ELECTRIC DISCHARGE IN THE TRANSVERSE AIR FLOW AT ATMOSPHERIC PRESSURE

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Physical features of the transverse arc discharge and its atmospheric pressure plasma were investigated for the different gas flow rates (gas flow velocity ~ 0…2/3 of the sound speed) and character of the gas flow (laminar/turbulent). Component composition of the plasmaforming gas; electronic excitation temperatures T_e^* of atoms, vibrational T_v^* and rotational T_r^* temperatures of molecules in the generated plasma were determined by optical emission spectroscopy. Founded difference of the temperatures T_e^*(Cu)>T_e^*(O, H) was explained by the additional mechanism of the population of the excited electronic states of cooper atoms (material of electrodes) due to the ion-ion recombination, which is almost absent for the blowing gas atoms. Non-monotonic character of the $T_r^*(N_2)$ and $T_r^*(N_2^+)$ dependence on the gas flow was connected with transition from laminar to the turbulent gas flow regime. It was shown that at large gas flows (at which the deviation from laminar flow occurs and the turbulence starts) plasma of TA becomes more isothermal.

PACS: 52.50. Dg, 52.80.Mg, 52.30.-q

INTRODUCTION

Non-equilibrium plasma sources are widely used for different plasmachemical applications. One of the ways to make such plasma generators is to provide an effective heat- and mass- transferring between plasma and environmental. It is realized in such transversal discharges as: gliding arc [1] and its different modifications [2-4], transverse arc [5] and glow discharge [6] due to the presence of gas flow, which is perpendicular to the current lines of the discharge. Results obtained in this work will show that even transverse gas flows can result in non-thermal and thermal plasma generation both. The level of the plasma non-isothermality partially depends on the gas flow rate and the discharge current.

1. EXPERIMENT

Experimental scheme of the electroarc discharge in the transverse blowing air flow (transverse arc – TA) was considered in details in [5]. Two copper horizontal electrodes with diameter d=6 mm placed opposite each other were used. A nominal gap between them was δ=1.5 mm. The axially symmetric steel nozzle, with inner diameter ∅=1 mm, was maintained vertically perpendicular to the electrode axis at the distance L=20 mm and was centred strictly between the electrodes. A standard dry air system supplied with the flow meters was used. There was enough high gas-dynamic pressure in the flow to blow out the electric arc downstream. TA discharge was powered by the DC source at the ballast resistance R = 2 kΩ in the circuit. All measurements were carried out for the discharge currents I_d=0.1...1 A and different gas flow rates G=0...220 cm^3/s.

Dependence of the discharge voltage U_d on the different air flow rates G is shown on Fig. 1. Such non-linear character of U_d(G) dependence can't be explained only by the fact that energy carries out from the discharge region with G increasing and to support the fixed discharge current it is necessary to increase the voltage on the discharge. Non-linear U_d(G) dependence on Fig. 1 can be connected with the secularities of the gas flow: i) a monotonic voltage increasing with the gas flow rate G increasing (laminar gas flow); ii) voltage on the discharge increases (for $I_d \leq 700$ mA) or remains almost constant (for $I_d > 700$ mA) with further increasing of G (this region corresponds to the transient gas flow regime: from laminar to the turbulent); iii) when the gas velocity becomes bigger than the drift velocity of ions in the electric field, further voltage increasing starts, which is escorted by the appearance of the filament plasma structures directed along the flow.

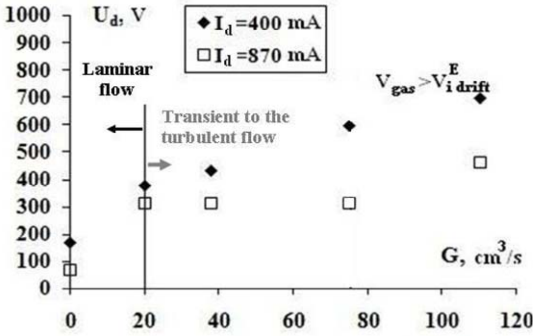

Fig. 1. Voltage dropU_d on the transverse arc discharge for the different air flow rates G

2. METHODS AND RESULTS

Emission spectra of TA plasma were measured by CCD based spectrometer SL 40-3648 *Solar TII* in the range of 200…1100 nm with spectral resolution ~ 0.7 nm.

