Multiphysics modelling and optical characterisation of a coaxial argon plasma jet: identifying stability limits and reactive species evolution

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Non-thermal atmospheric pressure plasma jets (APPJs) driven by noble gases are investigated for plasma medicine because they generate reactive species at near-ambient temperatures. Stable operation requires simultaneous control of breakdown dynamics, discharge stability, power coupling, and plasma-air interaction. This work presents the design, multiphysics modelling, and experimental validation of a coaxial dielectric barrier discharge (DBD) reactor operating with argon. A one-dimensional axisymmetric COMSOL model couples Poisson's equation, electron transport, and heavy-species conservation. Simulations predict a peak electron density of 1.4×10^{17} m^{-3} and an electron temperature of 3.7 eV, confirming a strongly non-equilibrium regime ($T_e \gg T_g$). Optical emission spectroscopy (OES) confirmed OH, N_2, and N_2^+ emissions. The optimum condition was 5 kHz and 4.5 kV, where stable operation coincided with efficient power coupling and gas temperature below 50 °C.

1. Introduction

Non-thermal atmospheric pressure plasma jets (APPJs) are used in plasma medicine, surface modification, and decontamination because energetic electrons can generate reactive oxygen and nitrogen species (RONS) while the gas remains near ambient temperature [1,2]. This non-equilibrium behaviour allows plasma interaction with heat-sensitive surfaces, provided discharge stability is maintained. Argon is a useful carrier gas because of its low breakdown voltage, chemical inertness, and efficient energy transfer to ambient air through Penning ionisation and metastable processes [3]. However, voltage or frequency changes can shift a glow-like discharge towards filamentary or arc behaviour [4]. This study therefore combines reduced-order modelling, stability mapping, and OES to define the Safe Operating Area (SOA) of a coaxial argon DBD plasma jet.

2. Methodology

The plasma jet was generated using a coaxial atmospheric-pressure DBD reactor containing a high-purity quartz dielectric tube, a concentrically positioned stainless-steel high-voltage electrode, and an external copper foil ground electrode (Fig. 1). The tapered outlet assists plume formation while the dielectric barrier limits current growth and prevents transition to a thermal arc.

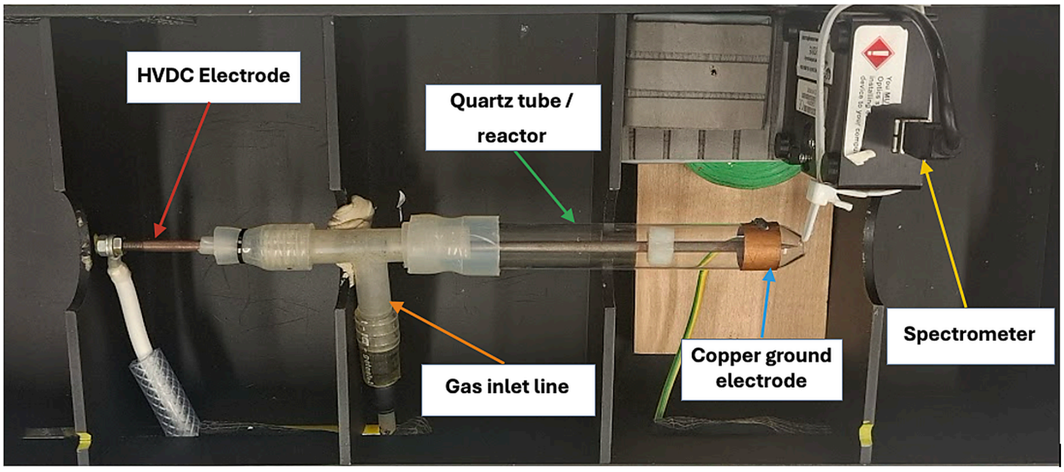

Figure 1: Schematic of the experimental setup.

The discharge was driven by a high-frequency pulsed DC power supply operating over 1-10 kV and 1-10 kHz. High-purity argon (99.999%) was used as the working gas and controlled using a mass-flow controller. OES was performed with an Ocean Optics USB2000+ spectrometer covering 186-1031 nm [3].

