Model of a surface-wave discharge at atmospheric pressure with a fixed profile of the gas temperature

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Abstract. We present a 3D model of a surface-wave-sustained discharge at 2.45 GHz at atmospheric pressure. A small plasma source creates a plasma column in a dielectric tube and a plasma torch is observed above the top. The plasma parameters and the axial profile of the gas temperature are significantly changed in the presence of the substrate above the plasma torch. The Boltzmann equation for electrons under the local approximation is solved, together with the heavy particle balance equations at a fixed axial profile of the gas temperature. The model of this finite length plasma column includes also the dispersion relation of azimuthally-symmetric surface waves. A detailed collisional-radiative model is also implemented for argon discharge at atmospheric pressure, which includes 21 rate balance equations for excited Ar atoms [(Ar(1s5-1s2), Ar(2p10-2p1), Ar(2s3d), Ar(3p)], for positive Ar+ and Ar2+ ions and for excited molecules. The changes in the EEDF shape and the mean electron energy along the plasma column are investigated and the axial structures of the discharge and plasma parameters are obtained.

1. Introduction
The surface-wave discharges at atmospheric pressure are an object of intensive investigations due to their applications for environmental and industrial purposes. Detailed modelling of the discharges can provide insight into the importance of various processes, their rate constants, collision frequencies of the electrons, the effective temperature and concentration of electrons [1], and some basic plasma characteristics (gas temperature, population density, etc.). It also provides a better understanding of the regime of operation, distribution of the components of the EM field, and gives guidelines for optimizing the operating parameters. Modelling these discharges is difficult because of the large number of reactions between the charged particles and neutrals and the complexity of the processes at atmospheric pressure, even in argon gas [2-4].

This study presents a self-consistent model of a plasma column sustained by surface waves in a small-radius ceramic capillary of a portable microwave plasma source [5] at a fixed profile of the gas temperature.

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temperature. The plasma parameters and the axial profile of the gas temperature are significantly changed in the presence of the metal substrate above the plasma torch. In this case, the electron density increases, while the profile of the gas temperature depends on the thermal conductivity of the metal and the cooling of the gas by the substrate [6]. This experiment is modelled under the assumption for a fixed profile of the gas temperature along the plasma column with a different trend. The Boltzmann equation for electrons under the local approximation is solved, together with the heavy particle balance equations at this fixed profile of the gas temperature.

2. Description of the model
Figure 1 shows a flowchart of the theoretical model presented in this study. The self-consistent model includes as a first step a solver for the dispersion relation of azimuthally-symmetric surface waves sustaining the discharge in a high-permittivity ceramic tube ($\varepsilon_d = 9.3$). The dispersion equation of surface waves is solved for the case of a thin-cylinder approximation in cylindrical coordinates, with waves propagating in axial direction along the plasma column. The components of the azimuthally symmetric mode (TM$_{00}$) are $E_z$, $E_r$ and $H_\phi$ with a maximum of the field amplitude at the plasma-dielectric interface. The plasma column is assumed homogeneous in radial direction and the plasma dielectric constant is calculated using an averaged value of the electron concentration $n_e$ and an effective value of the electron-neutral collision frequency $\nu_{en}$. By applying the boundary conditions across the three structure domains (plasma-dielectric-air), the dispersion relation is solved numerically via an iterative procedure. The values for the attenuation coefficient $\alpha$ and the phase constant $\beta$ are obtained for given initial values of the electron concentration and the electron-neutral collision frequency. The distribution of the electromagnetic field in radial direction is obtained. The value of the effective electric field at the local
position is calculated as \( E_0 = \sqrt{E_x^2 + E_z^2} \). The next part of the program is a numerical solver for the Boltzmann equation for electrons under the local approximation and a two-term approach for the EEDF. This equation is solved for the stationary regime of the discharge taking into account elastic and inelastic collisions, Penning ionization, etc. in the collisional integral.

After obtaining the effective electron temperature and concentration, all populations of the argon atom excited states, and the frequencies of excitation, ionization, de-excitation, etc. are calculated. These values are taken into account in the heavy particle balance equations. The populations of the argon atoms excited levels are calculated by the collisional-radiative model for argon plasma [7]. The following heavy particles are included in the model: Ar s-levels (1s\(_2\)-1s\(_5\)), the Ar 2p-levels (2p\(_1\)-2p\(_{10}\)), blocks for Ar(2s3d) and higher levels, atomic Ar\(^+\) and molecular Ar\(_2^+\) ions and excited molecules Ar\(_2^*\). The kinetic processes considered in the Boltzmann equation are: elastic collisions and inelastic collisions (excitation, de-excitation, ionization, step-wise ionization, dissociative recombination for Ar\(_2^+\) and three-body recombination, etc., and Penning ionization for the excited molecules) (table 1).

In this manner, the local parameters close to the exciter of SW waves are obtained.

### Table 1. Rate balance equations considered in the model.

| No. | Rate balance equation |
|-----|-----------------------|
| 1-4 | 4 ls-levels – Ar (1s\(_2\)-1s\(_5\)) |
| 5-14 | 10 2p-levels – Ar (2p\(_1\)-2p\(_{10}\)) |
| 15 | Ar (2s3d) |
| 16 | Ar (3p) |
| 17 | Ar (higher levels) |
| 18 | Ar\(^+\) ions |
| 19 | Ar\(_2^+\) ions |
| 20 | Ar\(_2^*\) molecules |
| 21 | Equation for the quasi-neutrality of the plasma |

3. Results

In this study, results are presented for the EEDF at three possible distributions of the gas temperature in the plasma column: constant value (line 1) and two linear profiles with increasing slopes (lines 2 and 3) (figure 2). The Boltzmann equation is solved via the iterative finite difference method, so that the electron energy distribution function (EEDF) at these three distributions is obtained. The shape of EEDF is close to the Maxwellian, but its slope in a semi-logarithmic scale increases with the increase of the gas temperature gradient (figure 3).

The mean electron energy (effective electron temperature \( T_e \)), calculated from the EEDF, as well as the electron concentration \( n_e \), decrease along the plasma column (figure 4 and figure 5).

By solving the dispersion relation of azimuthally-symmetric surface waves, values of the attenuation constant \( \alpha \) and the phase constant \( \beta \) are obtained and compared at the different profiles of the gas temperature (figure 6). It is observed that the attenuation constant approaches the phase constant much faster in the presence of a significant temperature gradient along the axis. Figure 7 shows the effective electric field which decreases monotonically along the plasma column.

**Figure 2.** Axial profiles of the gas temperature \( T_g \).  
**Figure 3.** Electron energy distribution function for different profiles of \( T_g \).
4. Conclusions
A model of a surface-wave discharge at atmospheric pressure in argon gas in a high-permittivity ceramic tube ($\varepsilon_d = 9.3$) is used for three fixed profiles of the gas temperature. The Boltzmann equation for electrons is solved, together with the detailed collisional-radiative model for argon plasma at atmospheric pressure. The values are obtained of the plasma parameters along the axis of the plasma column at increasing inclination profile of $T_g$. They show a steeper decrease with the distance, while the attenuation constant $\alpha$ and the phase constant $\beta$ have a steeper increase.

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