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Equivalent circuit of a microwave plasma source for hydrogen production from liquid substances

Abstract. *This paper presents a new concept of an equivalent circuit of a microwave plasma source (MPS). The presented MPS has an area of waveguide discontinuity which is a result of metal-cylinder structure entered into the plasma source. Furthermore, in this area the microwave discharge is generated. The novelty of the presented investigations is the use of the Weissfloch circuit as equivalent of the area with the discharge. The aim of this work is to increase an efficiency of microwave power transfer from electric field to the plasma and improve MPS operational stability.*

Streszczenie. *Niniejsza praca przedstawia nową koncepcje opisu mikrofalowego generatora plazmy (MGP) za pomocą układu zastępczego. Badany MGP posiada obszar nieciągłości falowodu, który jest wynikiem wprowadzenia metalowego cylindra do wnętrza źródła plazmy. W obszarze tym generowane jest wyładowanie mikrofalowe. Nowością prezentowanych badań jest ujęcie tego obszaru za pomocą obwodu Weissflocha. Celem pracy było zwiększenie efektywności transferu mocy mikrofal do generowanego wyładowania oraz zwiększenie stabilności pracy MGP. (**Obwód zastępczy mikrofalowego generatora plazmy przeznaczonego do produkcji wodoru z substancji ciekłych**).*

Keywords: equivalent circuit, microwave plasma source, Weissfloch circuit, diaphragm.
Słowa kluczowe: obwód zastępczy, mikrofalowy generator plazmy, obwód Weissflocha, przysłona.

Introduction

Hydrogen is being considered as a strategic fuel for the future [1, 2]. Microwave plasma sources operated at an atmospheric pressure seems to have a high potential for hydrogen production via hydrocarbon reforming [3, 4] or other liquid substances [5-7].

This paper presents an equivalent circuit of a waveguide-supplied metal-cylinder-based nozzleless MPS used for hydrogen production from liquid substances [4, 6]. The main advantage of the presented MPS is that it is electrodeless and therefore far less susceptible to chemical erosion from highly reactive species than other plasma reactors [4].

To meet industrial requirements for the production of hydrogen, the presented MPS requires optimization with the goal of achieving stability in operation and improving the efficiency of power transfer from electric field to the plasma. The efficiency of power transfer from electric field to the plasma can be expressed as a ratio P_R/P_I, where P_I and P_R are the power of the incident and reflected microwaves, respectively. The equivalent circuit allows to calculate the tuning characteristics of the MPS [8, 9]. The tuning characteristics of the MPS is a dependence of P_R/P_I on a normalized position of the movable plunger l_S/λ_g (l_S- distance between the MPS output plane and the movable plunger, λ_g = 437.7 mm - microwave wavelength in WR 975 waveguide, fig. 1). The MPS is efficient when the value of ratio P_R/P_I is low, and operates stable when the ratio does not depend on the movable plunger position [4, 8, 9].

The novelty of the presented investigations is to use of the Weissfloch circuit [10]. By comparing the calculated tuning characteristics with that measured experimentally, verification of the proposed method was carried out and the plasma impedance Z_P of the microwave discharges presented in this paper was determined.

