NON-EQUILIBRIUM PROPERTIES OF ELECTRIC ARC PLASMA AND COMBINED METHODS OF ITS DIAGNOSTIC

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Non-equilibrium properties of the dense plasma due to radiation transfer are investigated. Experimental technique and simulation-adaptive spectroscopy method of such non-LTE plasma investigation are suggested. They allow to overcome next problems of real sources' dense plasma diagnostic: pulsing properties of plasma in ms or μs temporal scale non-LTE as a result of resonance radiation transfer in radial non-uniform plasma and the self-absorption of the diagnostic spectral line.

Introduction

It is generally agreed the local thermodynamic equilibrium (LTE) takes place in the electric arc plasma. Individual authors have been investigated deviation from LTE in noble-gas plasma in electric arcs owing to diffusion processes or overpopulation of the ground atom's level due to resonance radiation [1]. Nevertheless, LTE-assumption has been universally accepted.

Our previous investigations [2,3] of free-burning electric arc plasma between copper electrodes have been shown its deviation from LTE. It is the result of radiation transfer in the real nonuniform plasma with temperature gradient. This paper deals with diagnostic of such non-LTE plasma. Addition problems are space non-stability of the arc owing to electrode's processes in real sources and the self-absorption of the typical for copper plasma diagnostic spectral line 510.5 nm. They are solved, too.

Experimental technique

The efficiency of this diagnostic procedure was checked on the "non-convenient" example of the free-burning electric arc between copper electrodes in the air. Plasma was produced between the end surfaces of the non-cooled electrodes, each having a diameter d_e of 6 mm, interelectrode distance L being 2÷8 mm. The current impulse up to 100 A duration of 30 ms was put on the "duty" weak-current discharge; the quasi-steady mode was investigated.The arc position was not stable on the surfaces of electrodes. It is corresponds to pulsing properties of the real sources' dense plasma in ms or μs temporal scale. In Fig. 1 are shown three separated profiles of plasma radiance J as

a function of distance ρ across interelectrode space during some period of observation and integrated one (dashed line). As may be seen integrated during this period profile J_Σ provides incorrect meaning of arc diameter $D' > D$, where D is its real size. That is why the method of the single tomographic recording of the spectral line's shapes and intensities was used [4,5].

The principal peculiarity of the tomographic spectrometer is using of the optical system having difference ΔF in sagittal focus F_s and meridional one F_m (Fig. 2). It allows to employ in this device any wide-aperture monochromator without limitation on astigmatism and image sensors of arbitrary type. A Fabry-Perot interferometer is used to give high spectral resolution. The interference pattern at the output contains information on the line shapes and the radial distribution, so it is not necessary to make repeat scans if the diagnostic is based on the line shapes. Naturally, the Fabry-Perot interferometer can be excluded as an optical element; in this case the spectrometer remains a convenient instrument for high-speed measurements of the radial profiles of spectral line radiation. Last improvements of this type tomographic spectrometer permit to use it for the absorption measurements during single high-speed process. As the result a space distribution of plasma particle species may be obtained. Fast scanning of radiation intensity space distributions was accomplished by an image dissector tube of electro-static type. Its advantage among another scanning photodetectors is providing a cycle of measurements over a single event of an investigated pulsed high-speed process [6].

In previous experiments the laser absorption spectroscopy technique was used [5]. As a source of external radiation a copper-vapor laser was employed. One of the lasing lines,
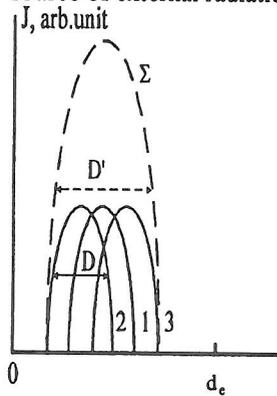

Fig. 1. The illustration of the necessity of high-speed resolution recording of the randomly moving arc.
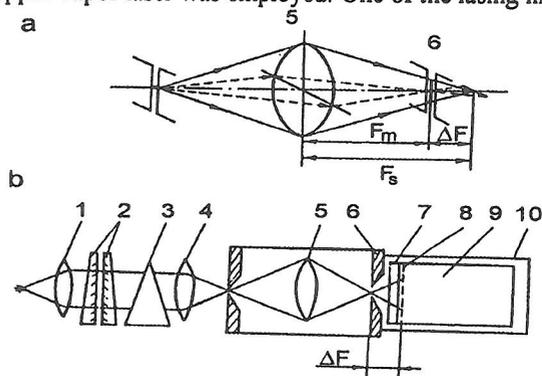

Fig. 2. Tomographic spectrometer: a) ray path; b) design; 1) collimator; 2) Fabry-Perot interferometer; 3) Dovet prism; 4) objective; 5) monochromator (shown schematically); 6) output slit; 7) dissector window; 8) photocatode; 9) dissector; 10) housing for dissector unit.

