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Coupling discharge and gas dynamics in streamer-less spark formation on the example of supercritical N_2

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A 2D cylindrically symmetric model is developed to study the streamer-less spark formation in a short gap on the timescale of ion motion. It incorporates the coupling between the electric discharge (described by reaction-drift-diffusion model on the timescale of ion motion and Poisson's equation) and the gas (described by Euler equations) through the heat generated by the discharge. The model is employed to study electrical breakdown in supercritical N_2. We present the simulation results of gas heating by the electrical discharge and the effect of gas expansion on the electrical discharge.

1. Introduction

Electrical breakdown in high-voltage switching technology is a well-known phenomenon. When it comes to designing better switches, one is interested in insulating media that have high dielectric strength and thereby prevent the formation of sparks. A popular medium in high-voltage switching domain is Sulphur-hexafluoride (SF_6) which is known to have excellent switching properties. But the downside is that SF_6 is an extreme green house gas (global warming potential of 23, 900 times carbon dioxide).

Supercritical fluids have drawn interest in the area of high-voltage switching due to their various properties, such as, high density and satisfying dielectric strength [1].

The goal of this work is to develop a general simulation framework to study streamer-less spark formation in supercritical N_2 and various other media.

2. Model

2.1 *Model for the electric discharge*

To describe the discharge dynamics, we adopt the first-order reaction-drift-diffusion model for electrons and ions (on the timescale of ion movement) as in [2, 3]. We consider the simple case in which we restrict ourselves to just the electrons and N_2^+ ions. As a source term for electrons/ions, we consider impact ionization. At the cathode we implement secondary electrode emission for the electrons, i. e., $n_e = \gamma n_p$, where γ is the secondary emission coefficient whose value is take to be 0.07 for simplicity. The charged species transport equations are solved via MUSCL scheme with a limiter function [4,5,6]. For time-integration, explicit 2nd-order Runge-Kutta (mid-point rule) is used. To solve Poisson's equation we used the FISHPACK solver as in [7].

2.2 *Model for the gas*

To describe the gas dynamics, we adopt the compressible Euler equations with no viscosity, as in [8]. The source term for energy transfer from the electric discharge to the gas is a Joule heating term as in [9]. The system is closed with the Ideal gas law. The Euler equations are solved via the same numerical scheme as the electric discharge transport equations.

2.3 *Coupling between gas and discharge*

As mentioned above the gas gets heated because of the Joule heating term in the Euler equations. This is how gas gets coupled to the electric discharge. For the electronic/ ionics mobilities we have an inverse relationship with the gas number densities. Hence, as the gas expands the gas density decreases, thereby increasing the electronic/ionic mobilities and diffusion coefficients. Now we have a completely coupled system in which the heating of the gas leads to its expansion and because of the expansion the electric discharge gets affected through the mobility/ diffusion coefficients.

3. Results and Discussion

Numerical simulations were performed with a code which was developed based on the model previously described. The electrode configuration was plane-to-plane. Simulations were carried out on a grid of 500(z-direction) x 250(r-direction) grid points with an initial pressure of 80 bar, initial temperature of 300 K, an applied voltage of 30 kV with a 0.3 mm gap between the electrodes. We started with a gaussian seed of electrons (with an equal number of positive ions) placed on the discharge axis at z=0.09 mm with a maximum value of 5×10^{16} cm^{-3} and $\sigma_r = 6.9 \mu m$ and $\sigma_z = 27.6 \mu m$. The mobilities, diffusion coefficients and rate coefficients were taken from [2] and scaled upto a pressure of 80 bar.

We have a cylindrical symmetry around the discharge axis (r=0). We set Neumann boundary condition on electron/ion densities on the left and right boundaries. On the top boundary (anode), we set positive ion density equal to zero. This means we allow no production of positive ions on the top boundary. Also we set the perpendicular component of diffusive flux for positive ions/electrons on top boundary equal to zero. For solving the Poisson's equation, Dirichlet boundary conditions were imposed on the lower plane (φ=0 at z=0) and the upper plane (φ=30kV at z=L). The electric potential varies linearly with z on the right lateral boundary. For the Euler equations, extrapolated boundary conditions were assumed [10].