Excitation temperatures of the electronic states of atoms (electronic temperature T_e^*) in TA plasma were determined by the relative intensity of the cooper (material of electrodes), oxygen, hydrogen spectral lines by Boltzmann plots. Vibrational T_v^* and rotational T_r^* temperatures of $N_2(C^3\Pi_u)$ molecule were evaluated by relative intensities of the emission bands of 2^+ system of nitrogen by using SPECAIR [7] simulation. The following ratio of the excitation temperatures $T_e^*>T_v^*>T_r^*$ were obtained in TA plasma. It was shown that T_e^* slightly decreases along the gas flow in the afterglow zone, while T_v^* remains constant. Founded difference of the temperatures T_e^*(Cu)>T_e^*(O, H) can be explained by the additional mechanism of the population of the excited electronic states of cooper atoms due to the ion-ion recombination, which is almost absent for the blowing gas atoms. The main recombination mechanisms were considered and corresponding recombination time τ_r was estimated for plasma of the transverse arc in air at N_e~10^{13}...10^{14}cm^{-3}, $T_g \approx T_r(N_2) \approx 2000$ K, T_e~1 eV, p=1 atm (table).

Main recombination mechanisms and its characteristics time

Recombination	Recombination time τ_r, s	Ref.
$e + A^+ + e \rightarrow A^*(n) + e(E)$	$10^2…1$	[8]
$e + A^+ + B \rightarrow A^*(n) + B(E)$	$10^2…1$	[9]
$e+A^++BC(j) \rightarrow A^*(n)+BC(j')$	30…3	[9]
$e+A^++BC(v) \rightarrow A^*(n)+BC(v')$	$2.5\times(10^{-2}…10^{-3})$	[9]
$A^+ + B^- \rightarrow A^* + B$	$10^{-5}…10^{-6}$	[10]
$A^++B^-+M \rightarrow A^*+B+M$	$6\times(10^{-5}…10^{-6})$	[10]

It was concluded that ion-ion recombination ($A^++B^- \rightarrow A^*+B$) is the main recombination process in the plasma of the arc discharge with copper electrodes in the transverse blowing air flow. It was shown that characteristic time of the ion-ion recombination τ_r~$6\times(10^5...10^{-6})$ s [10] is comparable with the time of optical transitions τ_{ki} in Cu I (λ=510.5 nm τ_{ki}~$5\cdot10^{-7}$ s; λ=578.2 nm τ_{ki}~$6\cdot10^{-7}$ s [11]), so it should lead to a noticeable contribution to the population of electronic levels of Cu atoms by the ion-ion recombination of the corresponding positive ion. In [12] was shown that main positive ions in electroarc discharges with copper electrodes are copper atomic ions. It was suggested that T_e^*(Cu)>T_e^*(O, H) since the population of Cu atoms occurs on the levels with excitation energy closed to the difference between atomic ionization energy and electron affinity energy of negative ions of air plasma (ε~2 eV) [10].

Dependence of the excitation temperatures of molecule N_2 in the TA plasma on the gas flow rate G was studied (Fig. 2). Vibrational and rotational temperatures were determined from the calibration curves [13] built as functions of the corresponding excitation temperatures with taking into account instrument function of used spectrometer. Besides $T_v^*(N_2)$ was also evaluated from Boltzmann plot by using relative intensities of such spectral bands of N_2 ($C^3\Pi_u$-$B^3\Pi_g$): (0-0) 337.1 nm, (1-2) 353.6 nm, (0-1) 357.7 nm, (2-4) 371.0 nm, (1-3) 375.5 nm, (0-2) 380.5 nm, (1-4) 399.8 nm.

The same dependence (as on the Fig. 2) with similar values of the vibrational and rotational temperatures was obtained for N_2^+ molecule (transition $B^2\Sigma_u^+$-$X^2\Sigma_g^+$). Non-monotonic character of the T_r^* temperature dependence on the G can be connected with transition from laminar to the turbulent gas flow with G increasing at fixed discharge current. Changing of the form and structure of the TA plasma column correlates with it good.

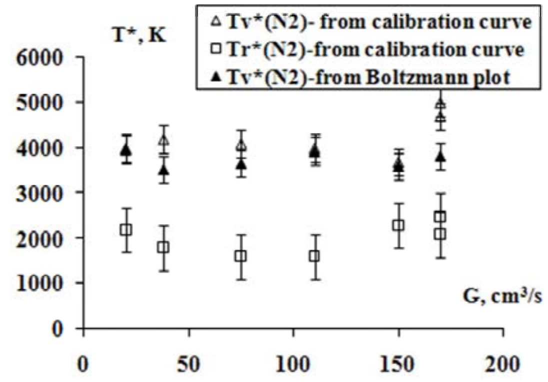

Fig. 2. Dependence of the excitation temperatures of nitrogen molecules in TA plasma on the air flow rate G (at the fixed discharge current I_d=400 mA)

Dependences of the excitation temperatures in TA plasma on the discharge current were studied for different air flow rates. It was shown that there is a convergence of T_v^* and T_r^* temperatures, which starts from the discharge current I_d~ 500 mA, thus plasma of TA becomes isothermal at G=0 cm^3/s. Similar behaviour of the temperature dependence was observed at big flows (G>150 cm^3/s). At large gas flows (where turbulent starts) plasma of TA becomes more isothermal. At the same time at low gas flows difference between excitation temperatures almost doesn't depend on the discharge current. Thus there are optimal regimes of gas flow rates that can provide the certain non-thermality level of the generated TA plasma for the investigated range of the discharge currents.

