Multi-Spark Plasma Actuator for Flow Control

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Plasma properties of spark discharge at multi-electrode actuator, designed for flow control, are discussed. Optical emission spectroscopy is used in investigation of such plasma. No effect of metal particles eroded from electrodes on properties of spark discharge plasma was observed. A method of excitation temperature determination by reconstructing of experimentally registered spectrum of the spark was developed.

Keywords: Spark plasma, optical spectroscopy, spectrum modelling

1 INTRODUCTION

Actuators are specially constructed devices mounted on an airfoil with the aim to enhance aerodynamic properties. Usually, the interaction between actuator and incident flow takes place. Various approaches for plasma actuators exploit different properties of ionized gas. The plasma actuator based on dielectric barrier discharge (DBD) used for generation of atmospheric pressure plasma. Such actuators induce additional flow near the airfoil surface. The flow caused by directional movement of ions in plasma due to high strength of electric field. It's known, that DBD actuators can induce flows up to few tens of m/s in simple paraelectric configuration, and up to hundreds of m/s in sophisticated peristaltic configuration [1]. So, these actuators are usually used for avoiding of flow separation, and therefore for improving of airfoil properties at large angle of attack. Fast conversion of electric energy into heat and expansion are used in spark discharge plasma actuators [2, 3]. Such actuators consist of small cavity with orifice, exhaust jets are generated by spark discharge between at least two metallic electrodes. Such devices work in repetitive pulsing mode, which can be separated on stages: initiation of spark discharge by high voltage applied to electrodes, fast expansion of gas (plasma) and exhausting through the orifice and refilling of cavity volume. Due to fast gas expansion, formation of blast wave and fast plasma jet has place.

This work is devoted to properties investigation of another type of spark plasma actuators, where discharge occurs near the streamlined surface.

2 EXPERIMENTAL SETUP

2.1 MULTI-SPARK PLASMA ACTUATOR

Special multi-electrode plasma actuator was developed. As Fig. 1 shows, it consist from 40 stainless steel electrodes, 3 mm in diameter, mounted into insulator. The distance between adjacent electrodes was of 1 mm. Central and lateral electrodes are mounted through the insulator plate to allow electrical connection. Thus, by high voltage pulse applying on the lateral electrodes, the discharges occurs between each neighbor electrodes along the actuator.

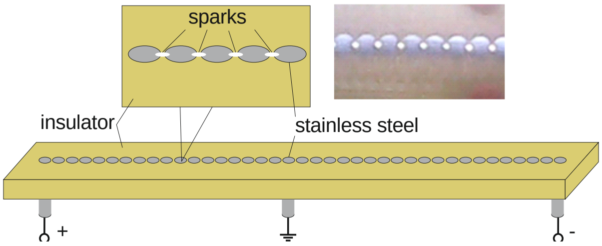

Fig.1: Multi-electrode plasma actuator

Special power source was developed to apply high voltage pulses on multi-electrodes plasma actuator. It consists of five high-voltage stages, which are switched in turn, one after the other. Every stage consists of two high-voltage transformers connected in series by secondary windings with the aim to increase the output voltage. The primary windings of the high-voltage transformers are operated by special transistor drivers. The drivers are connected through the shift switch to the built-in generator of rectangular signals with variable frequency.

Experimental measurements in this work were carried out at high-voltage pulses frequencies from 40 to 500 Hz.

2.2 REGISTRATION OF PLASMA EMISSION

Diagnostic technique for simultaneous registration of spectral and spatial distribution of emission intensity was developed earlier [4]. Grating spectrometer and digital camera on charge-coupled device (CCD) base were used in this technique. The realized configuration of an experimental setup with diffraction grating 600 g/mm enables simultaneous registration of spatial intensity distribution in spectral range 400-650 nm.

Graphical user interface for treatment of obtained spectra images was specially developed [5]. The interface allows the following: interpretation of spectra, calibration of CCD-matrix spectral sensitivity by tungsten ribbon lamp, determination of spatial intensity distribution and transformation of observed intensity of radiation into its local values.

