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Axial long and short range uniformity of plasma in a wall-stabilized arc

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Abstract

In this work, an axial uniformity of plasma in a wall-stabilized arc is studied by using the measurements of plasma temperature and electron density. The uniformity is considered both in the long range (as the differences between results of the measurements performed between different arc segments) and in the short range (as the differences between results of the measurements performed in the same gap between segments), but closer or further from the segment wall. The measurements were performed in argon, nitrogen and in argon–helium mixture and are compared to the theoretical model of the arc (calculations were performed for the pure argon plasma). The results and their differences between the cases of pure gases and in the mixtures are discussed.

Keywords: plasma diagnostics, arc plasma, demixing effect, plasma uniformity

1. Introduction

Arcs are popular plasma sources that are used both in technology (in arc welding and smelting), as plasma generators for various plasmatrons and jets, and in spectroscopic research. Wall-stabilized arcs are very popular for spectroscopic measurements of atomic and ionic structure related properties, Stark shifts and widths. Their usability is due to their stability, near-local thermal equilibrium (LTE) conditions, which facilitate the plasma diagnostics, and widely assumed homogeneity and uniformity of the plasma, especially in the axial (along the arc column) direction.

The wall-stabilized arc plasma is in fact mostly, but not completely, homogenous [1, 2]. In the case of the mono-element plasma, the sources of temperature gradients are the arc boundaries, those on the ends and those between the wall segments. In the mixture of gases, those gradients of plasma temperature and existing electric field between electrodes can (and frequently do) also change the composition of the mixture of gases introduced into the multi-element plasma. This effect (called demixing) and the resulting changes in plasma composition (both across and along the plasma column) can introduce additional gradients of plasma parameters or smooth the gradients considerably.

In the previous publication on this topic [3], it was shown that the modeling performed for argon arc suggests the existence of short-range nonuniformities in temperature (and therefore other plasma parameters) due to the plasma expansion between arc segments. The experiments described here were performed to find out if such nonuniformities actually exist in the studied plasma source.

2. Modeling

Modeling of the plasma was done assuming the LTE conditions for argon as the working gas, as described in publication [3].

Since the temperature differences for different regions between two arcs segments are not large and could be invisible due to experimental uncertainties of measured temperature (especially in the very interesting region around 1.5 mm from the arc axis), the electron density (also in the LTE assumption) was calculated. In the case of electron density, the differences close to the arc wall can be of the order of 30–50%, and such values can be much more easily measured. The axial and radial spatial distributions of calculated values for both temperature and electron density in different regions are shown in figure 1.

Although the radial distributions of electron density and of temperature in the middle of the gap region and close to the arc segments look similar, the differences between them in the regions where $r > 1$ mm can be significant, as is shown in the axial distributions.

3. Experimental setup

The experiment was performed using the cascade arc consisting of 11 copper segments of 6 mm width, separated by 1.5 mm thick Teflon® rings. The discharge channel diameter was about 4 mm. The weak and symmetrical gas flow through the discharge volume ensured that the distribution of the gas mixture in the absence of the arc current was nearly uniform.