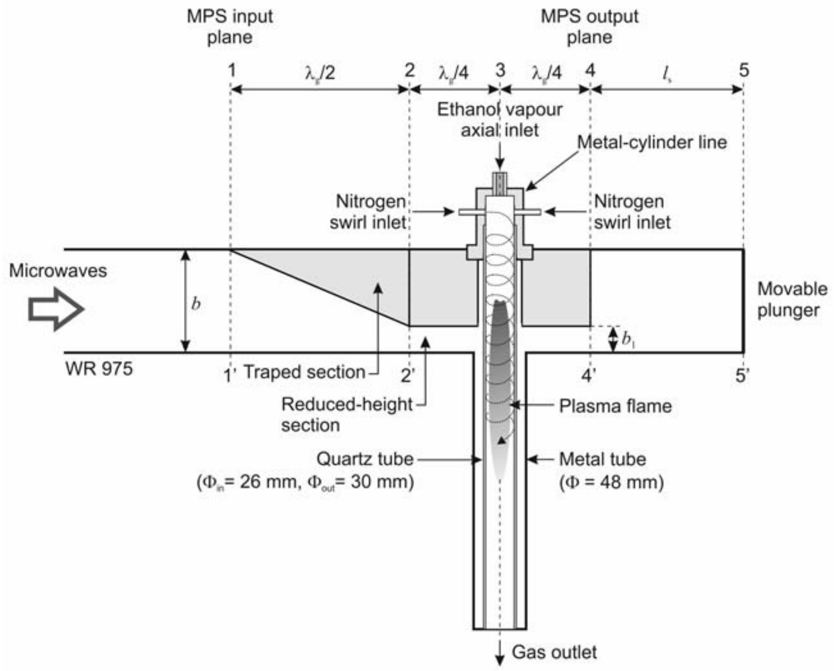


Fig.1. Sketch of the microwave plasma source

The tuning characteristics can be improved by adding a diaphragm in front of the MPS. The equivalent circuit of the MPS allows to compute the effect of diaphragm. The aim of this work is to calculate the gap of the diaphragm d and the distance L from the MPS input plane, which provides a minimum ratio of P_R/P_I to the fullest extent of the movable plunger position.

Sketch of the microwave plasma source

Sketch of the MPS is shown in fig. 1. The MPS, operating at the atmospheric pressure and frequency of 915 MHz, is based on a standard WR 975 rectangular waveguide with a section of reduced-height, preceded by tapered section. The reduced-height waveguide is a rectangular waveguide of standard width a = 247.7 mm and height b_1, smaller than that of the standard value b (b = 123.9 mm, b_1 = 31 mm). Microwave power is supplied to the MPS input plane (1-1’) via a standard rectangular waveguide WR 975. The MPS is followed by a movable plunger (output plane 4-4’).

The metal-cylinder (quartz tube + metal tube) penetrates the MPS on the axis of the reduced-height waveguide wide wall and protruded below bottom waveguide wall (plane 3-3’). Working gas was introduced to the plasma by four gas ducts which formed a swirl flow inside the quartz tube. The MPS was described in details in [6, 11].

Equivalent circuit of the microwave plasma source

The equivalent circuit allows to determine an admittance Y_{in} in the MPS input plane (plane 1-1'). Knowing the normalized input admittance y_{in} of the MPS [8, 9]:

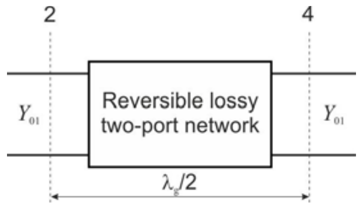
$$y_{in} = \frac{Y_{in}}{Y_0} \tag{1}$$

the tuning characteristics of the MPS can be calculated from [8, 9]:

$$\frac{P_R}{P_I}\left(\frac{l_s}{\lambda_g}\right) = \left|\frac{y_{in}-1}{y_{in}+1}\right|^2 \tag{2}$$

The presented MPS has the area of discontinuity which is a result of metal-cylinder entry into the MPS waveguide (fig. 1). Furthermore, in this area the microwave discharge is generated. In the investigation the reduced-height section of the MPS (between planes 2-2’ and 4-4’) was assumed as the two-port network [10, 12], fig. 2a. The reduced-height section of the MPS with the generated discharge is symmetrical to the axis of the metal-cylinder. This indicate that the microwaves propagate in the same way in both directions. This means that the assumed two-port network is reversible [10, 12]. It is important to notice that the generated microwave discharge causes losses in the assumed two-port network.

The Weissfloch concept is to extract a lossy part of the reversible two-port network (serial impedance $Z_S = R_S + jX_S$ and parallel resistance R_T), whereas the remaining part is expressed by the lossless two-port network [10], fig 2.b.



