Interpretation of temperatures from emission spectra in thermal arc plasmas

A. Mašláni, V. Sember

Institute of Plasma Physics AS CR v.v.i., Za Slovankou 3, 18200 Prague, Czech Republic
Email: maslani@ipp.cas.cz

Temperatures in water-argon plasma arc and plasma jet are obtained by standard methods of optical emission spectroscopy. Several examples from different regions of the plasma show that obtained temperatures must be interpreted carefully taking into account various factors influencing accuracy of the result.

1. Introduction

Optical emission spectroscopy is commonly used for evaluation of characteristics of thermal arc plasmas. Mainly temperature and composition can be obtained relatively simply, if emission spectra are available. In fact, spectroscopic methods became popular especially in last years with appearance of wide range of spectrometers suitable in various conditions. Even in industrial processes spectroscopic analysis can be beneficial [1]. In case of thermal plasmas, temperature is naturally one of the most important characteristics. However, determination of correct absolute value of temperature with requested space and time resolution is not always straightforward. Researchers often encounter situations, when utilization of different methods leads to different values of temperature for the same plasma source. Reasons of this discrepancy can be diverse: incorrect calibration of spectroscopic system, different signal to noise ratio of observed spectral lines, imprecise knowledge of spectroscopic constants, line of sight integration of radiation and impossibility or low accuracy of Abel inversion, high gradients of temperature in small plasma volume, departures from thermal or chemical equilibrium and possibly many others. Examples of measurements for dc electric arc plasmas, in which input parameters (torch geometry, applied arc current, plasma gas, surrounding pressure) influence measured temperature negligibly or substantially, can be found [2, 3]. It also turns out that different stage of temperature accuracy is obtained in the centre of the arc and in the arc fringes or in the free jet. In this paper, several aspects of temperature determination by spectroscopic methods are analyzed. Experimental data come from the thermal plasma generated by the plasma arc torch working with argon and water as plasma forming substances [4, 5]. Spectroscopic measurement is possible in the part of the arc column near anode as well as in the free recombining jet downstream.

2. Experimental Setup

Schematic view of direct current hybrid water-argon torch is shown in Fig. 1a. The arc is stabilized by the argon in the cathode region and by the water vortex surrounding substantial part of the arc column. The arc current can be varied between 200 A and 600 A and the argon flow rate between 8 slm and 40 slm. Water supply system contains high amount of water, from which only small part evaporates to plasma. It is thus difficult to determine how much water goes to the arc; estimations based also on the arc modelling give values of water evaporation rate about 0.3 $g.s^{-1}$. Disc-shaped anode with thickness 16 mm, manufactured from copper, is rotating with the frequency 50 Hz in order to assure uniform erosion and is cooled by water. The anode is located outside of the arc chamber 2 mm from the nozzle exit in horizontal direction. The nozzle connecting arc chamber with surrounding environment has diameter 6 mm. From this description and from Fig.1 it is evident that we are able to observe part of the arc between nozzle and anode, and also free jet downstream the arc expanding to the surrounding atmosphere. Fig.1 contains also two images of the plasma jet; first one (Fig.1b) shows the image taken by the camera Canon EOS 450D with exposure time 1 ms. The pink colour is caused by the excess of continuous radiation in ultraviolet end of visible spectrum together with the strong lines in the red region (mainly H_α). Image in Fig.1c was taken by high speed camera Photron producing monochromatic images; exposure time 0.29 μs reveals structure of the jet in one specific moment (turbulent character of the jet can be seen in movie with 225 000 frames per second, from which this image comes). One of

the interesting features of this image is possibility to clearly observe restricted anode attachment.

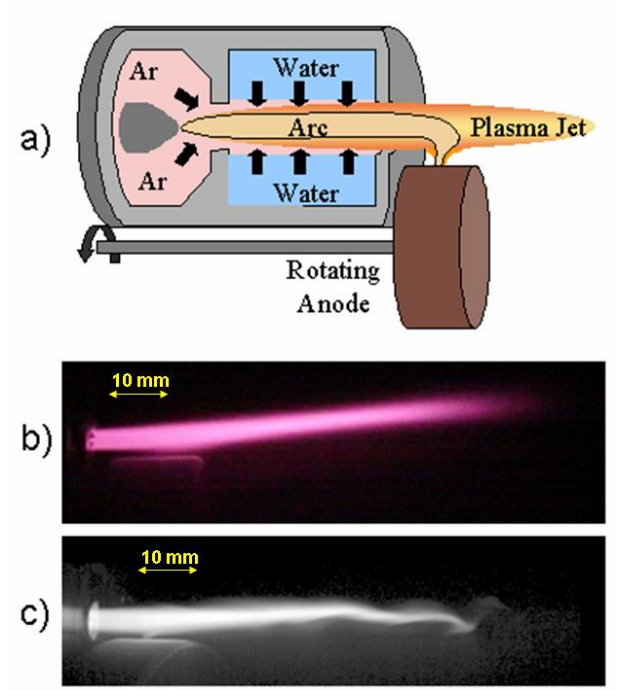

Fig.1 Water-argon plasma torch and jet: a) schematic view of the torch, b) image of the plasma jet (camera Canon EOS 450D, exposure time 1 ms), c) image of the plasma jet (high-speed camera Photron, exposure time 0.29 μs). Both images taken at arc current 500 A and argon flow rate 12 slm

