EFFECTS OF RADIATION TRAPPING IN A FREE-BURNING ARC ARGON PLASMA

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ABSTRACT

Radiation processes play an important role for deviations from ionization equilibrium in thermal plasmas. Beside continuum radiation, the reabsorption of resonance radiation may play a role in the establishment of plasma parameters. A conventional approach to account for radiation trapping in collisional-radiative modeling is based on an effective lifetime of resonance atoms and the spontaneous transition probability for highly excited states [1].

In the present work, the impact of the spatial redistribution of resonance atoms within the plasma column of a free-burning arc in argon due to trapping of radiation is considered. The method is based on a solution of the Holstein-Bibermann equation applying a matrix method [2]. The results show significant broadening of the radial distribution and enhanced values of the density of resonance atoms close to the arc axis as compared to the effective lifetime approximation.

1. INTRODUCTION

In order to get closer to the experimental results modern arc models include deviations from equilibrium plasma state, especially in the near electrode regions and in the arc periphery. As an example, a new model of a free-burning argon arc which takes into account the violation of chemical equilibrium through the inclusion of collisional-radiative model has been suggested in [1]. Direct description of the densities of the excited species allows for an exact description of line radiation. The latter is a constituent of the radiation of the thermal plasma along with the continuum radiation. Significant advantage of collision-radiative models is that the results for line radiation can be directly compared with the data of spectroscopic measurements and, hence, can be used among others for the model validation.

The densities of plasma species in [1] have been calculated from the solution of fluid equations which have a representation

$$\nabla\cdot\left(\rho\vec{U}Y_i\right)-\nabla\cdot\vec{J_i}=S_i\,. \quad (1)$$

Here ρ is the gas density, U is the average particle flux velocity, Y_i is the mass fraction of the species sort i, J_i denotes the particle flux and S_i is the source term which includes various plasma-chemical reactions. The differential operators in the left hand side of equation (1) describe the particle transport due to diffusion and convection. The line radiation has been accounted for by spontaneous lifetimes for high-lying excited states and by effective lifetime terms for the resonant radiation. Such an approach does not include the radiation transport due to emission-absorption sequences in the plasma. For the case of high-lying excited state and low absorption coefficients (small optical depth) the radiation transport can be neglected. However, for the resonant excited states which are connected with the ground states by radiation transitions, the absorption coefficients are rather high and the radiation transport becomes important. The specific feature of a free-burning arc is the presence of strong radial temperature gradients which lead to inhomogeneous distribution of ground state atoms (absorbing atoms) and, hence, to a significant spatial variation of the absorption coefficient. The situation is most pronounced for the resonant radiation, which ends on the ground state level.

The density of excited species which participate in radiation processes can be described by an integral radiation transport equation (so-called Holstein-Biberman equation [3, 4]). One of the possible solution approaches of the radiation transport equation, so-called matrix method, has been recently presented in [2]. This flexible techniques gives the opportunity to handle the radiation for varying value of the absorption coefficient. As a first step to the full coupling between the hybrid models and plasma-chemical model with adequate inclusion of radiation transport the resulting excitation source arising from the fluid equations has been used in the solution of Holstein-Biberman equation. In order to examine the influence of radiation trapping on the species distribution two cases have been considered, approximation of effective lifetime (conventional approach) and inclusion of the space-dependent radiation transport operator (matrix method). As an example the density of the first resonant excited argon state $Ar(1s_4)$ (Pashen notation) has been chosen. The results will be demonstrated for a plane which is perpendicular to the arc axis at a distance of 1 mm to the cathode. Here, the strong temperature gradients occur. It should be noted, that even in the case of more smooth temperature profile the, like e.g. in the central plane or near the flat anode, the results of calculations shows similar tendencies.

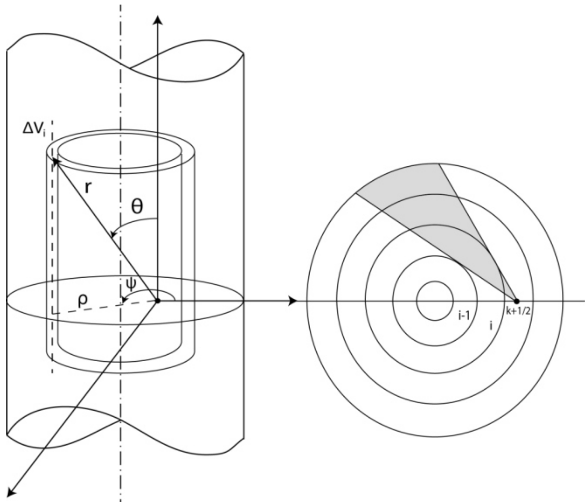

Fig. 1. Volume discretisation in case of infinite cylinder.

