Measurement of OH emission spectra in water-argon thermal plasma generated by the DC plasma torch

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Emission spectra of OH radical are studied in the plasma jet generated by the plasma torch with hybrid water-argon stabilization. Plasma jet is located in a chamber with pressures 4 kPa and 10 kPa. In spite of high temperatures of produced plasma, OH spectra are observed in a large area of the jet. OH spectra are used to obtain rotational temperatures from the Boltzmann plots of resolved rotational lines. Due to line-of-sight integration of radiation, interpretation of the temperatures is not straightforward. It seems that excited OH molecules can be formed by various mechanisms, mainly in the outer parts of the jet, where thermal processes are not as dominant as in the hot central region.

1. Introduction

OH molecules are frequently observed in different types of plasmas where water is at least partially present as an initial molecule. Understanding of OH production and measurement of its temperature and density is important from the point of view of its application as a reactive radical [1]. As for the arc plasmas and plasma torches, OH molecules are observed quite seldom. It is caused by the fact that plasma torches mostly work with plasma forming gases, which do not allow formation of OH in relevant amount. One of the exceptions is plasma torch with water or water-argon stabilization [2], in which some OH measurements were performed already [3]. OH can play important role in two main applications of this plasma torch, plasma spraying [4] and plasma aided gasification of waste materials [5]. In the latter case, for example, OH probably takes part in the complicated chemistry, before desired syngas (mixture of CO and H_2) is formed.

In this work the plasma torch with water-argon stabilization is studied. Produced plasma jet is characteristic by the plasma with high enthalpy, temperature and velocity, in comparison with arc plasma jets without water. The plasma jet is located in a low pressure environment, which simplifies OH observation by optical emission spectroscopy. Moreover, in these conditions the OH spectra are observable in large part of the jet, in the direction of the hot core of the arc column as well as in the outer parts of the free jet where the visible radiation is quite weak.

2. Plasma torch

Schematic view of the experiment is shown in Fig. 1. 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 at present experiment is 250 A (power about 50 kW) and the argon flow rate is 12 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 made from copper, which is rotating and is cooled by water, is located outside of the arc chamber 6 mm from the nozzle exit. Nozzle diameter is 5 mm. The torch is attached to the chamber evacuated by a rotary vacuum pump which allows to decrease pressure from atmospheric down to 350 kPa.

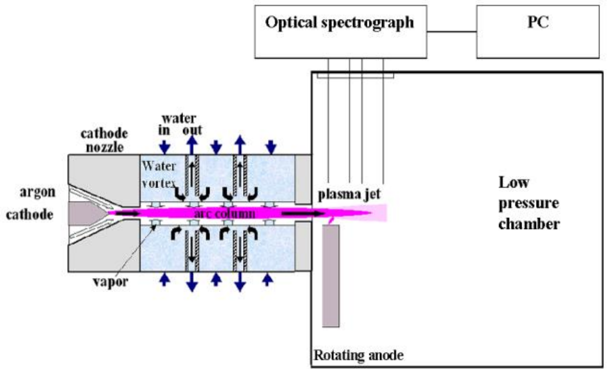

Fig.1 Schematic view of the plasma torch attached to the low pressure chamber and plasma jet observed by the spectrograph

Image of the plasma jet is projected onto the entrance slit of the monochromator Jobin Yvon – Spex Triax 550 equipped with gratings 300, 1200 and 3600 grooves/mm. The output spectrum is detected by the iCCD detector with 1024x256 pixels connected to the CCD 3000 controller and to the

PC. Measured spectra of OH are calibrated using deuterium lamp which is suitable as calibration standard in the spectral region 250-350 nm. All measurements are time averaged in the scale from hundreds of milliseconds to seconds.

