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Investigations of novel high power atmospheric pressure microwave plasma source designed for gas processing

***Abstract**. In the paper we present a new waveguide-supplied coaxial-line-based nozzleless microwave plasma source (MPS) designed for gas processing. This MPS allows to generate a 915 MHz microwave plasma at atmospheric pressure with high flow rate of process gas (several hundred liters per minute). In this work we focus on investigating the basic electrical properties of the device in terms of its energy efficiency and operation stability. For this purpose we measured the MPS electrodynamic characteristics (also known as the tuning characteristics [1]). Keeping in mind that this device may be used in industry, where cost of the generated discharge is a key factor, knowledge of the MPS electrodynamic characteristics is essential for proper selection the most favourable working conditions.*

***Streszczenie.** Niniejsza praca przedstawia nowe zasilane falowodowo mikrofalowe źródło plazmy o strukturze współosiowej przeznaczone do obróbki gazu roboczego o dużym natężeniu przepływu (kilka set litrów na minutę). Urządzenie to pozwala na generacje plazmy mikrofalami o częstotliwości 915 MHz pod ciśnieniem atmosferyczny. W pracy przedstawiono wyniki podstawowych badań własności urządzenia pod względem jego efektywności energetycznej oraz stabilności pracy. W tym celu zmierzono charakterystyki elektrodynamiczna urządzenia (określane również, jako charakterystyki strojenia [1]). Mając na uwadze, że urządzenie to zaprojektowano z myślą o zastosowaniu w przemyśle, gdzie koszt uzyskiwanego wyładowania mikrofalowego jest jednym z kluczowych czynników decydującym o przydatności, znajomość charakterystyk elektrodynamicznych jest niezbędna do wybrania najbardziej korzystnych warunków pracy urządzenia (**Nowe wysokiej mocy mikrofalowe źródło plazmy przeznaczone do obróbki gazu pod ciśnieniem atmosferycznym**).*

Keywords: microwave plasma source, tuning characteristics, gas processing, atmospheric pressure.
Słowa kluczowe: mikrofalowe źródło plazmy, charakterystyka strojenia, gaz roboczy, ciśnienie atmosferyczne.

Introduction

Microwave plasma sources (MPSs) have a wide range of potential applications in the industry, starting from gas treatment, microbial decontamination, and ending on a surface modification [1-13]. To use these devices effectively in the industry is needful to know their basic electrical properties and it is necessary to search for new design solutions.

This work presents investigations of novel high power atmospheric pressure microwave plasma source designed for gas processing. This device is classified as waveguide-supplied coaxial-line-based nozzleless MPS [2]. The main purpose of this work was to test the efficiency of microwave power transfer from the electric field to the generated plasma inside the MPS. In this test influences of kind and flow rate Q of process gases, and the incident microwave power P_I on the stability and efficiency of the presented MPS were analyzed.

The efficiency of microwave power transfer can be represented by the MPS electrodynamic characteristics. The MPS electrodynamic characteristics is a relation between the ratio P_R/P_I and normalized position l_s/λ_g of movable plunger, where P_R is the reflected microwave power, λ_g is wavelength in the WR-975 waveguide at 915 MHz and l_s is a distance between the MPS output plane and movable plunger [2]. It is easy obtainable experimentally and gives an important information about quality of the plasma source.

The ratio P_R/P_I can change from 0 to 1, where 0 means the complete absorption of microwaves in the MPS (no reflection), while 1 the lack of absorption (total reflection). One can say that the MPS has the highest energy efficiency when the value of P_R/P_I is equal to zero. Furthermore, it can be said that the MPS is stable in operation, when the ratio P_R/P_I is constant over a wide range of the l_s/λ_g position for various discharge conditions e.g. incident power P_I, kind and flow rate of process gases [2].

The cost of the generated discharge is one of the main factors that determine the suitability of the MPS for the industry. Therefore, knowledge of the MPS electrodynamic characteristics is important because it allows minimizing this cost by proper selection of the most favorable work conditions for the device.

Description of microwave plasma source

In brief, the structure of the MPS is based on a standard rectangular waveguide WR-975 with length of 437 mm, Fig. 1. The transverse dimension of the WR-975 waveguide is 123.9×247.9 mm. The incident microwave power is supplied through standard WR-975 waveguide to the input plane (1-1'), at the output plane MPS is terminated with a movable plunger.