Due to the low plasma emission of the discharge, all registrations were carried out with exposure time from 1/5 to 1 second. Namely, the registered emission was averaged over several tens of high-voltage pulses.

3 RESULTS AND DISCUSSION

The emission spectrum of the spark discharge at plasma actuator, which was operated at 200 Hz frequency in ambient air, is shown in Fig. 2. NIST [6], Zajdel [7] and Kurucz [8] databases were used to interpret obtained spectrum. The relative emission of N I, O I, N II, O II spectral lines, taken from these database, are also shown in Fig. 2. Detailed analysis of the spectrum allowed us to conclude, that spark emission consists mostly of the air species impact. The spectral lines of electrodes' material (i.e. Fe, Ni, Cr, Zn) were not observed in emission spectrum. Therefore, we concluded, that metallic species eroded from electrodes did not affect the properties of spark plasma.

Among the optical emission spectroscopy techniques, methods of relative intensities of spectral lines and the Boltzmann plot are the most common for the excitation temperature determination in plasma. For the application of one of these methods, it is necessary to select "convenient" for the diagnostics spectral lines, which must satisfy certain requirements. Namely, these lines should be well isolated in the radiation spectrum and have sufficient intensity to their reliable registration. In addition, the maximum difference between the excitation energy of the upper levels should be as large as possible to determine the temperature with minimum error. At the next step, we carefully analyzed registered spectrum with the aim to determine spectral lines, fitted with these criteria.

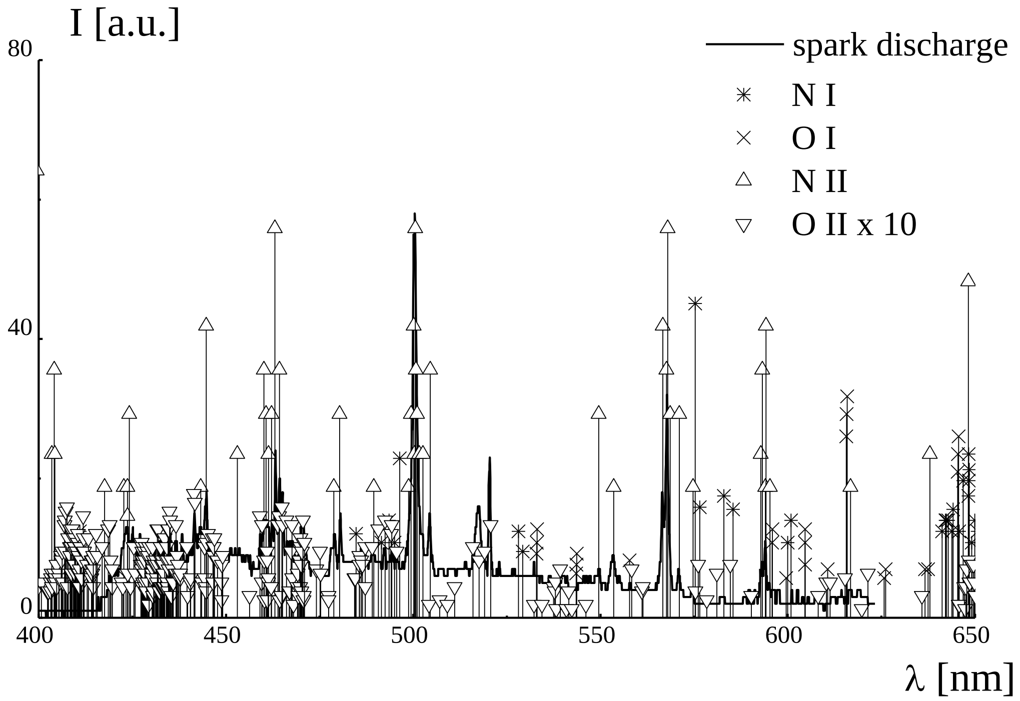

Fig. 2: Emission spectrum of spark discharge and spectral lines of air components

