COMPARISON OF KINETIC AND FLUID MODELS OF SURFACE-WAVE-SUSTAINED ARGON PLASMA

E. Benova, M. Pencheva, K. Pavlov

St. Kliment Ohridsi University of Sofia, Sofia, Bulgaria

1. Introduction

Detailed modelling of the discharges can provide insight into the interplaying physic-chemical processes and the basic plasma characteristics (electron density, electron temperature, gas temperature, species density, electric field etc.) that might be difficult to obtain via measurements. It provides better understanding of the regime of operation and gives guidelines for optimizing the operating parameters. Modelling is also used in diagnostics methods for obtaining the plasma characteristics from the measurements, especially in non-equilibrium plasma diagnostics.

The surface-wave sustained plasma is one type of those non-equilibrium plasmas. The interest in studying the high frequency (HF) plasmas ($\omega/2\pi > 1$ MHz), especially surface-wave-sustained discharges, has grown significantly in recent years because of the major application they find in a number of scientific and technological fields such as analytical chemistry, spectroscopy and surface processing. The most salient features of these plasmas are high flexibility, ease of handling and the possibility to obtain them under broad ranges of experimental conditions.

2. Theoretical description

A surface wave propagates along the plasma–tube wave-guide structure and the field has a maximum intensity at the discharge wall. For modelling the wave propagation and the plasma properties one needs to include both electrodynamic and gas discharge description. Fluid or kinetic approach can be use for the latter.

The fact that the wave propagates along a plasma column sustained by the wave itself makes the problem rather complex and requires a self-consistent approach. The self-consistent models used in our work are based on the complete set of equations describing both the electrodynamics of the wave propagation and the kinetics of the discharge.

2.1. Electrodynamic part of the model

The behaviour of the propagating azimuthally symmetric wave of angular frequency $\omega = 2\pi f$ is described by Maxwell's equations. We consider plasma column with radius R surrounded

by dielectric tube with radius R_d and vacuum [1]. The permittivity of the three media are ε_p, ε_d and $\varepsilon_v = 1$, respectively. The plasma permittivity depends on the plasma density via plasma frequency ω_p and on the electron–neutral collision frequency for momentum transfer ν:

$$\varepsilon_p = 1 - \frac{\omega_p^2}{\omega(\omega + i\nu)} = 1 - \frac{\omega_p^2}{\omega^2}\left(1 + \frac{\nu^2}{\omega^2}\right)^{-1} + i\frac{\nu}{\omega}\frac{\omega_p^2}{\omega^2}\left(1 + \frac{\nu^2}{\omega^2}\right)^{-1} \qquad (1)$$

At low pressure, when plasma is assumed to be weakly dissipative medium ($\nu < \omega$) the plasma permittivity is a simple real expression $\varepsilon_p \sim 1 - \omega_p^2/\omega^2$. At higher pressures such assumption is not applicable and the exact expression (1) for ε_p should be used.

