DEVELOPMENT OF THE LOCALIZATION METHOD: APPLICATION FOR THE DIAGNOSTIC OF A PLASMA HAVING A PLANE OF SYMMETRY

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Abstract

A technique is proposed for an optical emission spectroscopy (OES) diagnostic of transparent inhomogeneous thermal plasmas having a plane of symmetry. The technique is based on the approach used in the localization method, elaborated for plasma parameter measurements in axial symmetry volumes avoiding Abel inversion. An analytical solution and a numerical model have been developed for evaluation of radiative transfer in plane symmetry plasmas allowing to generalize the technique. It can be applied for plasma temperature and electron density measurements using spectral line intensity and profiles as well as continuum emission of plasma volumes with an arbitrary temperature distribution. The results have been applied to measure parameters of Ar plasma of a 200 A twin-torch DC arc at atmospheric pressure.

INTRODUCTION

Recently, a technique (the localization method) has been developed allowing local parameter measurements of axial symmetry thermal plasmas without any Abel inversion procedure [1, 2]. (Some familiar OES diagnostic methods have been later proposed showing the approach fertility [3, 4]). The technique has been successfully applied for measurements of plasma parameters in a plasma volume having a plane of symmetry thus avoiding a tomography use and simplifying the data treatment [5].

This work deals with a further extension of the localization method generalizing it for plane symmetry plasmas with different temperature profiles. The resulting technique allows OES determining the plasma temperature and electron density using emission intensity, shift and broadening of spectral lines, as well as plasma continuum. Experimental data of the technique application for the OES plasma diagnostic of a twin-torch DC arc are presented and discussed.

THEORETICAL

At OES plasma diagnostics one measures the plasma total intensity integrated along a line of sight. It has been shown, that for axial symmetry volumes of optically thin thermal plasmas with a monotonous parabolic-like temperature distribution, simple relations can be found between the measured intensity and local plasma parameters at the distribution maximum [1-4]. (The distribution maximum temperature has to be lower than « normal temperature » T_m of the spectral component under consideration). The approach can be applied to OES diagnostics of plasmas having a plane of symmetry and an arbitrary parameter distribution in the plane [5].

The method can be generalized for plasma volumes with an arbitrary monotonous temperature profile along the line of sight (y) having the maximum temperature T_0 in the symmetry plane. The profiles can be presented in the following way:

$$T(y) = T_0\left[1+(y/y_0)^l\right]^{-1}, \quad (1)$$

where y_0 is a parameter determining the volume dimension along y, and l gives the profile forms from a linear (l=1, plasma with a steep temperature gradient) to a rectangular one ($l=\infty$, homogeneous plasma). For the temperature distribution given by eq.(1), an analytical solution of the radiation transfer equation can be found and total emission intensity of the plasma volume in y direction can be evaluated. For an atomic spectral line with $T_m>T_0$ it gives:

$$I(x) = 2\varepsilon_0 \cdot y_0 \cdot \left(\frac{kT_0}{E_k}\right)^{1/l} \frac{\Gamma(1/l)}{l}\left(1+\frac{1}{l}\frac{kT_0}{E_k}\right), \quad (2)$$

where x is a coordinate in the plane, ε_0 is plasma emissivity at T_0, k is the Boltzmann constant, E_k is the transition upper energy level, and Γ is the Gamma function. For parabolic temperature profiles (l=2) eq.(2) coincides with results of [1] and [3] provided $E_k>>kT$. One can obtain analogous expressions for ion lines and continuum. For the latter, E_k is replaced by the atom ionization energy.

MODELLING

Eq.(1) has been used at a computer simulation of spectral line emission intensity of a plasma volume to find a relation between spectral profiles of the line intensity and those of local (T_0) plasma emissivity. The modelling area has been limited with low temperature (1000K<T<T_m) thermal plasmas at a constant pressure. Doppler and Stark broadening, as well as Stark shift have been taken into account to evaluate the spectral line profiles. Necessary parameters of the lines have been taken from [6-8]. Their dependence on plasma temperature and electron density, as well as calculated compositions and partition functions of the plasma have been approximated using polynomes. Local emissivity spectral profiles have been sampled at 4000 wavelength points. For each λ, the integration has been performed using Gauss method (24 points). Ratios of half-widths $\Delta\lambda_I$ and shifts $\delta\lambda_I$ of the intensity spectral profiles to half-widths $\Delta\lambda_\varepsilon$ and shifts $\delta\lambda_\varepsilon$ of the plasma emissivity profiles at the temperature distribution maximum have been evaluated. The model has been verified for plasma volumes of an axial symmetry with results of a common Abel inversion procedure.

