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PLASMA DIAGNOSTICS OF HIGH-PRESSURE SODIUM-CADMIUM AND SODIUM-MERCURY DISCHARGES

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We report measurements of electron temperature and pressures of neutral particles in plasmas of high-pressure Na-Hg-Xe or Na-Cd-Xe arcs. We applied the standard plasma diagnostic techniques developed for the Na-Hg-Xe discharge to the new Na-Cd-Xe discharge lamp. Electron temperature has been calculated from the shape of the sodium recombination continuum at 408 nm in the case of Na-Cd-Xe lamp. The results are compared with the temperature obtained from the shape of self-reversed sodium lines at 568.2 nm and 568.8 nm. Sodium, mercury and cadmium vapour pressures have been derived from the separation of maxima of self-reversed sodium resonance line.

1. Introduction

In this work we performed measurements of the plasma parameters of a Na-Cd-Xe discharge by using the methods of plasma diagnostics developed for the Na-Hg-Xe discharge lamp[1,2,3]. This includes sodium and buffer gas vapour pressures and electron temperature measurements. We first measured plasma parameters for the standard Na-Hg-Xe lamp, which was investigated by many authors[4-9] and then applied the same procedure to Na-Cd-Xe high-pressure discharge.

The sodium, mercury and cadmium vapour pressures were derived from the separation of the blue and the red wing maximum of the self-reversed sodium resonance line, respectively. This method was applied by Chien Yu-Min[4], Reiser and Wyner[5], Ozaki[6], Cayless[7], Jen[8] and Lowke[9].

Electron energy distribution can be deduced from the shape of the continuous spectrum resulting from radiative electron recombination. In the case of Na-Hg or Na-Cd equilibrium plasma the electron temperature may be determined from the shape of the sodium recombination continuum. This work is specifically concerned with the continuum resulting from the electron-ion recombination to the sodium $3p^2P_{1/2,3/2}$ states. This continuum starts at 408.4 nm and extends towards the ultraviolet part of the spectrum[10]. Our result was compared with the temperature determined from the shape of self-reversed sodium lines at 568.2 nm ($4d\text{-}3p_{1/2}$) and 568.8 nm ($4d\text{-}3p_{3/2}$) using Bartels method[11,12,13].

The measured plasma parameters have the meaning of effective parameters averaged over the inhomogeneous plasma source. Additional problem is the wall of translucent alumina burner which diffuses light from all parts of the discharge. This does not allow standard procedure of Abel inversion for obtaining the local values of measured plasma parameters.

2. *Experiment*

The experimental set up is shown in Fig. 1. A high pressure lamp equipped with a standard inductive ballast and ignition device was operated at 50 Hz sine voltage. The burner was made of translucent sintered polycrystalline alumina (inner diameter $2R = 7.6$ mm). Schematic representation of the light scattering produced by a slice of porous polycrystalline alumina is given on Fig. 2a, where λ is the wavelength of the incident radiation, $\tau(\lambda)$ the transmitted radiation and $\varrho(\lambda)$ reflected radiation[1]. The dependence of spectral transmittance $\tau(\lambda)$ and spectral reflectance $\varrho(\lambda)$ on the wavelength λ for the sintered polycrystalline alumina are

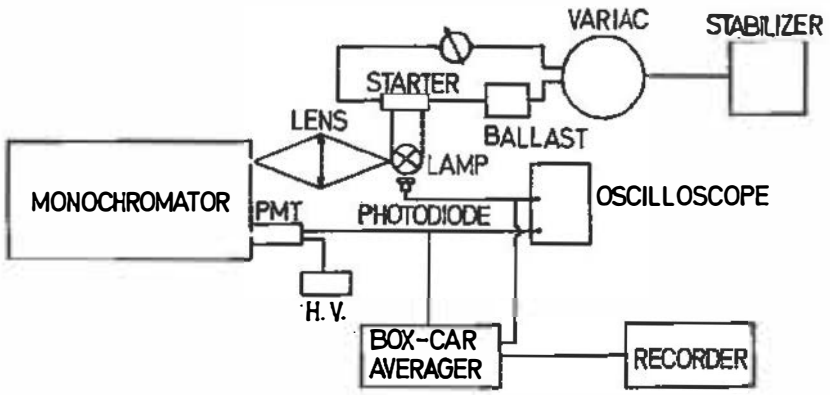

Fig. 1. Experimental arrangement.

approximately constant in Thc region 300—2500 nm (see Fig. 2b)[1]. The lamp voltage versus electric current through the lamp is shown in Fig. 3.