namely 510.5 nm, corresponds to a spectral line widely used for diagnostic of copper plasma [7]. In this experiment the entrance slit of the monochromator along its total height was illuminated by laser beam in the absence of any focusing system. The shadow of the arc in a practically parallel beam was imaged on the photocathode of the dissector. Lasing pulses had repetition frequency of 10 kHz. The duration of the scan of the dissector was established as sufficient for recording of several tens of lasing pulses on the screen of a storage oscillograph. The obtained radial profile of the absorption coefficient $\kappa_o(r)$ in the center of the spectral line 510,5 nm is shown in Fig. 3,a.
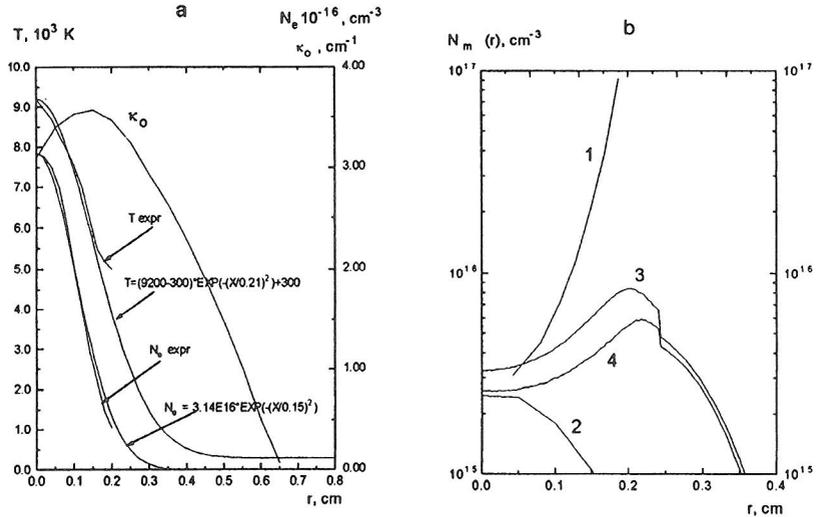

Fig. 3. Experimental data (a) and estimated populations N_m of metastable level (b): 1 - in LTE-assumption with experimentally obtained $N_{e\ expr}$ and T_{expr}; 2 - in LTE-assumption with experimentally obtained κ_o and T_{expr}; 3 - non-LTE without account of self-absorption; 4 - non-LTE optically thick plasma.

Temperature and electron density measurements

The pair of spectral lines of copper atom 510.5 and 521.8 nm are chosen in temperature measurements by the method of relative intensities. They are widely used in previous experiments [7,8]. Sufficient intensity as well as considerable difference of these lines upper level's energies (about 3 eV) have made fair accuracy in temperature determining possible. However it should be primarily taken into account the possibility of essential distortion of measured intensities in the result of self-absorption for spectral lines having slight exciting energy of lower level. In particular, it consists of only 1.39 eV for spectral line CuI 510.5 nm. This point of view is confirmed by the results of laser absorption

spectroscopy (Fig. 3,a). That is why the direct temperature measurements may be estimated only as first order approximation.

The methods of electron density measurements independent on temperature are preferable. One of them is measuring of Stark width of the spectral line 515.3 nm. Another possibility is measuring of the absolute intensity of spectral line, radiated from high-exited level of atom. It is easily provided in atom of copper owing to its system of shifted levels. Really, the normal configuration of the copper atom is $3d^{10}4s$ [9]. The ionization potential of exited s-electron terms consists of E_i=7.724 eV. However electron possessed by the d-shell is able to be easily excited too. As a result the second system of shifted terms is raised. It converges to the limits positioned above the copper ionization potential E_i. The problem is the possibility of autoionization depopulation of shifted levels, which may be resulted in its non-equilibrium with s-terms. Fortunately, the autoionization from levels $^4D_{1/2,7/2}$ is foreboded [10]. As the energy of upper level $^4D_{7/2}$ for spectral line CuI 465.1 nm consists of E_s=7.74 eV, the experimental temperature dependence may be usually neglected in measurements of radial profiles N_e:

$$I \sim N_e^2 \cdot T^{-3/2} \exp[(E_i-E_s)/kT] \sim N_e^2 \cdot T^{-3/2}.$$

Besides, the effect of self-absorption is negligible for this line. Therefore using of this line is very convenient at N_e - measurements. The calibration of absolute electron density values being carried out with the reference to high-temperature ($4 \cdot 10^4$ K) source of continuum radiation. The example of temperature $T(r)$ and electron density $N_e(r)$ obtained in the case of interelectrode distance L = 2 mm and the current impulse i = 30 A are shown in the Fig. 3,a. They have typically for free-burning electric arc the radial profiles. Their approximations are presented in this figure, too. The main peculiarity of data obtained is "catastrophic" increasing of the copper vapour density at the arc periphery if it is determined from $T(r)$ and $N_e(r)$ with Saha and Dalton equations. It corresponds to essential increasing of calculated in LTE-assumption the metastable level population N_m with r increasing in Fig. 3,b (curve 1). Such tendency is in full disagreement with experimentally observed radial profile of the absorption coefficient $\kappa_o(r)$ in the center of the spectral line 510,5 nm (Fig. 3,a), which with a precision of spectral line width $\Delta\lambda$ determines the metastable level population $N_m \sim \kappa_o \Delta\lambda$ (Fig. 3,b; curve 2). That is why we had abandoning of the LTE-assumption thereafter.

