Effect of Resonance Radiation Trapping on the Excited State Densities in Free-Burning Arc Plasmas

Gorchakov S.[1], Baeva M.[1], Golubovskii Yu.[2], Kalanov D.[2], Uhrlandt D.[1]

[1]*Leibniz Institute for Plasma Science and Technology, Felix-Hausdorff-Str.2 17489 Greifswald, Germany, gorchakov@inp-greifswald.de*

[2]*Saint-Petersburg State University, Ulyanovskaya st.3 198504 St.Petersburg, Russia, yu_golubovski@yahoo.com*

Modern arc models takes into account collisional-radiative schemes for better agreement with experiment [1]. Radiation transport phenomena play an important role in redistribution of excited species densities. Influence of resonance radiation transport on spatial distribution of excited atoms in argon arc plasma was studied by numerical model. Solution of the Holstein-Biberman equation was based on the matrix method [2]. Results are compared with conventional effective lifetime approach.

Keywords: free-burning arc, radiation transport, excited species, argon plasma

1 INTRODUCTION

Resonance radiation transport is the important mechanism which affects the formation of different spatiotemporal structures in gas-discharge plasmas. This transport type competes against other transport mechanisms of different plasma species, such as diffusion and convection. Thus, the correct consideration of radiation transport is important in gas-discharge modeling. The present work studies the role of the resonance radiation trapping in formation of the spatial distributions of excited atoms in free-burning arc plasma in argon. In Ref. [1] the self-consisted fluid model of non-equilibrium arc was presented. This model is based on joint solution of Navier-Stokes equations, which describe conservation of mass, momentum and energy. Equations of current continuity, Ohm and Ampere laws were used for determination of electric and self-induced magnetic fields. Furthermore, this model comprises the balance equations for excited species. At the same time, resonance radiation trapping was treated using local effective lifetime approximation. In the present work radiation transport is treated by accurate solution of the Holstein-Biberman equation for radiation from the resonance level $Ar(1s_4)$ (in Pashen notation).

The free-burning arc has a peculiarity consisted in sharp change of absorption coefficient values in radial direction. This change can reach about four orders of magnitude. In work [2] a matrix method for Holstein-Biberman equation solution was modified for the case of cylindrically symmetric plasma with inhomogeneous absorption coefficient and calculations for $Ar(1s_4)$ level considered independently of other excited levels were performed. In the present work the method is used for solution of the balance equation system for the group of excited states which include resonance, metastable and higher excited radiating levels taking into account radiation transport and collisional-radiative processes.

2 BASIC EQUATIONS AND SOLUTION APPROACH

The system of Ar excited states, which includes metastable $Ar(1s_5)$, $Ar(1s_3)$, resonance $Ar(1s_4)$, $Ar(1s_2)$, effective levels $Ar(2p_{10}..2p_5)$, $Ar(2p_4..2p_3)$, individual levels $Ar(2p_2)$, $Ar(2p_1)$ and the group $Ar(3d)$ has been considered in the model. Due to the higher density of $Ar(1s_4)$ atoms the resonance radiation from this state was treated with inclusion of transport effects. For the $Ar(1s_2)$ level effective lifetime approximation has been used to estimate the radiation trapping processes. For other radiation processes the plasma has been assumed to be optically thin and spontaneous transition probabilities were applied to calculate the radiation losses. Since the frequencies of the collisional-radiative processes are much higher than those of diffusion and convection the diffusive and convective transport was neglected. With these assumptions the balance equation for resonance state $Ar(1s_4)$ (Holstein-Biberman equation) reads

$$A\left(N_{s4}(\vec{r})-\int N_{s4}(\vec{r})K(\vec{r},\vec{r}')d^3r'\right)= \tilde{Z}^+_{s4}(\vec{r})-\tilde{Z}^-_{s4}(\vec{r})+W_{s4}(\vec{r}) \quad (1)$$

