (due to the attachment of electrons formed during the multiplication of those electrons that are formed due to ion-electron emission from the cathode) and the resulting field weakening near the cathode occur almost instantaneously, with respect to the arriving of positive ions at the cathode, realizing almost instantaneous negative feedback, which gives the stability to the steady-state mode of negative corona.

The propagation of the plasma space as an ionization wave stops when the discharge independence factor F (defined above), decreasing (through the length decrease of the field strength line parts where the strength gives the large ionization coefficient values), becomes less than unity. The time required for such plasma space propagation is determined by the velocity of both electrons and positive ions.

Due to the numerical simulations, it is known [6], that the deceleration of ionization wave propagation in the cathode direction is accompanied by the development of wave propagation in the direction transverse to the symmetry axis above the cathode surface, at such a distance from the surface that the multiplication of electrons emitted from the cathode, in a strong field, gives such their density, for which the Maxwell relaxation time is the value of the order of time between successive acts of ionization carried out by one electron.

The axial symmetry of the processes is embedded into the considered model. And it seems that the radial propagation of the ionization wave over the cathode surface is stable with respect to branching into several "streamers" that would propagate in different radial directions. To such conclusion it leads the consideration of a certain simplified model of the development of electron avalanches outside a positively charged perfectly conducting surface $\rho = \rho_\Phi(\varphi)$ (where $\rho_\Phi(\varphi) = \rho_{\Phi 0} + \rho_m \cos(m\varphi)$, m is a natural number) in cylindrical coordinates (ρ,φ), assuming a stepwise dependence of the ionization coefficient α on the absolute value of the field strength E,

$$\alpha = \{\alpha_0, E > E_0; 0, E < E_0\}.$$

Assuming that $|\rho_m| << \rho_{\Phi 0}$, in the approximation, linear with respect to ρ_m, taking the potential distribution, Φ, in the form

$$\Phi(\rho,\varphi) = \Phi_0 \ln(\rho_{\Phi 0} / \rho) + \Phi_m (\rho_{\Phi 0} / \rho)^m \cos(m\varphi),$$

with $\{\Phi_0 > 0, |\Phi_m| << \Phi_0\}$, and imposing the condition $\Phi(\rho_\Phi(\varphi), \varphi) = 0$, one gets $\Phi_m = \Phi_0 \rho_m / \rho_{\Phi 0}$, for the strength distribution one has

$$E(\rho,\varphi) = \rho^{-1}[\Phi_0 + m\Phi_m (\rho_{\Phi 0} / \rho)^m \cos(m\varphi)],$$

and for the surface $\rho = \rho_E(\varphi)$, defined with the equality $E(\rho_E(\varphi), \varphi) = E_0$, one comes to the equality

$$\rho_E(\varphi) - \rho_{E0} = f_m [\rho_\Phi(\varphi) - \rho_{\Phi 0}],$$

in which $\rho_{E0} = \Phi_0 / E_0$, $f_m = m (\rho_{\Phi 0} / \rho_{E0})^{m-1}$.

Therefore, with a stepwise dependence of the ionization coefficient on the field strength, in the field of a perfectly conducting cylinder, with a surface with an average radius $\rho_{\Phi 0}$, perturbed by an azimuthal harmonic with the number m, the ratio of the amplitude of the perturbation of the surface with an average radius ρ_{E0}, from which the multiplication of electrons begins (and hence, of the surfaces with the identical electron density), to the perturbation amplitude of a perfectly conducting surface, for $\{m \geq 2, \rho_{\Phi 0} << \rho_{E0}\}$, is a small value. It is worth to pay attention to the fact that for the perturbation of an ideally conducting surface with $m = 1$, the shift of reference center to the point $\{\rho = \rho_1, \varphi = 0\}$ deletes (in the linear approximation) the perturbation, in connection with the equality

$$[(\rho_{\Phi 0} + \rho_1 \cos\varphi)\cos\varphi - \rho_1]^2 + \\ + [(\rho_{\Phi 0} + \rho_1 \cos\varphi)\sin\varphi]^2 = \rho_{\Phi 0}^2 + \rho_1^2 \sin^2\varphi.$$

Unlike the considered two-dimensional model, in three-dimensional space, the process of the ionization wave propagation in the direction transverse to the symmetry axis is limited in the axial direction, due to which the field strength decreases even faster (when distance from the axis increases) and the stability of the ionization wave transverse propagation process is enhanced.

