Modelling of streamer propagation in dielectric liquids using a dense gas model

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Ultrafast electrical breakdown in dielectric liquids is of considerable interest for applications in high-voltage insulation. For liquids with high mobility of charged particles, the breakdown takes place on a nanosecond time scale, and its mechanism is similar to the streamer breakdown of gases which is caused by the electron impact ionization of particles, with a distinction that the electron–ion recombination in the streamer channel plays a significant role compared to streamers in gases. Also very high-voltage pulses of sub-ns duration provide an extremely high electrical field in the plasma formation region in the liquid and allow ionization directly in the condensed phase by direct electron impact. Thanks to the sub-nanosecond time scale, the fluid lacks time to expand, and so the discharge is formed directly in the liquid phase [1, 2]. In this contribution we present a study of positive streamer dynamics in dielectric liquid using a dense gas model [3].

Governing equations

The electric discharge propagation in liquid is described by the set of convection-diffusion-reaction equations for the electrons $\mathbf{n_e}$ and the positive ions $\mathbf{n_p}$

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \vec{v}_e) = \alpha ||\vec{v}_e|| n_e - \beta n_e n_p, \tag{1}$$

$$\frac{\partial n_p}{\partial t} + \nabla \cdot (n_p \vec{v}_p) = \alpha ||\vec{v}_e|| n_e - \beta n_e n_p, \tag{2}$$

coupled with Poisson's equation for the electric potential

$$\Delta V = -\frac{q_e}{\varepsilon}(n_p - n_e), \tag{3}$$

where $\vec{v}_{e,p}$ are drift velocities for electrons and positive ions, α and β are electron ionisation coefficient and electron-positive ion recombination coefficient respectively, e is unit electron charge and ε is permeability of liquid argon. All these coefficients are functions of the electric field computed as $\vec{E} = -grad\,(V)$ and they are mentioned in [3]. The recombination coefficient

$$\beta = \xi \frac{\vec{v}_e}{\varepsilon \|\vec{E}\|}, \tag{4}$$

is scaled by dimensionless parameter ξ in order to investigate the influence of recombination on the streamer propagation.

Problem formulation

We solved the system of equations (1-3) as axialy symmetric problem. The domain is bounded by two plannar electrodes generating uniform electric field E_0 with magnitude $400kV/cm$. In the center of the domain is placed spherical electrode with the radius $20\mu m$ and voltage $3000V$. We prescribed Neumann homogenous boundary conditions for the potential on free boundaries and for charged particles on all boundaries. The distance from the center of the sphere to the plannar electrodes is $1cm$ and between axis of propagation and the artificial boundary is $5cm$. We used the initial Gaussian seed with magnitude of $10^{15}cm^{-3}$ placed on the intersection of the sphere and axis of propagation and preionisation was $10^{8}cm^{-3}$.

Numerical method

We used the finite volume method for discretization of the equations (1-3). The convective fluxes are computed by a simple upwind scheme and its accuracy is stiffen to the second order by a linear reconstruction together with Bart-Jespersen limiter. Dissipative terms in equations (1-2) are discretized by the diamond scheme. The second order of accuracy in time was achieved by three steps Runge-Kutta method.

We used central approximation together with diamond scheme to discretized the Poisson equation similarly as for discretization of dissipative term. Then we got the system of linear equations with a sparse matrix which was solved by LU decomposition.

Results

Figure 1 shows the axial cuts of electron densities computed on grids with 9000, 19000, 38000 and 110000 cells at the time $2.8^{-9}s$. Clearly rather large number of cells is required for the simulation results to be independent on the number of grid cells.

