Surface-wave discharges in helium at atmospheric pressure: simulations vs. experiments

M. Santos [1], C. Noël [2], T. Belmonte [2], L.L. Alves [(*)1]

[1] Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade Técnica de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[2] Institut Jean Larmour, Department of Chemistry and Physics of Solids and Surfaces , Nancy Université, CNRS, Parc de Saurupt, CS14234, F-54042 Nancy Cedex, France
[(*)] llalves@ist.utl.pt

Simulations and experiments are used to study helium surface-wave-sustained discharges at atmospheric pressure. Simulations use a collisional-radiative model describing the behavior of the electrons, the He^+ and He_2^+ ions, the $He(n<7)$ excited states and the He_2^* excimers, coupled to the electron Boltzmann equation. Experiments use optical emission spectroscopy diagnostics to measure the electron density and the populations of different excited states, at various powers, gas flows and gas temperatures. Preliminary results show a good agreement between model predictions and measurements of the excitation spectrum and the plasma excitation temperature.

As many other rare gases, helium is often used as a buffer gas in different plasma applications, hence the interest in describing its kinetics. The development of a collisional radiative-model (CRM) for helium discharges at atmospheric pressure is a subject of some novelty, since the majority of the existing studies on pure helium plasmas are intended for low-pressure and/or afterglow conditions [1,2].

This paper uses simulations and experiments to study atmospheric-pressure helium discharges, sustained by surface-waves (2.45 GHz frequency) in capillary tubes (3 mm radius), at 150-300 W incident powers (corresponding to $2.5 \times 10^{14} - 3.5 \times 10^{14}$ cm^{-3} electron densities).

Simulations use a self-consistent, homogeneous and stationary CRM that solves the macroscopic equations (continuity and momentum transfer) for the $He(n<7)$ excited states, the He^+ and He_2^+ ions and the He_2^* excimers, coupled to the electron Boltzmann equation written in its classical two-term approximation. The source terms with the rate balance equations include the following mechanisms: electron-impact collisions (excitation / de-excitation / dissociation and ionization / recombination); atomic collisions (Penning reactions, l-exchange reactions, associative ionization, three-body association and dissociation); ion collisions (three-body ion conversion / dissociation); and radiative transitions (where the effects of radiation trapping are taken into account for all resonant transitions, the non-resonant transitions to metastable states and the intense $3^3D \rightarrow 2^3P$ transition). Transport phenomena (due to the diffusion of species and the gas flow) are considered for the metastable states, the excimers and the charged particles, assuming ambipolar diffusion conditions for the latter. The electron Boltzmann equation considers stepwise inelastic and superelastic collisions from the highly populated states 2^3S, 2^1S and 2^3P, as well as electron-electron collisions, adopting a coherent set of electron cross sections adjusted to ensure good predictions of the swarm transport parameters and the Townsend ionization coefficient [2,3].

Measurements are based on the following optical emission spectroscopy (OES) diagnostics: (i) the Stark broadening of the H_β line transition, which is used to obtain the electron density (n_e); (ii) the rotational spectrum of the OH 289 nm and 315 nm band-head transitions, which is fitted to deduce the rotational temperature (T_{rot}); (iii) the intensities of different spectral lines, related to the populations of the emitter (excited) states, whose Boltzmann-plot allows deducing the plasma excitation temperature (T_{exc}). Simulations use the experimental values of n_e and T_{rot} (assumed to represent the gas temperature T_g) as input parameters, calculating the populations of the different excited states and the excitation temperature. These quantities are compared to the OES measurements for model validation. Although model results suggest the existence of two excitation temperatures (associated with the low- and high-energy regions of the atomic states distribution function), we have preferred to obtain a single value of T_{exc} because of the dispersion observed in the experimental data, for excitation energies beyond 24 eV.

Figure 1 shows calculations and measurements of the excitation temperature, as a function of the electron density, for a constant gas flow of 0.7 slm and considering different gas temperatures (also

plotted in this figure, as a function of n_e). Both simulations and experiment show that T_{exc} is not affected by n_e variations. Model predictions for T_{exc} overestimate its measured values by about 10%, yet staying within the experimental errors bars. For the range of parameters considered, the simulations yield electron temperatures of about 1.7 eV, i.e. ~5 times higher than the excitation temperatures, hence revealing that the kinetics of the heavy species (particularly for levels above n=3) is not exclusively governed by electron-impact collisions.