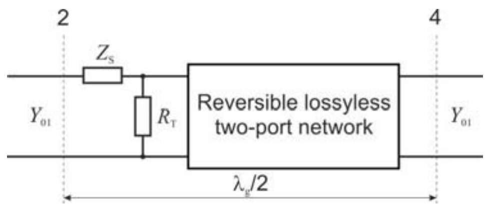


Fig.2. Diagram of: a) the assumed two-port network, b) the Weissfloch circuit

Diagram of the equivalent circuit of the microwave plasma source is shown in fig. 3. In this figure the lossless two-port network, which express the area of waveguide discontinuity, is represented by three impedances Z_a, Z_b and Z_c in T-type circuit. The values of impedances Z_a, Z_b and Z_c can be easily estimated by simulation an electromagnetic field distributions inside the MPS [10, 12].

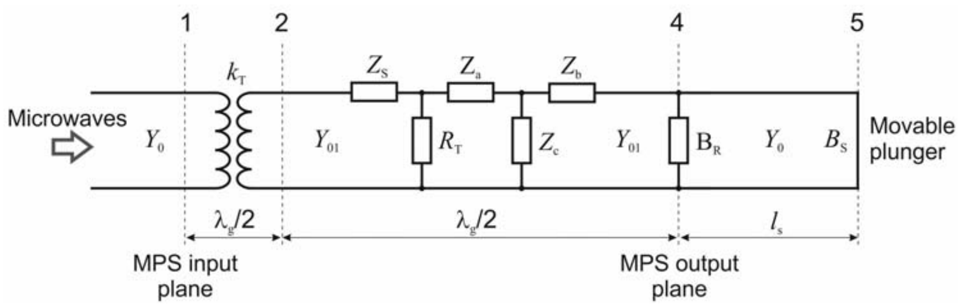


Fig.3. Diagram of the equivalent circuit of the microwave plasma source

The notation is as follows: Y_0, Y_{01} – characteristic admittance of the waveguide of standard and reduced-height, Y_0 = 0.0025 S, Y_{01} = 0.0101 S, respectively, $B_S = -Y_0\mathrm{ctg}(2\pi l_S/\lambda_g)$ - susceptance introduced by the movable plunger, B_T = 0.005 S – susceptance resulting from abrupt change of height in the MPS waveguide, $k_T = Y_0/Y_{01}$ - transformation factor of the tapered section.

According to the presented diagram and taking into account the above relations, the normalized input admittance y_{in} takes the form as follows:

$$(3)\qquad y_{\mathrm{in}}=\cfrac{Y_{01}^{-1}}{Z_{\mathrm{S}}\cfrac{1}{\cfrac{1}{R_{\mathrm{T}}}+\cfrac{1}{Z_{\mathrm{a}}+\cfrac{1}{\cfrac{1}{\cfrac{B_{\mathrm{T}}+B_{\mathrm{S}}}{-j+B_{\mathrm{T}}Z_{\mathrm{b}}+B_{\mathrm{S}}Z_{\mathrm{b}}}+Z_{\mathrm{b}}}+\cfrac{1}{Z_{\mathrm{c}}}}}}}$$

In the method described above the calculated tuning characteristics dependent on the parameters Z_S and R_T, which are unknown. These values can be estimated by comparing the calculated and measured tuning characteristics. In this paper the parameters Z_S and R_T will be called as a *plasma impedance* Z_P.

Experiment

The experimental setup used in investigations was described in [6, 7]. The main parts of the experimental setup were a microwave generator (magnetron), MPS, microwave power measuring system, and working gas supplying system.

The microwave power measuring system includes a directional coupler, two power meter heads and a digital dual-channel power meter. This system enables direct measurements of the incident P_I and reflected P_R microwave powers.