From Maxwell's equations one obtains the wave equation, which with appropriate boundary conditions for continuity of the tangential components gives the radial distributions of the wave field components and the local (for fixed axial position z) dispersion equation. The dispersion equation is solved point by point along the axially inhomogeneous column and gives the dependence of (i) the real and (ii) the imaginary part of the wave number on the plasma frequency, the so called (i) phase and (ii) attenuation diagrams at fixed wave frequency [2]. For solving equation (1) the electron–neutral collision frequency ν is necessary and it is calculated in the kinetic part of the model.
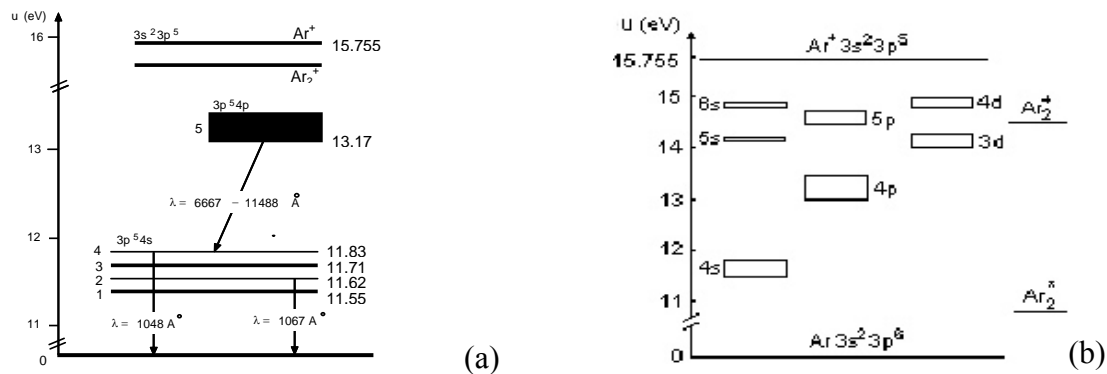
The other important equation in the electrodynamic part of the model is the wave energy balance equation obtained from Poynting's theorem, $dS/dz = -Q$. Here S is the wave energy flux, and Q is the wave power per unit column length absorbed by the electrons. This set of equations is not complete and can be solved only if we have one more relation giving the dependence between Q, respectively the electric field amplitude E, and the plasma density. It, as well as the electron–neutral collision frequency, can be determined by the elementary processes in the discharge and for this we need a gas-discharge modelling.

2.2. Gas discharge modelling

For gas discharge description the fluid [3] and the collisional-radiative models [4] with Maxwellian electron energy distribution function (EEDF) are widely used.

The kinetic approach includes the electron kinetics and the heavy particles one. The electron kinetics is based on the electron Boltzmann equation from which we obtain the EEDF, the electron energy balance equation giving us the mean power θ required for sustaining an electron–ion pair in the discharge, and the electron particle balance equation. The particle balance equations for excited atoms and for ions are included in the heavy particle kinetics. Depending on the gas pressure the appropriate Argon energy levels diagram
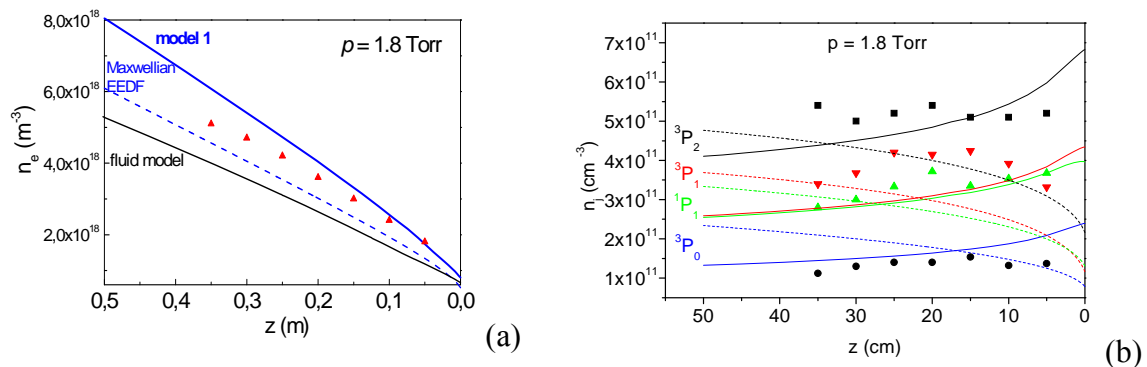
and corresponding set of elementary processes should be chosen. We are presenting here two kinetic models – one using a simplified energy levels diagram of Argon with 4s and 4p levels only taken into consideration (Figure 1a, [5]) and the other including more blocks of levels (Figure 1b [6]). The first one, denoted as **model 1** is applied to Argon in pressure range from 0.2 to 15 Torr. The **model 2** was developed for atmospheric pressure Argon surface-wave-sustained plasma but was applied also to lower pressures (from 5 Torr).

