High Temperature Material Processes **10** (2006) 33-38

Radial and axial distributions of the electron density and temperature in a cascade arc plasma

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Plasmas produced with cascade arcs at atmospheric pressure are supposedly in a state of local thermal equilibrium, or close to it. If we exclude near-electrode regions, the arc can be described as being cylindrically symmetric. In one-component plasmas, the uniformity of the plasma column along the arc axis can also be assumed. In many-component plasmas, due to the demixing effect there are spatial nonuniformities in the plasma composition. Gradients of plasma composition are connected with the gradients in other plasma parameters – temperature and electron density.

In the experiment described in this paper, the plasma gas consisted mainly of helium, with additions of argon. Registration of the spectrum was performed in a side-on configuration, measuring the light emitted by the plasma between arc segments, emerging through slits in the separating insulating rings. The electron density profiles were calculated from measured H_α linewidths.

Introduction

Wall-stabilized arcs are widely used as excitation sources of various atomic and ionic species [1-3]. In contrast to other light sources (hollow cathodes, barrier discharges) plasmas produced in cascade arcs can be assumed to be in the state close to LTE.

Many of interesting species supplied into the arc facilitate the stability of the arc operation, in most cases they can be introduced into the plasma only as trace gases. Usually noble gases (mainly Ar or He, as they are much cheaper than others) are applied as the working medium. The argon plasma is in most cases in a state close to LTE, the helium-based plasma is rather in PLTE. The key parameter for equilibrium conditions in those plasmas is the electron density, since the thermalization of the plasma is caused mainly by collisions of the plasma species with electrons. The much higher electron density, which is realized in argon plasmas, facilitates the achievement of LTE conditions, but on the other hand it results in significant line broadening, which can seriously affect the quality of the atomic and ionic line intensity measurements. Helium plasma can be also very useful for these kind of measurements of ionic parameters, because of higher excitation temperatures achieved in helium plasmas.

The aim of this work was to determine the distributions of the electron density both in the radial and axial direction in the wall-stabilized arc working in a gas mixture of helium and argon. In the case when the arc current is rather low (45 A), the helium can be considered as being only weakly ionized, so nearly all the electrons in the plasma were donated by ionization of admixtures (mostly, of course, argon). In the many-element plasma where external fields and temperature gradients occur, the so-called demixing effects appear [4-7], which means, that the composition of the plasma is not uniform – the value of the mass percentage of the admixtures at various plasma volumes can differ by a factor of ten. This can result in the strong differences in the electron density in those places, as it is dependent mostly on the admixtures' concentration.

Experimental setup

The experiment was performed using the cascade arc consisting of eleven copper segments of 6 mm width, separated by 1.5 mm thick teflon rings (Fig. 1). The discharge channel diameter was 4 mm. The thoriated tungsten electrodes were attached to the boundary segments. The mixture of argon and helium was inserted by 4 mm diameter inlets alongside the whole plasma channel. The arc current was 45 A.

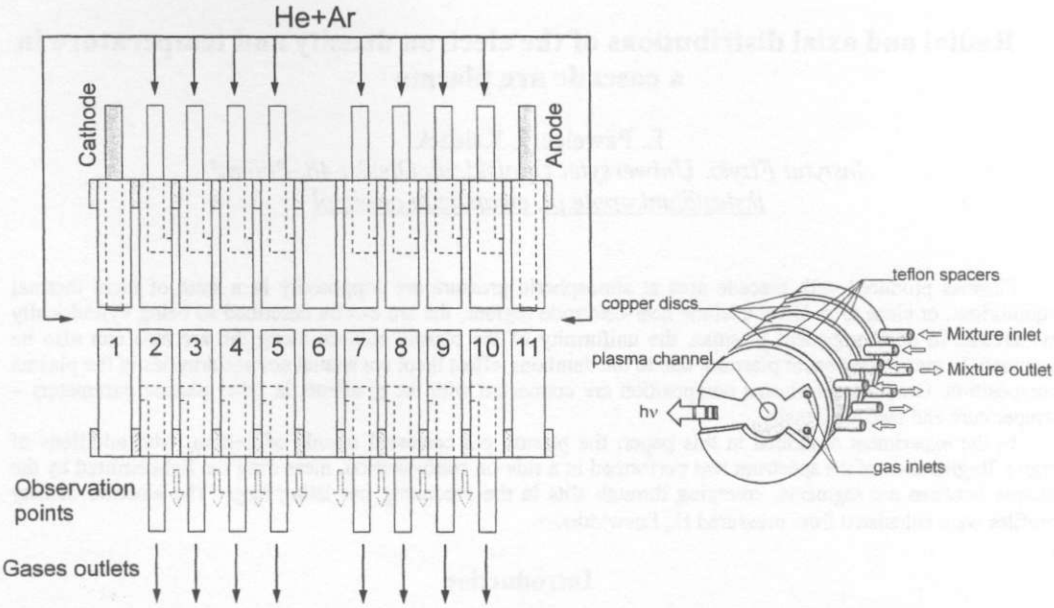

Fig. 1. Arc set-up, cut and view from the side (four of the inside segments only). Measurements were performed between segments from 2 to 10.

