Numerical analysis of high-electron-density atmospheric pressure argon streamer under a pin-to-plane electrode geometry: Effects of applying voltage polarity

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Atmospheric pressure plasma is used in a variety of applications, including surface treatment, gas decomposition, ozone generation, and medicine [1-3]. Streamer discharge is a fundamental aspect of atmospheric pressure plasma phenomena, in which a propagation of filamentary ionization waves called a streamer head is formed. This propagation can deliver a rich variety of reactive species, such as O atoms, N atoms, ·OH radicals, and ·NO radicals. To utilize streamer discharge in a wide range of practical application, it is important to realize stable discharge at low voltage. There have been few studies on streamers in rare gases compared with those in air.

In this study, we investigated the effects of the polarity and value of the applied voltage on the plasma electron density and discharge mode for argon streamers by using numerical simulations that can analyse behaviour at time scales on the order of nanoseconds. We conducted a parametric study for positive and negative polarity of the applied voltage under a pin-to-plane electrode geometry with a gap of 2 mm.

Self-consistent, multi-species, multi-temperature plasma fluid modelling was used. The model consisted of continuity equations for each species, an electron energy conservation equation, a bulk (gas) energy equation, and Poisson's equation for self-consistent electric fields. Fig. 1 shows the electrode geometry and computational mesh. The geometry is modelled axisymmetrically, and a hybrid mesh is used for geometric flexibility.

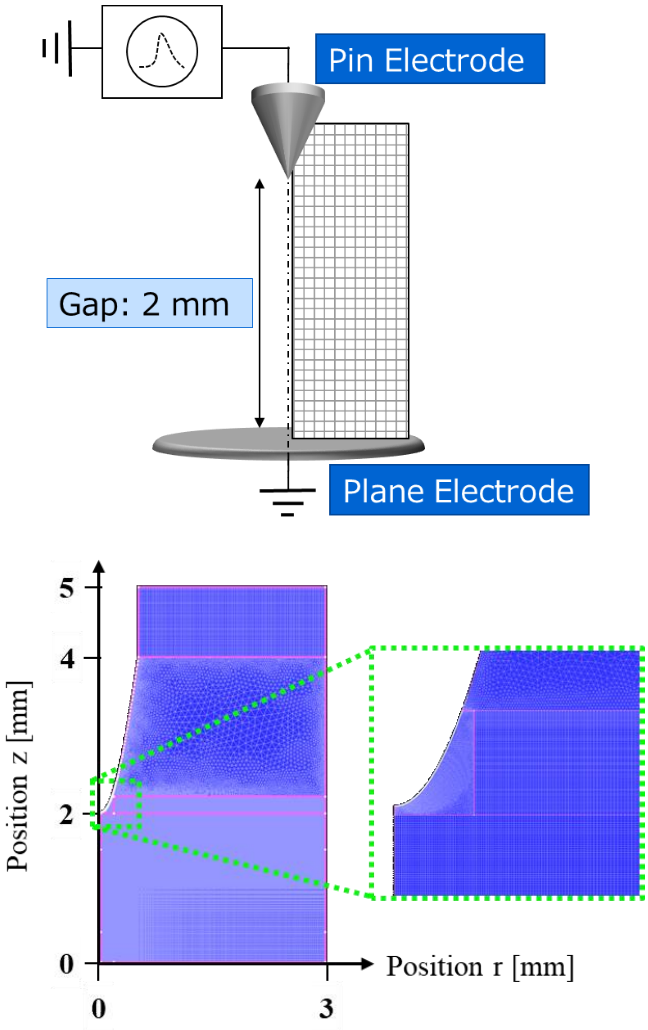

Fig. 1 Electrode geometry and computational mesh.

