Bartosz HRYCAK[1], **Mariusz JASIŃSKI**[1], **Jerzy MIZERACZYK**[1, 2]

The Szewalski Institute of Fluid Flow Machinery Gdańsk, Centre for Plasma and Laser Engineering (1)
Gdynia Maritime University, Faculty of Marine Electrical Engineering, Department of Marine Electronics (2)

Tuning characteristics of cylindrical microwave plasma source operated with argon, nitrogen and methane at atmospheric pressure

***Abstract**. The cylindrical microwave plasma source (MPS) is a device used to produce high temperature plasma at atmospheric pressure and high working gases flow rates. In our experiment the plasma was generated with 2.45 GHz microwaves at powers between 600 W and 6000 W. At optimal positions of movable plunger, the use of argon, nitrogen and methane as the working gases caused, that 15 %, 0 % and 17 % of the incident power was reflected, respectively. The MPS can be used in gas processing applications.*

Streszczenie.** Prezentowany cylindryczny mikrofalowy generator plazmy jest urządzeniem wytwarzającym plazmę o wysokiej temperaturze pod ciśnieniem atmosferycznym, przy wysokich przepływach gazów. Plazma wzbudzana jest mikrofalami o częstotliwości 2,45 GHz i mocy od 600 W do 6000 W. Odpowiednio dla argonu, azotu oraz metanu przy optymalnym położeniu ruchomego zwarcia moc fali odbitej wynosiła 15%, 0% oraz 17% mocy fali padającej. Generator plazmy może być używany m.in. do obróbki gazów. (**Charakterystyki strojenia cylindrycznego mikrofalowego generatora plazmy w argonie, azocie i metanie pod ciśnieniem atmosferycznym).

Keywords: plasma sources, microwave discharges, tuning characteristics, gas processing.
Słowa kluczowe: generatory plazmy, wyładowania mikrofalowe, charakterystyki strojenia, obróbka gazów.

Introduction

Microwave discharges offer significant advantages as plasma sources. When properly designed, they are very stable and the efficiency of microwave power transfer to plasma can achieve almost 100%. They allow obtaining plasmas of high purity. As a rule, microwave plasmas are characterized by high density of electrons and active species, such as ions and free radicals [1]. The microwave plasma at atmospheric pressure is one of the plasma techniques providing the electron temperature of 4000 - 10000 K and the heavy particle temperature of 2000 - 6000 K [2, 3]. Recently, microwave plasma sources (MPSs) operated at atmospheric pressure have been developed [4-19]. Such devices were used in spectroscopy, technological processes like surface treatment, deposition of thin films and sterilization. They also found applications in the processing of various gases. Treatment of hazardous gases [20-22] and production of hydrogen via methane conversion [23, 24] in microwave atmospheric pressure plasmas were reported lately.

This paper presents the results of the experimental investigations with the waveguide-based cylindrical microwave plasma source (MPS) operated at atmospheric pressure at high gas flow rates. The MPS can be used in gas processing applications.

Microwave plasma source MPS

The sketch of the cylindrical microwave plasma generator is shown in Fig. 1. The generator was based on a standard WR 430 rectangular waveguide with a section of reduced-height, preceded and followed by tapered sections. The MPS ensured nozzleless operation. The plasma flame was generated inside a quartz tube which penetrated microwave plasma generator through circular gaps on the axis of the waveguide wide wall and protruded below bottom waveguide wall. On the outside of the waveguide the quartz tube was surrounded by a cylindrical metal shield with a slit for visualization. The inner and outer diameters of the quartz discharge tube were 26 mm and 30 mm, respectively. The working gases created swirl flows inside the tube. The discharge was initiated using the metallic rod entered to the discharge area to increase local electric field. In case of methane the discharge was initiated in nitrogen or argon and then gases were changed.

Experimental setup

The photo of the experimental setup is presented in Fig. 2. The main parts of the experimental setup were: microwave generator (2.45 GHz and maximal power of 6 kW) secured with water insulator, rectangular waveguide (WR 430) as a feeding line, directional coupler equipped with diode sensors and dual channel power meter, cylindrical MPS terminated with movable plunger, ensuring the short at the end of microwave line and gas supplying and measuring system.

