PLAS-MA PROPERTIES OF TRANSVERSE BLOWING ARC UNDER ATMOSPHERIC PRESSURE

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Introduction

It is well known that for solving of different applied tasks plasmachemistry needs the sources of nonequilibrium atmospheric pressure plasmas with controllable level of nonisothermality. The most interesting from this point of view are dynamic plasma systems with transversal gas flows of atmospheric pressure: gliding arc *GA*[1,2], gliding arc in tornado *GAT*[3,4], transverse DC glow discharge[5], arc discharge in the transversal blowing gas flow (transverse arc *TA*)[6–8]. A transversal gas ventilation of the discharge increases efficiency of heat- and mass- exchange between plasma and environment. It is possible to influence on the plasma properties due to the choosing gas flow rate and discharge parameters (current, voltage). The results of researching of plasma properties of the transverse arc in airflow at atmospheric pressure are presented in this work.

Experimental setup

Transverse arc *TA* differs from the non-stationary *GA* of Czernichowski type[1,2] by the fixed arc length. It has also a convective cooling of the plasma column by the airflow but without conductive heat losses at walls since it is a free arc jet. The scheme of the *TA* discharge in gas flow is shown on Fig. 1.

The atmospheric airflow was directed from the nozzle across two horizontal opposite electrodes and formed a bright crescent-shaped electric arc. The rod copper electrodes with diameter d = 6 mm and nominal gap between them $\delta \approx 1.5$ mm were used. Axially symmetrical nozzle, with inner diameter ∅ = 1 mm made from stainless steel was maintained vertically perpendicular to the electrode axis at the length L = 20 mm and centered strictly between the electrodes. The arc discharge was powered by the DC source at the ballast resistance R = 2 kΩ in the circuit. To regulate the airflow rate G 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. The gas flow rates G = 0–110 $cm^3 s^{-1}$ and discharge current I_d (330–660 mA) were kept constant.

Current-voltage characteristics of *TA* discharge in airflow are shown on Fig. 2.

Diagnostics of plasma parameters was made by optical emission spectroscopy (OES). Computer operated CCD-based spectrometer SL40-2-3648USB with spectral resolution ~ 0.73 nm was used for spectra registration in the range of 210–1100 nm. Temperatures, which correspond to the population distribution of the excited electronic states of atoms (electronic temperature T^*_e), vibration and rotational levels of molecules (vibration T^*_v and rotation T^*_r temperatures) in investigated plasmas, were determined.

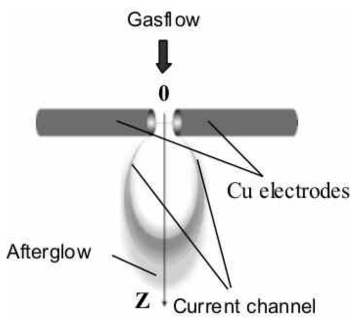

Fig. 1. **Experimental sketch of the transverse arc**

Metodology

Determination of mole fractions of the radiating components of nonequilibrium plasma at atmospheric pressure in the case of weakly known composition of plasmaforming gas is very interesting and actual problem. Method of evaluation of relative concentration of neutral and ionic components in generated plasma by using SPECAIR[9] was suggested in this work.

SPECAIR code allows modeling the absolute intensity of spectral radiation emitted by gases and plasmas of various compositions (N, O, C, NO, N_2, N_2^+, OH, NH, C_2, CN, CO) in the wide spectral range for different pressures Traditionally

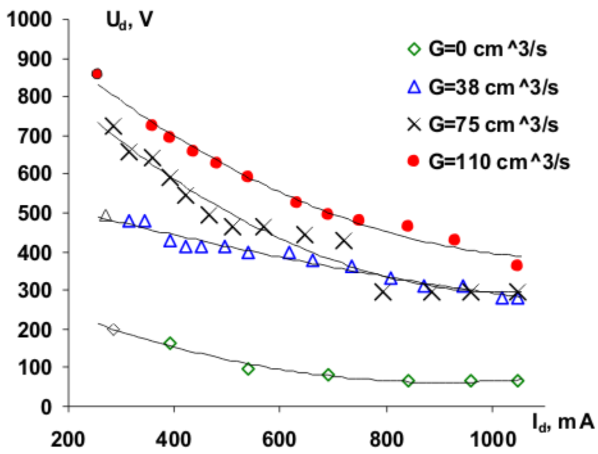

Fig. 2. **Volt-ampere characteristics of the *TA* discharge for different rates of airflow G**

SPECAIR uses database of an initial LTE species distribution in air at various temperatures (electronic, vibrational, rotational and translation) in the range T = 1000–14 000 K.