EXPERIMENTAL

The method development results have been applied to determine a distribution of temperature and electron density in Ar plasma of a twin-torch DC arc at atmospheric pressure. The arc consisting of two torches of opposite polarity is presented in details elsewhere [5]. A schematic diagram of the twin-torch arc is shown in Fig. 1. The twin-torch arc has been running at 200 A current (60 V) with 30 and 20 Nl/mn of Ar flows into the torch anode and cathode units, respectively. The electrode units have been mounted at 110° angle between their axis and with 70 mm distance between the nozzles, and have been oriented in such a way, that the electrodes axis are in a plane P (Fig.1).

Spatial distributions of the plasma spectral radiation intensity have been measured using a monochromator-2D OMA system. The observation direction y has been chosen perpendicular to the P-plane, which is supposed to be a plane of symmetry of the temperature distribution. The torch image has been formed on the monochromator entrance slit (with x-direction to be parallel to the slit edges) and moved point-by-point with the 5 mm step along z-direction by external optics. Spectral and spatial resolutions at the measurements have been 0.05 nm and 1 mm, respectively.

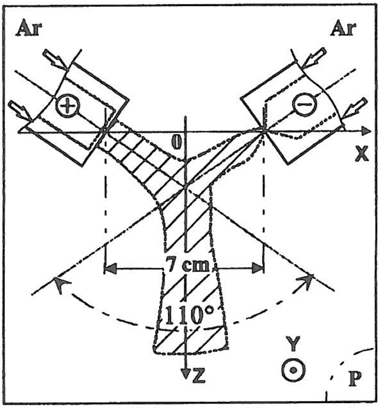

Figure 1 : Schematic diagram of the twin-torch DC arc

The plasma electron density has been evaluated using measured half-widths of ArI lines at λ=720.7 and 703.0 nm due to *6p-4s* transition and applying the halfwidth ratio of emissivity and intensity profiles, which was found from the modelling results. An intensity ratio of ArI line λ=696.5 nm (*4p-4s* transition) and of the plasma continuous emission at λ=634.0 nm (for 2 nm wavelength interval) has been measured to find the plasma temperature. The eq.(2) for the line and familiar one for the continuum have been used to pass from measured to local values. The continuum emission has been calculated using data of [9].

RESULTS AND DISCUSSION

Modelling results.

The modelling results give an evidence that for the plasma volumes under consideration, a relation between directly measured (along y) intensity of a spectral line (or continuum) and plasma emissivity at the maximum temperature is determined by the upper level energy of the line transition and by the parameter *l* of the volume temperature profile. Also, the modelling data have shown that for a spectral line emitted by the plasma volume, a ratio $r_\Delta = \Delta\lambda_I/\Delta\lambda_\varepsilon$ of a spectral profile halfwidth ($\Delta\lambda_I$) of directly measured intensity of the plasma volume emission to that ($\Delta\lambda_\varepsilon$) of the plasma emissivity at the symmetry plane (at T_0), as well as the ratio $r_\delta = \delta\lambda_I/\delta\lambda_\varepsilon$ for shifts of the intensity ($\delta\lambda_I$) and emissivity ($\delta\lambda_\varepsilon$) profiles depends mainly on the temperature profile parameter *l*.

Some of the modelling results are illustrated in Fig. 2. Here ratios r_Δ and r_δ are presented for ArI λ=703.0 nm spectral line as a function of the temperature profile parameter *l*. Data for ArI λ=720.7 nm spectral line practically coincide with those in the figure. The data can be used to evaluate local halfwidths and shifts of a spectral line emissivity profile at the symmetry plane from those of directly measured intensity profiles. Also in the figure the r_Δ value is presented calculated for a parabolic

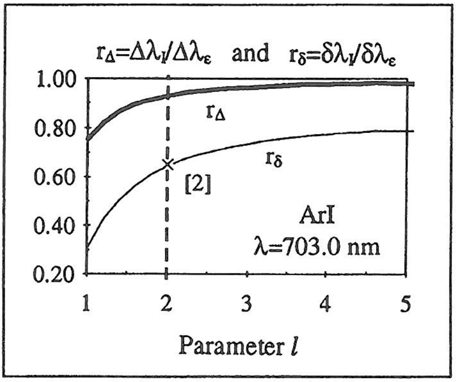

Fig. 2. Ratios of spectral line halfwidth ($\Delta\lambda_I$) and shift ($\delta\lambda_I$) in Ar plasma volume emission to those of the plasma emissivity profiles ($\Delta\lambda_\varepsilon$, $\delta\lambda_\varepsilon$) vs T-profile parameter *l*.