The construction of the arc reveals cylindrical symmetry. The gas inlets are located between each of the arc segments along the arc column. Also the arrangement of both electrodes at the end of the discharge channel was identical. The weak and symmetrical gas flow through the discharge volume assures, that the distribution of the gas mixture in the absence of the arc current was uniform. Thus, the departures from the uniformity (axial and radial gradients of the parameters) in the plasma column can be explained only as a result of the cooling originating from the arc walls and the demixing effects in plasma.

The light emitted from the plasma channel was registrated using a side-on geometry. The teflon spacers were slitted to allow the registration of light between nine inside cascade arc segments – from second to tenth. The plasma was imaged by applying the spherical mirror ($f = 730$ mm) onto the entrance slit of the PGS-2 spectrometer. The dispersed light was registrated by an Optical Multichannel Analyzer (OMA 4). The CCD matrix of the OMA was divided vertically to form 64 tracks, for measuring the spatial distribution of the emitted light. From the measured light intensity (integrated over the line of sight), assuming the axial symmetry, after Abel inversion the radial distribution of emission coefficients of atomic and ionic spectral lines were obtained. The width of one track corresponded to 0.09 mm distance across the arc channel. The observed plasma diameter was larger than the plasma channel (4 mm) due to the plasma expansion in the region between the copper segments. The optical thickness of the arc was determined using the mirror located after the arc, reflecting the arc light backwards into plasma.

To register the light emitted from the spaces between different arc segments, the arc was translated perpendicularly to the optical axis of the spectrometer. In this way, a three-dimensional map of the emission coefficients of different atomic and ionic lines have been determined.

Three experiments were performed with different plasma compositions: argon plasma, with only a trace of hydrogen for electron density measurement, the "intermediate" mixture, where the gas was mostly helium, but still with an important addition of argon (26% molar percentage), and the plasma close to the pure helium, with only 4.5% of argon.

