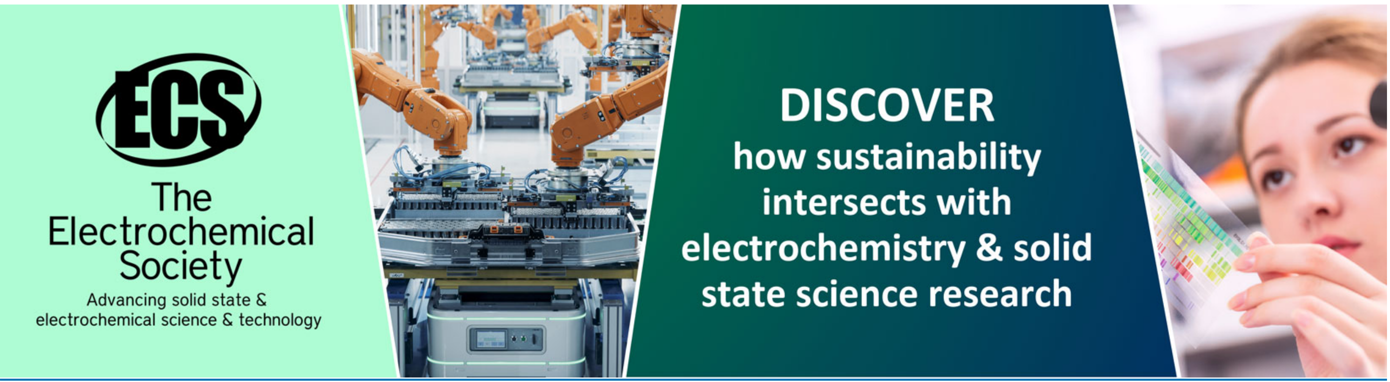
IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

Equivalent circuit of a coaxial-line-based nozzleless microwave 915 MHz plasma source

To cite this article: R Miotk *et al* 2016 *IOP Conf. Ser.: Mater. Sci. Eng.* **113** 012008



Equivalent circuit of a coaxial-line-based nozzleless microwave 915 MHz plasma source

R Miotk[1], M Jasiński[1] and J Mizeraczyk[2]
[1]*Centre for Plasma and Laser Engineering, The Szewalski Institute of Fluid-Flow Machinery Polish Academy of Sciences, ul. Fiszera 14, 80-231 Gdańsk, Poland*
[2]*Department of Marine Electronics, Gdynia Maritime University, ul. Morska 81-87, 81-225 Gdynia, Poland*

E-mail: rmiotk@imp.gda.pl

Abstract. This paper presents a new concept of an equivalent circuit of a microwave plasma source (MPS) used for gas treatment. The novelty of presented investigations is the use of the Weissfloch circuit as equivalent of an area of waveguide discontinuity in the MPS which is a result of entering a coaxial-line structure. Furthermore, in this area the microwave discharge is generated. Verification of the proposed method was carried out. The proposed equivalent circuit enabled calculating the MPS tuning characteristics and comparing them with those measured experimentally. This process allowed us to determine the impedance Z_P ofplasma in the MPS.

1. Introduction

To meet industrial requirements of gas treatment presented MPS has to be optimized in terms of efficiency of the power transfer from the feeding microwaves to the plasma. This efficiency is usually expressed as the ratio P_R/P_I, where P_I and P_R are the powers of the incident and reflected microwaves at the input of the MPS, respectively [1]. The tuning characteristics of the MPS is the dependence of P_R/P_I on the normalized position of the movable plunger l_S/λ_g, i.e. P_R/P_I (l_S/λ_g), where l_S is distance between the MPS output plane and the movable plunger (Figure 1) and λ_g is the wavelength of microwaves in the waveguide (in our case, at frequency 915 MHz and waveguide type WR 975 the λ_g is equal to 437.7 mm). The MPS operation is efficient when the value of ratio P_R/P_I is low and does not depend strongly on the movable plunger position [1, 2].

In this paper we present the equivalent circuit of the waveguide-supplied coaxial-line-based nozzleless MPS used for gas treatment at high flow rate [1]. The equivalent electric circuit concept serves to analyse the characteristics of the MPS without necessity of solving the full set of electromagnetic field equations [2]. The novelty of the presented equivalent circuit lies in using the Weissfloch circuit [3]. The proposed equivalent circuit of the MPS allowed to determine the impedance Z_P of the plasma and calculate the dimensions of a diaphragm which increases the efficiency of microwave power transfer from the feeding microwaves to the plasma.