The next stage of the Trichel pulse evolution is the destruction of the plasma space due to the recombination and drift of charged particles. If the plasma space contained one type of positively and negatively charged particles, then the time of its destruction due to drift would be determined by the smaller of two following drift velocities near the plasma space to the different sides from it, namely, of positive particle drift velocity to the cathode and negative particle drift velocity to the anode. Since the field strength (and the drift velocity determined by it) near the plasma space on the anode side is much smaller than one on the cathode side, the time for the destruction of the plasma space and the creation of conditions for the next pulse development is determined by the negative ion drift. Positive ions go to the cathode with a high velocity, but only after they are "released" by negative ions (the uncompensated charge of negative ions weakens the field near the plasma space on the cathode side). And recombination alone, without moving the remaining negative ions further from the cathode, does not change the field strength near the cathode. After the discharge independence factor exceeds the unit, the development of the next pulse may occur.

In Fig. 2, it is shown the change in the electron density distribution during the first (left column) and third (right column) ionization flashes near the cathode with a tip radius of 50 μm. The time step is 10 ns, the total current passes through a maximum between the second and third (from top to bottom) time instants. The range of colors (above) corresponds to densities

$10^{10}...10^{14}$ cm^{-3}, higher and lower densities are shown by extreme colors, the scale is logarithmic.

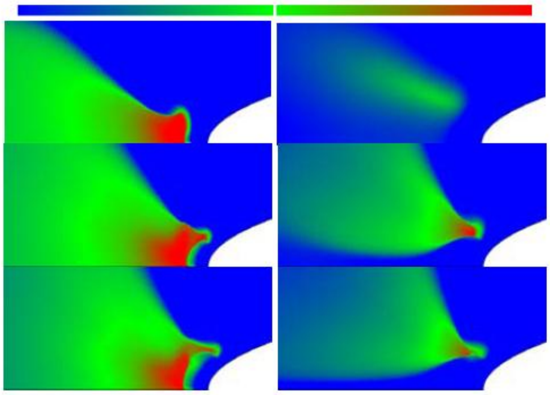


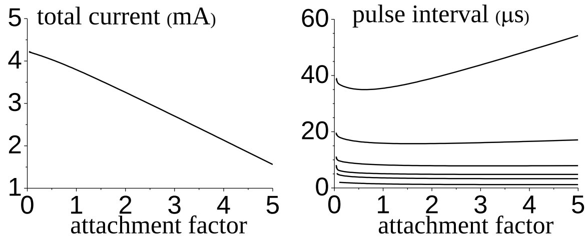
Fig. 2. Electron density distribution change during the first and third ionization flashes (in text)

In the calculations, the second and subsequent ionization flashes developed from the remnants of the destruction of the plasma space part that was formed at the end of the transverse propagation of the ionization wave, so, according to the calculations, the flashes in space had the shape of a ring. It is obvious that in an axially symmetric electrode system, but without imposing axial symmetry on the processes, such flashes are unstable with respect to perturbations, in which the development of avalanches, the formation and propagation of the plasma space occur earlier in some azimuthal sector, after which the ionization processes begin to fade in the entire ring.

3. CALCULATIONS RESULTS

In the calculations, in which at the beginning the gap is filled only with electrons with a low density, the approach of the process to a periodic one requires filling the gap with negative ions, with a time-varying distribution close to that corresponding to the mentioned limiting periodic process. At a small voltage applied, when the velocity of negative ions in the drift zone is low, such filling takes a long time. In the performed calculations, the only parameter that distinguishes the gas is the multiplier at the attachment frequency (hereinafter, the “attachment factor”). For dry atmospheric air, it has a value of 1. Also, values of 5 (approximately corresponding to oxygen), 0.1, 0.05, 0.04, and 0.037 have been used. The latter is close to such a value of the attachment factor, approaching which leads to the disappearing of the voltage interval, in which the realization of the Trichel pulse mode is possible in the given electrode system.

In the calculations, it was found that for a fixed value of the attachment factor, the peak value of the total current is practically independent of the voltage, differing for different values of the attachment factor. And the time interval between pulses at a voltage not very close to the lower threshold of the Trichel pulse mode, on the contrary, depends weakly on the attachment factor and increases as the voltage decreases, and when the voltage approaches the lower threshold of the Trichel pulse mode, the time interval between pulses increases significantly. When the attachment factor is reduced to a value below which the Trichel pulse mode is not realized in this electrode system, the range of voltage values in which the mentioned mode is realized is narrowed, mainly due to the reduction of the voltage corresponding to the upper threshold of the Trichel pulse mode, that is, by the voltage, the upper threshold is much more sensitive to the attachment factor change than the lower one.



a *b*

Fig. 3. Dependences of the total current peak value (a) and the time interval between pulses (b) on the attachment factor (in text)

In Fig. 3, it is shown the dependence of the peak value of the total current (a) and the time interval between pulses (b) on the attachment factor. The curve in Fig. 3,b correspond to the values of the applied voltage (3.23, 3.3, 3.4, 3.5, 3.6, 4) kV (the lower curve corresponds to a higher voltage). The obtained dependences are related to the processes that determine the pulse development and reproduction of the conditions for the next pulse development.