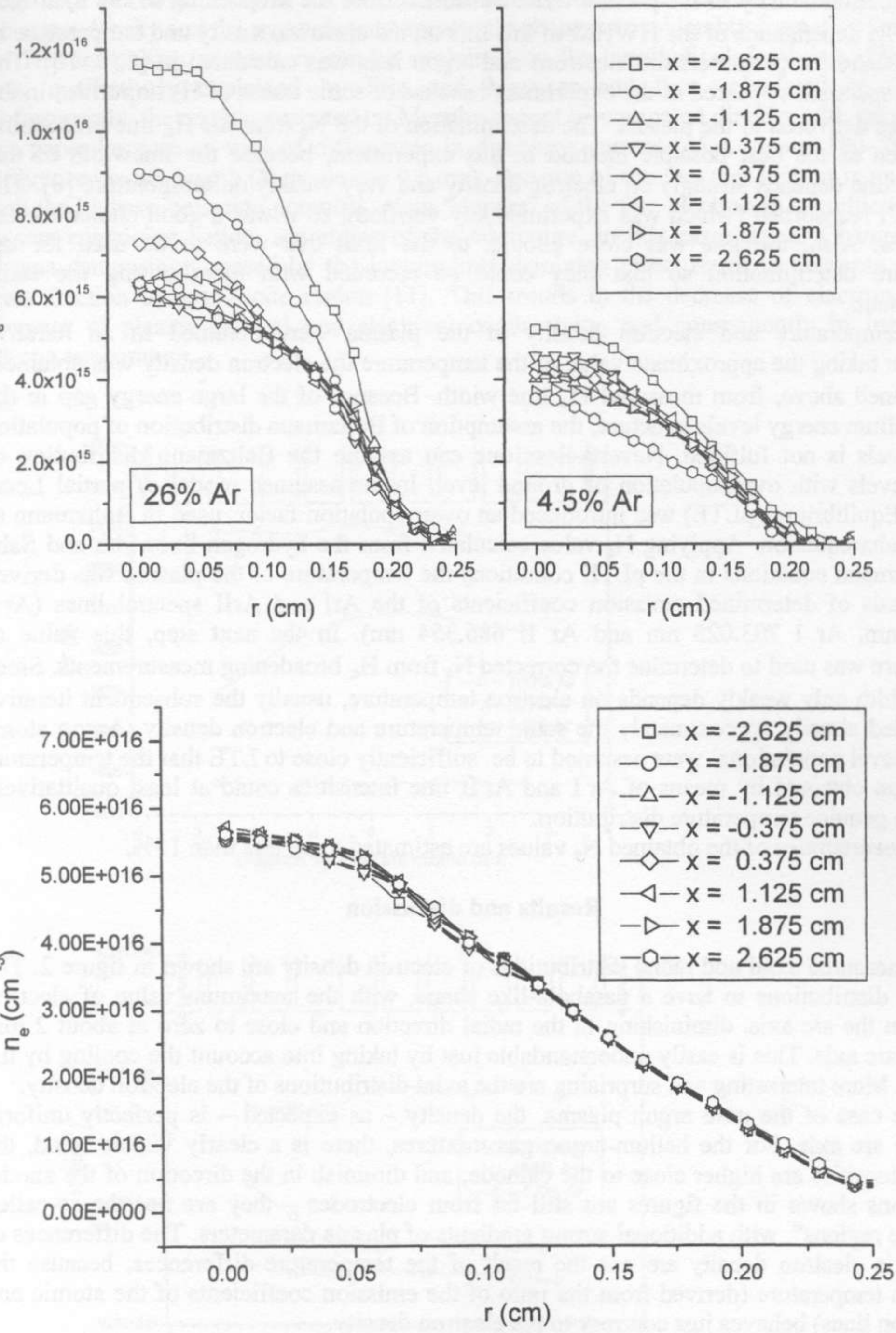

Fig. 2. Radial electron density distributions for different argon concentrations (molar percentage) – upper figure, and for the pure argon – lower figure.

The determination of the electron density and temperature

The electron density in the plasma was determined from the broadening of the hydrogen H_α line. The dependence of the HWHM of this line on the electron density and temperature in the case where the perturbers are electrons and argon ions was calculated in [8, 9, 10]. The hydrogen spectrum appeared in the experiment because of some traces of H_2 impurities in the noble gases delivered to the plasma. The determination of the N_e from the H_α line broadening was chosen as the best possible method in this experiment, because the linewidth of this hydrogen line depends strongly on electron density and very weakly on temperature [8]. The line wasn't reabsorbed (which was experimentally verified), so it was a good choice for the diagnostics. Also, the line was close enough to the lines that were to be used for the temperature determination so that they could be recorded with them during the same measurement.

The temperature and electron density of the plasma were obtained in an iterative procedure: taking the approximate value of the temperature the electron density was obtained, as mentioned above, from measured H_α line width. Because of the large energy gap in the atomic helium energy levels structure, the assumption of Boltzmann distribution of population of the levels is not fulfilled. Nevertheless one can assume the Boltzmann distribution of excited levels with overpopulation of ground level. In the assumed model of partial Local Thermal Equilibrium (pLTE) was introduced an overpopulation factor, used in Boltzmann as well as Saha equation. Applying N_e value calculated from the hydrogen linewidth and Saha and Boltzmann equations in the pLTE conditions the temperature of the plasma was derived on the basis of determined emission coefficients of the ArI and ArII spectral lines (Ar I 696.543 nm, Ar I 703.025 nm and Ar II 686.354 nm). In the next step, this value of temperature was used to determine the corrected N_e from H_α broadening measurements. Since the H_α width only weakly depends on electron temperature, usually the subsequent iterative step yielded already approximately the same temperature and electron density. Argon atoms and ions level populations' were assumed to be sufficiently close to LTE that the temperature distribution obtained by means of Ar I and Ar II line intensities could at least qualitatively reveal the genuine temperature distribution.

The uncertainties of the obtained N_e values are estimated to be less than 15%.

Results and discussion

The measured axial and radial distributions of electron density are shown in figure 2. The radial N_e distributions to have a parabola-like shape, with the maximum value of electron density on the arc axis, diminishing in the radial direction and close to zero at about 2 mm from the arc axis. This is easily understandable just by taking into account the cooling by the arc walls. More interesting and surprising are the axial distributions of the electron density.