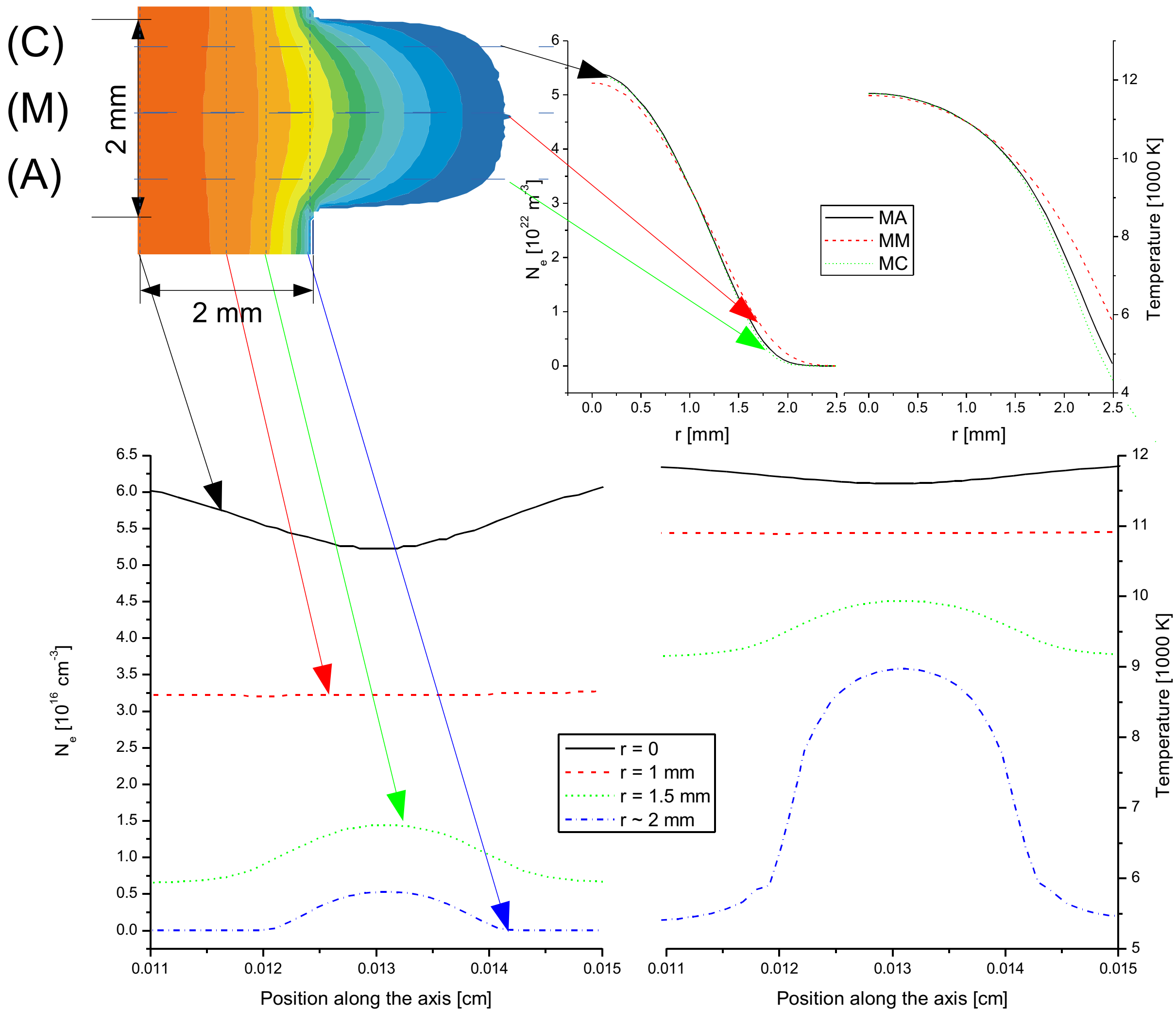

Figure 1. Temperature and electron density distributions in the different regions of the arc, in the radial and axial directions (calculated using the model in a pure argon case). First letter: C—region close to cathode, A—anode, M—middle of the arc; second letter: position inside the gap (close to cathode, anode, in the middle).

Thus, the deviations from the uniformity (axial and radial gradients of the parameters) in the plasma column could be explained mostly as a result of the cooling originating from the arc walls and the demixing effects in plasma because the experimental constrictions of the electrodes were kept in slightly higher argon percentage gas, which can change the overall gas composition in a plasma.

The experiments were performed with different plasma compositions: nearly pure argon (few per cent of N_2 was introduced for diagnostic purposes), pure nitrogen and argon/helium mixture (about 20% argon).

Plasma radiation was registered with an optical multichannel analyzer (OMA). The charge coupled device matrix of the OMA was divided vertically to form 256 tracks in order to measure the spatial distribution of the emitted light. Since the observations were performed side-on, the radial distribution of emission coefficients of atomic and molecular spectral lines were obtained by Abel inversion from the measured light intensity (integrated over the line of sight). Although the width of one track corresponded to 0.026 mm distance across the arc channel, during the data processing the signals were averaged over four tracks,