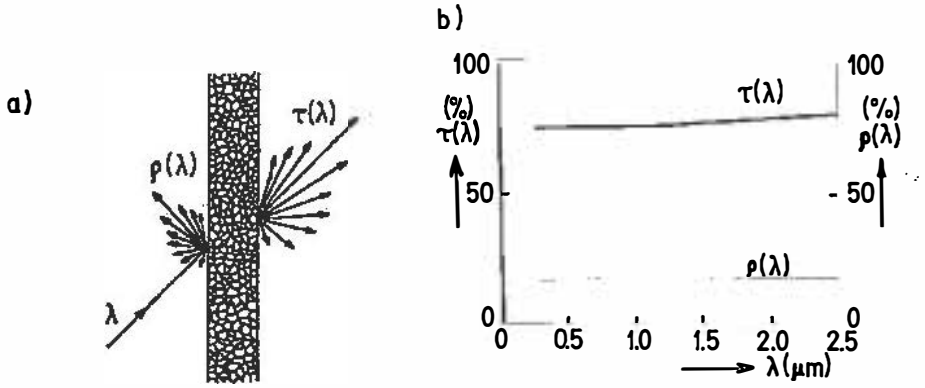

Fig. 2. (a) Schematic representation of the light scattering produced by a slice of porous polycrystalline alumina, where λ is the wavelength of incident radiation, $\tau(\lambda)$ the transmitted radiation and $\varrho(\lambda)$ reflected radiation.
(b) The dependence of spectral transmittance $\tau(\lambda)$ and reflectance $\varrho(\lambda)$ on the wavelength for the sintered polycrystalline alumina.

The lamp spectrum was resolved by a SPM-2 monochromator and detected by a EMI 9558 QB photomultiplier sensitive in the ultraviolet and visible spectral regions. Signal was processed by a box-car averager, used to sample out the spectrum at definite time instants. The signal from the box-car averager was recorded on the strip-chart recorder.

3. Results

Fig. 4 presents the typical spectrum of Na-Cd-Xe high-pressure lamp in maximum current mode, in the region 300—700 nm. One may readily observe sodium resonance doublet at 589 nm and 589.6 nm and other sodium atomic lines, which belong to nS-3P and nD-3P series. Some of them are self-reversed. Besides that one can see the cadmium atomic lines, Na_2 molecular bands and NaCd excimer bands. Below 408.4 nm recombination continuum into the 3P state is clearly visible. We can observe a few forbidden transitions induced by electric microfields in discharge plasma (d-s, p-p, f-p).

Sodium vapour pressure, P_{Na}, was calculated using the separation of the blue wing maximum, $\Delta\lambda_B$, from the center of gravity of the sodium resonance lines[5]:

$$\Delta\lambda_B = \frac{2e\lambda_0^2}{kc}(C_3/3.01\ \mathrm{mc}\ \lambda_0)^{1/2}(fR)^{1/2}\left(\int_0^1 \frac{e^{-E_0/kT(x)}}{T^2(x)}\,dx\right)^{1/2} P_{Na} \qquad (1)$$

where $C_3 = C_{31} + 2C_{32}$, C_{31} and C_{32} are interaction constants for sodium $3p_{1/2}$ and $3p_{3/2}$ states, respectively. Symbols e, m, c and k have their usual mea-

ning, and $\lambda_0 = 5.892 \times 10^{-7}$ m is the wavelength corresponding to the energy of center of gravity of sodium doublet $^2P_{3/2,1/2}$. Oscillator strengths f_1, f_2 are given by Griem[14], and E_0 is 16972 cm^{-1}. We adopted $C_3 = 1.4 \times 10^{-13}$ m^3/s given by Niemax and Pichler[15].