Fig. 2 shows contour maps for simulated distributions of the reduced electric field and the electron number density when positive voltages of +5 kV and +10 kV are applied to the pin electrode. The filamentary peak in the reduced electric field at each voltage is the streamer head. The positive primary streamer propagates between the electrodes with high electron density of 10^{20} to 10^{22} m^{-3}, which is higher than the typical density in air streamers (2×10^{19} to 10^{20} m^{-3}) [4]. The head size and propagation speed of the streamer increased with increasing applied voltage. Under the +10 kV condition, the primary streamer head arrived at the plane electrode at 1.4 ns and the effective propagation speed between the electrodes was approximately 1.4 mm/ns (1.4×10^{6} m/s). After the primary streamer arrives at the plane electrode, the secondary streamer further increased the plasma density.

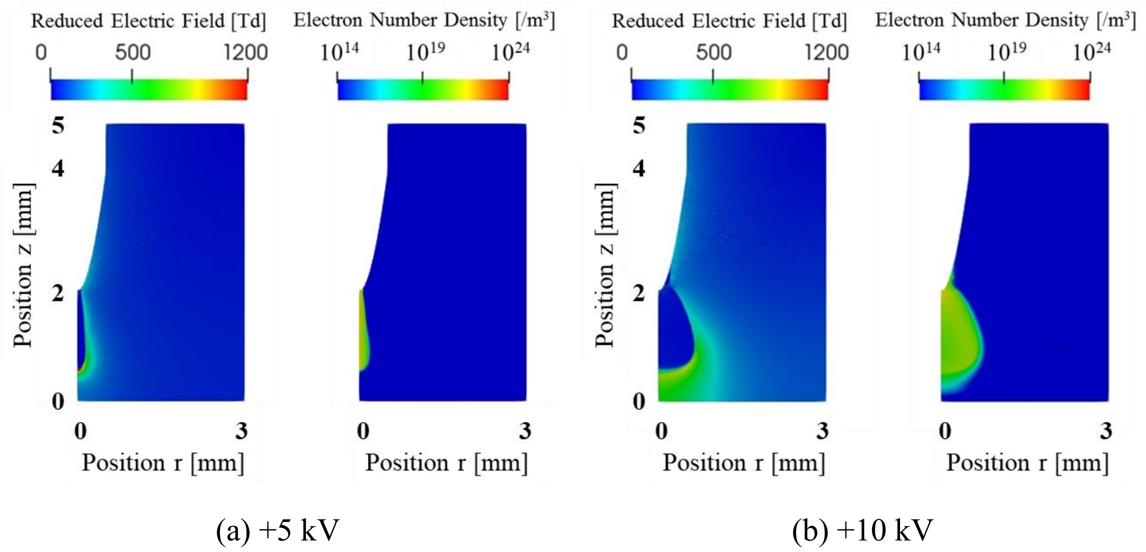

Fig. 2: Reduced electric field and electron number density of a positive streamer in atmospheric pressure argon discharge when positive DC voltages of +5 kV (a) and +10 kV (b) were applied to the pin electrode.

Fig. 3 shows spatiotemporal distributions of the reduced electric field and the electron number density when negative voltages of –5 kV and –10 kV were applied to the pin electrode. In the negative streamer, a distorted (sharp) streamer head propagates from the pin to the plane electrode under the –10 kV condition. Although it is difficult to evaluate the size of the streamer head, it appears smaller than in the positive case. Another difference between the positive and the negative cases was that the discharge mode changed to a corona-type discharge at low voltage when the voltage polarity was negative. These differences are likely attributable to differences in the direction of electron movement between positive and negative voltages. Electrons spread away from the pin electrode and central axis in negative streamers. This spread led to a diffuse shape of the negative streamer, resulting in a corona-type discharge.

Finally, we discuss low-voltage operation. Fig. 4 shows the electron number density in the streamer channel at a position z of approximately 1 mm as a function of the absolute value of applied voltage. It can be seen that the tendency is quite different between positive and negative streamers. In positive streamers, the electron number density decreased with increasing applied voltage up to 10 kV, and then increased up to 12 kV. In contrast, the electron number density simply increased with increasing applied voltage in the negative streamers. Positive streamers are suitable for low-voltage operations because of high-density and stable streamers, although the appropriate plasma properties depend on the application and objects to be treated.

