# Non-equilibrium atmospheric pressure discharge, sustained by focused CW gyrotron radiation with a frequency of 24 GHz

S. Sintsov, A. Vodopyanov, D. Mansfeld, M. Viktorov

*Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia*

**Abstract**: The study of the atmospheric pressure microwave discharge sustained by the focused CW microwave radiation was performed. The 24 GHz gyrotron was used as a source of microwave radiation. Quasi-optical focusing system made it possible to obtain a power density in the focal waist up to 5 kW per square centimeter. The electron temperature and electron density were measured in the microwave torch.

**Keywords**: gyrotron, microwave discharge, plasma torch, microwave diagnostics, plasma chemistry.

Currently, for a wide range of industrial plasma-chemical processes, there is a need to create a reliable source of non-equilibrium plasma. The use of non-equilibrium plasma, characterized primarily by significantly higher electron temperature, makes it possible to increase the rate of many plasma-chemical reactions and, possibly, realize new ones with dissociation and excitation of molecules by the electron impact. Non-equilibrium plasma can be created in spark, corona and glow discharges. Also a gliding arc discharge, a dielectric barrier discharge and a microwave discharge are promising plasmas for the gas conversion applications [1].

The main disadvantages of the currently used non-equilibrium plasma generators are low product rates, the necessity to operate at low pressure and the electrode's erosion contaminations. To solve these problems we implemented a continuous wave microwave discharge on the gas stream at atmospheric pressure. Gyrotron operating at a frequency of 24 GHz was used as a microwave source. The use of a quasi-optical focusing system [2] made it possible to obtain a power density in the focal waist up to 5 kW per square centimeter. Such record values of the power density make it possible to maintain non-equilibrium plasma torch even at atmospheric pressure. Also, this microwave discharge is electrodeless, which ensures high purity of the plasma-chemical processes. This paper presents the results of measuring the plasma torch parameters.

The discharge is realized by focused microwave radiation at a frequency of 24 GHz on the flow of argon from the gas tube at the ambient atmospheric pressure. The flow rate of argon was 5-30 l/min, which corresponds to a gas velocity of 100 m/s. The value of the electric field strength in the focal waist reached 1.8 kV/cm. A spark discharge is used to ignite the microwave discharge. The radiation power of the gyrotron varied from 900 to 5000 W. The discharge is an elongated torch from 1 to 5 cm in length and with a diameter of 4 mm equal to the size of the gas tube (see Fig.1).

**Fig. 1.** Photo of the plasma torch sustained by the focused beam of 24 GHz waves.

The length of the torch increases with the microwave power applied. In the experiments below, argon was used as the plasma-forming gas and the torch was ignited in the background air. For plasma-chemical applications, any other gas can be used as a torch external environment. In particular, carbon dioxide has already been tested as an external atmosphere. To assess the efficiency of the decomposition of highly stable molecules by the plasma torch measurements of the electron temperature and electron density were carried out.

To estimate the electron temperature plasma emission spectra were taken. For this purpose, the spectrograph-monochromator SOL series MS350 was used. Emission spectra were recorded in the range of 300-1000 nm with a resolution of 0.02 nm (see Fig. 2). The electron temperature was estimated from the obtained values of the relative intensities of argon emission lines in the framework of the collisional-radiative discharge model [3,4].

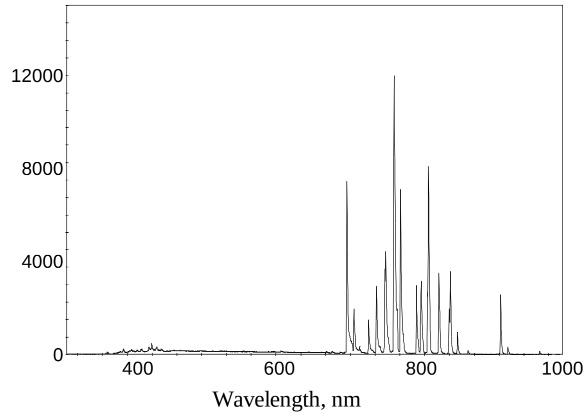


**Fig. 2.** The characteristic emission spectrum of the argon plasma torch.

In order of magnitude, the electron temperature was 1–1.5 eV. The electron temperature does not depend on the heating power and the gas flow rate within the measurement error. Estimates show that the gas temperature of such a torch does not exceed 0.1 eV.

Based on these temperature estimations, it can be asserted that the investigated atmospheric pressure discharge is non-equilibrium.

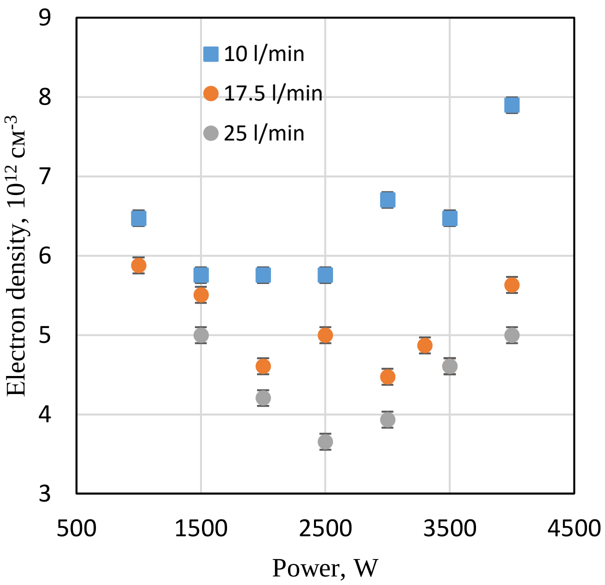


**Fig. 3.** The dependence of the electron density on heating power at different argon flow rates.

The electron density in the discharge was measured using a novel microwave probing technique. The essence of the method consists in the direct measurement of the probing radiation phase change as it passes through the plasma torch. Knowing the plasma size it is possible to determine the average value of the electron density. The Gunn diode with a frequency of 35 GHz was used as a source of probing wave. To determine the phase change the Keysight Infiniium Z oscilloscope with a transmission frequency of up to 59 GHz was used. It was possible to observe a phase change of the probing wave at a frequency of 35 GHz on the oscilloscope screen in real time. This method makes it possible to measure the phase shift even in a collisional plasma with the absorption. As a result, it was found that the average value of the electron density was close to the cut-off density for the frequency of 24 GHz and was $(5 \pm 2)\times10^{12}$ cm$^{-3}$. Depending on the heating power and the gas flow rate, the values of the average electron density remain constant (see Fig. 3).

The work was supported by the Russian Foundation for Basic Research, project No. 17-02-00785.

## REFERENCES


[1] Nunnally, T.; Gutsol, K.; Rabinovich, A.; Fridman, A.; Gutsol, A.; Kemoun, A. Dissociation of CO2 in a low current gliding arc plasmatron. J. Phys. D: Appl. Phys. 2011, 44, 274009.

[2] M. Glyavin et al., “A point-like source of extreme ultraviolet radiation based on a discharge in a non-uniform gas flow, sustained by powerful gyrotron radiation of terahertz frequency band,” *Appl. Phys. Lett.*, vol. 105, no. 17, 2014.

[3] Bogaerts A, Gijbels R and Vlèek J 1998 Collisional – radiative model for an argon glow discharge J. Appl. Phys. 84 121.

[4] Kano K, Suzuki M and Akatsuka H 2000 Spectroscopic measurement of electron temperature and density in argon plasmas based on collisional – radiative model Plasma Sources Sci. Technol. 9 314.