In order to study the effect of charge species recombination on the discharge propagation we have performed a series of simulations with coefficient ξ from eq. 4 varied from 0.1 to 0.4. Figure 2 shows axial cuts of electron densities computed on the grid with 110 000 cells, in time of $2.8^{-9}s$. The rate of recombination has two obvious effects: first the density of electrons in the

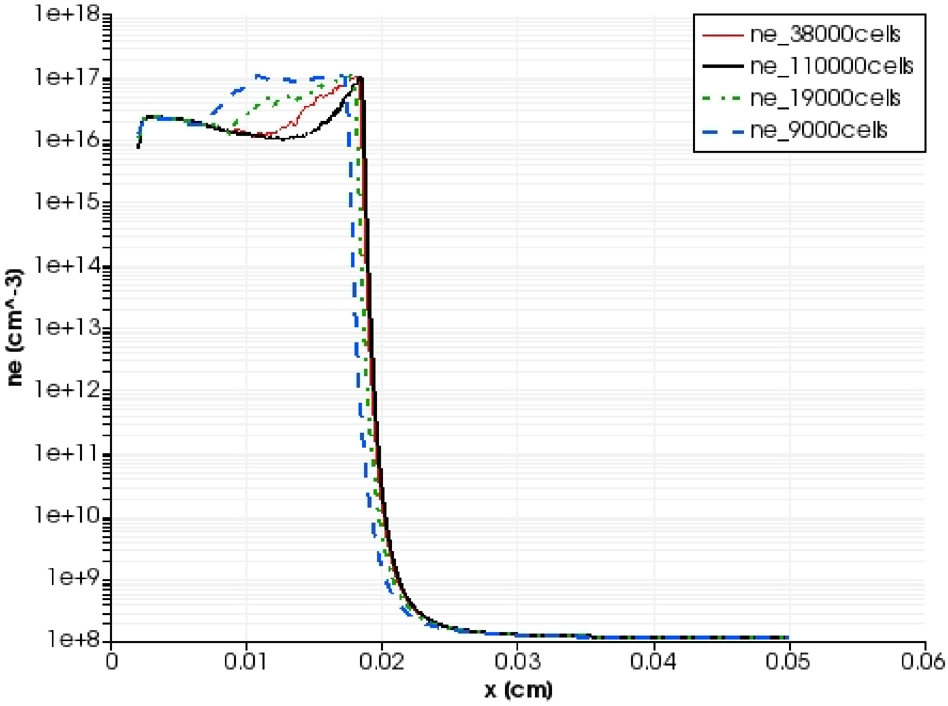

Figure 1: *The grid indenpendency test: axial cuts of electron densities computed on grids with various cell numbers and the end time of computation is* 2.8^{-9}*s for all cases*