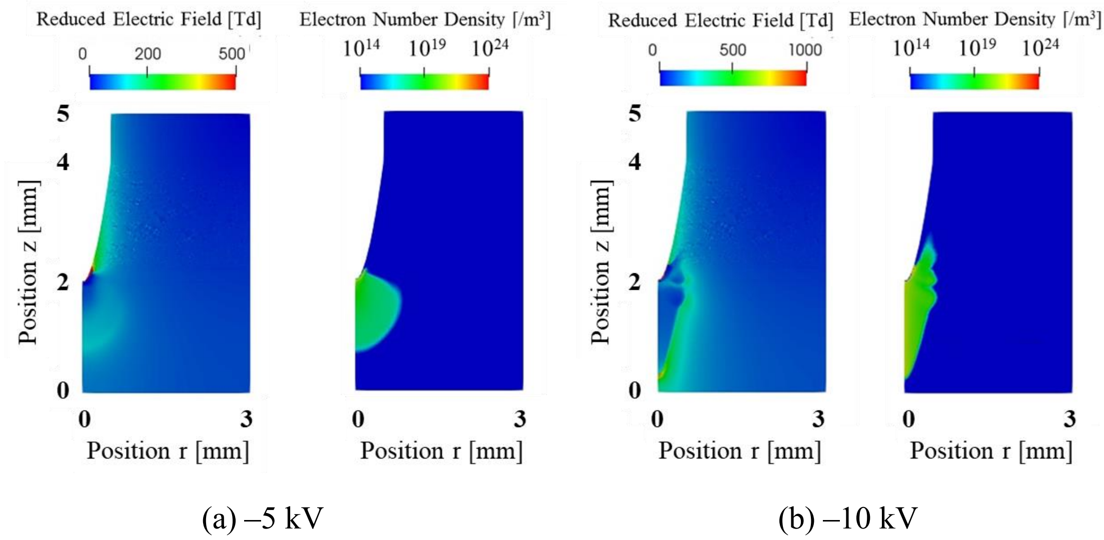

Fig 3: Reduced electric field and electron number density of a negative streamer in atmospheric pressure argon discharge when negative DC voltages of (a) –5 kV and (b) –10 kV are applied to the pin electrode.

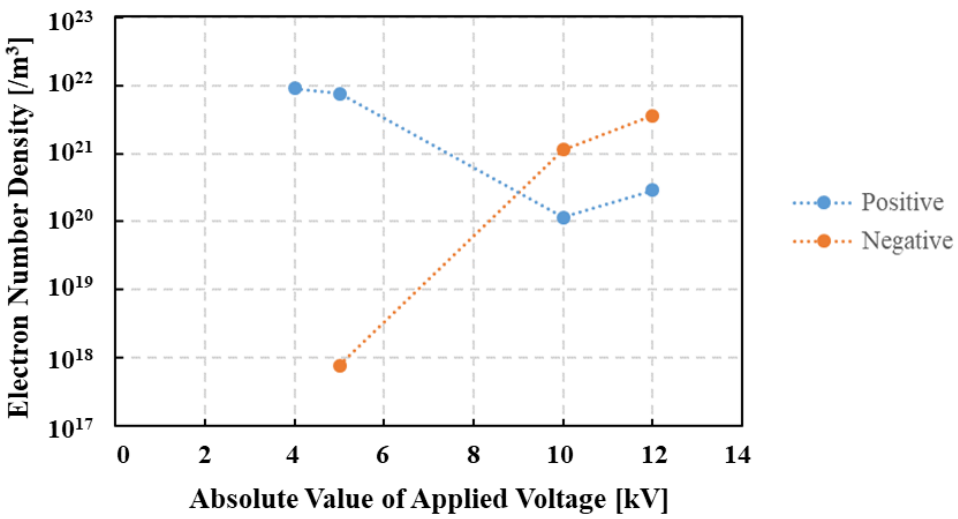

Fig 4: Electron number density in positive and negative primary streamers as a function of absolute value of applied voltage.

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