2. BASIC EQUATIONS AND SOLUTION APPROACH

The radiation transport equation for the case of stationary inhomogeneous plasma reads

$$A_{ik}N_i(\vec{r}) - A_{ik}\int_V N_i(\vec{r'})K(\vec{r'},\vec{r})d\vec{r'} = W_i(\vec{r}). \quad (2)$$

Here W_i is the number of excitations per unit of time at the unit volume, A_{ik} is the spontaneous transition probability. The kernel of radiation transport operator $K(\vec{r'},\vec{r})$ describes the probability for a photon emitted in the point *r'* to be absorbed in the point *r*. Taking into account the spatial inhomogeneity of the absorption coefficient the kernel becomes the representation

$$K(\vec{r'},\vec{r}) = \int_0^\infty \frac{\varepsilon_\nu(\vec{r'})k_\nu(\vec{r})}{4\pi}\frac{\exp(-\int_{\vec{r'}}^{\vec{r}}k_\nu(\xi)d\xi)}{|\vec{r'}-\vec{r}|^2}d\nu \quad (3)$$

where ε_ν and κ_ν are the line profiles of emission and absorption, and ν is the photon frequency. The expression under the integral gives the probability for a photon to pass the distance $|r'-r|$ without absorption.

The matrix solution approach [2] developed recently consists in replacement of the integral equation (2) through a system of algebraic equations by dividing the entire volume V into small volume elements ΔV_i. The resulting equation system gets the representation

$$A_{eff}\sum_i a_{ik}N_i = W_k, \quad (4)$$

where A_{eff} is the effective probability of radiative escape introduced by Biberman [4] and the matrix elements a_{ik} arise from integration over the volume ΔV_i and the line contours (frequency).

In the case of an infinitely long cylinder the volume elements ΔV_i are the cylindrical layers with infinite length and a thickness $h=R/N$, where R is the cylinder radius and N number of layers (Fig.1).

The method for calculation of the matrix elements was adopted from Ref. [2].

3. RESULTS AND DISCUSSION

The self-consistent fluid modelling of a free-burning argon arc in Ref. [1] predicts a pronounced radial inhomogeneity of the temperature and the atom density distribution, especially near the cathode (Fig. 2). The arc radius of computational domain was 21 mm, and the total arc current arises to 200 A.

The analysis of the radial density profiles of excited argon atoms in the resonant state $Ar(1s_4)$ has been performed by solving the Eq. (2) with an excitation source calculated in the model [1] for two different cases, the approximation of efficient lifetime and using the matrix method. The excitation source $W(r)$ is given in Fig. 3.

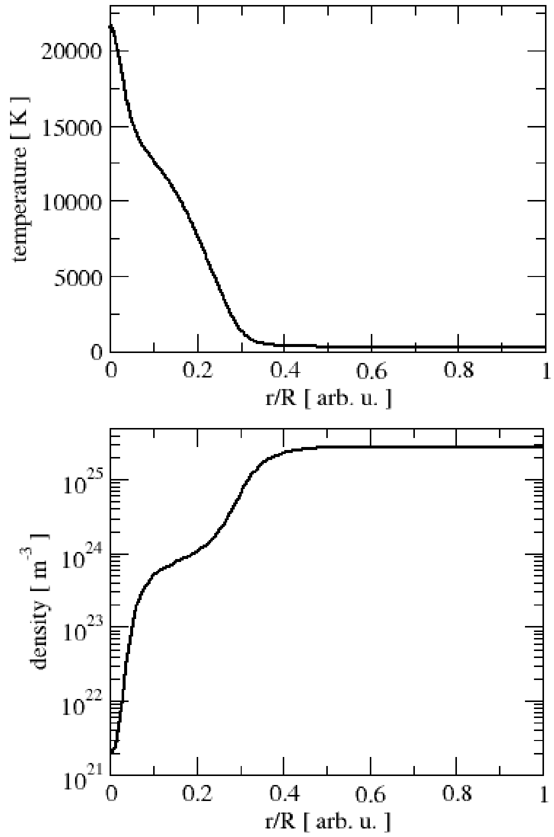

Fig. 2. Radial distribution of the gas temperature (top) and the density of argon atoms (bottom) at 1 mm near the cathode.

