ARC DISCHARGE IN A CROSS FLOW OF GAS

V.Ya. Chernyak[1], V.V. Naumov[2], V.V. Yukhymenko[1], I.L. Babich[1], V.A. Zrazhevskyy[1], Yu.V. Woewoda [1], T.V. Pashko [1]

[1]Radiophysical Department, Taras Shevchenko Kyiv National University, Volodymyrska st. 64, Kiev 01033, Ukraine, e-mail:chern@univ.kiev.ua;

[2] Department of Photoactivity, Institute of Physics, Ukrainian Academy of Sciences, Prospect Nauki 46, Kiev 03028, Ukraine, e-mail: kern@iop.kiev.ua

The experimental study of nonequilibrium air plasma flow of atmospheric pressure in the transverse arc discharge of high voltage is conducted. The high non-izothemality in the air plasma during its space evolution is shown in dependence on the gas flow rate and discharge energy deposition with a detailed emission spectroscopic diagnostics of excited atoms, molecules and radicals along the plasma jet.

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1. INTRODUCTION

Nonequilibrium air plasma in electric discharges is of permanent interest in many labs because of various important applications in plasma chemistry, materials processing, energy- and eco-biotechnologies [1]. Non-isothermality in plasma has a fundamental importance for efficiency of plasma chemical processes, especially at sub-atmospheric pressure conditions, when the temperature of electrons is higher than the character temperatures of heavy particles (ions, atoms, molecules, and radicals). While most of the discharge energy is directed into the energy of electrons and not just to gas heating, it gives desirable selectivity of plasma chemical transformations [2]. Among possible variants of non-thermal high pressure discharges: spark, corona, barrier, etc [3], one specific type is most interesting for us. This is a transverse arc in a blowing flow with a stationary current column or rotating in a vortex flow [4]. It is an intermediate case of the high-voltage low-current self-sustained discharge with a self-adjustable arc supported by the plasma flow, which provides a high level of ionization. It differs from the non-stationary gliding arc of Czernichowski type [5-6] by the fixed arc length. It has also a convective cooling of the plasma column by the air flow but without conductive heat losses at walls since it is a free arc jet. An intensive transverse ventilation of the arc plasma increases its ionization, nonequilibrium and non-izothermality. We successfully applied different schemes of transverse blowing arc with primary and secondary discharges in our current investigations in Kiev University, carrying out plasma-assisted processing of various homo- and heterophase gas and liquid substances [7-9]. Despite of achievements in practical applications there are still enough issues for research. The main point is mechanism of transition from quasi-equilibrium arc discharge to non-equilibrium, i.e. from thermal to non-thermal ionization.

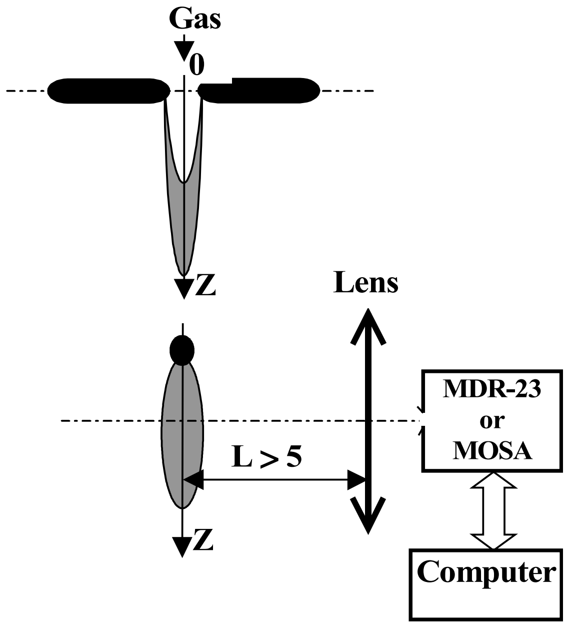

Fig.1.

In this paper we like to present results of spectroscopic characterization of the air plasma flow in the transverse blowing arc discharge with the fixed arc in order to get more deep understanding in the physics of processes.