Nitrogen (N_2) was used as a working gas. The experimental test were performed with the working gas flow rate Q of 2700 NL/h and incident microwave power P_I = 5 kW. Liquid ethanol (C_2H_5OH) was delivered to an inductively heated vaporizer and then its vapors (400^{o}C) were introduced by axial inlet to the MPS. The amount of liquid C_2H_5OH (96 % v/v) delivered to the inductively heated vaporizer was 0.5 L/h. For these working conditions the tuning characteristics of the presented MPS were measured (fig. 4). As observed experimentally, the generated plasma takes the form of a cylinder with the diameter of 12 mm and length of 10 cm. An increase of the microwave power increased the plasma length and also the plasma volume.

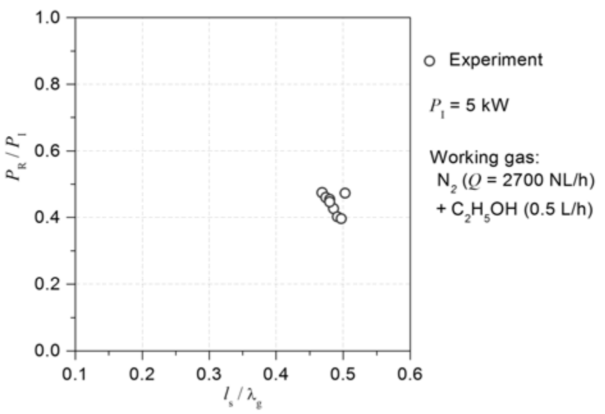


Fig.4. Measured tuning characteristics of the MPS

Results of calculations

Based on the concept of the Weissfloch circuit in present work the area of waveguide discontinuity in the MPS (between planes 2-2' and 4-4') was assumed as lossless two-port network. One of the form of description of properties of the two-port network is a scattering matrix **S**. The coefficients s_{11}, s_{12}, s_{21} and s_{22} of the **S** matrix are directly related to the amplitudes of waves propagating in waveguides connected to the gates of the two-port network [8-10,12]. Knowing the coefficients of the **S** matrix the impedance Z_a, Z_b and Z_c can be determined by following relationships [10, 12]:

$$(4)\qquad Z_{\mathrm{a}}=Y_{01}^{-1}\frac{-1-s_{11}+2s_{12}-s_{12}^2+s_{22}+s_{11}s_{22}}{-1+s_{11}+s_{12}^2+s_{22}-s_{11}s_{22}}$$

$$(5)\qquad Z_{\mathrm{a}}=Y_{01}^{-1}\frac{-1+s_{11}+2s_{12}-s_{12}^2-s_{22}+s_{11}s_{22}}{-1+s_{11}+s_{12}^2+s_{22}-s_{11}s_{22}}$$

$$(6)\qquad Z_{\mathrm{a}}=-Y_{01}^{-1}\frac{2s_{21}}{-1+s_{11}+s_{12}^2+s_{22}-s_{11}s_{22}}$$

A three-dimensional simulation of the electromagnetic field distributions inside the part of the MPS were performed using Comsol Multiphysics software [13]. COMSOL Multiphysic is a program that allows to solve systems of nonlinear partial differential equations using the finite element method.

The performed simulation allowed to obtain the coefficients of the scattering matrix **S**:

$$\mathbf{S}=\begin{vmatrix}-0.00363-\mathrm{j}0.07737 & 0.99591-\mathrm{j}0.04661\\ 0.99591-\mathrm{j}0.04661 & -0.00363-\mathrm{j}0.07737\end{vmatrix}$$

The simulated area of the MPS is symmetrical to the axis of the quartz tube, this causes the following relationships: s_{11} = s_{22} and s_{21} = s_{12}. Taking into account equation (4)-(6) our numerical calculations resulted an impedance Z_a, Z_b and Z_c as following: Z_a = -j1.6 Ω, Z_b = -j1.6 Ω and Z_c = -j793.5 Ω.