The simulation results in FIG. 1 show that within several nanoseconds the temperature of the channel rises to about a few thousand Kelvins. One can also observe the developed thermal shocks and induced pressure waves. The electric field in the system has more or less stabilised around applied values of 1000 kV/cm.

The simulation was carried on for longer times (t=1.06μs) than shown here. Because of the secondary electrode emission, we observe a cycle of electrons being released from the cathode, heating the gas, the gas affecting the discharge and the electrons being absorbed at the anode. This cycle might either lead to spark formation of discharge decay.

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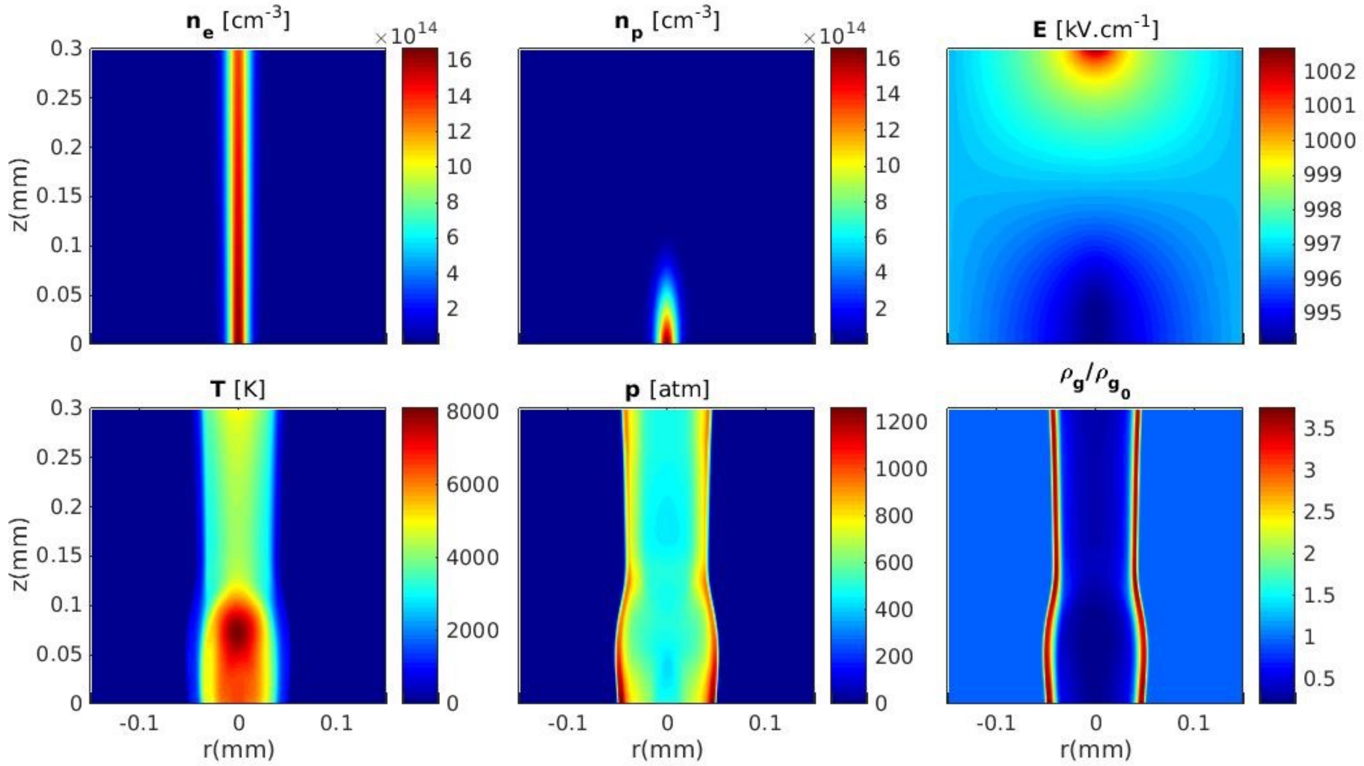

FIG. 1. Evolution of the coupled system of electric discharge at t = 212 ns. Plotted are the electron number density, ion number density, the modulus of electric field, temperature, pressure and density of the gas. The planar cathode is located at z=0 and planar anode at z=0.3mm

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