3. OH emission spectra

The spectra of OH transition $A^2\Sigma \rightarrow X^2\Pi$ with the bandhead at 306.4 nm were measured using the grating with 3600 grooves/mm, which gives resolution of 0.019 nm FWHM. With this relatively high resolution the individual rotational lines can be studied. Examples of typical spectra are shown in Fig.2. Two spectral windows with central wavelengths 310 nm and 316 nm were used, in order to cover main part of the spectrum.

Since the rotational lines are mostly resolved, the method of Boltzmann plot is used to obtain rotational temperature instead of comparison of experimental and simulated spectra. Two spectral windows allow to use resolved lines of Q_1 branch up to rotational quantum number $J = 24$.

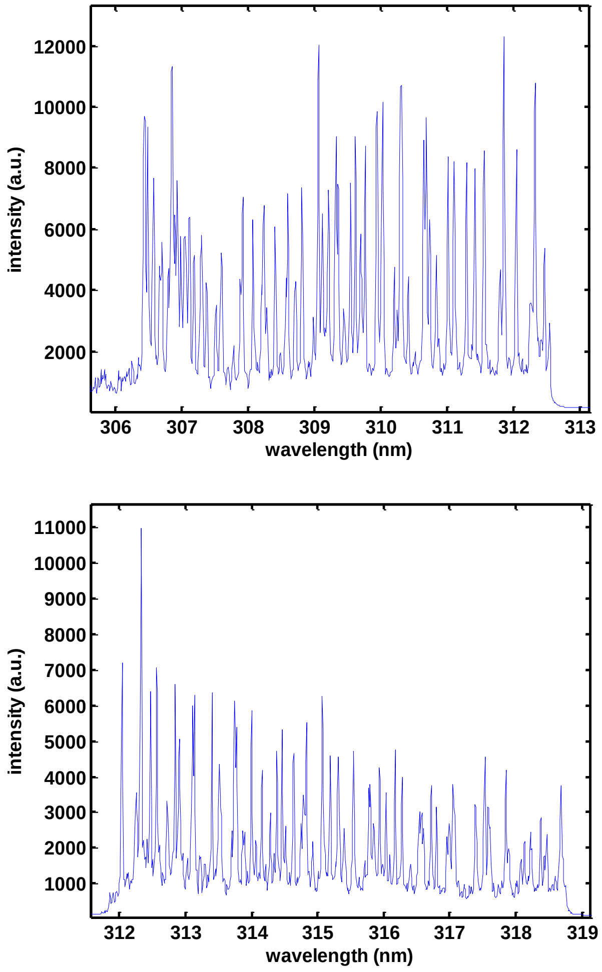

Fig.2 Typical spectra of OH with the central wavelengths 310 nm (upper) and 316 nm (lower).

4. Results and discussion

Rotational temperatures were calculated from the measured spectra in the large area of the jet; from the nozzle up to 70 mm in the axial direction and 5 mm from the jet axis in the radial direction. The jet axis (radial distance 0 mm) is defined as axis of the nozzle. Measurements were done for two chamber pressures, 10 kPa and 4 kPa. To imagine the plasma jet, the photographs for these pressures in visible light are included (Fig.3). For 10 kPa the jet structure is more pronounced, showing clearly the expansion region at approximately 10 mm from the nozzle with lower radiation intensity, where the supersonic velocity and low density of plasma is present. On the other hand, for 4 kPa the jet is more diffused and supersonic structure is not apparent in visible light.

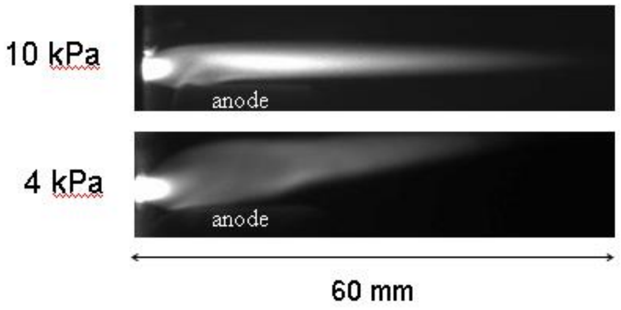

Fig. 3 Photographs of the plasma jet in visible light captured by fast shutter camera for chamber pressures 10 kPa and 4 kPa

