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DISCUSSION ON EMISSION SPECTROSCOPY MEASUREMENTS FROM A DENSE ELECTROTHERMAL LAUNCHER PLASMA

Baoming Li and Hongzhi Li

Ballistic Research Laboratory, Nanjing University of Science & Technology
Nanjing 210094, P.R. China

A pulsed plasma jet originating from an electrothermal capillary source has been observed by optical emission spectroscopy (OES) for years to determine the plasma parameters, such as plasma temperature, electron density and the species of the plasma and neutral gas. As opposed to most of the previous works, we found it is very important that the spectroscopic constants are selected correctly when the arc plasma temperature is measured by the method of the plot of the Boltzmann function. In this paper, we have discussed the effects of the spectroscopic constants, such as transition probability, A, the statistical weight of the upper level, g_u, and the energy of the upper level, E_u, of copper lines on calculating temperature with a plot of the Boltzmann function in detail. The results show that for a given spectrum a plot of the Boltzmann function taken suitable spectroscopic constants yields a straight line that both the linearity and the correlative coefficient are very good. Otherwise, it will lead to a great error of the temperature measurement. Additional analyses include the utilization of Saha-Eggert relationship for electron density determination. Furthermore, we measure the effects of geometric parameters of capillary and PFN (Pulse Forming Network) parameters on temperature and electron density of plasma in an electrothermal launcher.

INTRODUCTION

There is considerable current interest in the use of electrothermal-chemical (ETC) propulsion concepts for improving the performance of conventional ballistic weapons. It is important to measure the parameters of the capillary plasmas in order to understand and accurately model the interactions of the palsmas with solid propellants. Optical Emision Spectroscopy (OES) has been used for years to determine the plasma parameters, such as its composition, temperature and electron density. A number of investigators have reported the measurements of the average plasma temperature by using the relative line ratio method [1~3]. As opposed to most of the previous works, we found it is very important that the spectroscopic consants are selected correctly when the arc plasma temperature is

Home
Table of Contents

measuered by the method of the plot of the Boltzmann function. Otherwise, it will lead to a great error of the temperature measurement.

Emission resulting from transitions between several excited electronic states of neutral atomic copper was observed in the spectral region between 500–600 mm. The relative intensities in these lines can be used to give a measure of the plasma temperature using a Boltzmann plot with slope –1/kT. The calculated results show that for a given spectrum a plot of the Boltzmann function taken unsuitable spectroscopic constants yields a straight line that both the linearity and the correlative coefficient become very bad. In this paper, we recommend a set of spectroscopic constans of six atomic copper lines which it is suitable to construct a plot of the Boltzmann function.

Additional analyses include the utilization of Saha-Eggert relationship for electron density determination. Furthermore, the relation between the behavior of capillary discharges and the electron density and temperature of the capillary plasmas is discussed.

EXPERIMENTAL PROGRAM

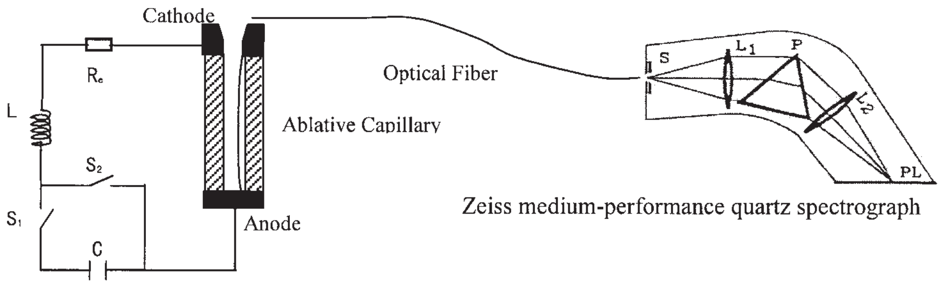

Figure 1. Schematic diagram of the electrothermal plasma generator.
S-slit, L_1-Collimating lens, P-Quartz prism, PL-Photographic plate holder, L2-Camera lens, Radial transmission system: Multimode fussed quartz optical fiber, C: Capacitor Bank, S1: Closing Switch, S2: Crowbar Switch.