Into the MPS waveguide a reduced-height section with tapered section was introduced. The linearly tapered section of length $\lambda_g/2$ = 218.5 mm changes the height of MPS waveguide from standard height b = 123.9 mm to reduced b_1 = 31 mm. This corresponds to the height of the subsequently introduced the reduced-height section. The reduced-height section increases the intensity of the microwave field in the region of the discharge inside the MPS. The reduced-height section contains coaxial-line structure, which consists of an inner electrode, a metal cylinder and a quartz tube. In this type of the MPS plasma occurred in a form of flame at the end of the inner electrode. The microwave discharge is initialize by entering a metal rod through inner electrode, which locally increases the intensity of the microwave field. Due to the erosive properties of the microwave discharge, the tip of the inner electrode was made from tungsten. This material is extremely resistant to high temperature of the plasma gas. The vertical slit in the metal cylinder allows to observe microwave plasma.

To the MPS the process gas is supplied axially through inner electrode directly to the generated discharge. To protect the quartz tube from overheating, an additional continuous flow of cooling gas is needed. The cooling gas is supplied by four gas ducts, which create a swirl flow inside the quartz tube. Photo of the presented MPS is shown in Fig 2. Description of this device could be also found in [2, 14-15].

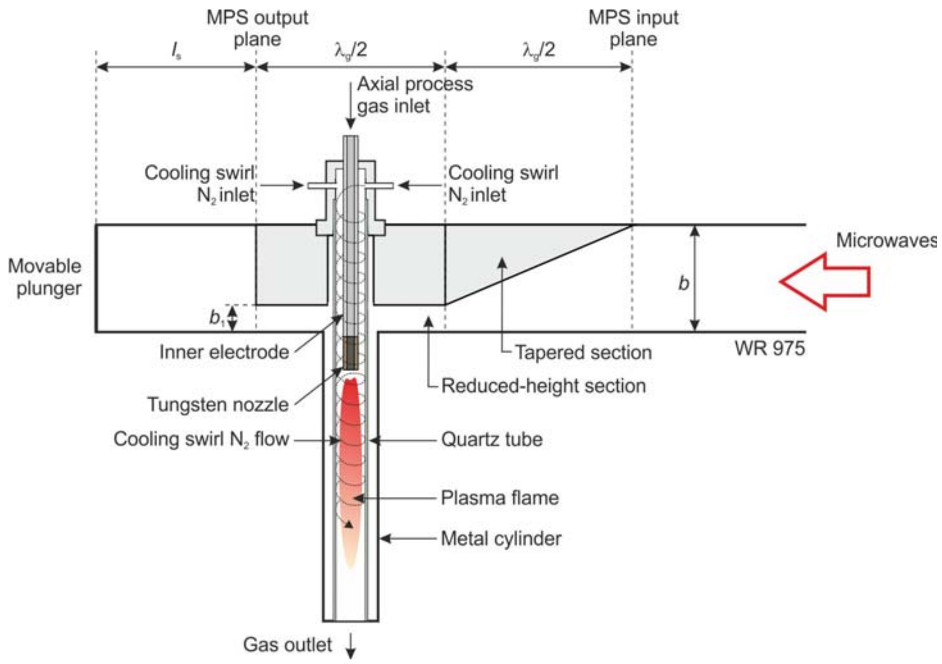

Fig. 1. Draft of the coaxial-line-based nozzleless MPS

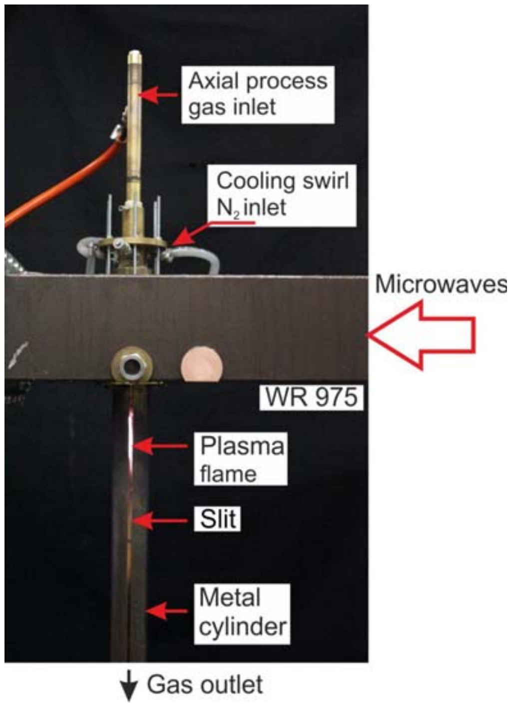

Fig. 2. Photo of the investigated MPS

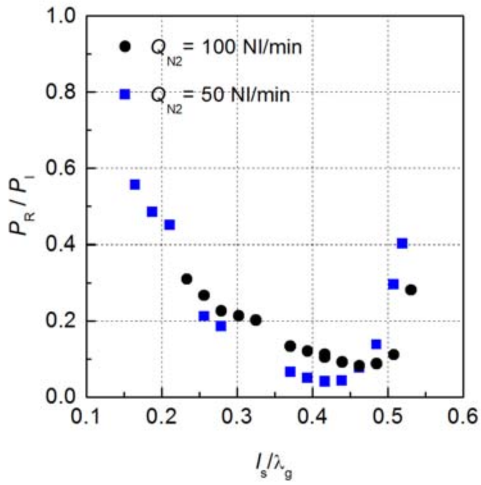