So far as using known methods of working with SPECAIR for determining relative concentrations of radiating species[10] is not possible in the case of weakly known compound of plasmaforming gas, we suggested to use the following procedure.

At the first stage the identification of emission spectra was made and T^*_v and T^*_r temperatures were determined by fitting experimental spectrum of the 2nd positive system of N_2 with results of SPECAIR simulation[10]. It is possible to determine electronic temperature T^*_e from Boltzmann plot by using relative intensities of spectral atomic lines (emission of blowing gas or electrodes material atoms)[7]. Besides T^*_e can be evaluated from the best fit of the relative intensities of N_2(C-B) and *NO* (A-X) in experimental spectrum with simulated one (after having T^*_v and T^*_r already determined) in the case of LTE for discharges with low rates of blowing gasflow or without any blowing[11].

At the next step the intensity (signal) of each radiating species $I_{exp}(A_i)$ was determine from experimental spectrum and corresponding to them wavelengths λ_i were fixed. It is better to carry out this procedure of signal determination in the range free from overlapping spectral bands and lines. After that we simulated emission spectrum of each radiating compound separately by using SPECAIR at previously determined T^*_e, T^*_v, T^*_r temperatures. The absolute intensities of calculated spectrum $I_{cal}(A_i)$ at wavelength (where the corresponding experimental signals $I_{exp}(A_i)$ were estimated) were determined.

Then the concentration ratio of two radiating species *A* and *B* can be evaluated by following formula:

$$\frac{[A_1]}{[A_2]} = \frac{I_{\exp}(A_1) \cdot I_{cal}(A_2)}{I_{\exp}(A_2) \cdot I_{cal}(A_1)} \qquad (1)$$

That makes possible to determine relative concentration of each component in the investigated plasma:

$$[A_1]^* = \frac{[A_1]}{\sum_i [A_i]} \qquad (2)$$

Results

Emission of N_2 2nd positive system ($C^3\Pi_u$ -$B^3\Pi_g$), 1st negative system of N^+_2 ($B^2\Sigma^+_u$-$X^2\Sigma^+_g$), of *NH* ($A^3\Pi^+$-$X^3\Sigma^-$), *NO* g system ($A^2\Sigma^+$-$X^2\Pi$), weak *OH* bands ($A^2\Sigma^+$-$X^2\Pi$), *O* lines (λ = 777.2; 844.6; 926.6 nm), *Cu* lines (electrode's material) (λ= 324.75; 327.4; 465.1; 510.5; 515.3; 521.8; 578.2 nm) was observed in plasma of the transverse arc in air. T^*_e was determined from Boltzmann plots by using intensities of oxygen spectral lines *O* (λ = 777.2; 844.6; 926.6 nm) and copper (electrode's material) lines *Cu* (λ= 465.1; 510.5; 515.3; 521.8; 578.2 nm) Fig. 3.

To verify Boltzmann population distribution of the excited vibrational levels of molecules in generated transverse arc plasma the relative intensities of nitrogen molecular bands of the 2nd positive system (λ = 337.1; 371; 375.5; 380.5; 399.8 nm) were measured. It was shown that population distribution character of the excited vibration levels of N_2 molecule in the investigated plasma is close to Boltzmann Fig. 4. Thus T^*_v can