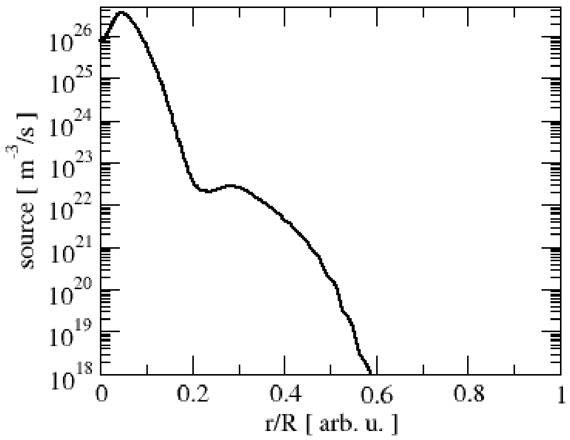

Fig 3. Radial distribution of excitation source for excited resonance argon level Ar(1s$_4$) in a plane 1mm away from the cathode surface

A nonmonotonous radial behaviour of the source term arises from a complex interplay between recombination and ionization processes and it is explained in detail in [1]. The first maximum results from increased radiative recombination on the arc axis. The reason for the second maximum is the increasing three-body recombination rate due to a high electron density and low electron energy.

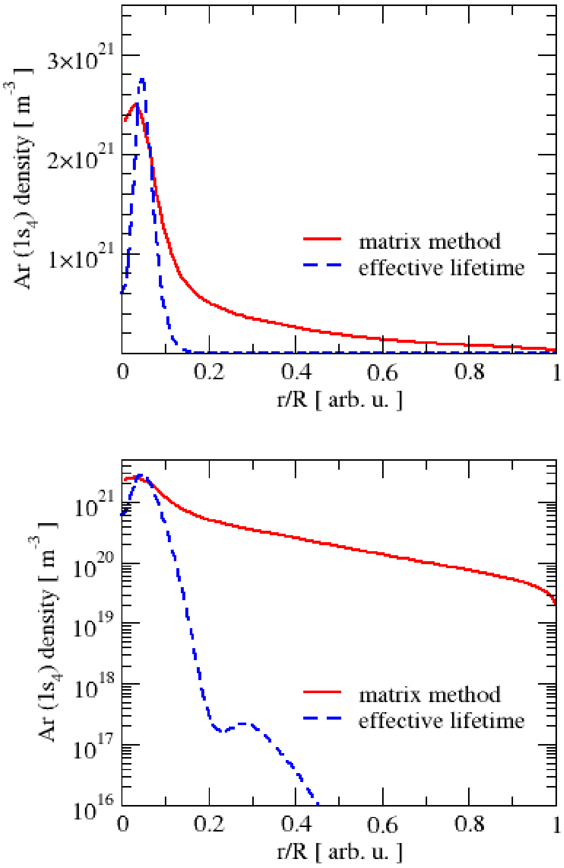

Fig. 4. Comparison of radial profiles of Ar(1s$_4$) atoms calculated with effective lifetime approximation (dotted lines) and using the matrix method (full lines).

Fig. 4 shows the resulting radial profiles of Ar(1s$_4$) density for both cases in linear (top) and logarithmic (bottom) scales. In the case of effective lifetime the density follows the profile of excitation source. The results of the calculations with radiation transport predict significant profile changes. The profiles become wider and the position of the profile maximum shifts toward the discharge axis. It becomes obvious that the trapping of the resonant radiation affects the atom density distribution. Therefore, including such effects would improve the arc description and provide a better agreement with spectroscopic measurements. Till now the equilibrium description of the arc plasma was mostly done in terms of net emission coefficients containing a dominant part of the continuum radiation due to the free-free and free-bound transitions. Nevertheless, the transport of the resonant radiation could be of interest for plasmas with more complex chemistry.

4. SUMMARY

Consideration of radiation transport in the case of a free-burning arc shows a significant influence of this process on the resulting spatial distribution of the excited species density. The analysis shows that the conventional approach of effective lifetime leads to a profile close to that of the excitation source, while the correct description causes significant profile broadening. Since the variation of spatial profiles of emitting species can cause changes in the spatial distributions of all plasma species, and, hence, can influence the energy balance of the arc column, the evaluation of the role of the transport effects will be a topic of future investigations.

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