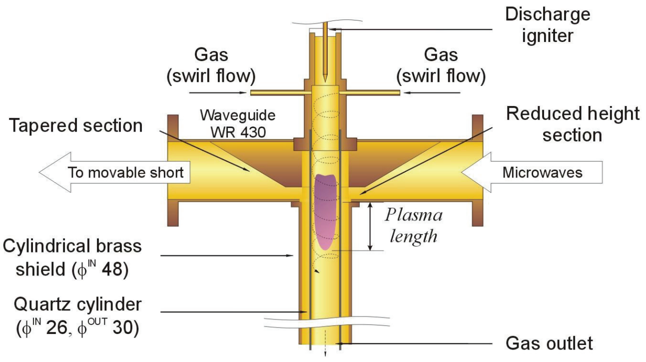

Fig.1. The sketch of cylindrical microwave plasma source

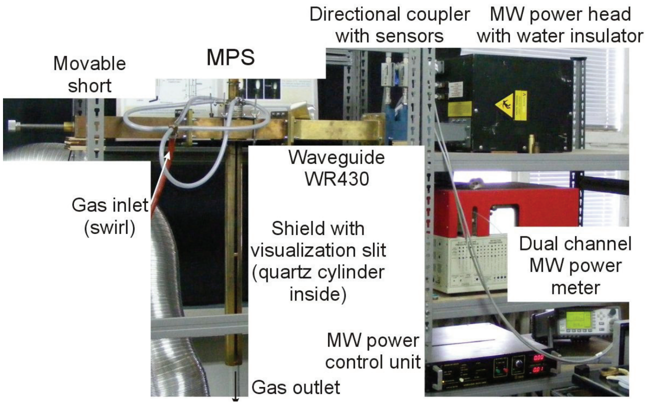

Fig.2. Experimental setup

The microwave power P_A absorbed by the plasma was determined from (P_I - P_R), where P_I and P_R are the incident and reflected microwave powers, respectively. This powers were measured directly by directional coupler with diode sensors and power meter. The tuning characteristics are defined as the dependence of the reflection coefficient P_R / P_I as a function of the distance l between the plasma axis and the movable short. This function is recurrent, with period λ_g / 2, where λ_g is the waveguide wavelength (147.7 mm for WR 430 waveguide).

The working gas flow rates were between 50 l/min and 200 l/min for argon and nitrogen and 88 l/min and 175 l/min for methane. The microwave power was varied from 600 W up to 6000 W.

Results

Minimal microwave absorbed powers required for sustaining plasmas were about 500W, 600 W and 1000 W for argon, nitrogen and methane, respectively. Fig. 3 shows the photos of argon and nitrogen plasmas.

The length of the plasmas were 30 - 300 mm and 30 - 200 mm for argon and nitrogen as the working gas, respectively. As it is seen in Fig. 4 the length of the plasma increased linearly with increasing microwave absorbed power. In case of argon plasma a slope of the increase was dependent on the flow rate. The plasma length decreased with increasing argon flow rate. For nitrogen the differences in the plasma length for working gas flow rates 50 and 200 l/min were not significantly.

The tuning characteristics is recurrent function, related with the half of the waveguide wavelength λg (147.7 mm for WR 430 waveguide). Thus, it could be normalized and presented as a l / λg function. The period of this function is then 0.5. Figure 5 presents the normalised tuning characteristics of the cylindrical MPS operated in argon and nitrogen (Fig. 5b) for different microwave incident powers and working gas flow rates. The characteristics from Fig. 5 were almost independent on discharge conditions. The use of argon as the working gas caused, that the tuning characteristics were the widest (Fig. 5a). Argon plasma required less microwave power to sustaining. Obviously, the lower value of the reflection coefficient P_R / P_I indicates more efficient transfer of the microwave energy to the plasma. For the nitrogen the reflection coefficient P_R / P_I at optimum position of movable plunger were about 0 % (Fig. 5b). The tuning characteristics of the cylindrical MPS operated in methane at atmospheric pressure were extremely narrow. Practically, only one position (l / λg ~ 0.43) of the movable plunger ensured sustaining of the discharge.

Figure 6 shows the fraction of the incident power reflected at the plasma generator input P_R / P_I for different conditions at fixed position of movable plunger (l / λg ~ 0.43 - minimum of tuning characteristics from Fig. 5). For argon this coefficient at optimal position of movable plunger was about 15 – 20 % depending on the argon flow rate and microwave incident power (Fig. 6a). The cylindrical MPS works very efficiency in nitrogen. The reflection coefficient were less than less than 3 % for entire range of microwave powers and working gas flow rates. (Fig. 6b). At the optimal position, about 17-34 % of the microwave incident power is reflected in case of the use methane as a working gas (Fig. 6c). In this case MPS worked more efficiently at higher microwave powers.

The cylindrical MPS works stable with different gases. Its impedance matching could be improved by further optimization. The advantage of the cylindrical MPS is a lack of nozzle, which is vulnerable to erosion.