Model results show that: (i) electrons are produced by direct/stepwise ionization and by associative ionization and He_2^+ (the dominant ion) is produced mainly by associative ionization and by three-body ionic conversion, while dissociative recombination is the main mechanism responsible for the losses of these two species; (ii) He_2^* is produced by dielectronic recombination of He_2^+ and by three-body collisions with $He(2^3P)$ (depending on n_e and T_g), and is lost by electron dissociation; (iii) $He(2^3S)$ and $He(2^3P)$ are mainly produced and lost by electron collisions and by radiative transitions.
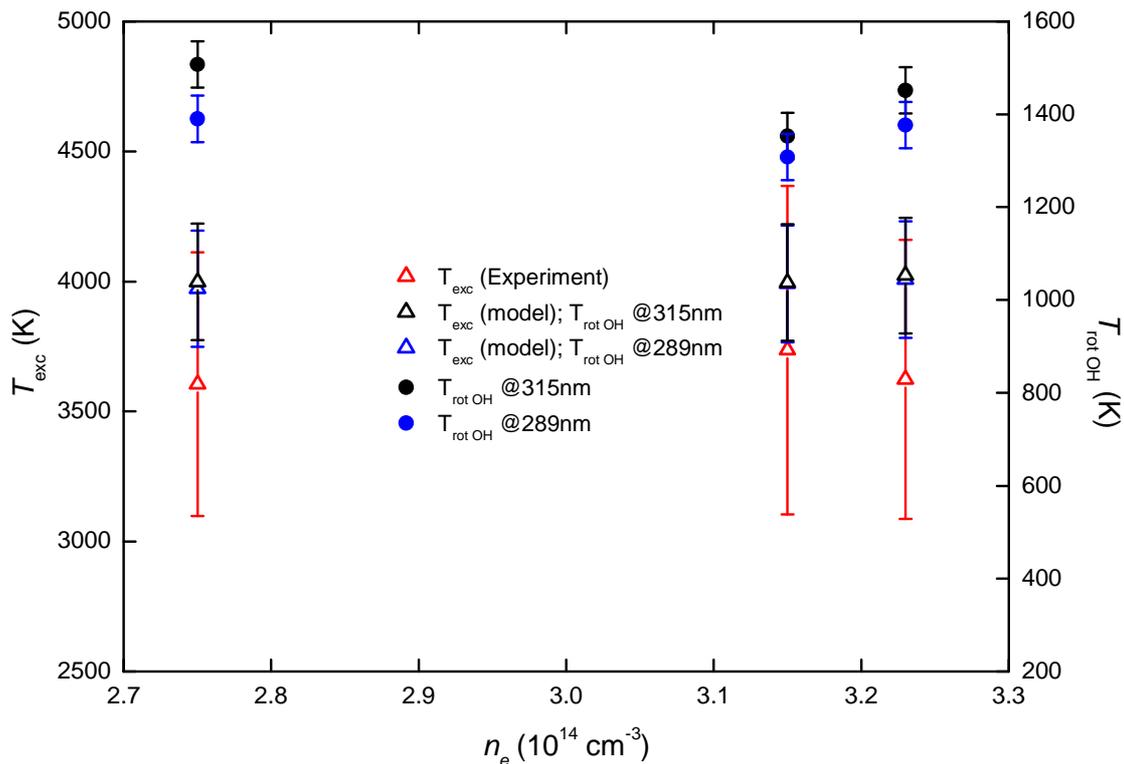

Fig. 1: Excitation temperature T_{exc} and rotational temperature T_{rot}, as a function of the electron density, for a gas flow of 0.7 slm. The rotational temperatures (adopted as gas temperatures in the model) were obtained from the OH 289 nm (●) and 315 nm (●) band-head transitions. The excitation temperatures, measured (△) and calculated assuming $T_g = T_{rot\ OH}$ for 315 nm (△) and for 289 nm (△), were obtained from the Boltzmann-plots of the excited state populations, with energies lying between 22.7 and 24.1 eV. The error bars with the calculated T_{exc} result from the logarithmic fit to the excitation spectra.

The paper will also present a comparison between the simulations and measurements of the main excited species populations, discussing a strategy to improve the model predictions.

Acknowledgements

References

[1] L.L. Alves, G. Gousset and C.M. Ferreira, *J. Phys. D* **25** (1992) 1713
[2] T. Belmonte, R.P. Cardoso, G. Henrion and F. Kosior, *J. Phys. D* **40** (2007) 7343
[3] L.L. Alves and C.M. Ferreira *J. Phys. D* **24** (1991) 581