Here A is a spontaneous emission probability, $\tilde{Z}^-_{s4}(\vec{r})$ is total de-excitation of the Ar(1s4) state per unit of time at the unit volume, $\tilde{Z}^+_{s4}(\vec{r})$ is the total excitation of this level due to transitions from other states of considered system, $W_{s4}(\vec{r})$ is a summary excitation due to transitions from ground state and recombination. The kernel of radiation transport operator $K(r',r)$ is the probability for a photon emitted in the point r' to be absorbed in the point r. Considering spatial inhomogeneity of the absorption coefficient the kernel can be represented in the form

$$K\left(\vec{r},\vec{r}'\right)=\frac{1}{4\pi}\int_0^\infty d\nu\frac{\varepsilon_\nu\left(\vec{r}'\right)\kappa_\nu\left(\vec{r}\right)}{\left|\vec{r}-\vec{r}'\right|^2}\exp\left(-\int_{\vec{r}'}^{\vec{r}}\kappa_\nu(\xi)d\xi\right),$$

where $\varepsilon_\nu\left(\vec{r}'\right),\kappa_\nu\left(\vec{r}\right)$ are the line profiles of emission and absorption, and ν is the photon frequency. The expression under the integral describes the probability of the photon travel between the points r' and r without absorption.

The matrix solution approach [2, 3] consists of discretization of the integral equation (1) by dividing the entire plasma volume into a number of small cells (n) in accordance with the chosen geometry (e.g. an infinitely long cylinder in the present case). The discretization procedure is described in detail in the previous works [2, 3].

After discretization the left side of equation (1) at the position r_k takes the representation

$$A\left(N_{s4}(\vec{r})-\int N_{s4}(\vec{r})K(\vec{r},\vec{r}')d^3r'\right)= \sum_{i=0}^{n-1}A_{eff}N_{s4}(r_i)b_{i,k}. \quad (2)$$

Here $b_{i,k}$ denotes the transport matrix and A_{eff} is the effective probability of radiative transition by Biberman [4].

Finally, the equation system at the radial point r_k takes the following form

$$\sum_{q\neq m}\sum_{i=0}^{n-1}N_m(r_i)\left[A_{eff}b_{k,i}\delta_{m=s4,q}+Z^-_{m,q}(r_i)\right] = W_m(r_k)+\sum_{q\neq m}Z^+_{q,m}(r_k). \quad (3)$$

Here Z^+,Z^- denote the rates of excitations and de-excitations due to collisional-radiative transitions from states with index q, to state with index m. Kronecker delta $\delta_{m=s_4,q}$ allows for to formalize the equation for the case of radiation transport inclusion, e.g. in considered case the resonance radiation trapping process, relating to the Ar(1s4) state.

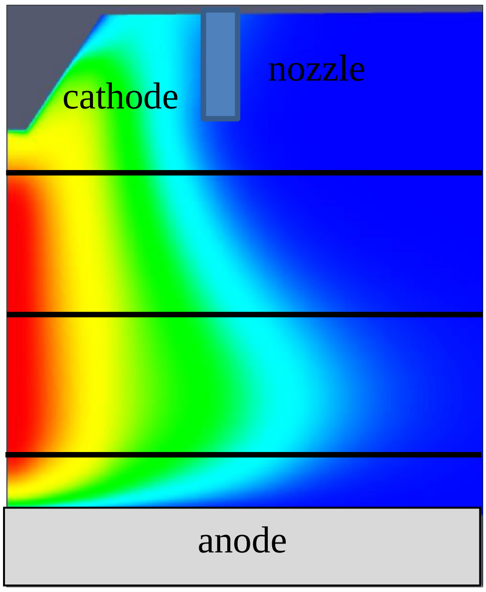

Fig.1: Schematic picture of the arc temperature distribution. Black lines show the axial positions for which the model has been applied

3 RESULTS AND DISCUSSION

For the analysis of radiation transport effects in a free-burning arc the plasma of a typical TIG welding arc has been used [1]. Figure 1 shows schematic temperature distribution in the arc. Discharge parameters considered in the present work correspond to an atmospheric pressure arc between a conical tungsten cathode and a water cooled flat copper anode. A gap between electrodes is 8 mm, radius of a computational area is 21 mm. Gas is fed through a nozzle near the cathode with a flow rate 12 slpm. The arc current is 200 A.

