NON-EQUILIBRIUM DISCHARGES IN AIR PLASMAS AT ATMOSPHERIC PRESSURE

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There are interesting applications of non-equilibrium diffuse discharges in molecular gases, particularly air, at atmospheric pressure. Desirable conditions are electron densities greater than $10^{12}$ cm$^{-3}$ at gas temperatures less than 2000K. However, conventional wisdom suggests that such discharges would either be impossible or unstable.

To assess the possibilities, we have constructed two-temperature ($T_e>T_i$) kinetic models for nitrogen and air discharges, accounting for ionizational, chemical, vibrational and electronic non-equilibrium, and incorporating a collisional-radiative model with over 11,000 transitions. These models predict that (even) at atmospheric pressure energetic electrons driven by the discharge and promoting chemical and ionizing reactions can establish and maintain electron-density non-equilibrium of over six orders of magnitude. An unexpected result is an “S-shaped” dependence of $n_e$ on $T_e$ at steady-state for a given gas temperature. This behavior results from a transition between predominately molecular ions to atomic ions at a critical value of $T_e$ and values of $n_e$ somewhat above the desired range. An abrupt transition is predicted to occur when dissociative recombination is no longer able to balance the ionization rate as the electron temperature is increased for at a given gas temperature. Above this critical value of $T_e$ the electron density increases dramatically so that three-body recombination can maintain a steady state.
The foregoing calculations are performed using Maxwellian distribution functions for the translational energies of the electrons and heavy particles. To investigate the limitations of this simplification, the electron Boltzmann equation has been solved for nitrogen plasmas in conjunction with a somewhat simplified form of the collisional-radiative model. The results do not differ significantly from the Maxwellian version.

To assess the feasibility of such non-equilibrium discharges, experiments have been conducted in atmospheric-pressure nitrogen and air at both room temperature and around 2000K with electrode spacings of cm scale. Emission and laser-based spectroscopy are used to probe the rotational, vibrational, electronic and ion distributions of the resulting non-equilibrium plasmas.

Stable, diffuse DC discharges have been achieved at atmospheric pressure for a range of gas flow and temperature conditions including those which produce \( n_e \) of \( 10^{12} \) to \( 10^{13} \) cm\(^{-3} \) without significant gas heating. For comparison with the kinetic model, the “S-shaped” curves of electron density vs. \( T_e \) have been converted more readily measured current density vs. electric field by use of Ohm’s law and the electron energy equation. The latter incorporates the results of the collisional-radiative model to account for non-elastic energy losses from the free electrons to the molecular species. Good agreement between this theory and the discharge experiments has been obtained for both air and nitrogen non-equilibrium discharges over a wide range of conditions at atmospheric pressure, including electron densities greater than \( 10^{12} \) in air and \( 10^{13} \) in nitrogen.

To reduce the power required to maintain such non-equilibrium, the finite electron recombination time (~10\(\mu\)s) has been exploited by means of pulsed discharges of 10 ns duration. Both single-shot and repetitively pulsed diffuse discharges at 100 kHz have been demonstrated, with time-average power reductions of over two orders of magnitude for average electron densities greater than \( 10^{12} \). Current experiments are exploring larger-scale discharges with multiple electrodes.