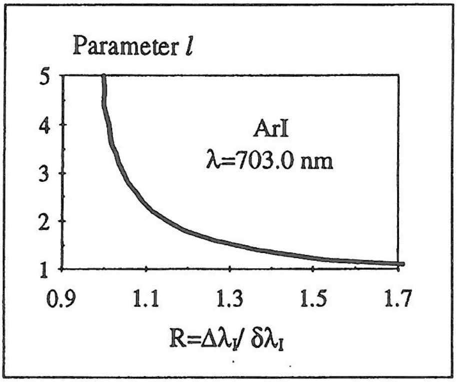

Fig. 3. T-profile parameter *l* vs a halfwidth-to-shift ratio R for a spectral line in Ar plasma volume emission.

temperature profile (*l*=2) according to the approximation given in [2], where spectral line shifts were not taken into account. It is seen that the shift negligence causes an underestimation of r_Δ. Generally, our data show a rather low difference between $\Delta\lambda_I$ and $\Delta\lambda_\varepsilon$ for a large family of plasma volume profiles (*l* parameters) especially in $l \geq 2$ region justifying the approximation $l \sim 2$ in [1, 2, 5] and showing a reasonable precision of measurements using the plasma homogeneity approximation. For plasmas with a high temperature gradient (l<2), the form of temperature profiles has to be taken into consideration.

The parameter l can be evaluated from a spectral profile of directly measured line intensity. In Fig. 3 the parameter is presented as a function of a width-to-shift ratio $R=\Delta\lambda_l/\delta\lambda_l$ of a spectral profile of ArI λ=703.0 nm line intensity emitted by an Ar plasma volume. The dependence is not sensitive to the volume maximum temperature in $T_0<T_m$ region. Due to strong R changes with l in l<2 region the data can be useful for detecting plasma volumes with very steep temperature gradients.

Plasma parameter measurement results.

The data presented above have been used for OES parameter measurements in Ar plasma of a 200 A twin-torch DC arc at atmospheric pressure. An example of a plasma temperature distribution in P-plane of the twin-torch arc is presented in Fig. 4. The distributions along x-direction are given only for several z-positions not to overload the figure.

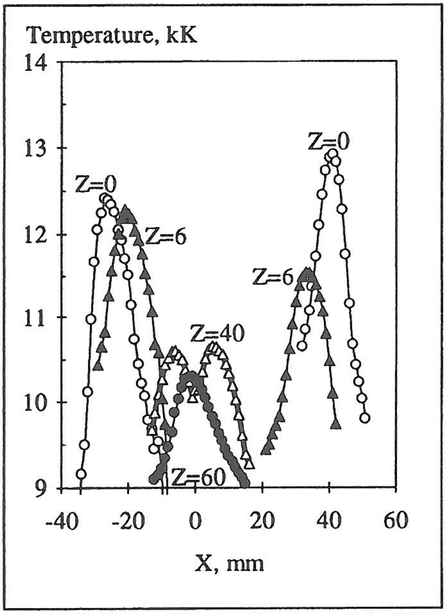

Fig. 4. Temperature distribution in P-plane of a 200 A twin-torch DC arc in argon.

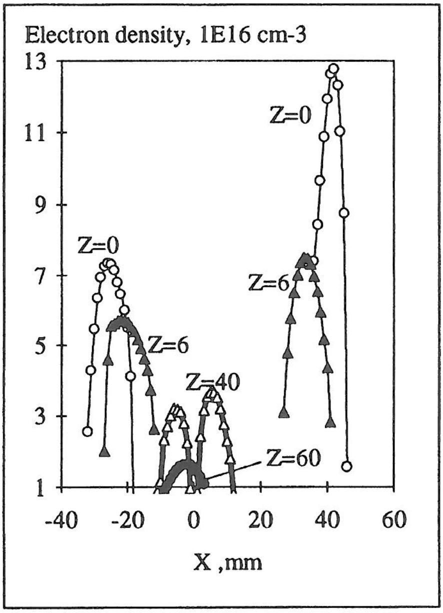

Fig. 5. Electron density distribution in P-plane of a 200 A twin-torch DC arc in argon.

Distributions of the plasma electron density along x-direction in P-plane for several z-positions is shown in Fig. 5. Due to a relatively low spectral resolution of the OES system used, measured electron density is limited by the value of 10^{16} cm^{-3}. A reasonable correlation has been observed between temperatures calculated from the Ar plasma LTE composition corresponding to the measured electron density and temperature values measured using a ratio of spectral line-to-continuum intensity. The largest difference between the values (~10%) is found near the electrodes, and it can be due to non-equilibrium effects. The results are fairly close to data of [5].

CONCLUSION

The analytical solution and the numerical model developed allow radiative transfer evaluating in axial/plane symmetry plasmas with different temperature distributions. The results show an influence of the form of the temperature distributions on the relation between spectral profiles of local emissivity and measured emission intensity of the plasma. A parameter governing the T-distribution form can be found from a spectral line profile in directly measured intensity of plasma volume emission. The data can be used to evaluate halfwidths and shifts of a spectral line for the plasma emissivity at the symmetry axis/plane from those of the directly measured emission intensity. The technique is applied to measurements of temperature and electron density of Ar plasma of a twin-torch DC arc using spectral line and continuum emission intensity as well as spectral line profiles.

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