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Correlation-Based Evaluation of Voltage Waveform Parameters on O and N Radical Production in Atmospheric-Pressure Streamer Discharges

Atsushi Komuro, Yoshiyuki Teramoto, Hyun-Ha Kim
[1] National institute of advanced industrial science and technology
e-mail (speaker): komuro.a@aist.go.jp

Atmospheric-pressure streamer discharges are widely used to generate reactive oxygen and nitrogen species (RONS), which play a central role in applications such as sterilisation, pollution control and plasma-enhanced catalysis [1]. Recent advances in pulsed power technologies have enabled greater precision in controlling voltage waveform parameters, providing new possibilities for adjusting plasma chemistry. However, the complex and non-linear nature of streamer dynamics makes it challenging to predict the influence of waveform parameters such as peak voltage, rise time, and pulse width on radical production. Furthermore, the variety of experimental configurations complicates the development of general design principles.

To address these issues, we conducted a thorough parametric simulation study employing a two-dimensional axisymmetric fluid model. A total of 70 pulsed voltage waveforms were generated systematically by independently varying the peak voltage (15–35 kV), rise time (3–40 ns) and pulse width (6–81 ns). For each condition, we computed the discharge energy and the properties of the streamer, as well as the total production of atomic oxygen (O) and nitrogen (N) radicals. The resulting multi-parameter dataset was analysed using correlation and principal component analyses to extract meaningful physical relationships and reduce dimensionality.

Figure 1 presents z–t diagrams of the reduced electric field (E/N) and electron density (n_e) for a waveform with V_{max} = 35 kV, pulse rise time of 6.4 ns and pulse width of 42.5 ns. Due to the fast voltage rise and relatively long pulse width, the primary streamer propagates fast while the applied voltage continues to increase, even after the streamer reaches the cathode plane at z = 13 mm. Consequently, a secondary streamer emerges from the needle electrode, accompanied by a redistribution of the electric field. It has been reported that the length of the secondary streamer is proportional to the instantaneous voltage, a trend that is supported by the behaviour observed in Figure 1.

The results reveal a remarkably strong correlation (r = 0.995) between the total O radical yield and total discharge energy. This indicates that energy deposition is the dominant driver of O radical generation across the explored parameter space. By contrast, the N radical yield exhibits the strongest correlation (r = 0.988) with the fourth power of the peak voltage (V_{max}^4), suggesting that N radical production is primarily governed by the maximum electric field strength at the streamer head. The rise time and pulse width of the waveform showed only weak correlations with radical yields, implying that these parameters are of secondary importance when considered in isolation.

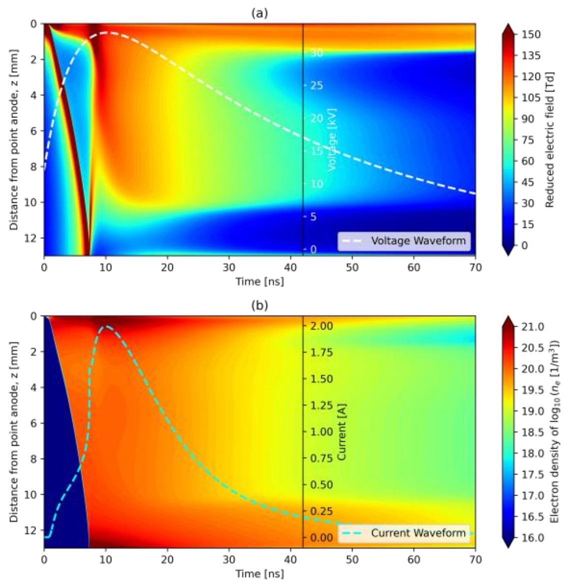

Figure 1: z–t diagrams of (a) E/N and (b) n_e for a fast-rise, long-pulse voltage (V_{max} = 35 kV, T_{rise} = 6.4 ns, T_{width} = 42.5 ns).

PCA results further support this by showing that energy-related parameters (V_{max} and total energy) and pulse-shape-related parameters (rise time and pulse width) form nearly orthogonal axes in parameter space. This suggests that pulse amplitude and waveform shape exert distinct influences on streamer dynamics, with pulse amplitude having a more direct impact on radical generation.

These findings have two major implications. Firstly, they provide a quantitative, physically grounded framework for screening and optimising voltage waveforms for plasma applications requiring specific radical species. Secondly, they emphasise the importance of analysing simulation results statistically as well as qualitatively in order to identify the parameters that govern complex, nonlinear systems such as streamer discharges. This approach complements conventional physical analysis and offers a way to evaluate simulation data more objectively and reproducibly.

References

[1] Komuro A 2025 *J. Phys. D: Appl. Phys*. **58** 133003.