Study of the Fine Structures of Streamer with Hydrodynamics in Nanosecond Surface Dielectric Barrier Discharges

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Abstract: A 2D parallel code coupling plasma and hydrodynamics is developed to study the fine structure of streamer and hydrodynamics of nanosecond surface dielectric barrier discharge (nSDBD). A detailed kinetics of 17 species and 34 reactions for fast gas heating is taken into consideration. The structure and propagation of streamers along dielectric surface are studied for positive and negative polarities. The results of calculation are in good agreement with experimental data.

Keywords: SDBD, nanosecond discharge, hydrodynamics, simulation.

1. Introduction

Nanosecond pulsed surface dielectric barrier discharge (nSDBD) is one of the most promising tools for a lot of plasma applications. Production of active species (excited species, radicals, high energetic photons) is important for gas pollution control, surface treatment, plasma actuators for aerodynamics and combustion/ignition. Thus, nSDBD has been studied intensively both experimentally and numerically in recent years.

Experimental study of nSDBD is a challenging work, the fineness of the plasma layer and presence of the dielectric surface in a close proximity to the discharge complicates the diagnostics of SDBD plasma. As a result, most experimental works concerning nSDBD focus on discharge morphology and induced hydrodynamics [1-3].

Numerical simulation, has become another important tool for studying evolution of nSDBD. Many high quality simulation papers [4-6] and new techniques including adaptive mesh [4], fluid/MC coupled method [6] have been presented in recent years. However, most simulations of nSDBD are either lack of enough support and validation from experimental part, or taking too much time with detailed kinetics (weeks to month) when it comes to 2D/3D simulation.

In the present work, a discharge/hydrodynamics coupled model is proposed for detailed and fast simulation of nSDBD. 17 species and 34 reactions are taken into consideration. Recent experimental results of nSDBD have been used for validation and discussion.

2. Model and schemes

The model used in present work, is a combination of plasma part and hydrodynamics part. For the plasma modelling, a set of transport equations for charged particles in the drift diffusion approximation and local field approximation are solved for charged species and neutral species, respectively:

\[ \frac{\partial n_i}{\partial t} + \nabla \cdot \bar{\Gamma}_i = S_i \]  

where \( n_i \) is the number density of species \( i \), \( \mu \) and \( D \) are mobility and diffusion coefficients of corresponding charged species. \( S_i \) is the source term from kinetics. It is a challenging work to involve a complete set of plasma kinetics into a 2D model, thus in this work the kinetics are mainly selected for streamer propagation and fast gas heating, based on the detailed works of [7] and [8]. EEDF is calculated by BOLSIG+ package [9], with dataset from [10] for oxygen and [11] for nitrogen.

Poisson equation is solved together for electric field in presence of dielectric and surface charge accumulation:

\[ \nabla \cdot (-\varepsilon_r \varepsilon_0 \nabla \Phi ) = q_e (n_p - n_e - n_n) \]  

Photoionization that provides seed electrons for streamer propagation is described using the 3 term Helmholtz equations instead of classical integral model:

\[ \nabla^2 S_{ph}^l (\vec{r}) - (A \delta p_{O_2})^2 S_{ph}^l (\vec{r}) = -A_1 p_{O_2}^2 I (\vec{r}) \]  

where Sph(\( \vec{r} \)) is the source term of electron and ions from photoionization. \( p_{O_2} \) is the partial pressure of \( O_2 \) and \( I(\vec{r}) \) the ionization intensity term. The values of fitting coefficient, \( A \), and \( A_1 \) can be found from [12].

For hydrodynamics part, reactive Euler equations are solved taking into account thermal conductivity and multi species diffusion:
The performance of the code depends on the implicity, the fast solution of Poisson/Helmholtz matrix, and the complexity of kinetics. To gain high performance, the time integration of transport equations is done explicitly while elliptic equations are solved semi-implicitly. A preconditioned Conjugate-Gradients solver is used for solving matrix from Poisson/Helmholtz equations, and a RKC stabilized ODE solver is used to solve kinetics. To make it possible solving larger kinetics in 2D domain, a MPI-OpenMP hybrid approach is used, by solving kinetics on distributed memory HPC structures.

3. Results

Numerical simulation is conducted for atmospheric pressure and for the geometry shown in Fig.2 (b), with input voltage plotted in Fig.2 (a). A voltage pulse of ±24kV with rising time 2ns is applied on the exposed electrode, leading to the start and propagation of a discharge along the dielectric surface.

![Fig.2 Configuration of an experimental SDBD electrode system.](image)

Discharges driven by opposite polarities shows different properties in morphology, propagation and in the spatial and temporal distribution of charged species and electric field.

![Fig.3 shows the calculated temporal-spatial propagation of a positive streamer, with corresponding longitudinal electron density and electric field along OX axis 20 μm above dielectric surface shown in Fig. 4 a) and b).](image)

Electron density in a positive streamer is rather uniform (~ 10^{13} cm^{-3}), while electric field relative low (~25 Td) along the discharge channel. There is a high peak electric field at streamer head, which results in strong photoionization and high propagation velocity of 2.2 mm/ns.

Similar calculations were done for negative streamers in Fig.5 and Fig.6 a) and b). Significantly different from a positive streamer, electron density is more concentrated near the exposed electrode and decrease quickly during propagation due to constantly loss of electrons on the surface. Electric field within negative streamer channel is higher and more uniform than in a positive streamer.
Fig. 3 Spatial & temporal distribution of electron density in a positive streamer.

Fig. 4 Longitudinal plot for positive streamer along OX axis, a) Electric field and b) Density of negative charged species

Fig. 5 Spatial & temporal distribution of electron density in a negative streamer.

Fig. 6 Longitudinal plot for negative streamer along OX axis, a) Electric field and b) Density of negative charged species
The velocity of propagation for both polarities in experiments and simulation are plotted together in Fig. 7, which shows a good agreement between calculation and experiment. Both positive and negative streamer propagate fast at initial stage when voltage is rising, and then slows down when voltage reaches plateau, but negative streamers propagate much slower than that of positive ones. Numerical results and experimental data show a good agreement.

4. Conclusions
A fully coupled plasma/hydrodynamics code based on fluid method and hybrid parallelization for nanosecond discharge is proposed and validated by detailed experiments. Discharge characteristics are studied for SDBD under atmospheric pressure. The different discharge morphology, propagation velocity together with detailed distribution of species and electric field are obtained in calculations and are in good agreement with the experiments.

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References