As can be seen in fig. 5, a good agreement has been found between the tuning characteristics obtained experimentally and numerically. The best fitting was obtained for the plasma impedance Z_P described with Z_S = (22 + j15) Ω and R_T = 10 kΩ. It is an important to note that the estimated parameters Z_S and R_T unequivocally determine the lossy part of the reversible two-port network [10].

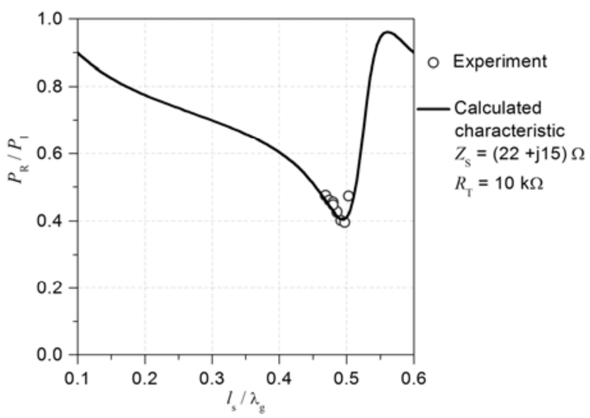


Fig.5. Comparison of measured and calculated tuning characteristics of the MPS

As it was mentioned at the introduction the aim of the work was to provide a minimum ratio of P_R/P_I to the fullest extent of the movable plunger position. Investigations of the equivalent circuit and determination the plasma impedance Z_P gives the ability to theoretical determine an effect of introduced diaphragm on the calculated tuning characteristics.

In this paper the effect of the symmetrical induction diaphragm on the calculated tuning characteristics was analyzed. Sketch and diagram showing location of the diaphragm in the MPS input cross-section are presented in figure 6.

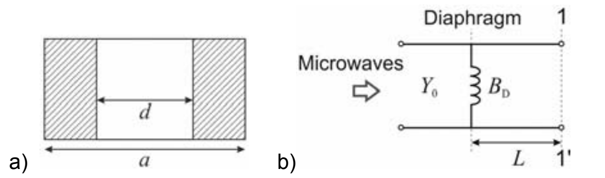


Fig.6. Symmetrical induction diaphragm: a) sketch, b) diagram of location to the MPS input plane

The B_D is susceptance induced in the waveguide by introducing the diaphragm. Susceptance B_D is expressed by formula [11]:

$$B_D = Y_0 \frac{\lambda_g}{a} \mathrm{ctg}^2\left(\frac{\pi d}{2a}\right) \tag{4}$$

Introducing diaphragm to the equivalent circuit resulted that the calculated tuning characteristics become very sensitive against change the width of the gap d and distance L. Calculations shown that the most efficient microwave energy transfer in the MPS was obtained for the width d = 112 mm and the distance L = 80 mm, fig 7. In calculations the estimated value of plasma impedance Z_P were used.

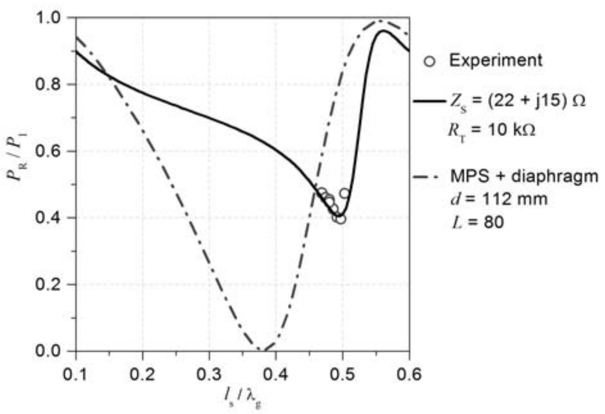


Fig.7. Effect of the symmetrical induction diaphragm on the calculated tuning characteristics

Conclusions

The MPS described in this paper requires optimization. The presented results of calculations allow to improve significantly the tuning characteristics of the MPS, however it must be confirmed experimentally.

The presented concept of the equivalent circuit of the MPS has an universal properties and can be applied to other MPS structure.

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