2. The coaxial-line-based nozzleless MPS

A sketch of the MPS is shown in Figure 1. The MPS was described in details in [1]. The MPS, operating at the atmospheric pressure, was based on the standard WR 975 rectangular waveguide with a section of reduced-height. Before this section a metal tapered section was placed. The coaxial-line structure (consisted of coaxial quartz, inner electrode and metal tube) extends through the wider wall of the reduced-height waveguide section (plane 3-3'). The microwave power was supplied to the MPS input plane (1-1') also via the standard rectangular waveguide WR 975. At the MPS output plane 4-4' a movable plunger was attached.

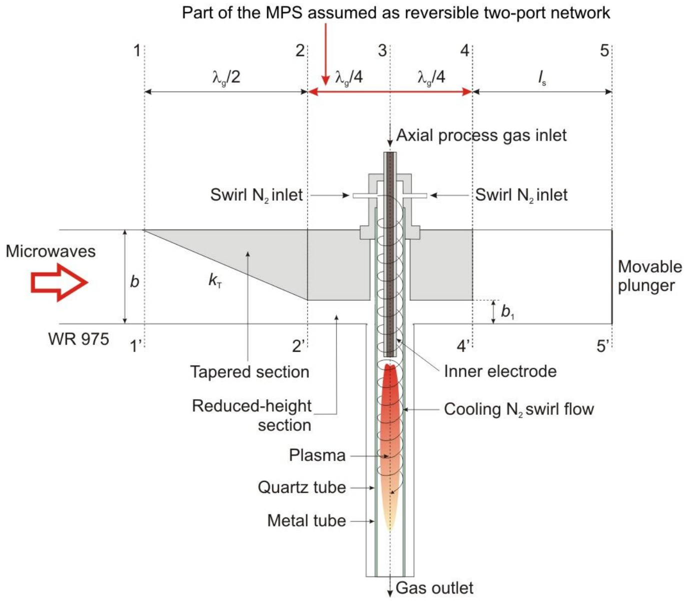


Figure 1. Sketch of the microwave plasma source.

In this MPS, two flows are formed in a quartz tube: central flow (the processed gas) and an additional swirl flow (nitrogen - 50 NL/min). The processed gas flow was introduced to the discharge zone through the inner cylindrical electrode. The additional swirl flow was supplied tangentially through the four inlets, creating a spiral vortex flow in the quartz tube. The swirl flow stabilized the discharge in the center of the quartz tube and protected the quartz wall from overheating [1].

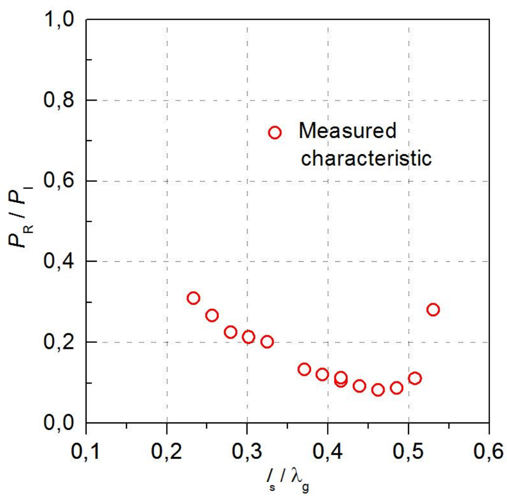


Figure 2. Measured tuning characteristics of the MPS

The experimental setup was described in [4]. The experiment was performed with the nitrogen as process gas with flow rate Q equal to 100 NL/min and incident microwave power P_I = 3 kW. For these working conditions the tuning characteristics of the MPS was measured. The measured characteristics shown in Figure 2 has a minimum at $l_S/\lambda_g \approx 0.46$. This means that at this position of the movable plunger, the efficiency of power transfer from electric field to the plasma in the MPS is highest.