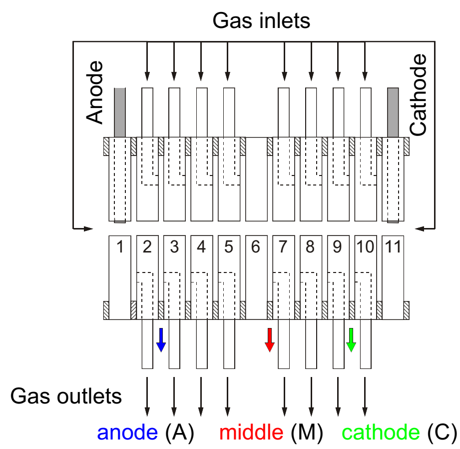

Figure 2. Arc and measurement scheme.

so the effective track width was 0.104 mm. The observed plasma diameter was larger than the plasma channel (4 mm) due to the plasma expansion in the region between the copper segments, especially in the case of argon–helium

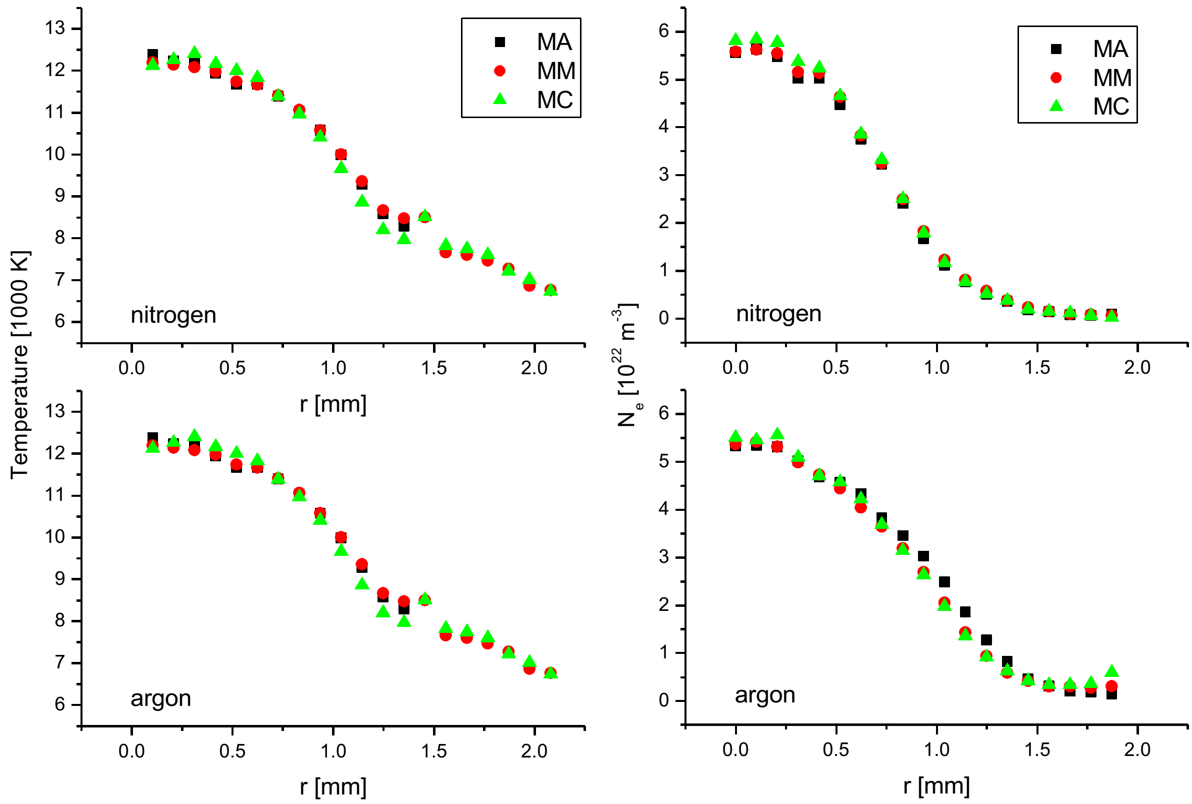

Figure 3. The temperatures and electronic densities for argon and nitrogen. In the case of temperature, filled symbols correspond to the diagnostics using the atomic line intensities, open symbols—the molecular line intensities.

plasma. To register the light emitted from different places in the spaces/gaps between different arc segments, the arc was transposed perpendicularly to the optical axis of the spectrometer.

