Pulsed and streamer discharges in air above breakdown electric field

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A 3D particle model is developed to investigate the streamer formation in electric fields above the breakdown threshold, in atmospheric air (1bar, 300 Kelvin). Adaptive particle management, adaptive mesh refinement and parallel computing techniques are used in the code. Photoionization and electron detachment from natural background ionization in the form of O_2^- are included in the simulation. Many discharges grow up from different locations, instead of double-headed streamers present in previous fluid models. Our findings are in agreement with the experimental observation. We also estimate the 'ionization screening time' when the electric field drops below breakdown, due to the effect of space charge separation. We conclude that single isolated streamers hardly exist in air in the electric fields well above the breakdown value.

1. Introduction

Streamers are fast growing filaments that can penetrate into non-ionized regions, due to the electric field enhancement in their tips. Two types of streamers are distinguished depending on the net charge in their tips and the propagate directions. They play an essential role in the earlier stage of atmospheric discharges in nature, for instance, in the inception of lightning in the troposphere and in sprite discharges in the mesosphere [1]. They are also widely used in industry: in water/gas cleaning [2-3], ozone generation [4], or plasma assisted ignition/combustion [5].

In the past several years, a number of models were developed to study streamer formation in electric fields above breakdown [6-9]. Most of them are 2D axis-symmetric fluid models; double-headed streamers are observed in their simulations, both in atmosphere of troposphere and of mesosphere.

Our 3D particle simulation shows very different findings from the results cited above. We mark that electron detachment from natural background ionization in the troposphere is included, while Luque et al. showed that a similar mechanism accounts for delayed sprite formation in the mesosphere [10].

2. Methods, results and discussion

We developed a 3D particle code with Monte Carlo collision scheme. Electrons are tracked as particles, ions are immobile on the short time scales considered in the paper. Neutral molecules are set as background density. An adaptive particle management algorithm is applied to control the number of super-particles. Adaptive mesh refinement is used as presented in [11], but it is now extended to 3D. MPI (Message Passing Interface) is used in the code to speed up the simulation.

Photoionization is included in the same way as in [8]. We also include electron detachment from negative ions. We note that an ionization level of 10^3 cm^{-3} was measured at 5 km altitude [12] and ground [13].

We perform simulations in atmospheric air (1bar, 300 Kelvin). A homogeneous electric field of 80 kV/cm is applied in the negative z direction. The simulation domain is cubic, of size $(4mm)^3$. A natural background ion density of 10^3 cm^{-3} initializes in the simulation, in the form of O_2^-.

Fig. 1 shows the electron density and the electric field at 1.77 ns and 1.92 ns, respectively. We found that the results largely different from the results of 2D fluid model simulations: instead of a double-headed streamer, many discharges are triggered in the whole domain. This is because with background ionization, free electrons are detached from O_2^- ions, many avalanches start from detached electrons or from photo-electrons. We note that detachment can happen almost anywhere in higher electric fields.

Thus, discharges distributed over the whole domain are observed, as shown in the first row of Fig. 1. Single isolated streamers no longer exist due to the overlapping between avalanches, which are close together, reducing the electric field enhancement at their tips.

Similar phenomena were observed in laboratory experiments of high voltage pulsed discharges, in air [14-15]. 'Inception cloud' appears around a needle shaped electrode, where the field is above breakdown. Streamer channels only form further away from the electrode, where the electric field drops below breakdown.