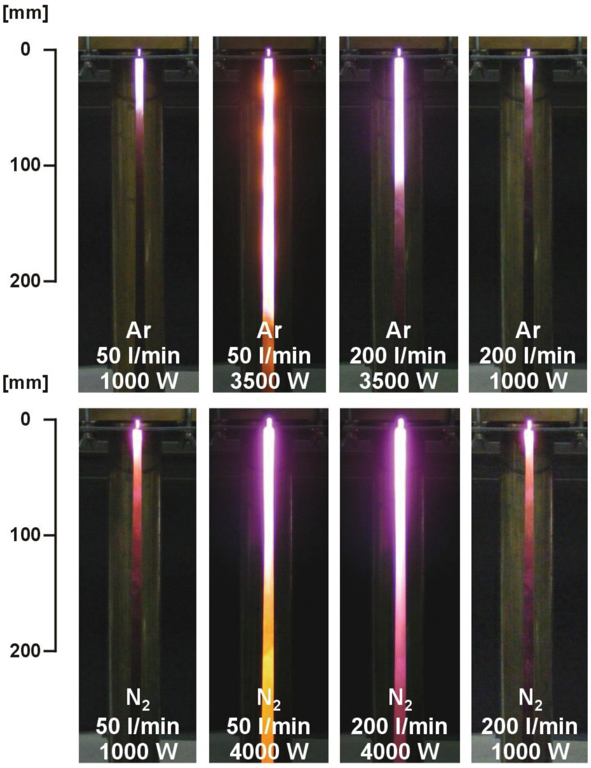

Fig.3. Microwave argon and nitrogen plasmas

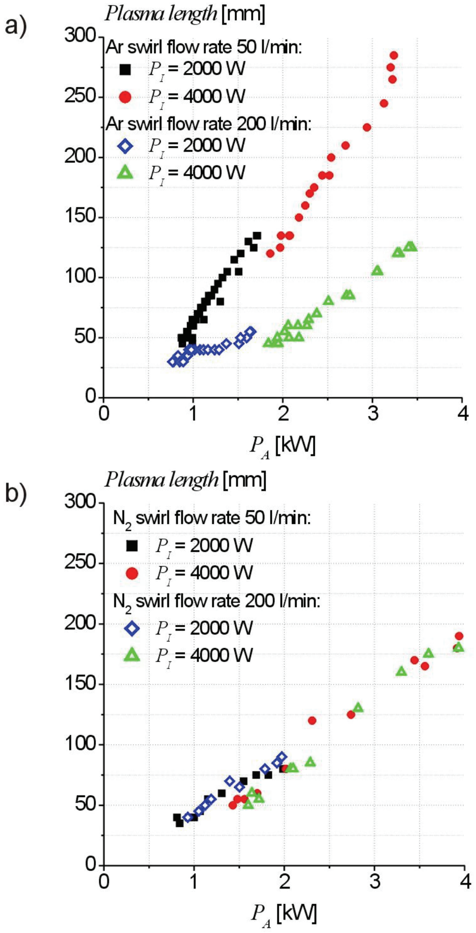

Fig.4. The length of argon (a) and nitrogen (b) plasma (measured from waveguide) as a function of microwave absorbed power P_A (P_A = P_I - P_R) for different working gas flow rates and incident microwave powers

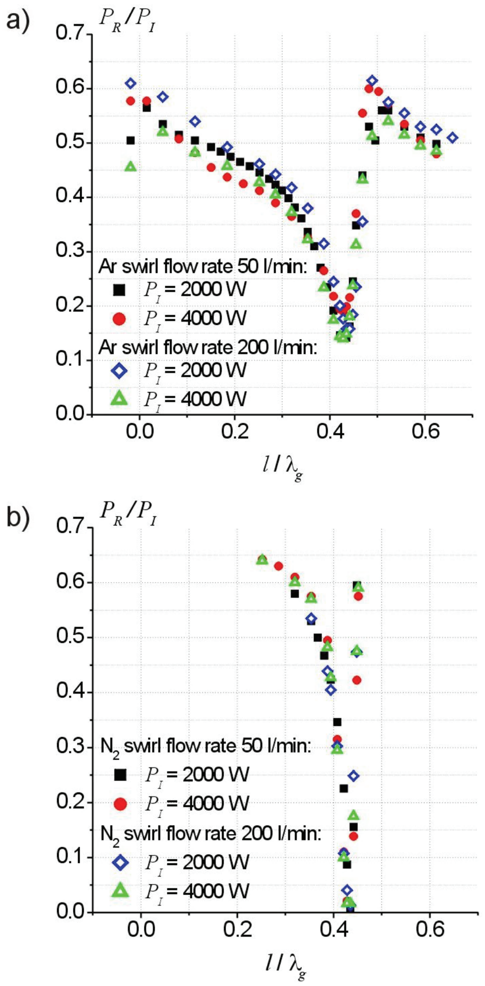

Fig.5. Normalized tuning characteristics of the cylindrical MPS operated with argon (a) and nitrogen (b), l – distance between the plasma axis and movable plunger, λ_g – waveguide wavelength (147.7 mm)

Conclusions

This paper concerns the tuning characteristics of the cylindrical MPS operated with argon, nitrogen and methane at atmospheric pressure. Investigations of the tuning characteristics showed that at optimal positions of movable plunger, the use of argon, nitrogen and methane as the working gas caused, that 15 %, 0 % and 17 % of the incident power was reflected, respectively, according to the discharge conditions. It could be improved by further optimization.