In the case of the pure argon plasma, the density – as expected – is perfectly uniform along the arc axis. For the helium-argon gas mixtures, there is a clearly visible trend, the electron densities are higher close to the cathode, and diminish in the direction of the anode. The regions shown in the figures are still far from electrodes – they are not the so-called "electrode regions", with additional strong gradients of plasma parameters. The differences of the on-axis electron density are not the result of the temperature differences, because the ionization temperature (derived from the ratio of the emission coefficients of the atomic and ionic argon lines) behaves just contrary to the electron density.

The discrepancies from the uniformity are the strongest in the case of the intermediate argon density. As the argon ionizes much easier, so in the case of the sufficient argon density, the free electrons in the plasma originate mostly from argon ionization. Only when the argon density is very low, the temperature rises enough for helium atoms to get ionized as well. Because of that, in the case of the very high argon density the changes in those density cannot be very high and so the electron density is rather uniform also. In the case of the very low argon density, electrons reflect rather the helium density, which doesn't change much (e.q. from 95% to 100%). Only in the intermediate density case, the electron density still reflects the argon density and the argon density apparently changes considerably from place to place.

The arc plasma parameters can be explained by the longitudinal demixing effect [4-7], first, qualitatively explained by Frie and Maecker and then calculated by Murphy. Unfortunately, the results presented by Murphy cannot be compared directly with presented in this paper because as well of differences in discharge current (45 A versus 180–200 A) as differences in arc length (8 cm versus 0.5 cm). Because of the fact that helium is an element with the highest ionisation potential, main “donors” of the free electron in a multicomponent plasma containing helium are atoms of the admixture, in this case, argon. Changes in the plasma composition caused by the longitudinal demixing effect result in decrease of argon mass fraction in near-anode region [11]. This results in the decrease of electron density, decrease of plasma thermal and electrical conductivity, and consequently in increase of plasma temperature.

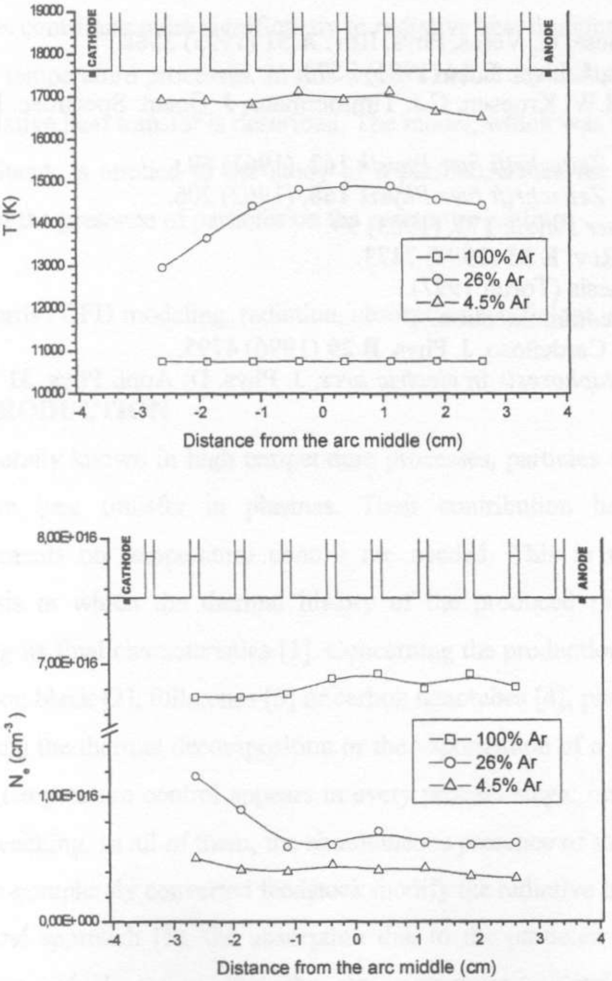

Fig. 3. Axial distribution of the excitation temperature and electron density for different plasma compositions (cathode and anode position shown)

Conclusions

The measurements presented in this work have shown, that the demixing effects in the helium-based plasma can result in serious gradients of the plasma parameters not only in the radial, but also in the axial directions of the plasma channel. This fact must be taken into account in the diagnostics of helium plasmas used for determination of spectroscopic atomic and ionic constants. The end-on measurements were nearly always considered to be more simple and straightforward, especially in the case of the helium-based plasmas, where the reabsorption of the admixture's lines is normally weak, and can be in most cases neglected. However, as depicted in this article, there is one more source of error in this type of experiments – namely the longitudinal demixing, resulting in axial gradients of plasma parameters. It looks, that in helium-based plasmas with sufficient percentage of admixtures, the along-axis uniformity of the plasma parameters cannot be simply assumed, but it must be checked and proved during the end-on measurements.

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