2. METHODOLOGY

Experiments have been done for a scheme of the transverse blowing arc as shown in Fig.1. A free jet of atmospheric air ran from the nozzle across two horizontal opposite electrodes and formed a bright crescent-shaped electric arc as well as a highly reactive afterglow. We used the rod electrodes with diameter d = 5 mm. A nominal gap between the electrodes from which we started usually was δ = 1 mm. Since the electrodes were not cooled, the electric discharge energy was transferred totally to the air plasma flow. We applied electrodes made from different materials: copper and graphite, in order to see spectroscopic difference. The air nozzle was axisymmetric, with inner diameter $\varnothing$ = 1 mm, made from stainless steel. It was maintained vertically perpendicular to the electrode axis at the length L = 5-10 mm and was centered strictly between the electrodes. We used a standard technical dry air system supply with the flow meters. It was enough high gasdynamic pressure in the flow to blow out the electric arc downstream. In fact, we can regulate the arc discharge geometry as by the gap δ

between the electrodes and by the length L between the nozzle exit and the electrodes. The last allows to control both the air blowing of the arc and air cooling of the electrodes. Then, we can regulate the air flow rate, G, and arc discharge current, I_d. The arc discharge is powered by the DC source at the ballast resistance R = 2 kΩ in the circuit. Electric current-voltage parameters were measured with the standard electronics.

For optical diagnostics, the emission UV-VIS-NIR spectroscopy was applied. Plasma radiation was measured by two means: 1) portable rapid PC-operated CCD-based multi-channel optical spectra analyzer (MOSA), which has a wide wavelength survey (200-1100 nm) but medium spectral resolution (~0.2 nm), and 2) spectral combine KSVU-23, including a scanning monochromator (DMR-2), PMT detector (FEU-100) and PC recorder, which provides a high spectral resolution (up to 0.01 nm) but low scanning speed. Measurements were conducted in different cross-sections along the arc and afterglow. The spatial resolution was of 0.1 mm. The images were normally focused by quartz lens at the bench 5-focus distance from the arc directly on the entrance slit of the spectral device. With MOSA we used a fine optical fiber with a microlens. For calibration, a set of etalon spectral sources: mercury, deuterium, xenon and tungsten lamps were applied.

Within available spectrum of wavelengths from 200 to 1100 nm we conducted monitoring of all remarkable emissions and identified all basic atomic lines of N, O, H as well as molecular bands of NO, N_2, O_2, OH, CO, CN which we were able to recognize. For analytical diagnostics, we utilized relative intensities of analytical CuI lines (in case of copper electrodes) and N_2 2^+-system bands in order to determine the temperature of excitation of electronic states of Cu atoms, T_e, and the temperature of excitation of vibrational states of N_2 molecules, T_V, as commonly accepted method in case of optically thin plasma [10]. The temperature of excitation of rotational states, T_R, because of non-resolved rotational spectral structure at conditions of atmospheric pressure, was estimated by comparison of the measured spectra of N_2 $2^+(0,0)$ band at 337.1 nm and the corresponding synthetic spectra calculated on the known spectral constants for N_2 $C^3\Pi_u$-$B^3\Pi_g$ *E-V-R* transitions, using the Gauss-like instrumental function. On this base, we draw curves of changes of the specific emission intensities along the plasma, depending on the arc discharge power and the air flow rate.

3. RESULTS AND DISCUSSIONS

A transverse arc discharge in the air flow was ignited with a high voltage at the shortest distance between the electrodes that corresponds to breakdown when the electric field reached ~3 kV/mm [3]. Under the action of gasdynamic pressure of the incident air flow, the electric arc was forced to bow down and elongated along the stream, so that the current increased and the voltage dropped down a little bit. The air flow led not only to bending and blowing of the arc current channel but also to stabilization of the plasma column due to the convective withdrawal of energy (radiative losses are neglected). Due to a high speed flow, the air plasma had to be turbulized, and it additionally contributed to suppression of ionization-overheating instability. Thus, gas dynamics and convective heat/mass transfer favored the steady-state arc burning. The resulting current-voltage characteristics of the blowing arc discharge have a typical for the high-voltage high-pressure arc dropping character. It is practically independent on the flow rate of the plasma-forming gas at the given geometry of electrodes. It points out that the transverse arc has a self-adjusting length and the current channel is autostable in the air plasma flow despite of visible non-uniformity and fluctuations in time and in space.