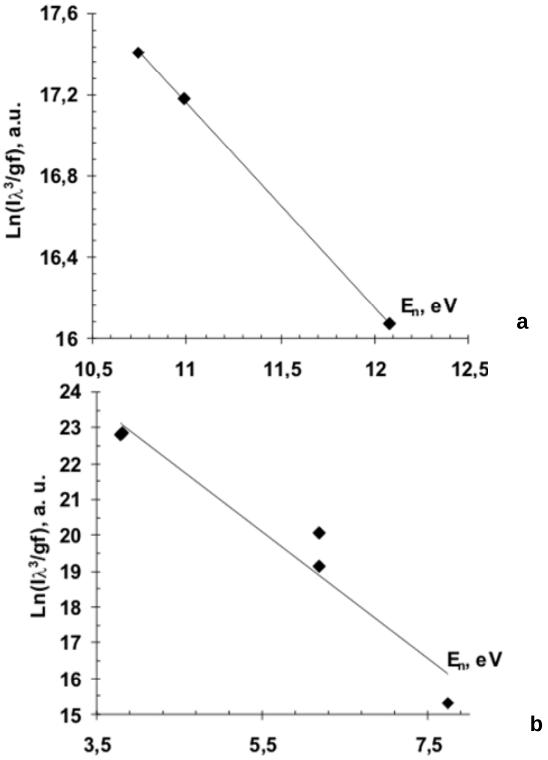

Fig. 3. **Characters of population distributions of the excited electronic states of O (a) and Cu (b) atoms in plasma of TA in air** (airflow rate G = 75 cm^3 s^{-1}, discharge current I_d = 480 mA) at the distance from electrodes z = 7,2 mm

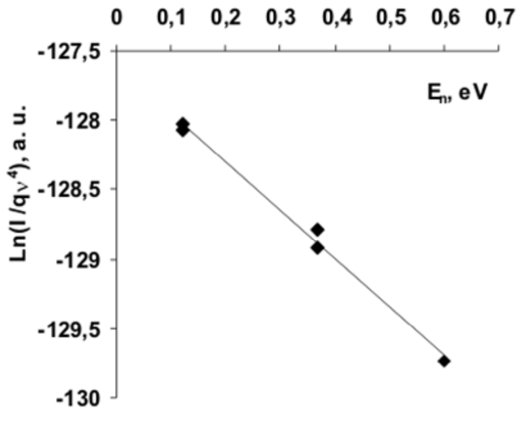

Figure 4. Character of the population distribution of the excited vibrational levels of the N_2 molecule in *TA* plasma (G=75 cm^3/s, I_d=480 mA, z=1,6 mm). T^*_v=3400 K was obtained from this Boltzmann plot.

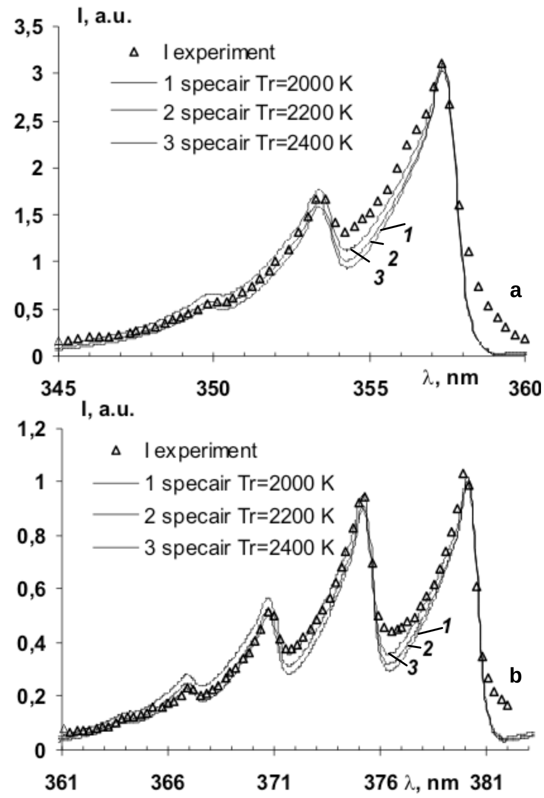

Figure 5. Fitting experimental spectral bands of N_2 (C-B) (z=1,6 mm, G=75 cm^3/s, I_d=480 mA) and results of modelling by SPECAIR for different T^*_r. The best-obtained accurancy of this technique is ±200 for T^*_r and ±500 for T^*_v temperature correspondingly.

be determined from Boltzmann plot[7] or by using SPECAIR program, which calculations are valid in LTE case.

In this work $T^*_v \approx$ 4000–4600 K and $T^*_r \approx$ 2000–2800 K were estimated from 2nd positive system of nitrogen by fitting the experimental spectra with the simulated ones Fig. 5. For determining rotational temperature by the 2nd positive system of N_2 it is better to use spectral bands in the region 360–385 nm since it is free from overlapping with other lines and bands. As we can see from Fig. 5a, a noticible discrepancy between experimental spectrum and calculated one in the region 354–360 can be explained by overlapping with some of the bands of the 1st negative system of N_2^+ (λ = 354.8, 356.2, 358 nm).