3. Results and discussion

Problems connected with temperature determination by emission spectroscopy are illustrated in several examples from this water-argon plasma arc/jet. In order to elucidate the complexity of this issue, we present data from different parts of the plasma arc and plasma jet, we use spectral lines of various species and apply several different methods. Emission spectra were measured by spectrograph/monochromator Jobin Yvon Triax 550 equipped with iCCD detector with 1024x256 pixels.

First example shows results of temperature measurement about 2 mm from the nozzle exit, i.e. the place where arc exits the plasma torch body and enters surrounding atmosphere. The method is based on the fact that the plasma forming media in this region are known – water and argon. Then equilibrium composition of plasma as a function of temperature can be calculated. From the composition emission coefficients corresponding to individual transitions can be obtained theoretically and from emission spectral lines we have them also experimentally. Comparison of experimental and theoretical emission coefficients (or their ratios) gives the temperature. In addition we can obtain temperature also by comparison of experimental and theoretical electron number density (n_e). Details about this method can be found in one of our previous articles [6]. The advantage of this method is that one spectral window from 470 nm to 500 nm gives enough information (H_β, ArII, OII) to obtain temperature in the arc axis as well as in the arc periphery up to 3 mm from the axis. Example of such radial profile with the gradient of temperature from 22 000 K down to 8 000 K is in Fig.2.

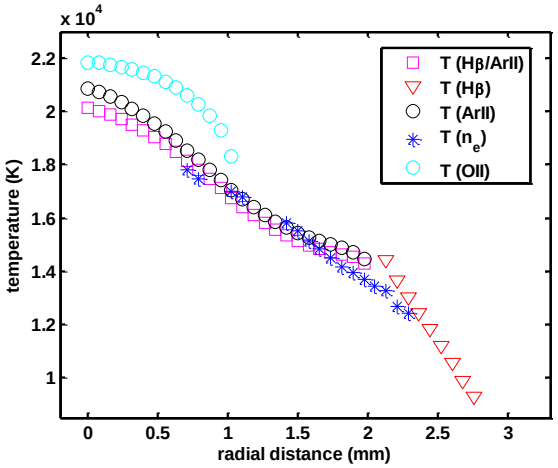

Fig.2 Radial profiles of temperatures 2 mm from the nozzle exit, arc current 400 A, argon flow rate 12 slm

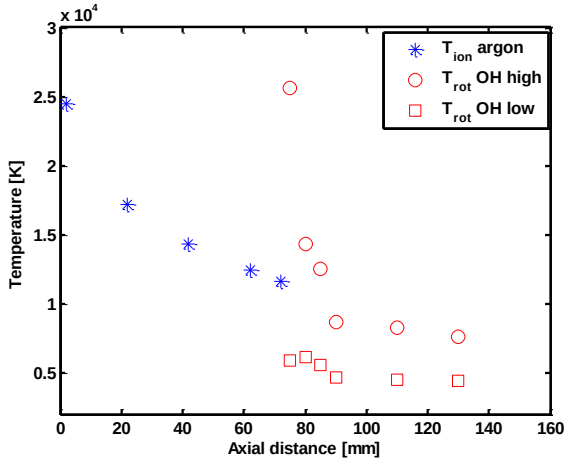

Fig.3 Axial profiles of temperatures, arc current 400 A, argon flow rate 12.5 slm

Second example shows axial profile of temperatures obtained by two different methods (Fig.3). Firstly the ionization temperature using lines of argon (ArI and ArII) is obtained from the nozzle of the torch down to 70 mm. In this case measurement is limited by the availability of argon ionic lines, since they are intensive mainly in the central regions of the arc and jet. Argon atomic lines are observed in larger region, but because of longer optical path they have also stronger tendency for self-absorption. Therefore, in order to increase accuracy, large amount of both atomic and ionic

lines are used. This approach however requires longer measurement and also more spectral windows must be used. Consequently the calibration of the sensitivity of the spectroscopic system must be done very carefully to avoid additional error.

More downstream – from 70 mm to 130 mm – molecular spectrum of OH is utilized for rotational temperature determination. However, this method gives ambiguous results: two temperature distributions indicate that OH radicals in excited state are formed by different reactions. As the Abel inversion is not possible to perform in this turbulent part of the jet, these values come from line of sight integrated measurements. Therefore the interpretation of these temperatures is quite complicated. This problem was also discussed in our previous works [7, 8].