The temperature profile is assumed to be parabolic:

$$T(x) = T_0 - (T_0 - T)\, x^2,$$

where we adopted the values of T_0 and T of 4000 K and 900 K, respectively[4], $x = r/R$, R is discharge tube radius and r is the radial coordinate inside the dischar-

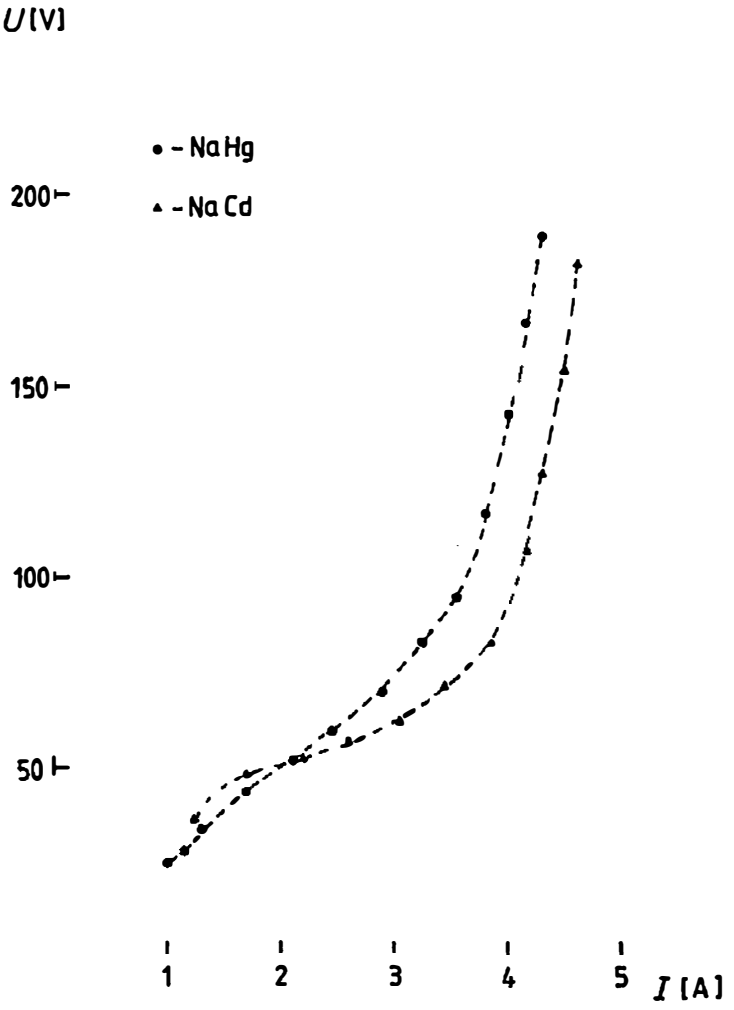

Fig. 3. Current versus voltage characteristics of Na-Hg-Xe and Na-Cd-Xe high-pressure lamps.

ge tube. The results are shown in Fig. 5a for Na-Hg-Xe lamp and 5b for Na-Cd-Xe lamp for different lamp powers. In Fig. 5a we have plotted the values of sodium vapour pressure obtained by Ozaki[6], who used different C_3 constant.

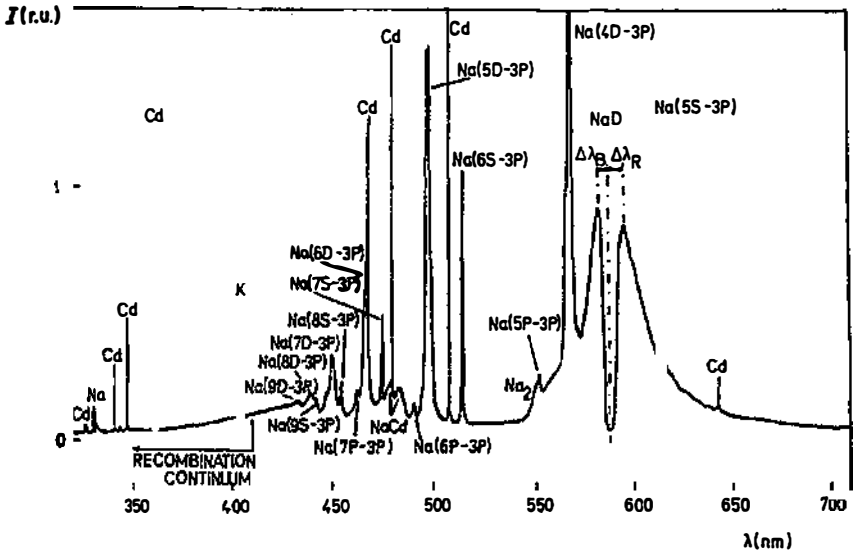

Fig. 4. The spectrum of Na-Cd-Xe high-pressure lamp in the maximum current mode in the region 300—700 nm.