Fig. 3. The MPS tuning characteristics for discharge in nitrogen, P_I = 3 kW

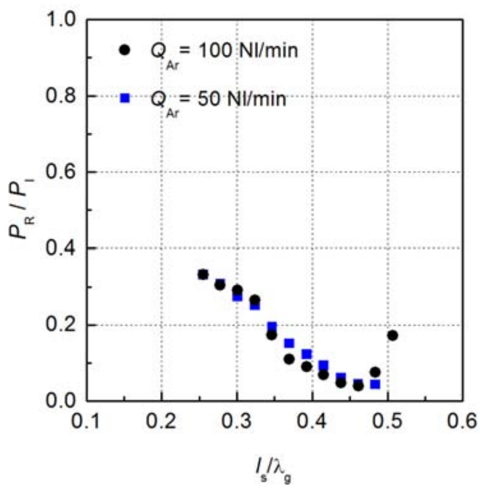

Fig. 4. The MPS tuning characteristics for discharge in argon, P_I = 3 kW

Results and discussion

The experimental set up consists of: microwave source - magnetron head operating at 915 MHz microwaves up to 20 kW, the MPS, system for measuring microwave power and system for supplying process gas. The magnetron head is equipped with a water cooled circulator which protects it against damages caused by the reflected microwave power. The microwave power is supplied from the magnetron head to the MPS via a standard rectangular waveguide WR-975. The system for measuring microwave power includes a directional coupler equipped with two power meter heads and a digital dual-channel power meter. This system enables to direct measure the incident P_I and reflected P_R microwave powers. Descriptions of experimental set up that we used in our investigation can be found in [2,11-14, 16].

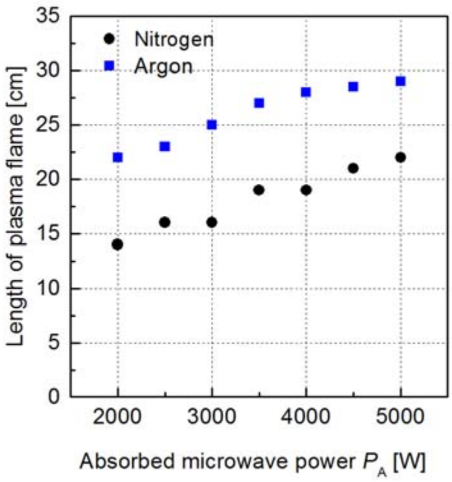

Fig. 5. Influence of absorbed microwave power P_A on the length of the plasma flame, process gas flow rate Q = 100 l/min

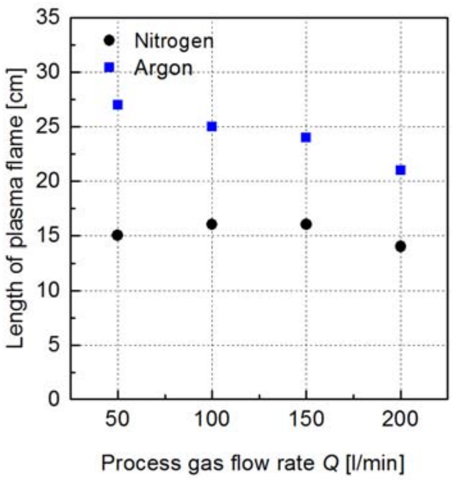

Fig. 6. Influence of process gas flow rate Q on the length of the plasma flame, absorbed microwave power P_A = 3 kW

All experimental tests were performed with process gas (nitrogen and argon) flow rate Q varied from 50 to 200 l/min. The MPS tuning characteristics were measured for incident microwave power P_I = 3 kW. In all tests to protect the quartz tube walls from overheating, nitrogen was used as the cooling gas with flow rate equal to 50 l/min. The measured relationships P_R/P_I (l_s/λ_g) are shown in Fig. 3 and 4.