Fig. 4 shows the maps of rotational temperatures in the jet for 10 kPa and for 4 kPa. The resolution is higher for radial direction, where the distance between -5 mm and 5 mm is covered by 166 pixels of CCD chip (the second dimension of the CCD represents spectral resolution). On the other hand, in the axial distance the individual points of measurement correspond to manual movement of the optical fibre along the image of the jet. Hence the resolution in this direction is lower; the distance from the nozzle up to 70 mm is covered by only 15 points.

It should be mentioned that presented temperatures do not represent local values; measured spectra are integrated along the line of sight, since the symmetry of the measured profiles of OH is insufficient to perform Abel inversion. Thus, in fact spectra can be composed of OH emissions from various parts of plasma with different properties; this will be discussed also further. Moreover, in spite of low pressure, even the self-absorption cannot be excluded, since the amount of OH might be high in relatively thick plasma column. These restrictions should be kept in mind before drawing any conclusions; however, at least some information can be obtained from presented results.

Both images in Fig. 4 reveal minimum of temperature at about 10 mm from the nozzle. This corresponds to the expansion region observed in photograph in Fig. 3 for 10 kPa. For 4 kPa the local minimum in the radiation intensity in this region is not visible anymore, however, rotational temperature has minimum in this position similarly as for 10 kPa. For 10 kPa, one more relatively strong minimum of temperature is observed at 48 mm, in spite optical image does not indicate it. For 4 kPa the variations of temperature along the jet axis downstream the first minimum are smaller, which corresponds to diffused and more uniform jet.

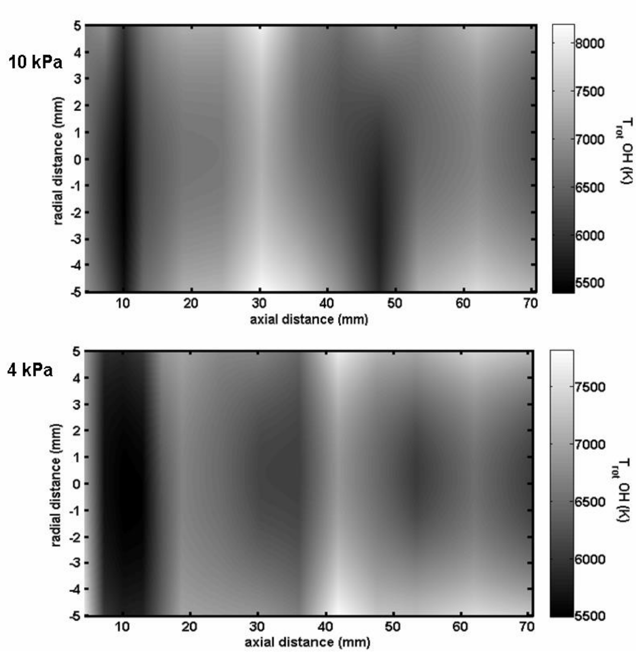

Fig. 4 Rotational temperature distribution in the jet for chamber pressures 10 kPa and 4 kPa

As for the radial profiles of temperatures, they have always minimum near the jet axis with slight increase towards the jet periphery. Relatively small differences in temperatures in different parts of the jet can be attributed to line-of-sight integration of spectra. Indeed, OH spectra are measured in even higher radial and axial distances than presented here. Thus, when measuring spectrum in the direction of jet axis, contributions from the whole thickness of the plasma column are summed. Moreover, hot core of the plasma, which has temperature, according local measurements of atomic and ionic lines, more than 10 000 K, is in principle completely dissociated and contains negligible amount of OH.