The pressure of Hg or Cd has been determined using the separation of the wing maximum from the center of sodium resonance line. This separation, $\Delta\lambda_R$, depends on both sodium and mercury (cadmium) vapour pressure, where the latter is given by the following formula[6]:

$$P_{\substack{Hg \\ Cd}} = \frac{\lambda_0}{(C_6 c \Delta\lambda_R)^{1/2}} \left(\frac{(6.016\lambda_0\, mc^3 k^2\, (\Delta\lambda_R)^2}{\pi e^2\, \mathrm{fR}\, \lambda_0^4\, I\, P_{Na}} - 2C_3\, P_{Na} \right) \tag{2}$$

where

$$C_6^{1/2} = C_{61}^{1/2} + C_{62}^{1/2}$$

$$C_6^{1/2}\,(\text{Na-Hg}) = 1.5 \times 10^{-21}\ \mathrm{m^3/s^{1/2}}$$

$$C_6^{1/2}\,(\text{Na-Cd}) = 2 \times 10^{-21}\ \mathrm{m^3/s^{1/2}}\ (\text{Unsöld}^{16})$$

C_{61} and C_{62} are interaction constants for the interaction between the ground state Hg (Cd) atom and sodium atoms in $3p_{1/2}$ and $3p_{3/2}$ states, respectively. The temperature dependent factor I is given by the following relation[1]:

$$I(T) = \int_0^1 \frac{e^{-E/kT(x)}\, dx}{T^2(x)}\ .$$

The results are plotted in Fig. 5a and 5b (right hand ordinate).

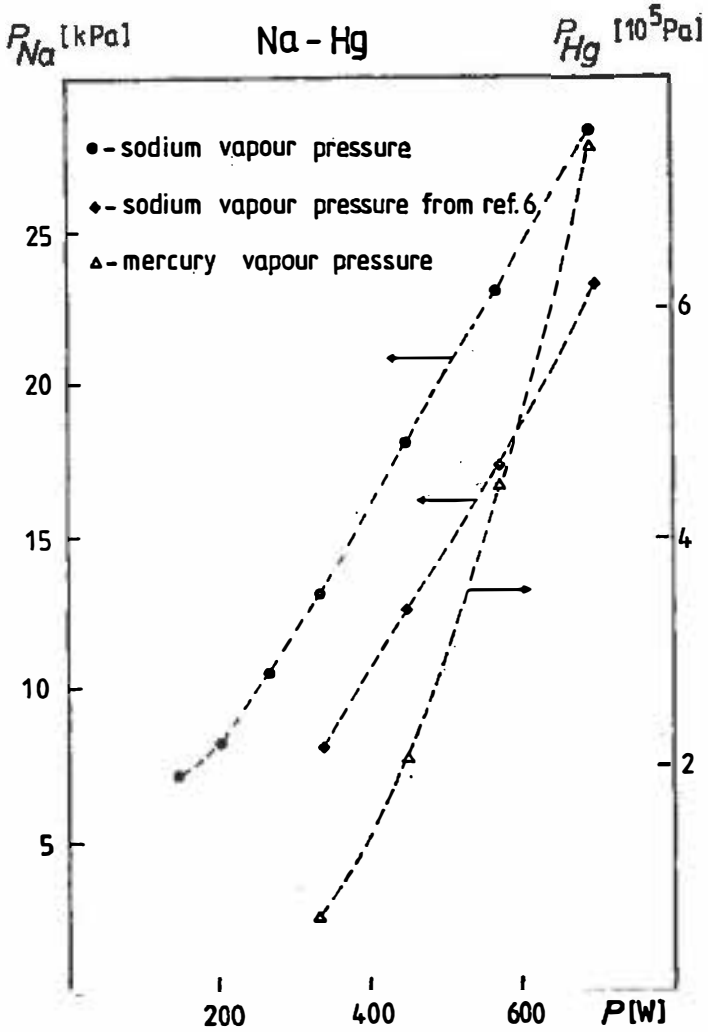

Fig. 5 (a) Sodium and mercury vapour pressure in Na-Hg-Xe discharge calculated from the separations of the blue and the red wing maxima from the center of gravity of sodium resonance line.