The optical system used in our work is shown in Fig. 1. It consits of a spectrograph and radiation system. The spectrograph is a zeiss medium-performance quartz spectrograph. The spectral range of the spectrograph is from 200 to 600 nm. The light from plasma source enters the spectrograph through multimode fussed quartz optical fiber. Two kinds of plasma generators are used to conduct the measurements of plasma parameters. A a.c. arc plasma generator is shown in Fig. 2, its arc current is 8 A, the breakdown voltage of the arc gap, A2, is about 10 kV. Another electrothermal plasma generator is shown in Fig 1. This generator produces high density (>10^{25} m^{-3}), low temperature (1–4 eV) plasmas by the ablation of the capillary liner.

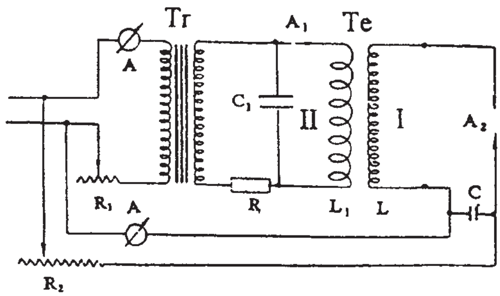

Figure 2. Schematic circuit diagram of the a.c. arc generator with Tesla transformer transmission of the ignition current.
The circuit I: arc plasma current circuit (or work current). The circuit II: Tr – Transformer of 3 kV; Te – Tesla Transformer of 10 kV.

DETERMINATION OF PLASMA TEMPERATURE

A Spectroscopic Measurements

From the theory of atomic emission spectroscopy, the plasma temperature generally is estimated by the relative emission intensities of spectral lines. The relative intensities of the spectral lines are used in the following equation

$$\ln\left(\frac{\lambda I}{A g_u}\right) = C - \frac{E_u}{kT} \tag{1}$$

Where I, λ, A, g_u ,E_u k and T are the relative intensity, wavelength, the transition probability, the statistical weight of the upper level, the energy of the upper level, Boltzmann's constant and temperature. The g_u, A and E_u can be obtained from the handbooks of the spectroscopic constants, chemistry and physics.

For measuring precisely temperature of the arc plasma, a number of spectral lines for a measured element are used. For a given spectrum a plot of the Boltzmann function, the logarithmic term, versus E_u yields a straight line whose slope, S, is equal to –1/kT, assuming a Boltzmann distribution in the populations. Thus we can obtain the arc plasma temperature from the slope, S, of the straight line. We write

$$T = -\frac{1}{kS} \tag{2}$$

The copper lines and their spectroscopic constants used in this work are listed in Table 1. The statistical weight, g_u, and transition probability, A, and energy level transition are get from Corliss and Bozman[4].

Home
Table of Contents

Table 1. Transition probabilities and energy levels for the copper lines from [4]

Spectrum	Wavelengt hnm	Energy level transition K	Energy of the upper level K	eV	g_uA 10^8/sec
CuI	510.55	11203-30784	30784	2.65	0.051
CuI	515.32	30535-49935	49935	4.30	4.7
CuI	521.82	30784-49942	49942	4.30	5.8
CuI	529.25	43514-62403	62403	5.38	3.2
CuI	570.02	13245-30784	30784	2.65	0.014
CuI	578.21	13245-30535	30535	2.63	0.054

Table 2. The relative intensities of copper lines for the arc plasma

CuI(nm)	510.55	515.32	521.82	529.25	570.02	578.21
LnI	2.12	2.76	4.33	1.75	1.75	2.60

Measured relative intensities of copper lines for the arc plasma shown in Fig. 2 are listed in Table 2.

The Boltzmann plot for temperature measurement of the arc plasma is shown in Fig. 3. This method gave Boltzmann temperature T=5946.9 K.

The linear equation is

$$\ln[\lambda I/(g_u A)] = -1.951 E_u + 16.886$$

The correlative coefficient $\gamma = -0.965$.

The experiment obtains very good linear relationship between ln[$\lambda I/(g_u A)$] and E_u.

The method of measuring temperature gives a relative standard deviation of 1.7%.

Hankins et al[1] had used the spectroscopic constants listed in Table 3 taken from [5] for temperature diagnostics of a dense electrothermal plasma by Boltzmann plot using the relative intensities of copper lines. When we utilize the spectroscopic constants listed in Table 3 to process the experimental data listed in Table 2, the Boltzmann plot for temperature measurement is shown in Fig 4.