A time-dependent 1D axisymmetric COMSOL model was developed to examine breakdown dynamics (Fig. 2). The model couples Poisson's equation, the drift-diffusion approximation for electron transport, and heavy-species conservation. Electron transport was governed by:

$$\partial ne / \partial t + \nabla \cdot \Gamma e = Re \qquad (1)$$

where ne is electron density, Γe is electron flux, and Re is the collisional source term. Argon excitation, ionisation, and elastic scattering rate coefficients were derived using LXCAT cross-section data and the BOLSIG+ solver.

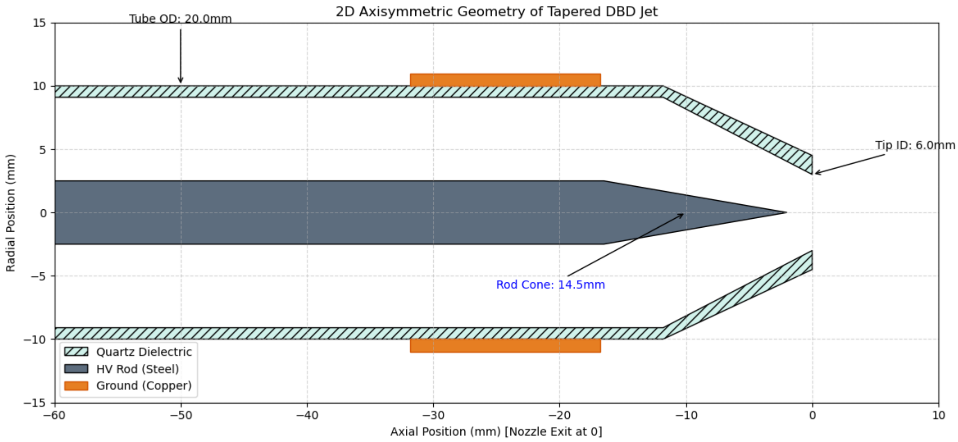

Figure 2: Tapered coaxial DBD reactor geometry and dimensions.

3. Results and Discussion

The model was evaluated over five RF cycles until a periodic steady state was reached. The electron density peaked at $1.4 \times 10^{17}\ \mathrm{m}^{-3}$ near the dielectric boundaries (Fig. 3), indicating sheath formation and local field enhancement. The electron temperature reached 3.7 eV during breakdown, while the gas temperature remained close to 400 K (0.03 eV). This large Te/Tg separation confirms that the reactor operates in a non-equilibrium, non-thermal regime.

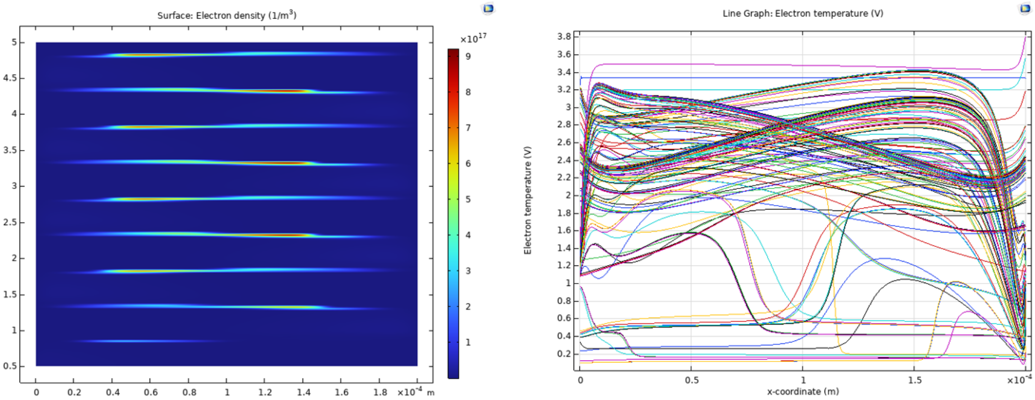

Figure 3: Simulated electron density and electron temperature across the discharge gap.

External stability was assessed by sweeping voltage from 1 to 10 kV and frequency from 1 to 10 kHz. Argon showed a broad SOA, and the optimum balance between discharge stability and power-coupling efficiency occurred at 4.5 kV and 5 kHz (Fig. 4). Under these conditions, the plasma plume extended to 36 mm in ambient air while the effluent temperature remained below 50 °C, satisfying the practical thermal limit for biomedical exposure [6].