3.1. Temperature measurements

Electron temperature was determined using fitting procedure to the shape of the recombination continuum at 408 nm given by formula[10]:

$$I(\lambda) = \frac{2^{1/2} h^4 c^2 n\, n_+ g_n \sigma_P(\lambda)}{\lambda^5 (\pi m k T_e)^{3/2} g_+} \exp\left(-hc\,(\lambda^{-1} - \lambda_1^{-1})/kT_e\right) \qquad (3)$$

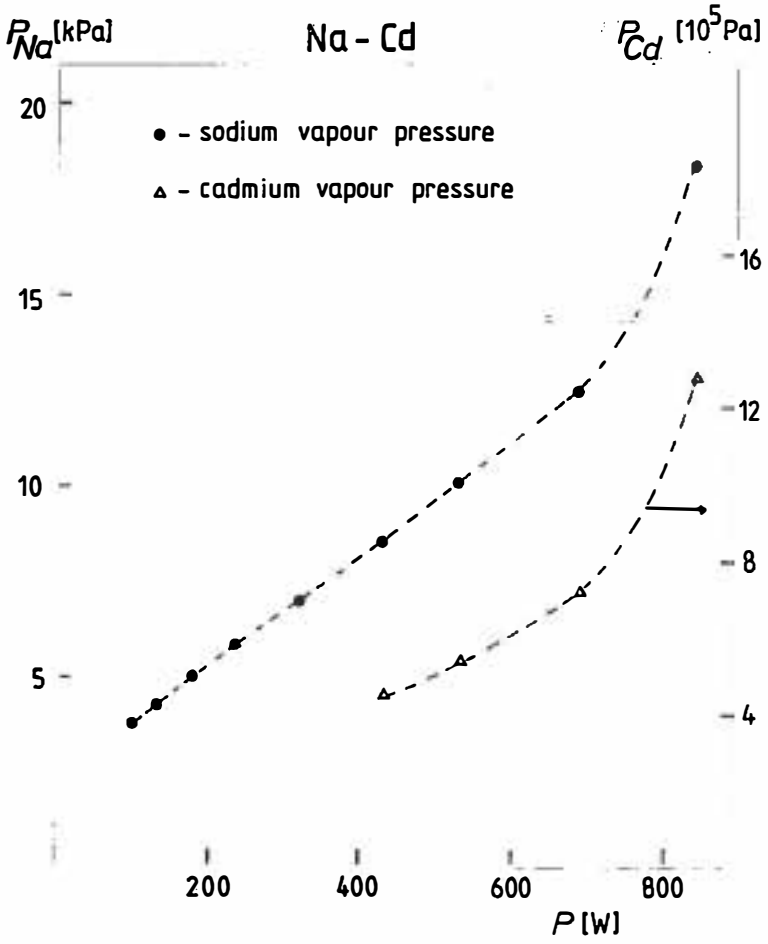

Fig. 5. (b) Sodium and cadmium vapour pressure in Na-Cd-Xe discharge.

where n and n_+ are electron and ion densities, g_+ and g_n are statistical weights of ionic and neutral states involved in the free-bound transition, $\lambda_1 = 4.083 \times \times 10^{-7}$ m and T_e is the electron temperature. $\sigma_P(\lambda)$ is the photoionization cross section given by the following expression:

$$\sigma_P(\lambda) = 1.12 \cdot 10^{-4} \lambda^3.$$

According to the approach of Ref. 10 formula (3) may be finally rewritten in the following form:

$$\log I(\nu) = \text{const.} - h\nu/(kT_e). \qquad (4)$$

The temperature determined in this way has a meaning of an effective temperature, averaged over the actual plasma profile. The dependence of thus determined averaged electron temperature (at current maximum) versus lamp power is shown in Fig. 6. In addition to this, we present in Fig. 6 the electron tem-