3. Equivalent circuit of the microwave plasma source

Rigorous analysis of behaviour of microwave plasma sources requires solving the Maxwell equations, which is difficult for the microwave structures formed of waveguides and tubes with plasma. However, some properties of the MPSs can be found by using the electric circuit analysis base on the concept of equivalent electric circuit of the MPS [2, 5]. The circuit allows us to determine the normalized admittance y_{in} at the input plane of the MPS (plane 1-1'). The relation between the tuning characteristics P_R/P_I (l_S/λ_g) and the admittance y_{in} is [5]:

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

Diagram of the proposed equivalent circuit of the MPS is shown in Figure 3. The presented MPS has a region of discontinuity in term of microwave propagation, which is a result of inserting the coaxial-line into the waveguide. Furthermore, the microwave plasma is generated in the discontinuity region. We propose to solve the problem by the use of the Weissfloch circuit [3].

In this paper we assumed that the part of the MPS between planes 2-2' and 4-4' is a two-port network [6]. This section of the MPS is symmetrical to the axis of the inner electrode which means that the assumed two-port network is reversible [6]. For the point of view of the microwave propagation through this region the microwave plasma can be regarded as a loss structure. The idea of the Weissfloch circuit [3] is to represent the reversible lossy two-port network into two sections. The first section represent the losses of the reversible lossy two-port - serial impedance Z_S and parallel resistance R_T. The remaining part, which expresses the area of waveguide discontinuity is represented by the second section in the form of a lossless two-port network. The parameters Z_S and R_T will be called as *plasma impedance* Z_P. The lossless two-port network can be expressed 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 determined by the simulation of electromagnetic field distribution inside the MPS in the absence of the plasma [6].

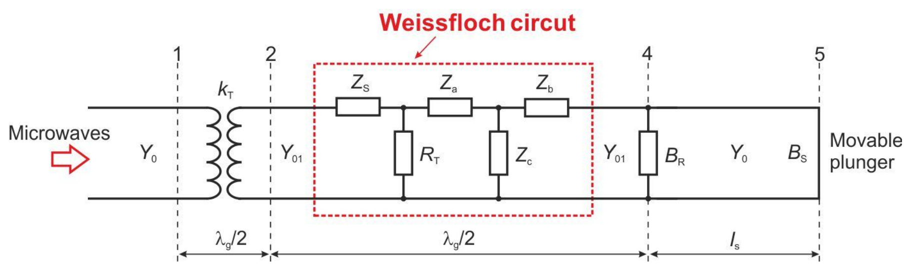


Figure 3. Diagram of the equivalent circuit of the microwave plasma source.

The notation used in figure 3 is as follows:

Y_{01} - characteristic admittance of the waveguide of reduced-height, $Y_{01} = 0.01$ S,
Y_0 - characteristic admittance of the standard WR 975 waveguide, $Y_0 = 0.0025$ S,
$B_S = - Y_0\text{ctg}(2\pi\, l_S/\lambda_g)$ - the susceptance introduced by the movable plunger,
B_R - susceptance resulting from abrupt change of height in the MPS waveguide, $B_R = 0.005$ S,
k_{T1} - the transformation factor of the tapered sections, $k_{T1} = Y_0/ Y_{01}$.

Taking into account the above relation, the normalized input admittance y_{in} takes the form:

$$y_{\text{in}} = \frac{1}{Y_{01}} \left(\frac{1}{\frac{1}{R_T} + \frac{1}{Z_a + \frac{\left(1 + B_S Z_b + B_R Z_b\right) Z_c}{1 + B_S \left(Z_b + Z_c\right) + B_R \left(Z_b + Z_c\right)}}} + Z_S \right)^{-1} \tag{2}$$

As seen from equation (2) the tuning characteristics P_R/P_I (l_S/λ_g) depends on the value of plasma impedance Z_P, which actually is unknown. The compilation of the measured and calculated tuning characteristics may result in finding the unknown electric parameters Z_P of the equivalent circuit.

4. Results and calculations

A three-dimensional simulation of the electromagnetic field distributions inside the part of the MPS were performed using Comsol Multiphysics software [7]. The performed simulation allowed to obtain the impedances Z_a, Z_b and Z_c as follow -j1.6 Ω, -j1.6 Ω and –j793.5 Ω, respectively.

Comparing the calculated tuning characteristics with that measured experimentally a good agreement has been found (Figure 4). The best fitting was obtained for parameters of the plasma impedance Z_P equal to Z_S = (69 - j271) Ω and R_T = 700 Ω.