Measurements were performed in three places between the copper segments—in the middle of the region, close to the segment in the direction of the anode and close to the segment in the direction of the cathode (figure 2). In argon and nitrogen, the results in the different gap regions (between different segments) were very similar and the arc has shown no long-range nonuniformities, which is in agreement with publication [2]. Therefore, the results from only one region are shown in figure 3. In the mixture of argon and helium, the results were different for the different gap regions along the arc column (also in agreement with publication [2]); therefore, three results are shown in figure 4—close to the cathode, in the middle of the arc and close to the anode. In each of these regions the measurements were also performed in the three above mentioned positions inside the gaps between-segments.

The temperatures were calculated from two-line Boltzmann diagram (Ornstein method) using atomic and molecular lines registered in the experiment. In the case of the argon and nitrogen, nitrogen atomic and molecular lines were used:

- *atomic lines:* N I 1054.9 nm with excitation energy of 13 eV and 1059.2 nm with excitation energy 14.9 eV [4]; and
- *molecular lines:* P(40) and R(13)—from the resolved first negative spectrum of N_2^+ in the 390 nm band [5].

The atomic lines were used for measurement of the temperatures above 8000 K and the molecular lines for the temperatures below 8000 K. The obtained values agree very well in the region where both of those methods could be used (in the region around $r = 1.5$ mm). The temperature obtained from molecular spectrum is the rotational temperature, which can be used as an estimation of the gas temperature.

In the case of argon–helium mixture, only argon atomic lines—Ar I 738.4 nm with excitation energy 13.3 eV and 737.2 nm with 14.75 eV were used [6].

The electron density in all cases was determined using the Stark width of the hydrogen H_α line and the temperature was derived from atomic or molecular line intensity measurements [7].

The results of the measurements exhibit experimental uncertainties. In the case of temperature, the experimental uncertainty is around 10%, which is mostly due to uncertainties of the Einstein coefficients. In the case of electron density it is around 10–15%, which is due to uncertainty of the line width measurement and uncertainty of the temperature value used in N_e calculation.

4. Results and discussion

The measured spatial distributions of temperature and electron density are shown in figures 3 and 4 (for the pure gases and for the mixture). The examples of the temperature and electron density results are marked in the following way:

The first letter corresponds to the location of the measurement region (between which segments it is located)—close to the cathode (C), in the middle of the arc (M), close to the anode (A) (marked red, green and blue in figure 2).