Table 3. Transition probabilities and energies of upper levels for the copper lines from [5]

Spectrum	Wavelength nm	Energy of upper level eV	g_u	A 10^8/sec	g_uA 10^8/sec
CuI	510.55	3.82	4	0.02	0.08
CuI	515.32	6.19	4	0.60	2.40
CuI	521.82	6.19	6	0.75	4.50
CuI	529.25	7.74	4	0.109	0.436
CuI	570.02	3.82	4	0.0024	0.0096
CuI	578.21	3.79	2	0.0165	0.033

Linear equation is

$$\ln[\lambda I/(g_u A)] = -1.281 E_u + 16.396$$

The correlative coefficient $\gamma = -0.716$.
The arc plasma temperature measured T=9059.2 K.

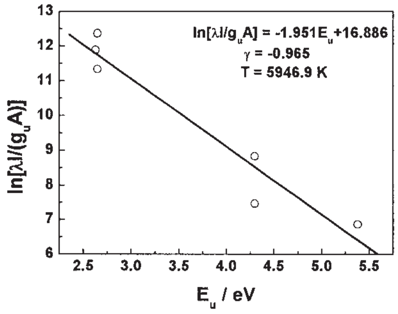

Figure 3. Boltzmann plot for temperature measurement using optical fiber transmission and spectroscopic constants get from [4].

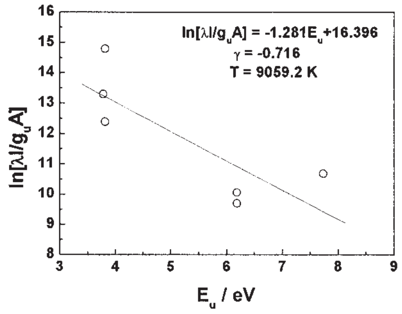

Figure 4. Boltzmann plot for temperature measurement using optical fiber transmission and spectroscopic constants get from [5].

Above experimental results show: (1) We all know that the maximum temperature for this kind of the a.c. arc plasma shown in Fig. 1 does not exceed 6500 K[6]. So measured temperature 9059.2 K by the spectroscopic constants listed in [5] is incorrect; (2) For a given spectrum a plot of the Boltzmann function taken spectroscopic constants from[5], the logarithmic term, versus E_u yields a straight line that both the linear and the correlative coefficient are very bad. It leads to a great error of the temperature measurement.

Therefore, from the experiments it is unsuitable that the spectroscopic constants taken from [5] for copper lines are used for processing the plot of the Boltzmann function to measure the temperature of the arc plasma. We recommend that it is better for the spectroscopic constants for copper lines listed in [4] to measure Boltzmann temperature of the arc plasma.

Listed in Table 4 are the logarithmic term $\ln[\lambda I/(g_u A)]$ of copper lines for the capillary plasma experiment shown in Fig. 1. Fig. 5 shows the waveform of the discharge current and the voltage across the capillary. The capillary sample was polyethylene and the input energy was 4.5 kJ.

Table 4. The relative intensities of copper lines for the capillary plasma at a discharge energy of 4.5 kJ

CuI (nm)	510.55	515.32	521.82	529.25	570.00	578.21
$\ln[\lambda I/(g_u A)]$	13.06	9.29	9.38	9.11	13.12	12.09

The Boltzmann plot for temperature measurement of the plasma capillary is shown in Fig. 6.

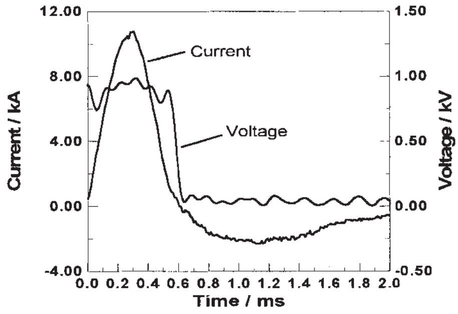

Figure 5. Waveforms of the discharge current and voltage across the capillary.

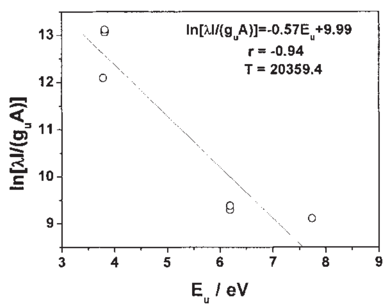

Figure 6. Boltzmann plot for temperature measurement of the capillary plasma.

The linear equation is

$$\ln[\lambda I/(g_u A)] = -0.57E_u + 9.99$$

The temperature measured T=20359.4 K.
The correlative coefficient $\gamma = -0.94$.