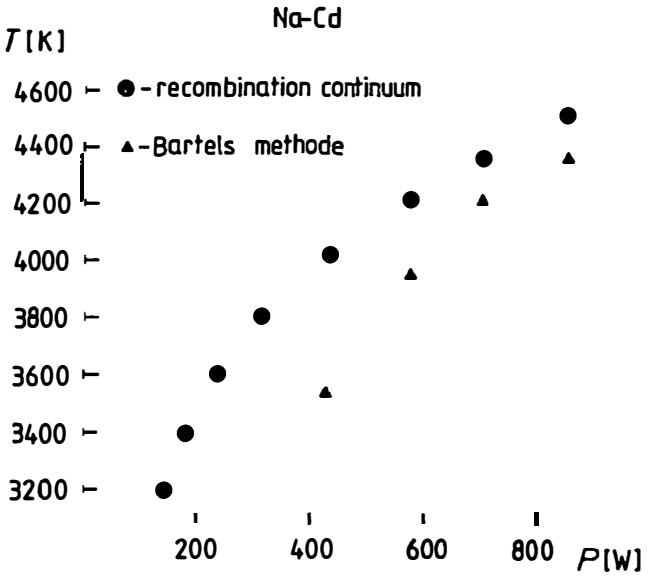

Fig. 6. Electron temperature versus lamp power determined from recombination continuum and using Bartels method.

perature determined by the Bartels method[11,12], which is outlined below. In the Bartels method the spectral line profile is given by the following formula:

$$I(\nu) = 2h\nu^3/c^2 \exp(-h\nu/kT)\, MY(t_0, p), \tag{5}$$

where M, p, $Y(t_0, p)$ and t_0 are given as follows:

$$M = ((E_n + E_i/2)/(E_m + E_i/2))^{1/2}, \tag{6}$$

$$p = 6/\pi \operatorname{Arctg}(M^2/(1 + 2M^2)^{1/2}), \tag{7}$$

$$Y(t_0, p) = \exp(-t_0/2)\,(t_0(1 - p)/2 + p \cdot \operatorname{sh}(t_0/2) + \operatorname{sh}(t_0 p^{1/2}/2)/p^{1/2}), \tag{8}$$

$$t_0 = \int_{-R}^{R} k_\nu(\nu, x)\, \mathrm{d}x. \tag{9}$$

E_i is the ionization energy (24447 cm^{-1}) of the 3p level, E_n is the excitation energy of the lower 3p level (16972 cm^{-1}), E_m is the excitation energy of the upper level (34559 cm^{-1}), t_0 is optical depth and the temperature profile is assumed to be

parabolic. By fitting the calculated line shape to experimental line shape one may find the temperature which best fits experimental data. Fig. 7 shows a characteristic set of measured and calculated line profiles.