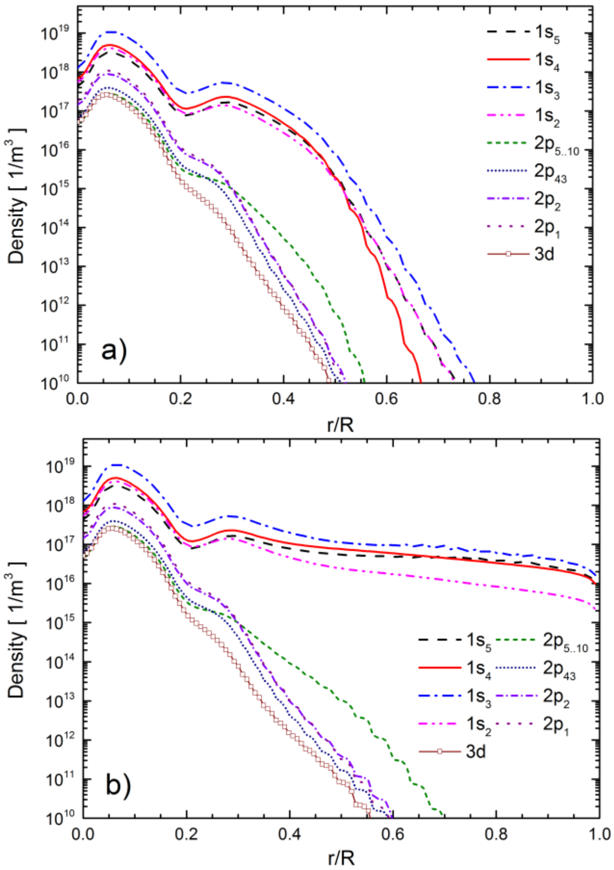

Fig. 2: Radial distributions of excited atom densities at the distance of 1 mm from the cathode calculated using effective lifetime approach (a) and matrix method (b).

A set of 127 reactions was used to calculate Z^+, Z^- in the equation system (3). This set includes reactions which describe collisional-radiative interaction of the considered Ar states, as well as ionization and emission to the ground state [1]. The calculations of the radial density profiles were performed both in effective lifetime approximation and using the matrix solution method. The three axial positions were chosen: 1 mm, 4 mm and 7 mm from the cathode (Fig. 1). The influence of resonance radiation trapping is illustrated by the case of homogeneous absorption coefficient κ=1. It was shown in [2] that differences between results for various absorption inhomogeneities (e.g. variation of κ along the radius) has smaller influence on the radial profile in comparison with changes which arise from inclusion of radiation trapping in the model.

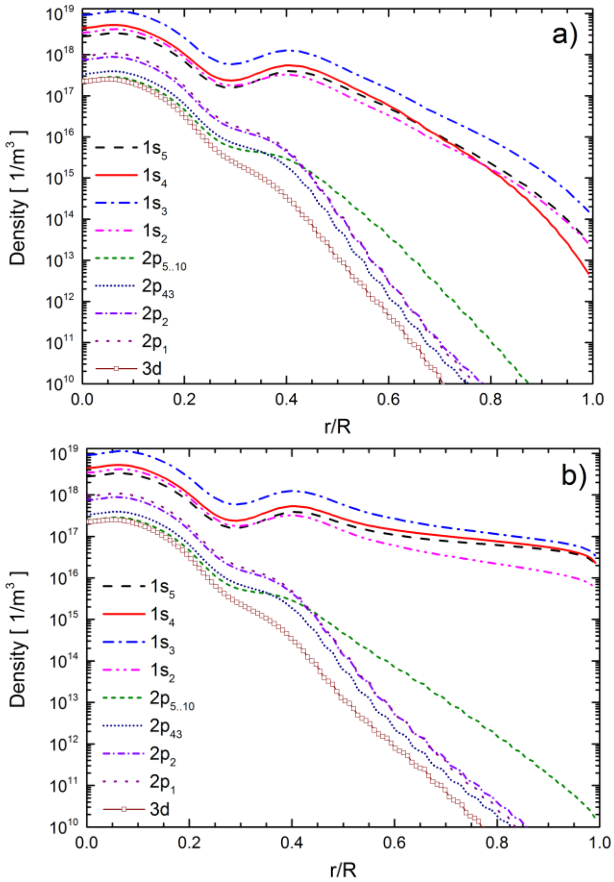

Fig. 3: Same as Fig. 2 but for the distance 4 mm away from the cathode.