B Results and Discussion

Shown in Fig. 7 are the calculated temperatures by OES for the capillary plasma in the source. It is interesting to note in Fig. 7 that for a given capillary dimension the calculated temperatures increase with the input energy over the 4.5 to 10 kJ range with the temperatures ranging from 2 eV to 2.22 eV. However, at the higher input energies, the calculated temperature seems little change with the increase of the input energy. This can be attributed to the fact that the lines change from emission to absorption for spectra.

One of the experimental features of this kind of capillary discharge, such as the presence of maximum plasma temperature with respect to the length to diameter ratio, is observed. Also plotted are average temperature calculations from our numerical code[6]. These results are shown in Fig. 8. There is same trend between two methods with the increase of the length to diameter. But the calculated temperature from the numerical code based on the measured source potentical and arc current is greater than the value from Boltzmann plot. This treatment implies that the emitting material is not well in local thermodynamic equilibrium with the surrounding plasma and that the plasma tempereature has relatively change over pulse lengths of 600 µs in the source. Shown in Fig. 9 is the numerical results of temperature and electron density at the position of the exit bore.

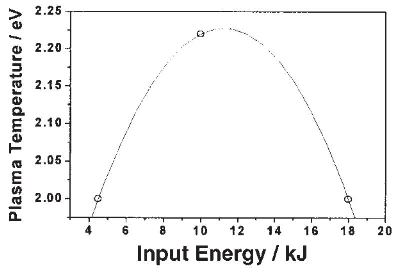

Figure 7. Temperature of the capillary plasma as calculated by OES.

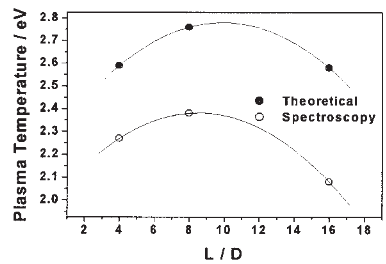

Figure 8. Dependence of the temperature as calculated by OES on the L/D.

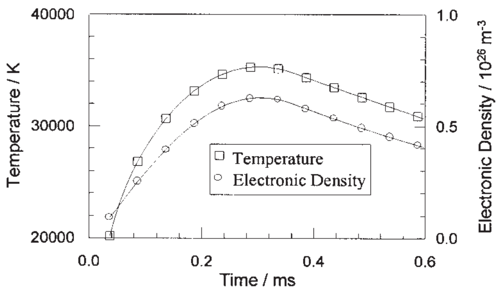

Figure 9. Numerical results of plasma temperature and electron density in the source at a discharge energy of 18 kJ.

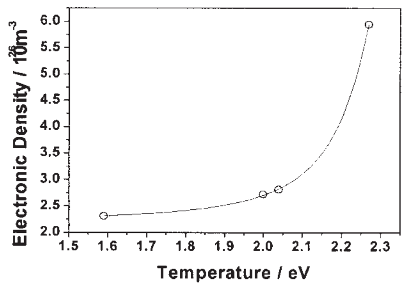

Figure 10. Dependence of electron density as calculated by Saha-Eggert relationship on plasma temperature as calculated by OES.

DETERMINATION OF ELECTRON DENSITY

The relationship of Saha-Eggert is a useful technique for determing the electron densities within a plasma. The relative intensities of the neutral atomic lines and singly charged ionic lines are used according to the relationship.

$$N_e(r) = 4.83\times 10^{15}\frac{I^0(r)g^+A^+\lambda^0}{I^+(r)g^0A^0\lambda^+}T(r)^{3/2}\exp[\frac{E^+ + \Delta E_1 - E^0 - E_1}{kT(r)}] \tag{3}$$

Where (^{0}, $^+$) represents the neutral atom, singly charged ion, respectively, $I^0(r)$ is the relative emission intensities of the atomic lines at the radius r within a plasma, $I^+(r)$ is the relative emission intensity of the singly charged ionic lines at the radius r within a plasma, E^+ is the energy of the excited electronic states of singly charged ion, E^0 is the energy of the excited electronic states of neutral atom, E_1 is the first ionization potential, ΔE_1 represents the lowering in the ionization potential that results from nonideal plasma effects, T(r) is the excited temperature at the radius r within a plasma, k is Boltzmann's constant. The electron density is estimated by using the transitions from iron atomic lines (252,285 nm) and singly charged ionic lines (258,588 nm).

Shown in Fig. 10 is the dependence of the calculated electron density by the Saha-Eggert relationship on the plasma temperature. The results show that the electron density has a small dependence on the plasma temperature. Therefore, there is a well agreement between the value of theoretical calculation and the diagnostic value.

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