The emission spectrum of of air plasma flow is rich of spectroscopic information. We recognized here nitride oxide NO γ-system ($A^2\Sigma^+$-$X^2\Pi$: (0-0) 226.9 nm, (0-1) 236.3 nm, (0-2) 247.1 nm, etc); hydroxyl OH UV system ($A^2\Sigma$-$X^2\Pi$: (0-0) 306.4-308.9 nm); oxy-gen O_2 Shumann-Runge bands ($B^3\Sigma^-_u$-$X^3\Sigma^-_g$: (0-14) 337.0 nm); nitrogen N_2^+ 1^- system ($B^2\Sigma^+_u$-$X^2\Sigma_g^+$: (1-0) 358.2, (1-1) 388.4, (0-0) 391.4 nm, etc); N_2 2^+ system ($C^3\Pi_u$-$B^3\Pi_g$: (0-0) 337.1, (0-1) 357.7, (0-2) 380.5, (1-0) 316.0 nm, etc); and even week N_2 1^+ system ($B^3\Pi_g$-$A^3\Sigma^-_u$: 570-750 nm). Among atomic lines, we recognized HI Balmer α line 656.3 nm, OI lines (777.3, 844.6, 926.0 nm), and NI lines (746.8, 818.8, 868.3 nm). There are a lot of Cu lines due to evaporation of copper electrodes (in case of graphite we saw nothing), but intensities of the most strong CuI lines 324.7 and 327.4 nm were overlap with N_2^+ $1^{(-)}$ bands, therefore we used CuI lines 465.1, 510.5, 515.3, 521.8, and 578.2 nm. The interference of N_2 2^+ system also precluded diagnostics of OH (A-X) band at 308 nm.

All dependencies of emission intensities I_λ for the CuI line and $I_\lambda(z)$ for the N_2 2^+ and spectral distributions along the z-axe downstream $I_\lambda(z)$ are of non-linear character. The comparison of $I_{\lambda Cu}(z)$ and $I_{\lambda N2}(z)$ tells that $I_{\lambda N2}(z)$ distributions are sufficiently larger and are somewhat shifting downstream relatively to $I_{\lambda Cu}(z)$.

On the base of the measured values $I_{\lambda Cu}$ (465.1, 510.5, 515.3, 521.8, 578.2 nm) and $I_{\lambda N2}$ (337.1, 353.6, 357.7, 371, 375.5, 380.5 nm) using the Boltzmann plot, we determined corresponding temperatures of electronic excitation of Cu atoms, T_e, and vibrational excitation of N_2 molecules, T_V. As expected, these temperatures differenced very much. At that, the level of non-izothermality is not permanent along the plasma flow. It depends not only on the current of arc discharge but also on the velocity of air flow that is blowing the arc plasma column, providing convective heat/mass transfer. Especially large differences occur in afterglow.

Along the flow the temperature T_e is 0.7-0.6 eV while the temperature T_V is 0.4-0.35 eV. In the afterglow, T_e decreases while T_V keeps longer. Then increasing the discharge current I_d, the temperature T_e becomes larger. At a lager flow rate G the gradient T_e becomes smaller.

The non-equilibrium of air plasma in the blowing arc discharge follows also from the estimation of rotational temperature T_R obtained at the same conditions. Fig. 2 shows the results of simulation of V-R spectra for the N_2 $2^+(0\text{-}0)$ band 337.1 nm, calculated at different T_R = 0,05-0,5 eV with the step of 0,05 eV (from curve 1 that is

T_R = 0,05 eV to curve 10 that is T_R = 0.5 eV), as compared with the measured data in the discharge at I_d = 200 mA for G = 40 cm^3/s (curve 11) and 80 cm^3/s (curve 12) at the distance z ≈ 7 mm. Our estimation of T_R is 0,2–0,25 eV. It differenced from T_V more then twice. This evidences about really strong non-isothermality in afterglow.