Unfortunately, there were no any convenient spectral lines observed in the spectrum. Typical part of the spectrum is shown in Fig. 3. Figure shows, that only a few spectral lines are well isolated, all others are significantly overlapped. Therefore, it is not possible to use traditional methods of relative intensities of spectral lines and the Boltzmann plot to obtain plasma temperature. To solve this problem we decided to obtain temperature by reconstruction of experimentally registered spectrum of the spark. This procedure is based on expression of radiation intensity I:

$$I(\lambda) = \phi(\lambda) \cdot N \cdot \frac{g_j f_{ji}}{\lambda^3 \cdot U(T)} e^{-\frac{E_j}{kT}}, \qquad (1)$$

where $\phi(\lambda)$ – line profile, which we considered as Gaussian, N – concentration of particles, g_j – statistical weight of lower level of radiation transition, f_{ji} – oscillator strength, $U(T)$ – partition function and E_j – energy of upper level. Simple program interface was developed to provide radiation intensity modelling. The 490-510 nm spectral region was selected for further consideration (see Fig. 4). It consist mainly of N II spectral lines, which spectral data is given in Table .1. These data were used in the calculation of radiation intensity as a function of excitation temperature. We tried to choose the value of temperature to have maximum coincidence of experimental and modelled curves. The results of such modelling is shown in Fig. 5.

The spectrum was modelled with temperature step 2000 K from 22000 to 30000 K in assumption of Boltzmann distribution of population density. Intensity distribution was normalized by isolated N II 504.5 nm spectral line.

Fig. 5. shows the maximum coincidence between experimental and modelled curves for temperatures T = 26000 ± 2000 K. Such temperature corresponds to maximal current of high-voltage discharge. Obviously, this value of temperature is obtained on the base of only a part of the emission spectrum. It is planned to expand modelling to wider spectral region to check both Boltzmann distribution assumption and the value of temperature.

Table 1: Spectroscopic data of ion nitrogen lines in 490-510 nm spectral region [6]

λ, nm	E_j, eV	g_j	$log(g_j f_{ji})$
498.7	23.43	3	-0.584
499.4	27.98	5	-0.164
500.1	23.13	5	0.435
500.3	20.94	1	-1.028
500.5	23.14	7	0.587
500.7	23.42	3	0.145
501.1	20.94	3	-0.625
501.6	23.12	5	-0.524
502.6	23.13	7	-0.558
504.5	20.94	5	-0.413