The measured MPS tuning characteristics show that the range 0.4-0.5 l_s/λ_g is a region of stable plasma generation, regardless of the kind and flow rate of processed gases. In this range the ratio P_R/P_I is less than 0.1, which provides good energy efficiency of microwave power transfer inside the MPS. Nevertheless, in the case of nitrogen, the results show that the increase of the flow rate leads to reduction in the power transfer efficiency. This observation is highly unsatisfactory considering that the device is designed for gas conversion at high flow rate. This suggests to perform modelling of electric field distribution inside the device in order to improve energy efficiency [17-18].

Additionally during the experiment we estimate the length of generated plasma flame. In Fig. 5 and 6 influences of absorbed microwave power P_A and process gas flow rate Q on length of the plasma flame are shown, respectively. The value P_A was determined as the difference of P_I and P_R [2]. According to the figures the length of the plasma flame can be changed by choosing proper working conditions. The lengths of nitrogen and argon plasma flame were in the ranges of 14 - 20 cm and 22 - 29 cm, respectively, depending on gas flow rate and microwave power absorbed by the plasma.

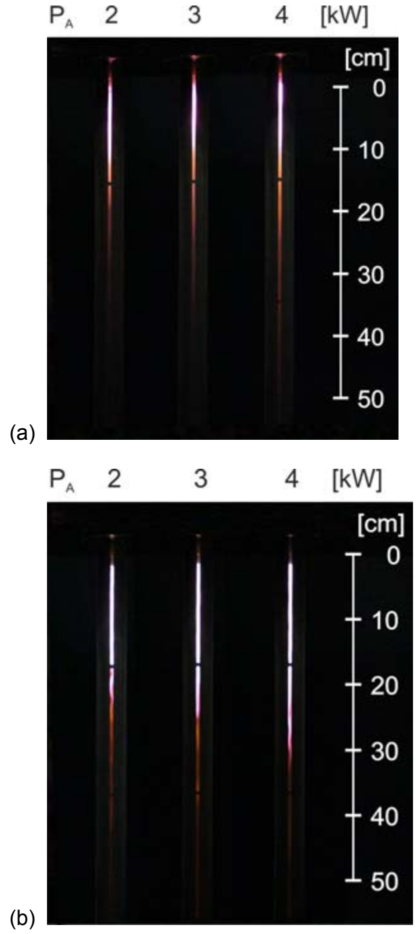

Fig. 7. Photos of microwave discharge in nitrogen (a) and argon (b) for various values of absorbed microwave power P_A, process gas flow rate Q = 100 l/min

Photos of generated plasmas in nitrogen and argon are present in Fig. 7. The photos were taken for different values of absorbed power of microwaves P_A. It should be noted that the microwave discharge generated in nitrogen occurs in a form of cylinder with a diameter approximately equal to the diameter of the inner electrode. On the other hand in case of the plasma generated in argon the discharge takes the characteristic irregular filaments form that fills the entire quartz tube. The axis of both plasma cylinders was coincident with the axis of the inner electrode. These observations are especially valuable to adopt a correct model of plasma in modelling the electromagnetic field distribution inside the MPS.

Conclusions

In this work the novel high power plasma source and its basic electrical properties are presented. The MPS can be used in process of harmful gases deactivation (e.g. destruction of various VOCs including Freon-type refrigerants) or for hydrogen production from gaseous/liquid fuels.

The tested device in range 0.4-0.5 of normalized movable plunger position provides stable microwave discharge for various process gases with high flow rates, where the ratio P_R/P_I is lower than 0.1. However, improvement of this device in terms of increase the energy efficiency should be performed. The order is to obtain the ratio P_R/P_I lower than 0.05 in wider ranges of movable plunger positions. The presented results constitute a solid base for modelling the electromagnetic field distribution inside the MPS, which is a first step in process of improving the energy efficiency of the device. This improvement will increase the MPS attractiveness for industry. Furthermore when the coaxial-line MPS is properly improved, the electric field is high enough to initialize and the plasma.

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