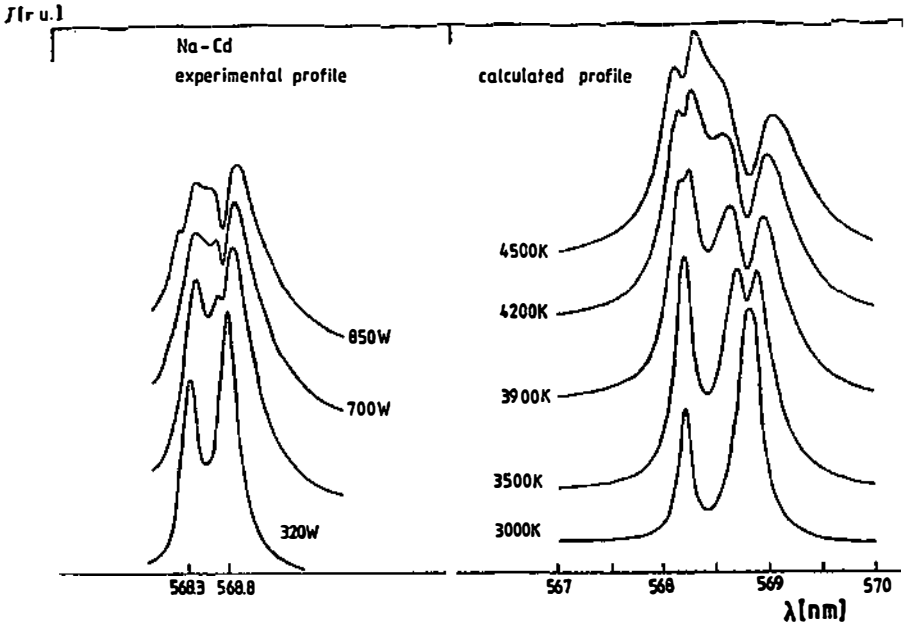

Fig. 7. Experimental and calculated shape of self-reversed sodium line at 568.3 and 568.8 nm for different electron temperatures.

4. *Discussion*

Sodium vapour pressure is determined from the blue maximum of the self-reversed sodium resonance line. The pressure dependence on the lamp power, determined by two different sets of interaction constants[5,15], shows that the curves differ only by an additional constant. This suggests that the main uncertainty in the determination of sodium pressure stems from the uncertainty of the C_3 constant (Fig 5b).

Similar argument holds for Cd and Hg pressure determination, but the uncertainties in C_6 constants exceed 50%.

Electron temperatures, derived by the least square method from recombination continuum, are not very accurate because in the region 300—400 nm some additional continua may appear. In Na-Hg-Xe lamp they stem from the Na_2, NaHg and Hg_2 molecular bands. In the case of the Na-Cd-Xe lamp the relevant bands are outside of the 300—400 nm spectral region or are much weaker. Consequently they can be neglected. The spectra in that region were corrected taking into account the spectral response, measured by standard tungsten ribbon lamp[19]

(W3 KGH 11 i). We assumed the transparency of the sintered alumina to be independent of wavelength (see Fig. 2b). Comparing these two different methods of determination of the electron, temperature (recombination continuum and Bartels method) we may conclude that the electron temperature determination by Bartels method[11,12] gives more accurate values. This is because the shape of self-reversed line is rapidly varying with temperature, and thus we can easily distinguish two profiles that differ in temperature by 200 K. At the temperature of 4000 K, this gives the accuracy of about 5%. Two curves in Fig. 6 approach each other at higher temperatures, since both methods are more accurate for higher temperatures. The difference between two temperature curves may reflect the difference between assumed parabolic temperature profile (Bartels method) and the actual temperature profile (recombination continuum).

5. *Conclusion*

Using plasma diagnostics methods for Na-Hg-Xe high-pressure lamp we determined plasma parameters of Na-Cd-Xe high-pressure lamp. We found that current-voltage characteristics show similar behaviour. Sodium vapour pressure is higher in Na-Hg-Xe lamp and buffer vapour (Hg or Cd) pressure rises more rapidly in Na-Hg-Xe lamp than in Na-Cd-Xe lamp. Electron temperature is in the region from 3000 K—4500 K in both lamps. We hope that present investigation will help in further understanding of Na-Cd-Xe discharge lamp, where we recently found many interesting diffuse and satellite bands of NaCd excimer origin[17,18] More accurate analyses could be achieved with single crystal sapphire burner, which will enable Abel inversion for obtaining local spectral intensities.

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DIJAGNOSTIKA PLAZME VISOKOTLAČNIH NATRIJ-KADMIJ I NATRIJ-ŽIVA IZBOJA

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Mjerili smo elektronsku temperaturu i tlakove neutralnih čestica u plazmama visokotlačnih Na-Hg-Xe i Na-Cd-Xe izboja. Na novoj Na-Cd-Xe žarulji primjenili smo standardnu dijagnostiku razvijenu za Na-Hg-Xe žarulje. Elektronsku temperaturu smo računali iz oblika natrijevog rekombinacionog kontinuuma na 408 nm u slučaju Na-Cd-Xe žarulje. Rezultati su uspoređeni s temperaturom odredenom iz oblika samoinvertiranih natrijevih linija na 568,2 nm i 568,8 nm. Tlakove para natrija, žive i kadmija određivali smo iz razmaka maksimuma samoinvertiranih natrijevih rezonantnih linija.