Comparison of Figs. 2 and 3 shows how different values of the temperature can be obtained for the same conditions (arc current 400 A, argon flow rate 12 slm) – axis temperature at 2 mm from the nozzle reaches values between 20 000 K and 25 000 K. In spite this is the region of the arc with good cylindrical symmetry and with plasma properties fulfilling theoretical assumptions (mainly local thermodynamic equilibrium) very well, the temperature is determined with accuracy worse than 25 %.

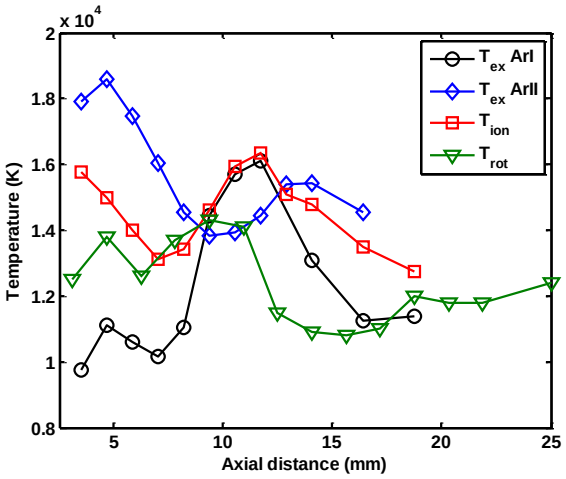

Fig.4 Axial profiles of temperatures, arc current 200 A, argon flow rate 12.5 slm, surrounding pressure 10 kPa

Another situation is presented in Fig.4 (taken from [9]). In this case applied arc current is 200 A, which is lower than in previous examples (400 A). Moreover the jet is expanding into the low pressure environment (10 kPa) unlike the atmospheric pressure in previous cases. Axial profiles from the nozzle down to 25 mm include excitation temperatures from argon atoms and ions together with ionization temperature from them. Also the profile of OH rotational temperature is included, as for this case of lower torch power OH can be observed even in direction of arc axis at the nozzle exit. Interpretation of these temperatures is again complicated task. At the nozzle the temperatures are completely different, which is probably influenced by self-absorption of argon atomic lines and abovementioned unreliability of OH radical. On the other hand, at 10 mm temperatures tend to reach similar values; however, in a low pressure environment this is the position of the shockwave caused by supersonic speed of the flow and by difference of pressures between the nozzle and the chamber. Similar values of temperature are rather accidental, as the measured emission lines are influenced by too many potential errors, including departures from thermodynamic equilibrium of excited states. In any case, temperature is determined again with relatively high inaccuracy even in the arc column at the nozzle exit.

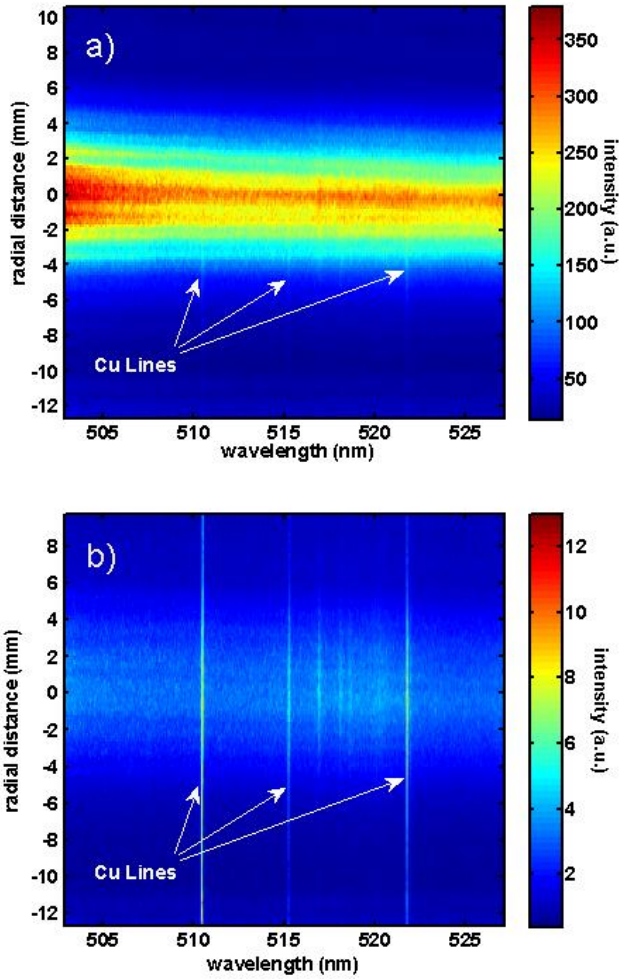

Fig.5 Radial profile of spectrum near spectral lines of CuI (510.6, 515.3 and 521.8 nm): axial distance a) 40 mm, b) 90 mm. Torch parameters are: arc current 500 A, argon flow rate 12 slm