It must be noticed some authors explained periphery increasing of a copper density as a result of demixing due to ambipolar diffusion. We have specially examined this viewpoint by simulation of the axially symmetric diffusion problem [3]. The conclusion is the demixing does not essential effect in electric arc plasma.

Radiation transfer

We consider the adequate explanation for obtained results is evident from the partial LTE-assumption (PLTE) in such plasma. The PLTE is caused by resonance radiation

transfer. This radiation from the hot arc core is able to overpopulate the resonance level of Cu atoms at the arc periphery, where the temperature is relatively small. The overpopulation is identified by collision-radiative model with account of radiation transfer. Such simulation includes iteration processes until the Dalton equation and PLTE model be satisfy simultaneously at each point of arc radius. The result is illustrated by a curve 3 in Fig. 3,b. Its essentially more corresponds to experimental values of $\kappa_o(r)$ in Fig 3,a. Below is this simulation procedure have been included in simulation-adaptive spectroscopy method.

Simulation-adaptive spectroscopy method

A deficiency of temperature data presented in Fig. 3,a is neglect of self-absorption of the spectral line 510.5 nm. This problem with account of PLTE is solved by suggested method. The next idea of simulation-adaptive diagnostic procedure is proposed (see diagram). Starting with the LTE approximation plasma parameters are calculated. In this case observed profiles of plasma radiance's (integrated along spans) as a function of distance ρ from axis in a number of spectral ranges $J(\rho,\lambda_n)$ are used as initial data. In the result of inverse problem solving they are transformed to radial distribution of the emission $I(r, \lambda_n)$ in the assumption of optically thin plasma. Next stage includes iterative process of collision-radiative population of the ground and metastable levels of plasma particles with account of radiation transfer in resonance lines. The calculated plasma parameters are to be satisfied simultaneously the supposed model of the non-LTE and
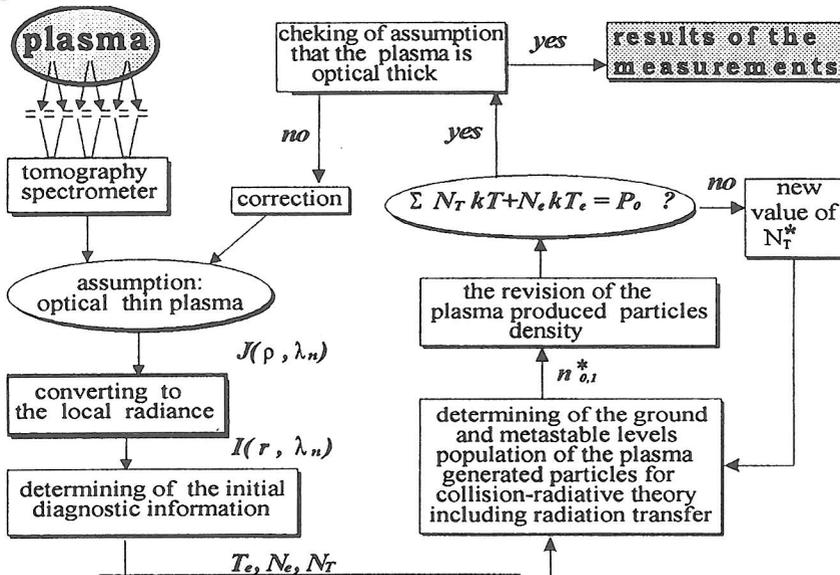

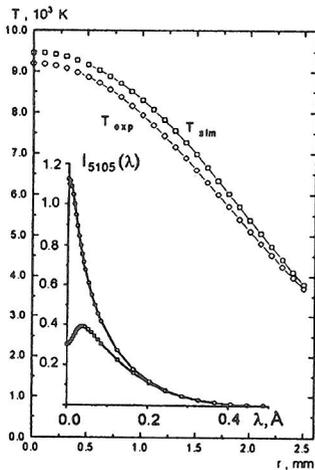Fig. 4. The diagram of the simulation-adaptive spectroscopy method.

Fig. 5. The illustration of the self-absorption effect on the plasma temperature measuring T(r) and contours I(λ) of the spectral line 510.5 nm radiated from the arc axis: o - without account of self-absorption; □ - optically thick plasma.

initial values I(r, λ_n). Boltzman, Saha and Dalton equations were used in determining of the plasma condition. The last operation in this cycle is checking of plasma optical thickness in diagnostic spectral lines. The simulation is over if the plasma is optically thin. In the contrary case the initial values I(r, λ_n) would be corrected to new values I_k (r, λ_n) and temperature T_k. Further previous cycle would be repeated until the result of integration of radial distribution of the emission along spans with account of radiation transfer will be coincide with initial experimental data J(ρ,λ_n). This iterative process is over if the result of optical thickness checking corresponds to calculated temperature and level's population.

Conclusions

As authors known this paper presents most full investigation of the plasma in copper vapour. Due to including in proposed diagnostic method of considerable number of spectroscopy information its allows to examine non-LTE thick plasma and on the other hand to do selection of spectroscopy constants.

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