Figure 1. Energy level diagram of argon atom used in model 1 (a) and in model 2 (b).

3. Results and discussion

The axial distributions of plasma densities obtained by different models are compared with experimental data. For this purpose in the fluid model we need the electron–neutral collision frequency which is taken from our kinetic models or from the experimental data, where available. At relatively low pressure (1.8 Torr) all models (fluid [7], collisional-radiative with Mexwellian EEDF [8] and model 1) give similar results for plasma density z-dependence and pretty good agreement with the experimental data (Figure 2a). In these discharge conditions the EEDF is far from Maxwellian and this result only shows that plasma density is not very sensitive to the gas discharge modelling and we can even use a fluid model instead. But this conclusion is not correct when the excited states population is compared (Figure 2b).

Figure 2. Axial distribution of plasma density (a) and 4s excited states populations (b).

The fluid model cannot give any results here and the axial distribution of 4s levels is completely different from model 1 (solid lines) and assuming Maxwellian EEDF (dashed lines). The elementary processes rates and transport coefficients strongly depend on the EEDF and this leads to strong dependence of the excited atoms populations on the modelling approach. The applicability of model 1 decreases with pressure increasing and then model 2 is in best agreement with experiment. This can be seen in Figures 3a and 3b for pressure 5 Torr and 15 Torr, respectively.
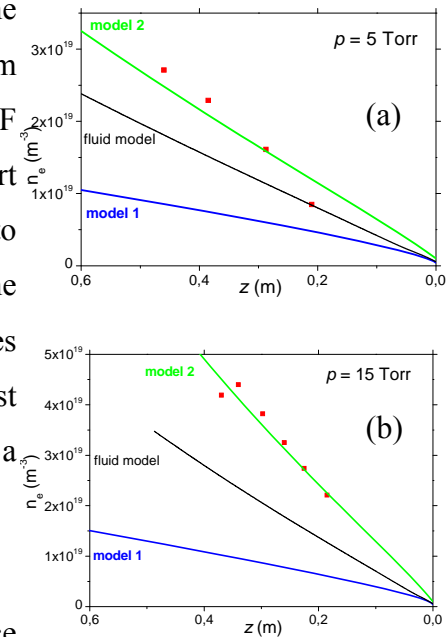
4. Conclusion

The kinetic approach is obligatory for these plasmas since the electron energy distribution function (EEDF) is non-Maxwellian one in the whole pressures range. The fluid model, considering only the electrons, cannot give any sufficient information about the excited states, radiative transitions and other processes usually necessary for the surface-wave-discharge applications and diagnostics. Thus it is not applicable for these purposes. It is shown that model 1 gives good results when the gas pressure is not very high but with pressure increasing the model 2 should be used.

Figure 3. Axial distribution of plasma density at various pressures

5. Acknowledgements

References

[1] Pencheva M, Benova E, Zhelyazkov I 2007 *Journal of Physics: Conference Series* **63** 012023

[2] Margot J and Moisan M 1993 *J. Plasma Phys.* **49** 357

[3] Koleva I, Makasheva K, Paunska Ts, Schlüter H, Shivarova A, Tarnev Kh 2004 *Contrib. Plasma Phys.* **44** 552–557

[4] Yanguas-Gil A, Cotrino J, González-Elipe A R 2004 *Phys. Plasmas* **11** 5497

[5] Petrova Ts, Benova E, Petrov G and Zhelyazkov I. 1999 *Phys. Rev.* **E 60** 875–886

[6] Benova E in 2006 *MICROWAVE DISCHARGES: Fundamental and Applications*, edited by Yu. A. Lebedev, Yanus-K, Moscow 9–18

[7] Zhelyazkov I, Benova E and Atanassov V 1986 *J. Appl. Phys.* **59** 1466-1472

[8] Benova E, Petrova Ts, Blagoev A and Zhelyazkov I 1996 *J. Appl. Phys.* **79** 3848-3852