The important advantages of the presented microwave plasma sources(MPSs) are: stable operation in gases, including methane, at high flow rates, lack of a special cooling system, no need for a 3-stub tuner, and discharge initiation and operation without any admixture of a noble gas. This advantages allows the concluding that MPS can be very attractive tool for different gas processing at high flow rates. The device was successfully used for hazardous gases treatment and hydrogen production via methane decomposition. The results showed that microwave plasma sources (MPSs) operated at atmospheric pressure have a high potential in this applications. Even taking into account the energy losses in the microwave power supply (~33%), the energetic parameters of the Freon HFC-134a destruction and the hydrogen production were attractive. The $C_2H_2F_4$ mass yield rate was 34.5 kg[$C_2H_2F_4$] h^{-1} with the energetic $C_2H_2F_4$ mass yield - 23.5 kg[$C_2H_2F_4$] kWh^{-1} [22]. The hydrogen production rate was 866 g [H_2] h^{-1} and the energy efficiency 381 g [H_2] kWh^{-1} of the total electric energy used [23, 24].

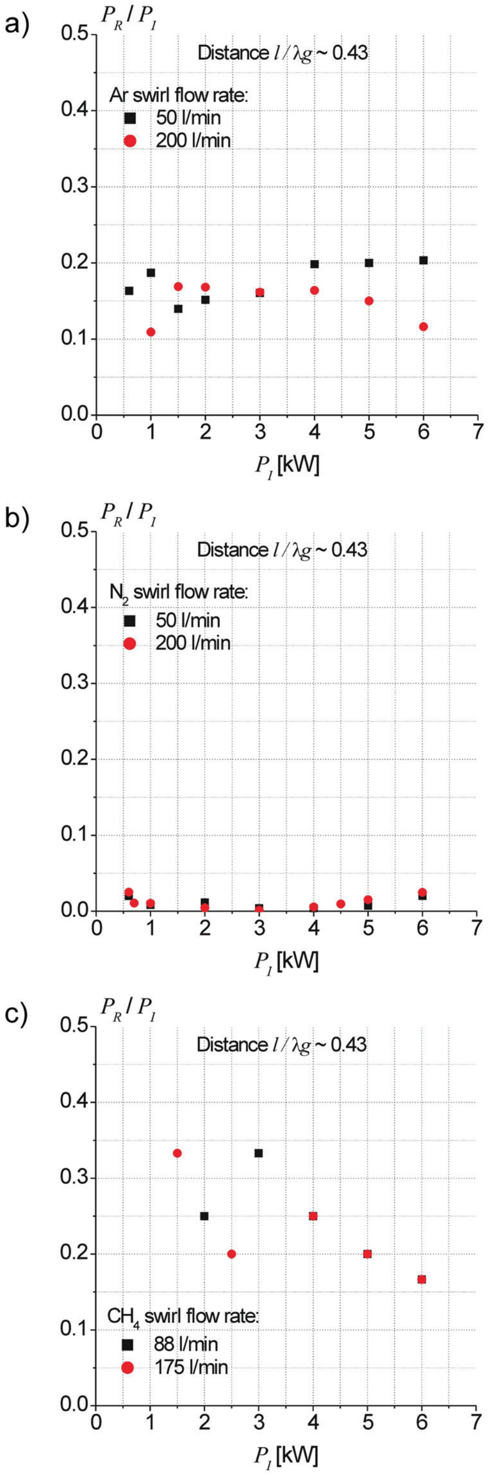

Fig.6. The fraction of the incident power reflected at the MPS input as a function of incident power for argon (a), nitrogen (b) and methane (c) as a working gas at fixed position of movable plunger l/λ_g ~ 0.43

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***Authors**: mgr inż. Bartosz Hrycak, dr inż. Mariusz Jasiński, The Szewalski Institute of Fluid-Flow Machinery, Polish Academy of Sciences, ul. Fiszera 14, 80-952 Gdańsk, E-mail: bhrycak@imp.gda.pl; mj@imp.gda.pl;*

prof. dr hab. inż. Jerzy Mizeraczyk, The Szewalski Institute of Fluid-Flow Machinery, Polish Academy of Sciences, ul. Fiszera 14, 80-952 Gdańsk and Gdynia Maritime University, Faculty of Marine Electrical Engineering, Morska 81-87, 81-225 Gdynia, E-mail: jmiz@imp.gda.pl.