Emission spectrum analysis of an atmospheric electrode microwave discharge in argon flow and of a cold plasma jet on its base

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Abstract. The measurements and analysis of the emission spectra both of atmospheric-pressure electrode microwave discharge in argon flow and cold plasma jet induced by the discharge are conducted. We used experimental setup based on the previously developed multipurpose 2.45-Hz-plasmatron with the external portable discharge chamber (plasma torch) with the outlet of 2.5 cm in diameter and power of about several hundred watts. Discharge chamber has 6 rod-like electrodes which form a regular hexagon in a cross section of the torch. Discharge channels are formed between the ends of the electrodes and the inner wall of the chamber. Molecular bands of NO, OH, N₂, NH and atomic lines of Ar were found in the spectrum of the discharge channels. Based on the analysis of the spectra, it was shown that the gas temperature in the discharge channel was about 1200 K. In the cold plasma jet spectrum, due to its weak luminescence, only the molecular lines OH and N₂ were reliably observed.

Introduction

In recent decades, there has been intensive development of plasma-chemical methods for modifying the surface of materials, including such non-heat-resistant materials as synthetic and natural polymers [1]. The most important feature of a non-equilibrium gas-discharge plasma, using for this aim, is a large (up to two orders of magnitude) difference between average energy of electrons and the energy of heavy particles. As a result, the effective formation of various active particles (i.e. charged and excited particles, free atoms and radicals) leads to an extremely high chemical activity of the gas influenced by the plasma at a relatively low gas temperature.

Plasma jets (or streaming-afterglow plasmas) based on atmospheric-pressure discharges are intensively investigated for purposes of plasma modification in practical medicine, microbiology, agriculture and the food industry [1-7]. Such jets are characterized by high reactivity and low gas temperature, which can be reduced to room temperature (so-called, cold plasma jets). The effect of a cold plasma jet on a surface is complex and includes the following main factors: UV radiation, chemically active particles, and energy of charged particles. By choosing the appropriate treatment parameters it is possible to perform such processes as plasma cleaning, plasma surface activation, plasma deposition and plasma etching.

It is known that an atmospheric-pressure microwave discharge and a cold plasma jet on its base are characterized by a much higher charge density and, therefore, a greater reactivity in comparison with other atmospheric pressure discharges at the same power [8]. As a result, microwave plasma treatment could lead to new effects and the emergence of unique properties of materials. In previous years, increased attention has been paid to the development and investigation of microwave plasma sources (see, for example, [9-11]). In contrast, there are only few studies on microwave plasma jet diagnostics, including active species generation study. Earlie, UV optical emission of the cold plasma jet induced by electrode microwave argon discharge was measured by Shimizu et al [9] (MicroPlaSter device). Then,
spectrum measurements of the field near discharge region inside the MicroPlaSter torch was made by Ermolaeva et al [7]. As to other pulsed discharges, Keller et al [12] applied optical emission spectroscopy to the so-called argon plasma coagulation (APC) discharge for biological object treatment. Wang et al [13] used spectrum measurements for characterization of argon cold plasma jet array formed by set of mm-size tubes. In this work, optical emission spectroscopy was applied to study both electrode microwave argon discharge in the wide-outlet plasma torch recently developed and cold plasma jet induced by the discharge behind the torch outlet.

**Experimental apparatus**

The experimental setup based on the previously developed multipurpose atmospheric-pressure microwave plasmatron was used [14, 15]. The plasmatron consists of microwave generator with power supply, waveguide, water load, cable assembly of 2 m in length with 50 Ohm N-connectors and of discharge device (plasma torch) with an outlet of 2.5 cm in diameter. The plasmatron operates at a frequency of 2.45 GHz, has a microwave power in the waveguide of up to 2.5 kW and a power in the torch of up to couple of hundreds of watts. The plasma torch consists of cylindrical common chamber with 6 rod-like electrodes forming a regular hexagon in a cross-section. Discharge channels are formed between the ends of the electrodes and the inner wall of the discharge chamber. In this case, the discharges are situated close to the torch outlet. Ar of high purity (99.998%) was used with the flow rate in the range from 0 to 10 standard liters per minute.