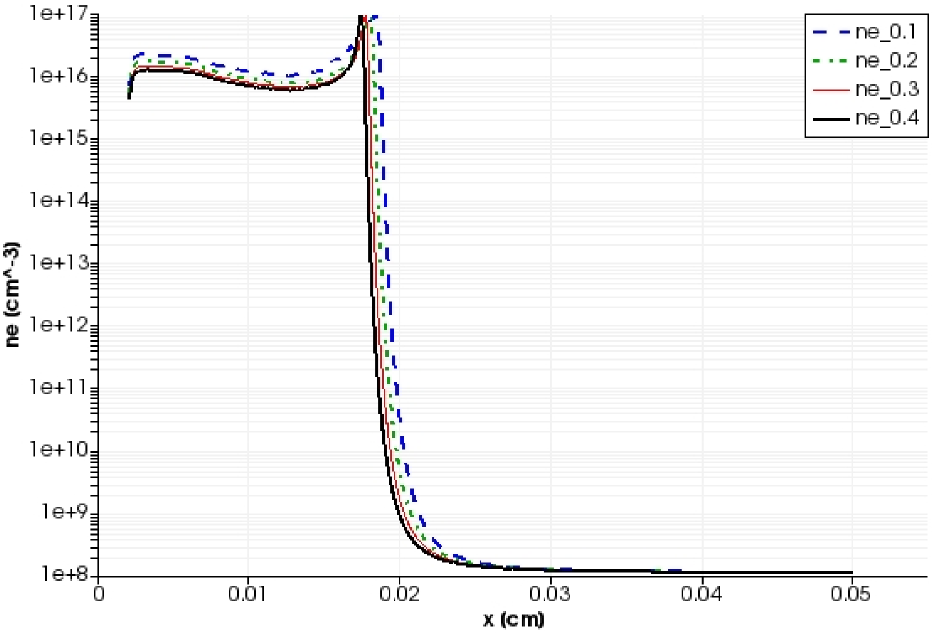

Figure 2: *The dependency on recombination coefficient: axial cuts of electron densities computed on grid with 110 000 cells, the end time of computation is* 2.8^{-9}*s and the* ξ *varied from* 0.1 *to* 0.4

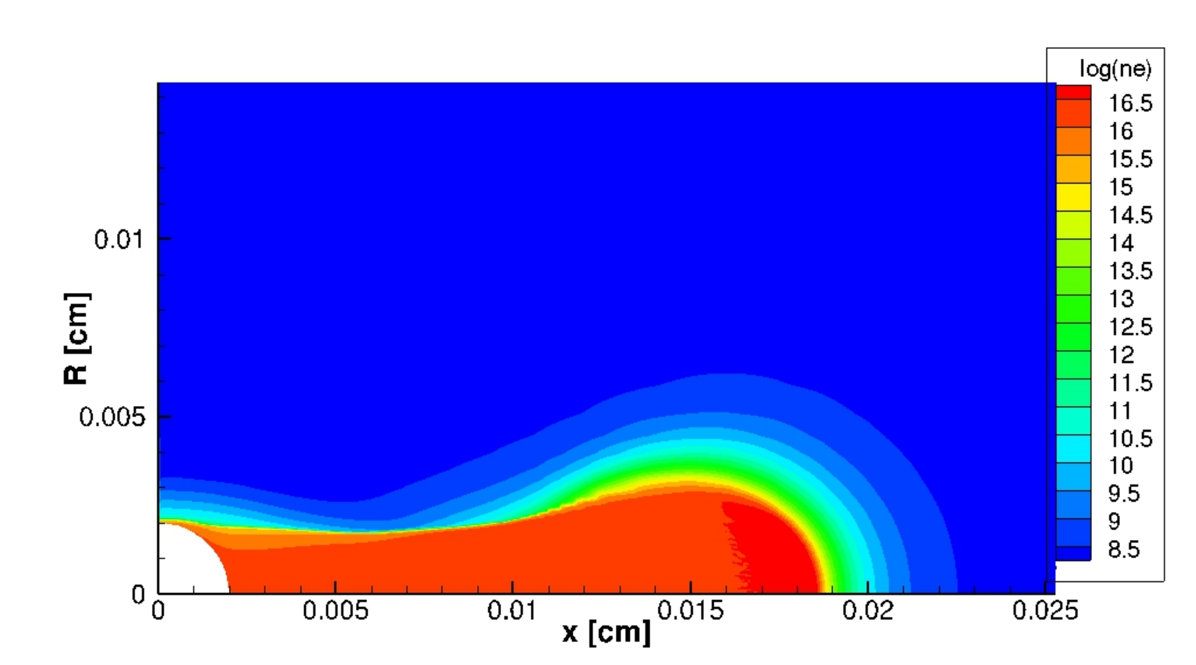

Figure 3: *The isolines of* $log_{10}(n_e)$ *from streamer simulation in liquid argon (*$t_{end} = 2.8^{-9}$*s and* $\xi = 0.1$*)*

discharge channel is significantly lowered with higher recombination rate, second, the streamer propagation is slowed down.

The contures of electron density distribution in the discharge are shown in figure 3 (coefficient ξ from eq. 4 is equal to 0.1). Electron density has a maximum behind the streamer head, while in the streamer channel we observe almost flat profile as a result of electron ion recombination.

Acknowledgements

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