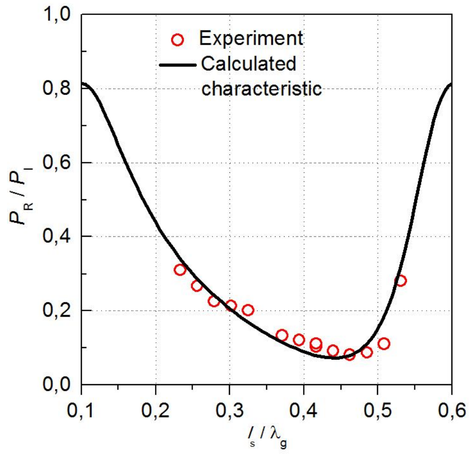


Figure 4. Comparison of measured and calculated tuning characteristics of the MPS.

The equivalent circuit allows to calculate the effect of a metallic diaphragm introduced in the input plane of the MPS which can lead to decrease the ratio of P_R/P_I. Determined reactance of plasma impedance parameter Z_S is capacitive (Im(Z_S) < 0). This indicates that in order to minimize the ratio of P_R/P_I a compensate induction diaphragm should be introduced to the MPS supplied waveguide. In this paper we analyze effect of the symmetrical induction diaphragm [5, 6] on the calculated tuning characteristics of the MPS. Using the presented equivalent circuit the most optimal gap d of the diaphragm and its positions were calculated. The criterion selected in the calculation was to provide a minimum ratio of P_R/P_I to the full extent of the movable plunger position. Sketch and diagram showing location of the diaphragm in the MPS input cross-section are presented in Figure 5, where B_D is susceptance induced in the waveguide by introducing the diaphragm [5, 6].

The calculations showed that the most efficient microwave energy transfer in the MPS was obtained for the gap width d = 150 mm and the distance L = 115 mm (Figure 6). In the calculations the estimated value of plasma impedance Z_P was used. The presented results of calculations allowed to increase efficiency of power transfer from electric field to the plasma, however, experimental confirmation must be performed.

Figure 5. Symmetrical induction diaphragm: a) sketch, b) diagram of location to the MPS input plane.

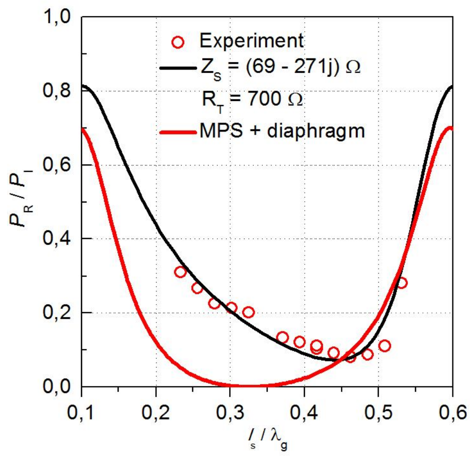


Figure 6. Measured and calculated tuning characteristics of the MPS including the diaphragm.

5. Conclusions

This work presents a version of the equivalent circuit correctly describing the properties of the MPS. A lossy two-port network, as countertype of the area of waveguide discontinuity with the discharge, was used. The proposed concept of the equivalent circuit of the MPS has a versatile properties and can be applied to other MPS structures.

The MPS presented in this paper showed a stable operation, although, optimization of this device is required. The presented investigations are the first step in optimization of the MPS. The aim of the next step will be finding, by numerical modeling, an optimal dimensions of the structural elements of this device which will ensure the minimum ratio P_R/P_I in the wide range of the movable plunger position.

Acknowledgments

We are grateful to The National Science Centre (programme no. 2013/11/N/ST8/00802) for the financial support of this work.

References

[1] Mizeraczyk J, Jasiński M, Nowakowska H and Dors M 2012 *Nukleonika* **57** (2) 241
[2] 1992 *Plasma technology, 4 Microwave Excited Plasmas* ed M Moisan and J Pelletier (Amsterdam: Elsevier) chapter 2 pp 11–52
[3] Weissfloch A 1942 *Hochfrequenz Tech.* **60** 67
[4] Hrycak B, Czylkowski D, Jasiński M and Mizeraczyk J 2012 *Electrical Review* **11b** (88) 310
[5] Sobański M, Lubański M, Jasiński M and Mizeraczyk J 2013 *Electrical Review* **5** (89) 254
[6] Panecki M, Litwin R and Drozdowicz L 1961 *Teoria i Technika Mikrofalowa* ed B Paszkowski and T Gawron (Warszawa: Wydawnictwo Naukowo Techniczne) chapter 2 pp 34–56
[7] http://www.comsol.com