The practical independence of the total current peak value on the voltage is due to the fact that the discharge independence factor is practically independent of the field distribution in the drift space, but is mainly determined by the field near the tip, and the equality $F = 1$ corresponds to a fairly certain field distribution in almost empty space near the tip, with a fairly certain value of the potential difference between the cathode and some fixed point not far from it. And the field weakening, due to which the increase of the total current stops, occurs due to the accumulation, not far from the cathode, of negative ions, which are formed more intensively in the gas with a higher attachment factor, weakening the field and stopping the increase of the total current at a smaller value.

As for the time interval between consecutive peak values of the total current, the main part of it is the time required to restore the high field strength near the cathode. The restoration is carried out mainly due to the negative ion drift from the cathode, with a velocity determined by the distribution of the field strength in the drift space. At a higher voltage, the ion drift velocity is higher, the field near the cathode is renewed faster, the time interval between successive Trichel pulses decreases. The dependence of the field strength distribution in the drift space on the content of electronegative components in the gas (in the considered range of attachment factor values) is weak. And a significant increase of the time interval between pulses when the voltage approaches the lower threshold, and its exceeding the time required for the negative ion to drift through the entire gap, in the field corresponding to the voltage threshold, is due to the fact that with such a degree of the discharge gap cleaning from the negative ions, which takes place when the relation $0 < F - 1 << 1$ holds, the total current and a number of other discharge characteristics increase although exponentially, but with a very small increment, approximately corresponding to the product of the small value, ln(F), with the inverse time of positive ion drift from various points of the gap to the cathode averaged with taking into account the probability of ion formation at a given point. Since the dependence of the F value on the applied voltage near the threshold is approximately linear, the time interval between pulses is approximately inversely proportional to the difference between the given voltage value and the threshold, so, formally, it increases infinitely when the voltage decreases to the lower threshold.

The sensitivity of voltage values corresponding to the lower and upper thresholds of the Trichel pulse mode to the attachment factor change can be estimated from the conditions that determine those values.

For the voltage corresponding to the lower threshold, the condition $F \approx 1$ should be held, and the F value is approximately proportional to the integral of the difference of the ionization and attachment coefficients over the field strength lines in the empty gap. The value of relative change of the mentioned integral is of the same order as the value of the absolute change of the attachment factor, and, to compensate the change, the relative change of the voltage corresponding to the lower threshold should also have the value of the order of the absolute change of the attachment factor, and an increase in the attachment factor requires an increase in the specified voltage.

And the voltage corresponding to the upper threshold is determined by the ability of the electric field to remove negative ions further from the cathode and to reduce their density in the drift space to a certain level, for which, with an increase of the attachment factor and an approximately proportional increase of the negative ions flux from the plasma space, the voltage should increase approximately proportional to the attachment factor, and therefore the value of relative change of the voltage corresponding to the upper threshold is of the same order as the value of the relative change of the attachment factor.

So, the value of the ratio of sensitivities to the change in the attachment factor for those voltage values which corresponds to the lower and upper thresholds of the Trichel pulse mode is of the same order as the value of the attachment factor.

CONCLUSIONS

Numerical simulations of the negative corona at a constant applied voltage in the Trichel pulse mode for different contents of electronegative components in the gas are carried out. It is found that the peak value of the total current practically does not depend on the value of the applied voltage and increases with a decrease in the content of electronegative components. The interval between pulses at a voltage not very close to the lower threshold of the Trichel pulse mode, on the contrary, depends weakly on the content of electronegative components and increases with voltage decrease. At the small values of the relative content of electronegative components (in the range of the Trichel pulse mode realization, in the given electrode system), the voltage corresponding to the upper threshold of the Trichel pulse mode is much more sensitive to change of the mentioned content than the voltage corresponding to the lower threshold.

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ЧИСЛОВЕ МОДЕЛЮВАННЯ ВІДТВОРЕННЯ УМОВ РОЗВИТКУ НАСТУПНОГО ІМПУЛЬСУ ТРИЧЕЛА У НЕГАТИВНІЙ КОРОНІ

В. Остроушко

Виконувалося числове моделювання негативної корони при постійній докладеній напрузі у режимі імпульсів Тричела для різного вмісту електронегативних складових у газі. Отримано залежності пікового значення повного струму та інтервалу між імпульсами від значень докладеної напруги та вмісту електронегативних складових. Результати певною мірою пояснені з використанням спрощених моделей.