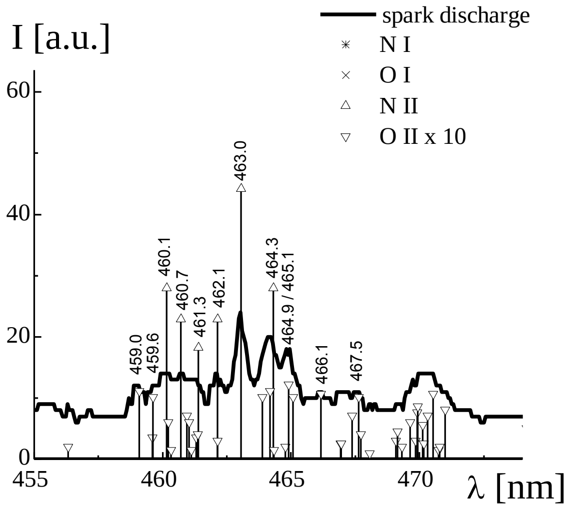

Fig. 3: A part of emission spectrum of spark discharge from 455 to 475 nm

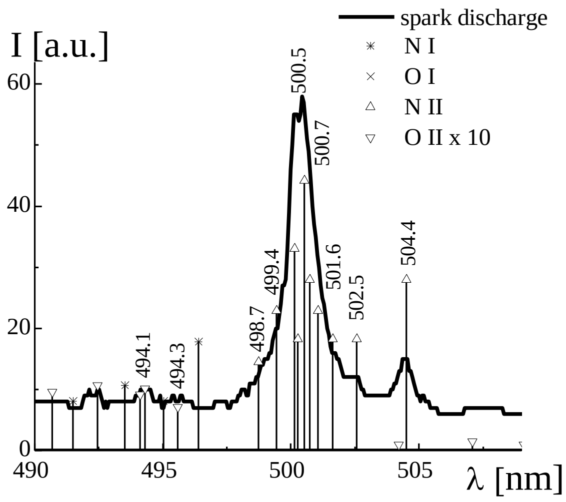

Fig. 4: A part of emission spectrum of spark discharge from 490 to 510 nm

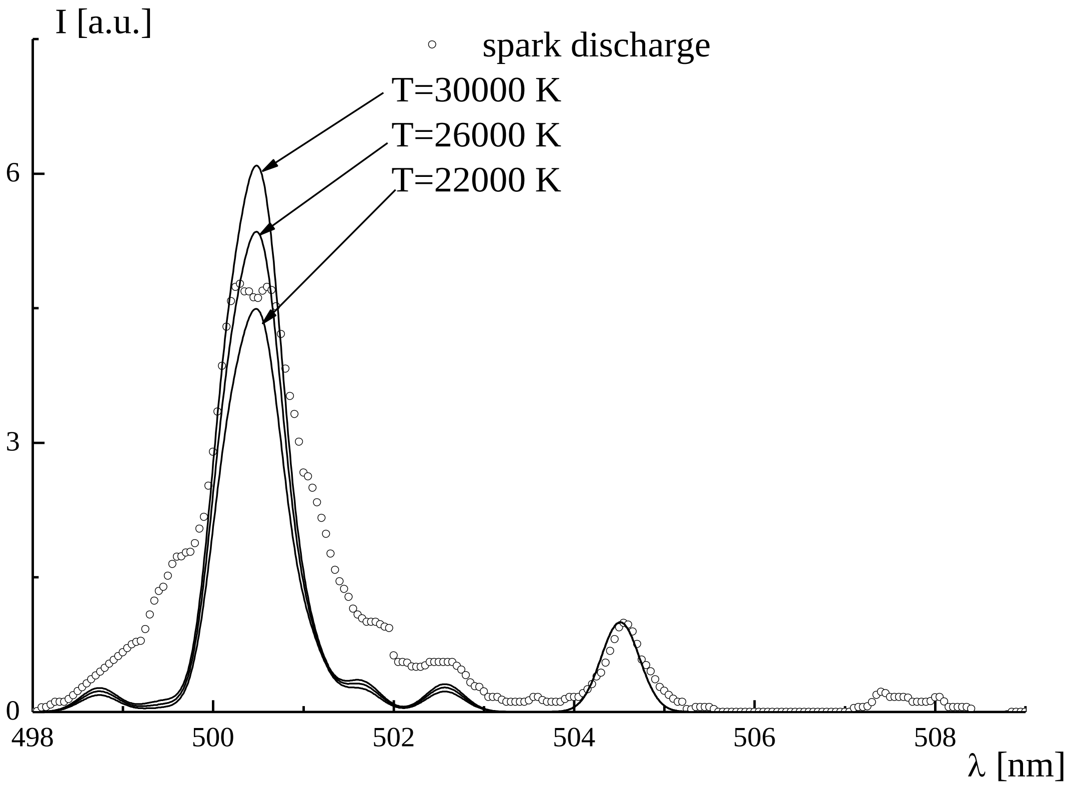

Fig. 5: Modelled (lines) and experimental (circles) emission spectrum of spark discharge from 498 to 509 nm

4 CONCLUSIONS

A special high voltage power source was developed to feed multi-electrode plasma actuator for flow control.

An optical spectroscopy technique was used for investigations of emission in different discharge modes. No electrode material spectral lines were observed. It implies that metal particles, sputtered from electrodes, did not affect on properties of spark discharge plasma. A method of excitation temperature determination by reconstructing of experimentally registered spectrum of the spark was developed. Simple program interface was developed to provide radiation intensity modelling in the 490-510 nm spectral region. The results showed the excitation temperature of N II ions, emitted by spark discharge, is T = 26000 ± 2000 K.

Acknowledgements

This research has been supported by the CRDF grant No. #UKE2-31103-KV-12.

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