CONCLUSIONS

- Non-linear character of the dependence of the voltage drop on the transverse arc discharge (U_d) on the gas flow rate and character was found. It was shown that U_d is almost constant (at the discharge currents I_d>700 mA) in the region, which corresponds to the transitional regime of the gas flow (from laminar to turbulent). When the gas flow rates attain values, which are larger than ion drift rate, U_d increases with G increasing and filament plasma structure along the gas flow are observed.
- Non-monotonic character of the $T_r^*(N_2)$ and $T_r^*(N_2^+)$ dependence on the gas flow was found. It can be connected with transition from laminar to the turbulent gas flow regime. At large gas flows (where turbulence starts) plasma of TA becomes more isothermal. So to obtain non-thermal plasma of TA we should operate with optimal gas flow rates and discharge currents. Without gas flow or under large currents and large gas flows TA plasma becomes more thermal.
- It was concluded that recombination influences on the population of the excited electronic states of Cu I. It was shown that characteristic time of the ion-ion recombination is comparable with the time of optical transitions in copper atom. Thus founded difference between the temperatures T_e^*(Cu)>T_e^*(O, H) can be explained by the additional mechanism of the population of the excited electronic states of cooper atoms due to the ion-ion recombination, which is almost absent for the blowing gas atoms.

ACNOWLEDGEMENTS

This work was partially supported by the State fund for fundamental researches (Grant F41.1/014), Ministry of Education and Science of Ukraine, National Academy of Sciences of Ukraine.

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Article received 19.09.12

ЭЛЕКТРИЧЕСКИЙ РАЗРЯД В ПОПЕРЕЧНОМ ПОТОКЕ ВОЗДУХА АТМОСФЕРНОГО ДАВЛЕНИЯ

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Физические особенности поперечного дугового разряда и его атмосферной плазмы исследованы для различных воздушных потоков (скорости потока ~ 0…2/3 скорости звука) и режимов газовых течений (ламинарного, турбулентного). Состав плазмообразующего газа, электронные температуры заселения T_e^* атомов, колебательная T_v^* и вращательная T_r^* температуры заселения молекул в генерируемой плазме определены с помощью оптической эмиссионной спектроскопии. Выявленное отличие между температурами $T_e^*(\mathrm{Cu})>T_e^*(\mathrm{O,\ H})$ объяснили дополнительным механизмом заселения возбужденных электронных уровней атомов меди (материал электродов) за счет ион-ионной рекомбинации, который практически отсутствует для атомов обдувающего газа. Немонотонный характер зависимостей $T_r^*(N_2)$ и $T_r^*(N_2^+)$ от величины газового потока связан с переходом течения газа из ламинарного в турбулентный режим. Показано, что при больших газовых потоках (при которых начинается отклонение от ламинарного режима и появление турбулентности) плазма поперечной дуги становится более изотермичной.

ЕЛЕКТРИЧНИЙ РОЗРЯД У ПОПЕРЕЧНОМУ ПОТОЦІ ПОВІТРЯ АТМОСФЕРНОГО ТИСКУ

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Фізичні особливості поперечного дугового розряду та його атмосферної плазми досліджено для різних повітряних потоків (швидкість потоку ~ 0…2/3 швидкості звуку) і режимів газових течій (ламінарної, турбулентної). Склад плазмоутворюючого газу, електронні температури заселення T_e^* атомів, коливальна T_v^* і обертальна T_r^* температури заселення молекул у генерованій плазмі визначені за допомогою оптичної емісійної спектроскопії. Виявлену відмінність між температурами $T_e^*(\mathrm{Cu})>T_e^*(\mathrm{O,\ H})$ пояснено додатковим механізмом заселення збуджених електронних рівнів атомів міді (матеріал електродів) за рахунок іон-іонної рекомбінації, який практично відсутній для атомів газу, що обдуває дугу. Немонотонний характер залежностей $T_r^*(N_2)$ і $T_r^*(N_2^+)$ від величини газового потоку пов’язаний з переходом течії газу з ламінарного у турбулентний режим. Показано, що при великих газових потоках (при яких починається відхилення від ламінарного режиму та поява турбулентності) плазма поперечної дуги стає більш ізотермічною.