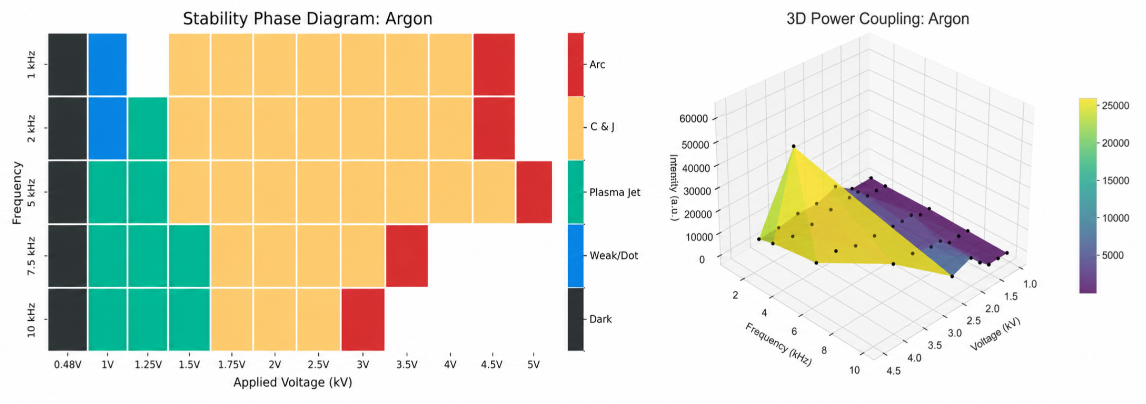

Figure 4: Operating window and power-coupling profile of the argon discharge.

OES at the optimised SOA condition showed strong argon emission lines at 696.8, 763.6, and 826.4 nm (Fig. 5). A clear hydroxyl radical band was detected at 308.5 nm, although no water vapour was added to the feed gas, indicating interaction with ambient humidity. Emissions from the Second Positive System of N_2 and the First Negative System of N_2^+ were also observed between 330 and 410 nm, confirming RONS generation through plasma-air mixing.

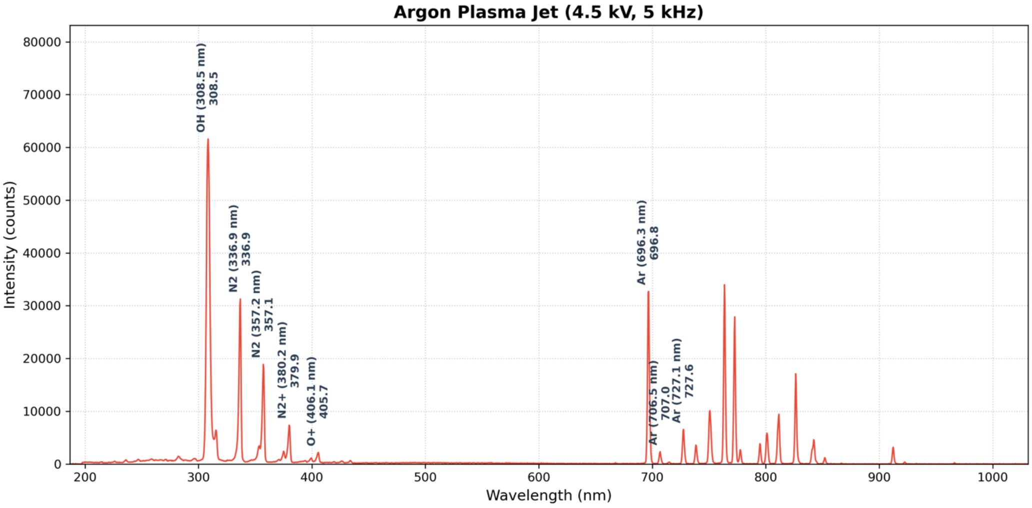

Figure 5: Optical emission spectrum of the argon plasma jet at 4.5 kV and 5 kHz.

4. Conclusion

This study demonstrates a combined modelling and experimental framework for defining the SOA of coaxial argon APPJs. The COMSOL model confirmed a strongly non-equilibrium discharge with Te ≈ 3.7 eV and Tg ≈ 0.03 eV, while experimental characterisation identified 5 kHz and 4.5 kV as the optimum stable operating condition. OES verified OH and nitrogen-related species formation, showing that the optimised argon jet can generate biomedical RONS while maintaining a gas temperature below 50 °C.

References

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