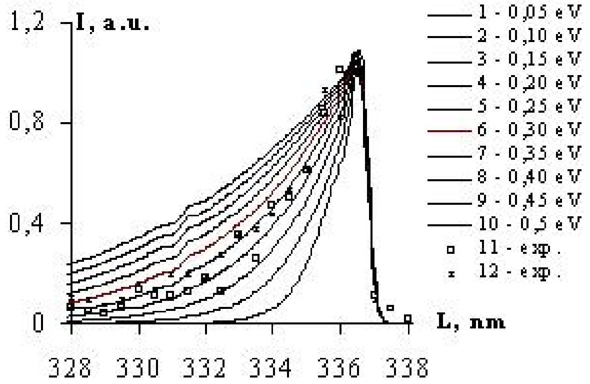

Fig. 2

4. CONCLUSIONS

We see that a high-voltage low-current transverse blowing arc discharge in the air flow of atmospheric pressure can be a source of non-isothermal plasma with a high level of ionization. We found that there is no local LTE in this arc discharge air plasma flow during its space/time evolution, and the measured/estimated temperatures of electrons and molecular states are within the relations $T_e \sim T_{exc} > T_V > T_R \sim T_g$. The temperature of electron excitation of heavy particles T_{exc} undertaken through the partially resolved emission of N_2^+ $1^{(-)}$ bands differenced from the temperature of vibrationally and rotationally excited molecules more then twice. Therefore, usual two-temperature approach with T_e for electrons and T_g for heavy particles is not valid here. Another character effect is an “ignition” of the molecular emission downstream the arc resulted from the kinetic non-equilibrium conditions. The highest temperature (~1.5 eV) is measured in the center of the arc. In the afterglow zone, the temperature T_e decreases rapidly while the temperature of excited metastable molecules T_{exc} keeps longer. The factors, which effects on plasma nonequilibrium are not only electric parameters of arc discharge but also gas dynamics and convective heat/mass transfer in the plasma flow. Due to suppression of ionization-overheating instabilty at highly turbulized flow, the plasma space and its interaction with environment can be increased significantly. Taking into account high plasma density, high electron temperature, easy control of discharge potential and possibility of stimulation of selective chemical reactions at relatively low gas temperatures, we may conclude that this type of nonequilibrium arc discharge is very suitable for technological applications including plasma-assisted ignition/combustion of gas-liquid hydrocarbon fuels and plasma-enhanced modification of combustion products.

REFERENCES

1. *Proc. 16th Intern. Symp. on Plasma Chemistry, Taormina, Italy /*Eds. M.Capitelli et al., 2003 and *Proc. 3rd Symp. on Theoretical and Applied Plasma Chemistry, Plyos, Russia /*Eds. D.I.Slovetsky et al., Moscow. 2002.
2. V.D. Rusanov, A.A. Fridman. *Physics of Chemically Active Plasma*. Moscow: “Nauka”, 1984.
3. Yu.P.Raiser. *Gas Discharge Physics*. Berlin: Springer, 1997.
4. V.Ya. Chernyak // *Proc. 3rd Intern. Seminar on Electrophysical and Thermophysical Processes in Low-Temperature Plasma.* Brno, 1999, p.94-99.
5. A.Czernichowski // *Pure & Appl. Chem.* 1994, 66(6), p.1301-1310.
6. A. Fridman, S. Nester, L.A. Kennedy, A. Saveliev, O.Mutaf-Yardimci // *Prog. Energy. Combust. Sci.* 1999, v.25, p.211- 232.
7. V.Ya.Chernyak, V.V.Buchnev, S.D.Koval, et al. // *Nonequilibrium Processes and their Applications,* HMTI, Minsk, 2000, p.75-78
8. V. Chernyak, S. Koval, V. Naumov // *Proc. 15th Intern. Symp. on Plasma Chemistry /Eds. A.Bouchoule, J.-M.Pouvesle.* GREMI, Orleans, 2001, v. IV, p.1447-1452.
9. V.Ya. Chernyak // *Bull. Kyiv University. Series: Physics*, 2002, 4 (1), p.362-370.
10. V. Zhivotov, V. Rusanov, A. Fridman. *Diagnostics of Non-Equilibrium Chemically Active Plasma.* Moscow: “Atomizdat”, 1985.

ДУГОВОЙ РАЗРЯД В ПОПЕРЕЧНОМ ПОТОКЕ ГАЗА

В.Я. Черняк, В.В. Наумов, В.В. Юхименко, И.Л. Бабич, В.А. Зражевский, Ю.В. Воевода, Т.В. Пашко

Проведены экспериментальные исследования неравновесной воздушной плазмы атмосферного давления в поперечном дуговом разряде высокого напряжения. С использованием спектров излучения атомов, молекул и радикалов показана эволюция уровня неизотермичности в плазме воздуха в зависимости от скорости газового потока и энерговклада в разряд.

ДУГОВИЙ РОЗРЯД У ПОПЕРЕЧНОМУ ПОТОЦІ ГАЗУ

В.Я. Черняк, В.В. Наумов, В.В. Юхименко, І.Л. Бабіч, В.А. Зражевський, Ю.В. Воєвода, Т.В. Пашко

Проведені експериментальні дослідження нерівноважної повітряної плазми атмосферного тиску в поперечному дуговому розряді високої напруги. З використанням спектрів випромінювання атомів, молекул та радикалів показана еволюція рівня неізотермічності в плазмі повітря в залежності від швидкості газового потоку та енергії, що вкладається в розряд.