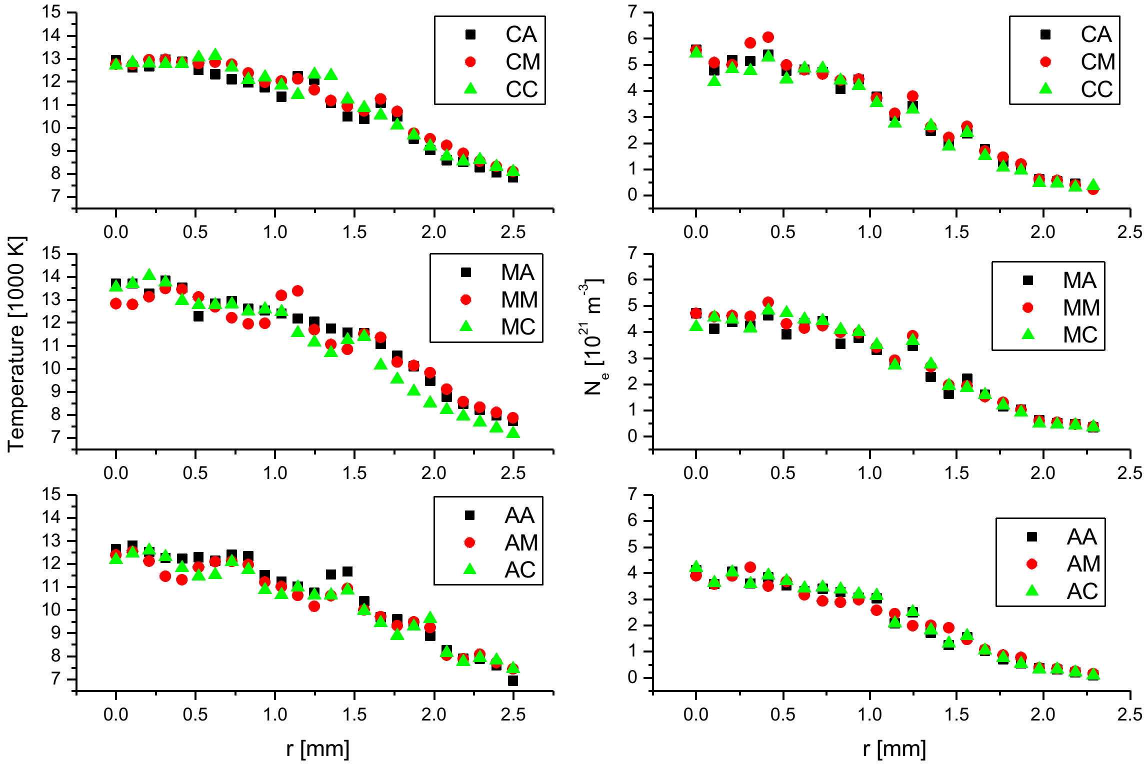

Figure 4. Temperatures and electron densities in argon–helium mixture (∼20% argon).

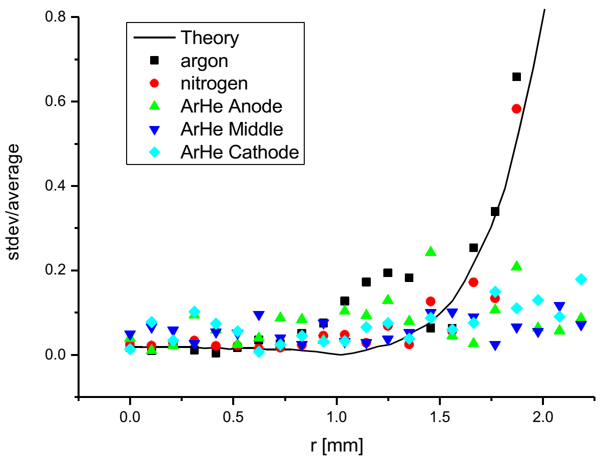

Figure 5. Ratio of the differences between values of the electron density measured in different places of the same gap region and its mean value.

The second letter corresponds to the location of the measurement in the space between arc segments—closer to the segment in anode direction, cathode direction or exactly in the middle.

The spatial distributions very clearly show the long-range nonuniformities in argon–helium gas mixture (e.g. the maximum electron density shows an upward trend from the anode to the cathode). The differences between the spatial distributions measured in the same gap between arc segments are much less visible. To better show these differences, the ratio of the standard deviation of three values measured in the same distance from the arc axis (radial coordinate r) to their mean value was calculated, and its spatial distribution was used for the comparison with model calculations (figure 5, experimental points). A similar value was calculated for the electron density values obtained from model calculations (figure 5, solid line).

The ratio is rather small in the middle of the arc and it increases significantly in the direction of the arc walls. The measurements performed in argon and nitrogen seem to follow the theoretical curve, which would mean that the short-range axial nonuniformity of such kind of the plasma exists and increases in the regions close to the arc wall. Although in the argon–helium mixture the ratio is rather big due to experimental uncertainties, it does not increase in the direction of the arc wall.

5. Conclusions

The argon–helium arc shows significant long-range nonuniformity, with electronic density significantly increasing close to the cathode (which agrees with previous experiments [2]). In addition, the temperature differences along the plasma channel measured in the Ar–He arc agree with the previously published results, with slightly higher temperatures in the middle of the arc and lower close to the anode.

On the other hand, the argon–helium arc does not show the results predicted by model calculations short range nonuniformities. When the measurements are performed in pure or mostly pure gases (Ar, N_2), the results seem to be close to the results of the model. It is possible that the demixing effect in argon–helium mixture actually smoothes these nonuniformities. It is also possible that, since the nonuniformities were predicted using the modeling in the LTE approximation, they do not correctly reflect the argon–helium plasma, in which the departures from the thermal equilibrium are significant.

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