Fitting of experimental spectrum of the transverse arc plasma with calculated one is shown on Fig. 6.

From Fig. 6 can be seen that a good fit was obtained. Discrepancy between spectra in the region of 325 nm can be deal with presence of *Cu* lines (λ = 324,75 and 327,4 nm) and not identified bands (at λ = 282,5 and λ = 296 nm), which were not taking into account by SPECAIR calculations.

Temperature distribution in plasma of *TA* along gas flow z is shown on Fig. 7.

Since the basic ions in low-current arc are ions of electrode material, an additional mechanism of populating the excited electronic levels in copper atoms, besides the excitation by electrons, can appear owing to electron-ion recombination; this mechanism is inactive for the atoms of a blowing

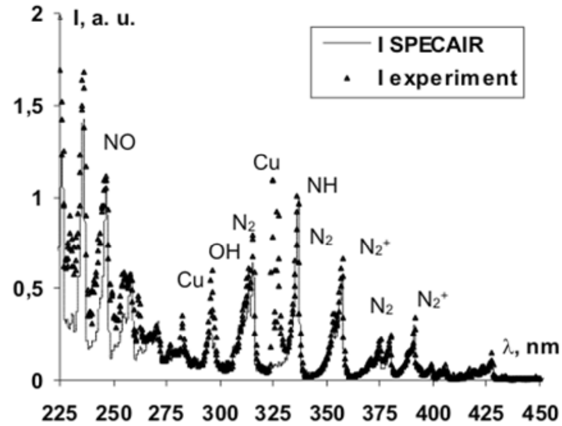

Figure 6. Emission spectrum of *TA* air plasma at atmospheric pressure (G=75 cm^3/s Is=480 mA at the distance z=1,6 mm from electrode axis) and spectrum simulated by SPECAIR at T^*_e=4600 K, T^*_v=4200 K, T^*_r=2200 K.

Table I
Relative concentrations of radiating species in generated plasma of the transverse arc in air flow

z, mm	$[NH]/[N_2]$, $\times10^{-8}$	$[OH]/[N_2]$, $\times10^{-7}$	$[N_2^+]/[N_2]$, $\times10^{-9}$	$[NO]/[N_2]$, $\times10^{-4}$	$[NO]/[N_2\times10^{-2}$ Database SPECAIR
1,6	6,3	4,9	6,8	1,2	1,7
3,2	4,4	5,8	3,3	1,0	2,5
4,8	6,3	13,0	2,8	1,7	3,5
6,4	7,5	10,9	1,1	1,3	4,6

gas. In our opinion it can explain the revealed difference between the values $T^*_e(O) \approx$ 4200–4600 K and $T^*_e(Cu) \approx$ 6800–8200 K.

At atmospheric pressure, rotational temperature equilibrates with the gas temperature ($T_g \approx T^*_r$) owing to fast collisional relaxation.The increasing character of rotational tem-

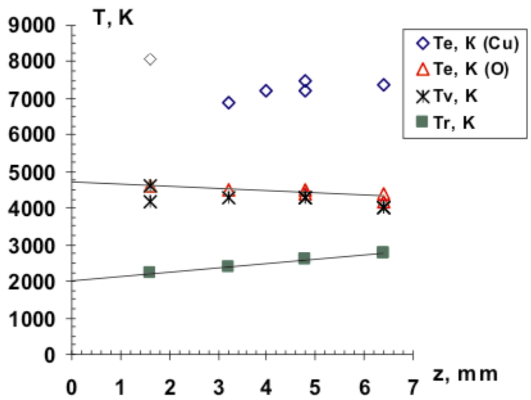

Figure 7. Temperature distributions along air flow z (z=0 – point at electrode axis) in plasma of *TA* at atmospheric pressure (G=75 cm^3/s, Is=480 mA).