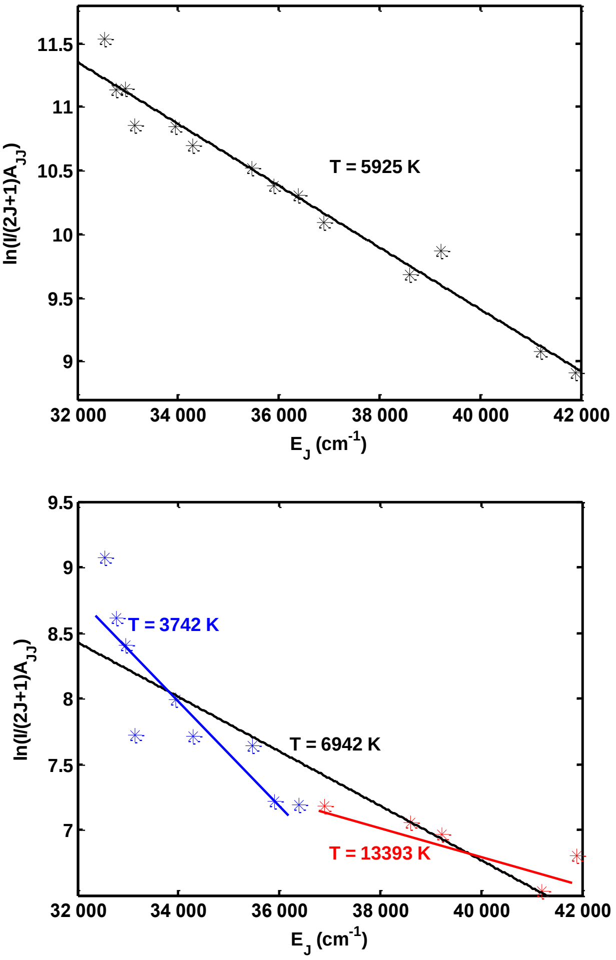

Fig. 5 Typical Boltzmann plots in the jet axis (upper) and in the jet periphery (lower)

Nevertheless, increase of temperature in the jet periphery is evident. We can try to understand it with the help of examples of Boltzmann plots from different radial positions, see Fig. 5. In this figure, first Boltzmann plot corresponds to the position on the jet axis. It is clear that temperature is well-defined with good accuracy. Points which do not fit the line perfectly, probably rather correspond to not ideally resolved lines than to some non-equilibrium effect. Second graph in Fig. 5 shows typical Boltzmann plot from the jet periphery. In this case temperature is higher than in the axis (T = 6942 K), but also with higher statistical error. Moreover, it is possible to choose lines with low rotational number (up to approximately J = 16) and higher one (from J = 16 to J = 24), which define substantially different temperatures with lower error (T = 3742 K and T = 13393 K). It means that higher temperature from all lines is caused by the higher population of higher rotational states with respect to lower ones. This effect is described in literature even for atmospheric pressure plasmas [6]; it has to do with different ways of OH formation. However, its application to arc plasmas is not necessarily straightforward.

As the atomic and ionic lines reliably show axis temperatures higher than 10 000 K, presented rotational temperatures near the jet axis, in spite of well-defined Boltzmann plots, apparently do not represent kinetic temperatures of this hot plasma. These temperatures rather describe the region surrounding the hot core, where the plasma is still thermalized to establish Boltzmann distribution even for high rotational numbers and where at the same time there is already low enough temperature for considerable amount of OH molecules to exist. On the other hand, in the jet periphery where thermal equilibrium is probably violated, excited OH can be formed favouring higher rotational states.

5. Conclusion

Plasma jet generated by plasma torch with water-argon stabilization was studied by optical emission spectroscopy. Thermal plasma originating from water naturally contains considerable amount of OH molecules. Measurement of its emission spectrum allows studying rotational population distribution of excited OH and calculating rotational temperature. The results indicate that OH production in recombining free jet is complicated process and obtained rotational temperature should be interpreted with care.

6. Acknowledgements

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7. References

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