Previous examples showed limitations in temperature determination in the arc column as well as in the free jet downstream the anode. In the free jet, the problems are caused mainly by turbulent character of the jet and impossibility of Abel inversion. In addition, lines of ions, which are usually optically thin, are not available in this region. Therefore we tried to obtain temperature from the lines of atomic copper, which is evaporated from the anode. Indeed, lines of metallic species coming from electrodes are often used for temperature calculation in arcs, for instance in welding arcs.

However, in case of the plasma torch studied in this work we encounter some specific complications. The anode is located asymmetrically with respect to jet axis and distribution of evaporated copper is thus asymmetrical as well. This is demonstrated in Fig.5a for axial distance 40 mm (i.e. approximately 22 mm downstream the anode edge), where the lines of copper are observed only on the side of the radial profile closer to anode. Moreover, continuum radiation of the jet itself is stronger than these lines on the jet axis. Situation changes for longer axial distance; for example for axial distance 90 mm lines of copper are measured across the radial profile (Fig.5b). It means that for this distance copper is distributed more symmetrically and the lines are less disturbed by the jet continuum.

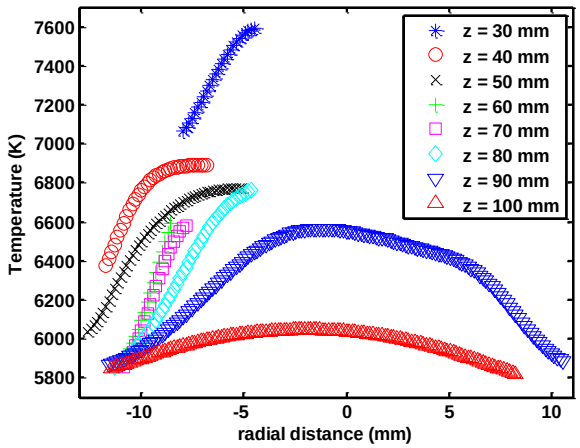

Fig.6 Radial profiles of CuI excitation temperatures for different axial distances; arc current 500 A, argon flow rate 12 slm

Using the abovementioned CuI lines (510.6, 515.3 and 521.8 nm) and two weaker lines if available (570.0 and 578.2 nm) we obtained excitation temperatures in several axial positions, see Fig.6. Radial profiles are obtained from line of sight integrated measurements. Between 30 mm and 80 mm only part of the profile closer to anode is possible to get. Full profiles with the width about 20 mm are obtained for axial distances 90 mm and 100 mm. It means that at least in this region we can get relatively reliable value of temperature.

4. Conclusion

Temperature measurements by optical emission spectroscopy in water-argon arc plasma jet are presented. Large gradients of temperature between the arc axis and arc periphery and also between arc column and the free jet require using different spectral lines and different methods. Each method has several limitations; therefore to reach the final aim – temperature map of the arc and jet for given conditions with adequate accuracy – we need to reduce sources of errors and probably also increase space and spectral resolution of measurements.

Acknowledgement

The work was supported by the Grant Agency of the Czech Republic under the project GA15-19444S

5. References

[1] P. Monkhouse, *Prog. Energ. Combust.* **37** (2011) 125-171

[2] J. Peters, B. Bartlett, J. Lindsay, J. Heberlein, *Plasma Chem. Plasma Process.* (2008) 28:331-352

[3] M. Rajabian, D. V. Gravelle, S. Vacquié, *Plasma Chem. Plasma Process.* (2004) 24:285-305

[4] M. Hrabovský, *Pure Appl. Chem.* **74**, No. 3 (2002) 429

[5] M. Hrabovský, V. Kopecký, V. Sember, T. Kavka, O. Chumak and M. Konrád, *IEEE Transactions on Plasma Science*, Vol. 34, no. 4 (2006) 1566-1575

[6] V. Sember, A. Mašláni, , *Journal of High Temperature Material Processes*, Vol. 13, issue 2 (2009) 217-228

[7] A. Mašláni, V. Sember, Journal of Spectroscopy, vol. 2014, Article ID 952138, 6 pages (2014). doi:10.1155/2014/952138

[8] A. Mašláni, V. Sember, Spectroscopic observation of diatomic molecules in plasmas generated by non-transferred electric arcs, *Proceedings of XIX International Conference on Gas Discharges and Their Applications*, July 6-11, Orleans, France, 219-222, 2014

[9] A. Mašláni, V. Sember, *Journal of High Temperature Material Processes*, Vol. 13, issue 2, (2009) 205 – 215