Table II
Parameters of non-equilibrium atmospheric pressure plasma sources

Type	Electric power, W	Gas flow rate G, cm^3 s^{-1}	T^*_e, eV	T^*_v, eV	T^*_r, eV
GA[1, 2]	200–1000	$(2–50)\times10^3$	$^*T$: 0.52 $^{**}NT$: 0.86	$^*T$: 0.27–0.34 $^{**}NT$: 0.17–0.26	$^*T$: 0.2–0.34 $^{**}NT$: 0.07–0.18
GAT[3]	90–300	$(0.5–2.5)\times10^3$	> 0.9		0.17–0.34
DGCLW[8]	260–300	0.11´10^3	(Cu) 0.6 (O) 0.35 (H) 0.35	(N_2) 0.3–0.35	(OH) 0.35–0.4
TA[7, 8]	220–330	$(0.04–0.2)\times10^3$	*in air:* (Cu) 0.6 (O) 0.35 (H) 0.35	(N_2) 0.35	(N_2) 0.1–0.2

*T – thermal regime of GA, **NT – non-thermal regime of GA[2]

perature distribution along gasflow may testify that the gas heating occurs owing to the convective heat exchange between gas particles and the current channel at the periphery of the transverse arc. Plasma at the periphery of the discharge tends to isothermality.

Relative concentrations of radiating plasma components of the investigated *TA* in airflow (G = 75 cm^3 s^{-1} and Is = 480 mA) were calculated by using suggested method of working with SPECAIR and their values are presented in the table I.

Calculated relative concentrations should be taken as a very rough estimate, just indicating the order of magnitude.

Distribution of the relative mole fractions of radiating species in the investigated plasma along gasflow is represented on Fig. 8.

Decreasing of [N_2^+] concentration with increasing of distance from electrodes is in good correlation with excitation temperature distributions. It is clear that ionization processes decreases at the periphery of the discharge.

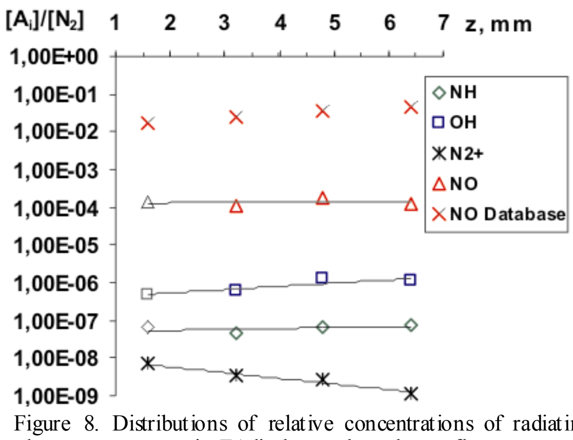

Figure 8. Distributions of relative concentrations of radiating plasma components in *TA* discharge along the gasflow z.
(Is=480 mA, G=75 cm^3/s, z- distance from electrode's axis)

As can be seen from Fig. 8, amount of *NO* radicals in plasma of the transverse arc is much lower than corresponding values in SPECAIR database for air at the same temperatures. We supposed that it could be explained by the following: the characteristic time of *NO* producing reaction is larger than transit time of initial components (N_2^*, O_2^* and etc.) through plasma column.

Regime of the arc in air (under the same geometry but without of gasflow G = 0 cm^3 s^{-1}) with discharge current I_d=660 mA was investigated and the excitation temperatures were determined ($T^*_e \approx T^*_v \approx$ 6950 K and $T^*_r \approx$ 1750 K). Relative concentration of the *NO* radicals ([NO] / [N_2] ≈ $4{,}5\cdot10^{-3}$) in generated plasma was evaluated in this case. Obtained value is comparable with $4{,}38\cdot10^{-3}$ represented in SPECAIR database under similar temperature $T \approx$ 1800 K. It can be considered like one more confirmation of our assumption.

The comparative analysis of plasma parameters of investigated *TA* discharge in airflow with other known sources of non-equilibrium atmospheric pressure plasma was made and the main results are presented in table II.

Conclusions

– Transverse arc generates non-thermal plasma $T^*_r(N_2) < T^*_v(N_2) \approx T^*_e(O,H) < T^*_e(Cu)$ with noticeable increasing of rotational temperature along the gas flow.
– Obtained T^*_e of blowing gas atoms (O and H) are smaller than corresponding values of Cu atoms (material of electrodes) due to the additional electron-ion recombination mechanism of excited electronic states population of copper atoms, which is almost absent for atoms of a blowing gas.
– The relative concentrations of radiating plasma species (N_2, N_2^+, *NO*, *OH*, *NH*) in the transverse arc were estimated by using SPECAIR. It was shown that relative

concentration of [*NO*] evaluated from experimental spectra is significantly lower then data in SPECAIR database for air at the same temperatures.

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