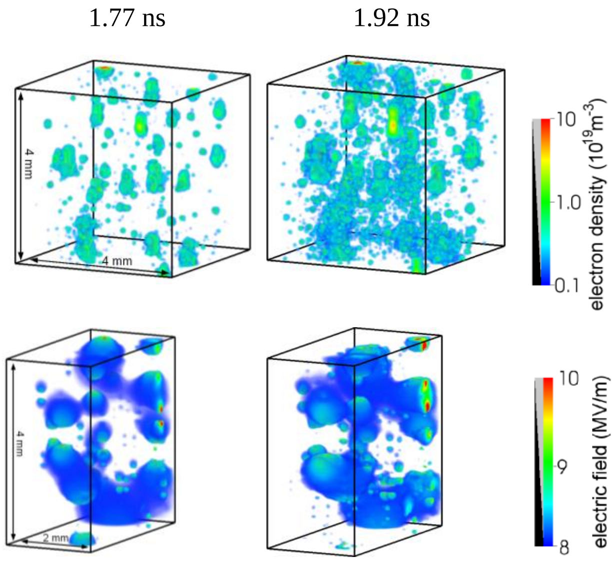

Fig. 1 The electron density (first row) and electron density (second row). Times are indicated above each column. The simulation started with a background ionization level of O_2^- ions of 10^3 cm^{-3} and the same number density of positive ions. The gas is air, 1 bar and 300 Kelvin. A downward homogenous background electric field of 80 kV/cm is applied. For figures in the second row, the right half of the domain is removed to show the inner structures of electric field.

We note that our simulation only presents the discharge in a few nanoseconds, so we here give a prediction on what happens later. We define an 'ionization screening time' that can be approximated analytically:

$$\tau_{is} \approx \ln\left(1+\frac{\alpha\varepsilon_0 E_0}{e n_0}\right)/(\alpha v_d)\,, \qquad (1)$$

where α is the effective ionization efficient; ε_0 is the vacuum permittivity; E_0 is the background electric field; n_0 is the initial density of electrons or O_2^- ions; v_d is the drift velocity of electrons.

The assumptions in eq. (1) are: we start with free electrons, there is no diffusion and the electrons keep their initial drift velocity $v_d(E_0)$ and ionization coefficient $\alpha(E_0)$. The physical meaning of τ_{is} is the time required for electric field to drop below the breakdown threshold in the interior, due to the space charge separation effect. A more detailed explanation can be found in [16].

Fig. 2 shows the ionization screening time as a function of the background electric field, with an initial density of 10^3 cm^{-3} of free electrons or O_2^- ions. The electron detachment time from [17] and the streamer formation time based on the Raether-Meek criterion are also plotted. We can see in Fig. 2 that the ionization screening time is very close to the streamer formation time when the background electric field is sufficiently high above breakdown. Then we predict that due to the natural background ionization, single isolated streamers hardly exist. It is worth to mark that in a recent experiment of discharges in air at ground pressure, an 'initiation cloud' forms firstly, which expands into a light-emitting shell, eventually, the shell stops expanding and extinguishes [18]. In another experiment of discharges in liquid, 'dark phase' presents when the applied voltage increases to the maximum value, then the electric field in the gap well above the breakdown [19-20]. The authors explain it as the effect of space charge that decreases the electric field. Those observations are in agreement with our prediction.

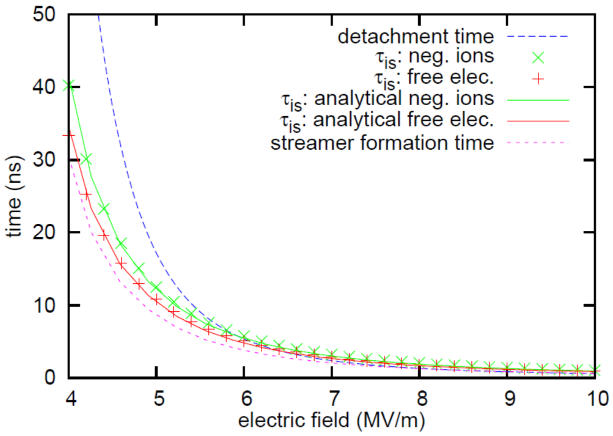

Fig.2 The comparison of ionization screening time τ_{is}, detachment time from background O_2^- ions and the streamer formation time based on the Raether-Meek criterion.

3. Conclusions

We perform simulations on discharges in air at ground pressure, in electric fields well above the breakdown value, with a 3D particle model. Due to the electron detachment from natural background ionization (in the form of O2-), many discharges triggered from different locations fill the whole domain eventually. Our simulation agrees with experimental observation that an 'inception cloud' appears around the needle electrode [14-15], where the electric field well above breakdown.

We further analytically estimate the ionization screening time. We predict the electric field will eventually drop below breakdown, due to the space charge separation. Our prediction agrees with recent experiments of discharges in air [18] and in liquid [19-20].

4. References

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