**Figure 1.** Scheme of the experimental setup for emission spectra measurements in I) discharge channel in the plasma torch, II) cold plasma jet: 1 – cold plasma jet, 2 – plasma torch, 3 – microwave unit (including magnetron and waveguide), 4 – plasmatron power supply, 5 – spectrometer (Avaspec 2048), 6 – optic fiber, 7 – lens, 8 – discharge channel (diameter of the rod-like electrode is 3 mm, distance between the central axis of the electrode and the inner wall of the chamber is 4 mm). The inset shows the microwave discharge in the torch (view from the outlet side, gas flows towards an observer).

To conduct spectral measurements, three-channel spectrometer Avaspec 2048 with a wavelength range of 200-1100 nm and a spectral resolution of 0.15 nm was used. The experimental setup for spectrum
diagnostics of the microwave discharge in the plasma torch and of the plasma jet behind the torch outlet of the torch is shown in Fig. 1. The image of an area under study was formed by a quartz lens on the plane where the inlet of the optical fiber connected to the spectrometer is located. This made it possible to obtain the spectra of selected regions of a discharge channel or plasma jet.

**Results of spectra measurements**

The view of spectral distribution of radiation intensity of Ar plasma in a discharge channel in the plasma torch in wavelength ranges of 200-400 nm and 700-1000 nm.

![Figure 2](#). View of emission spectrum of argon microwave plasma in a discharge channel of the plasma torch in wavelength ranges of 200-400 nm and 700-1000 nm.
An analysis of the atomic lines of excited argon in the emission spectra obtained in different zones of the discharge channel made it possible to estimate the electron temperature in the microwave discharge plasma, which ranged from 2000 K in the central part of the channel, to 6000 K in the near-electrode regions – close to rod-like electrode and the chamber wall. The electron temperature was calculated by applying “Boltzmann exponent” method [16] using a number of atomic lines of Ar I in the spectral range of 700-950 nm (more than 20 spectral lines that are presented in Fig. 2).

The gas temperature was estimated on the basis of rotational temperature of N₂. The rotational temperature of N₂ in atmospheric pressure plasmas is widely used as gas temperature (which corresponds to the translational temperature) since rotational relaxation is fast due to high collision frequencies ([17, 18] and so on). It was also shown [12, 13] that a small nitrogen admixture is reliable tool to determine the gas temperature of argon plasma jets in atmospheric air. The gas temperature was calculated using Specair software by modelling the spectra of N₂ molecules and overlapping them over the spectra attained from the experiments. Specair modelling showed an insequencial difference between rotational and vibrational temperatures of molecules. The value of the temperature averaged over the discharge channel was 1200±100 K.

Fig. 3 shows the emission spectrum of the cold plasma jet in the wavelength range of 300-400 nm in the region close to the torch outlet at a gas flow rate of 5 l/min (scheme II in Fig. 1). It should be noted that the plasma jet has a very weak glow, which is not distinguished by naked eye. In this case we had a high level of noise-to-signal ratio that led to indistinguishability of the NO – only the OH and N₂ molecular bands were observed. Similarly, it was hard to detect Ar spectral lines in the wavelength range of 400-1100 nm – only a few Ar lines were distinguishable over the background noise, not enough to conduct an accurate spectral analysis. From thermocouple measurements it was obtained that gas temperature in the plasma jet is about 100°C at a distance of 2 cm from the torch outlet [15].

![Figure 3. View of emission spectrum of the cold plasma jet (plasma of a discharge streaming afterglow) in argon flow near the outlet of the plasma torch.](image-url)
Conclusion
New multipurpose 2.45-Hz plasmatron with the external electrode plasma torch previously developed was investigated. Optical emission spectroscopy was applied to study both argon discharge in the plasma torch and cold plasma jet induced by the discharge behind the torch outlet. The results show that there is an effective formation of various active particles (charged and excited particles, free atoms and radicals), namely NO, OH, N₂, NH, in the gas influenced by microwave induced plasma. In this case, the gas temperature in the microwave discharge channel can reach about 1200 K, and the electron temperature – 6000 K.

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