Results of calculations are presented in Fig. 2 - Fig. 4. As it was shown in [2] the shape of the radial distribution is influenced by temperature dependency of the ground state density (minimum on the axis) and enhanced recombination when the plasma temperature decreases below a certain value (off-axis maximum). This structure preserves for all considered axial positions, even in the anode vicinity where the temperature profile is rather wide. Effect of the resonance radiation transport is obvious when comparing the results presented in part (a) and part (b) of each figure. In the case of a conventional description (effective lifetime approximation) presented in part (a) the radial courses of excited atoms densities follow the excitation sources profiles. The profiles for higher excited states (2p and 3d) are slightly narrower comparing with these of (1s) group.

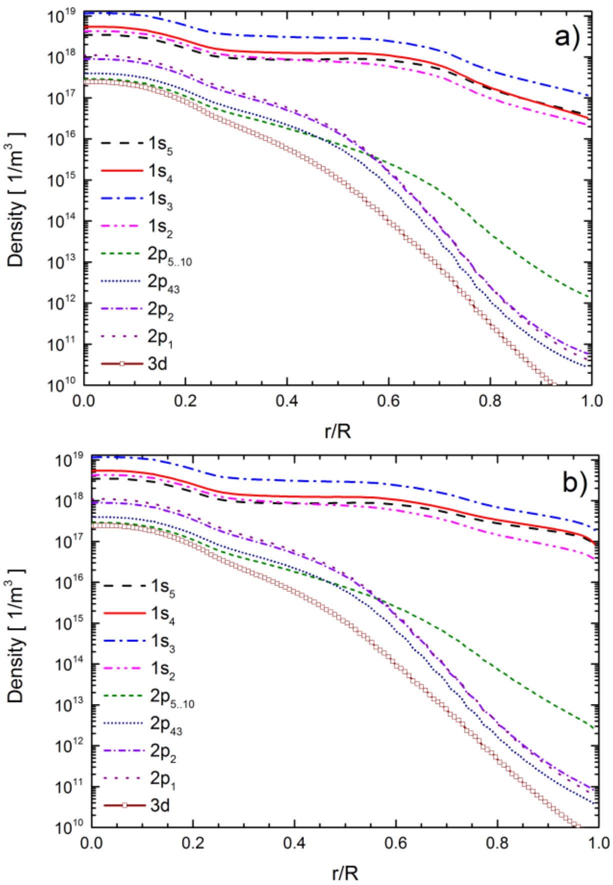

Fig. 4: Same as Fig. 2 but for the distance 7 mm away from the cathode.

In the case when the radiation transport matrix is included (Fig. 2b, 3b, 4b) the collisional-radiative mixing due to excitation to 2p states and subsequent radiation back to a different 1s level [5] causes an increase of all densities on the periphery in the arc fringes. The effect is more pronounced for the 1s states, which are strongly coupled with each other. For the radiative atoms Ar(2p) and Ar(3d) groups the effect of radiation trapping is much weaker. However, also for these levels the density in the arc fringes increases by a factor of 2 - 10 depending on the axial position. Increasing the distance from the cathode the excitation zone broadens and the radiation trapping effects becomes less pronounced. The density of the group of Ar(1s) atoms increases in the radial direction by several orders of magnitude at the axial position close to the cathode, while in the case of anode this difference is of about factor of two only. This finding coincides with previous results for non-isothermal plasma which predict stronger influence of radiation transport in the case of localized constricted source [6].

4 CONCLUSIONS

A role of the resonance radiation trapping in formation of spatial density profiles of resonance, metastable and highly-excited atoms is demonstrated in full-scale modelling of the non-equilibrium free-burning Ar arc. A significant growth of the 1s states population in the arc fringes takes place due to resonance radiation transport. These states are highly mixed due to collisional-radiative processes. For the higher excited levels 2p and 3d which have a short lifetime this effect is less pronounced. The influence of the resonance radiation trapping is the most intense near the arc cathode and becomes weaker moving towards the anode.

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