Propagation of Cathode-Directed Streamer Discharges in Air

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Outline

• Introduction
• Drift-diffusion model of streamer discharges in air
• Model implementation
• Simulations of positive streamers
• Concluding remarks
Electrical gas discharges

• Phenomena associated with transport of electrical charges through neutral gas due to applied electric fields.

• Transport processes are usually strongly dominated by space charge effects.

• Examples of non-thermal discharges: electron avalanches, streamers, coronas, stationary glow discharges, dielectric barrier discharges (DBD).

• A streamer discharge is a self-sustained ionization wave propagating in neutral gas.
Positive streamers in air

- Streamers develop as thin plasma channels sustained by production of electrons in the strong field region at the head.
- Depending upon conditions (pressure, length, power input, overvoltage, etc.) they may experience branching.


Drift-diffusion model of air discharges

• Charge carriers are represented as electronic and ionic “fluids” and are characterized by averaged properties.

• Mass conservation equations for electrons and ions:

\[
\frac{\partial n_e}{\partial t} + \nabla \cdot (-n_e \mu_e E - D_e \nabla n_e) = S_e(E)
\]
\[
\frac{\partial n_p}{\partial t} + \nabla \cdot (n_p \mu_p E - D_p \nabla n_p) = S_p(E)
\]
\[
\frac{\partial n_n}{\partial t} + \nabla \cdot (-n_n \mu_n E - D_n \nabla n_n) = S_n(E)
\]

• Poisson equation for electric potential $\phi$:

\[
\nabla \cdot (\varepsilon_0 \varepsilon \nabla \phi) = -q(n_p - n_e - n_n), \quad E = -\nabla \phi
\]

• Appropriate (problem dependent) boundary and initial conditions are to be provided for all the PDEs.
Incorporating photoionization in air

• Mechanism:
  
  \[ e + N_2 \rightarrow N_2^* + e \Rightarrow N_2^* \rightarrow N_2 + h\nu \ (98 \div 102.5 \text{ nm}) \Rightarrow O_2 + h\nu \rightarrow O_2^+ + e \]

• Non-local ionization: electrons are created by photons at a distance from a source of radiation.

• The photoionization rate is included as
  
  \[ S_{ph}(\mathbf{r}) = \sum_j S_{ph}^j(\mathbf{r}) \]
  where the terms \( S_{ph}^j(\mathbf{r}) \) satisfy Helmholtz equations\(^(*)\)

  \[ \nabla^2 S_{ph}^j(\mathbf{r}) - (\lambda_j p_{O_2})^2 S_{ph}^j(\mathbf{r}) = -A_j p_{O_2}^2 I(\mathbf{r}) \]

• Two exponential fit is used with the parameters \( \lambda_j \) and \( A_j \).

Model implementation

- Set of PDEs: three drift-diffusion, Poisson’s, two Helmholtz.
- Source term stabilization is implemented for the DD PDEs.
- Mesh size at streamer front is ~10 µm, within the plasma channel ~70 µm and larger in the rest of the domain.
- The mesh was refined manually.
- Solver: direct, segregated (two steps) with continues Jacobian update.
- Time stepping: BDF with variable order.
Simulations of streamers in air

- Hyperbolic needle-plane electrodes, pressure 760 Torr, temperature 293 K, voltage rise time 0.1 ns.

- A single discharge is considered and the model is implemented in 2D utilizing axial symmetry.

- The discharge is initiated from a seeding charge spot of Gaussian shape \( n_e = n_p = 10^{20} \text{ m}^{-3}, \sigma = 30 \mu\text{m} \) located at 0.1 mm from the needle tip.

- Drift of ions is neglected due to the short duration of the discharge.

- Two study cases:
  - gap length 5 mm (applied voltage +15 kV dc)
  - gap length 30 mm (voltage +40 kV dc).
Short streamer: dynamics of electrons

Electron density log10(Ne)
Short streamer: electric field

Electric field strength, kV/cm

- 0.1ns
- 0.2ns
- 0.3ns
- 0.5ns
- 1.0ns
- 1.5ns
- 1.8ns
- 2.0ns
- 2.1ns
- 2.13ns
Long streamer: dynamics of electrons

Electron density $\log_{10}(Ne)$

- plane
- z-coordinate (mm)
- needle

- 0.1ns
- 0.5ns
- 1.0ns
- 2.0ns
- 5.0ns
- 10ns
- 15ns
- 20ns
- 23ns
- 25ns
- 26ns
- 26.3ns
Long streamer: electric field

Electric field strength, kV/cm

- 0.1ns
- 0.5ns
- 1.0ns
- 2.0ns
- 5.0ns
- 10ns
- 15ns
- 20ns
- 23ns
- 25ns
- 26ns
- 26.3ns

plane

z-coordinate (mm)

needle
Calculated discharge current

Streamer 5 mm

Streamer 30 mm
Calculated parameters of streamers

• Velocity at stable propagation:
  5 mm streamer - \( \sim 1.8 \cdot 10^6 \) m/s
  30 mm streamer - \( \sim 1.0 \cdot 10^6 \) m/s

• Channel radius at stable propagation:
  5 mm streamer – 600-700 µm (strongest field)
    400-500 µm (strongest \( S_{ph} \))
  30 mm streamer – 500-600 µm (strongest field)
    200-300 µm (strongest \( S_{ph} \))
Typical parameters of streamers


- Type 1 streamers are very thick with a diameter of about 2.5 mm; their velocity is just over 1 mm ns\(^{-1}\) and they carry currents of up to 25 A.
- Type 2 streamers are thick with a diameter of about 1.2 mm, a velocity of 0.5 mm ns\(^{-1}\) and currents of the order of 1 A.
- Type 3 streamers are thin; their diameter is 0.2 mm which can only be properly determined by zooming in sufficiently with the camera (cf table 1), their velocity is \(\sim 0.1\) mm ns\(^{-1}\) and their current \(\sim 10\) mA.

Concluding remarks

• The drift-diffusion (fluid) model of non-thermal discharges in air has been implemented.

• Lessons learnt: meshing, numerical stability, setting proper boundary conditions, optimizing solver properties, etc.

• “Wish list”:
  - implementation of a moving frame with a fine mesh for resolving gradients at streamer front;
  - implementation of a high order numerical scheme or technique allowing for flux correction;
  - implementation of finite volume approach for drift-diffusion equations (to preserve positivity).
Thank you for your attention!!