Axis-Symetric Electromagnetic Modeling of Microwave Plasma Torch

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***Abstract*—This paper presents calculations of electromagnetic field distributions of microwave (2.45 GHz) plasma torches working at atmospheric pressure. Results are by using a two-dimensional numerical simulation tool that solves Maxwell's equations for an axis-symmetric TM mode. The electromagnetic field equations solved using a finite elements formulation. The tool is applied to a coaxial waveguide, a circular wave guide, and a plasma reactor operated by an axial injection torch (AIT).This reactor consists of a circular cavity powered by a coaxial waveguide assembled to a nozzel, and creates a micro-plasma that affects only very locally the electric field distribution.**

Keywords-micro-wave plasma; modeling; electric field; frequency.

I. INTRODUCTION

The electromagnetic (EM) modelling of microwave plasma source is of importance application, as it can contribute to the optimization of these devices [1].

Among the different types of microwave plasma torches, the axial injection torch (AIT) has been used for several years to create chemically active species, in applications such as gas analysis, surface processing, and gaseous waste treatments [2].

Developed by Moisan et al, AIT is coupling a rectangular waveguide to a coaxial excitation structure in order to obtain a Maximum outside this structure and thus create a plasma microwave field [3].

A micro wave plasma torch operating at atmospheric pressure is a promising tool for plasma chemical applications, such as e.g gas pollution control. A satisfactory model of the torch may help to explain its feature and provide plasma characteristics required for effective designing and operation of this device [4].

In the confined mode the plasma (AIT) is created within a quartz tube (transparent to microwaves), where the gas flows through an electromagnetic wave that settles generally in a cylindrical structure. This wave is a surface-wave, a plasma wave- mode which creates the plasma medium while it propagates along it. In the non-confined mode the plasma is created at the outlet of the nozzle that terminates a coaxial waveguide. The gas flows inside the inner metallic tube of the coaxial structure, where a TEM mode propagates, and the electromagnetic field couples to the plasma at the nozzle's exit, where the gas exhausts [2].

Our study is about the modeling of a AIT, to understand the distribution of its electromagnetic field. This paper presents a tutorial on the calculation of EM field distributions. We have developed a two dimensional (2D) simulation tool that solves Maxwell's equations for an axis-symmetric TM, by considering a frequency description.

II. GOVERNING EQUATIONS

The distribution of the electromagnetic field in the presence of plasma is calculated by solving the equation for the electric field E, derived from the laws of Maxwell-Ampere and Faraday [2], [5]:

$$\vec{\nabla}\times\vec{H} = \sigma\vec{E} + \frac{\partial(\varepsilon\vec{E})}{\partial t}\,. \quad (1)$$

$$\vec{\nabla}\times\vec{E} = -\mu\frac{\partial\vec{H}}{\partial t}\,. \quad (2)$$

E is the electric field [V/m], H is the magnetic field [A/m], ε is the permittivity [F/m], μ is the permeability [H/m] and σ is the conductivity of the medium [S/m].

By writing

$$\vec{E}(x,y,z,t) = \vec{E}(x,y,z)e^{j\omega t}\,. \quad (3)$$

And:

$$\vec{H}(x,y,z,t) = \vec{H}(x,y,z)e^{j\omega t}\,. \quad (4)$$

The two laws can be combined to obtain the electric field wave equation:

$$\vec{\nabla}.\left(\frac{1}{\mu_r}\vec{\nabla}\times\vec{E}\right) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)\vec{E} = \vec{0}\,. \quad (5)$$

where ε_r and μ_r are the relative permittivity and permeability, respectively, of the different media (vacuum and plasma); ε_0 is the permeability of vacuum; σ is the (plasma) conductivity; and

$$k_0 = \omega\sqrt{\varepsilon_0.\mu_0}\,. \quad (6)$$

is the wave-number in vacuum.

In these equations, the plasma is considered as a vacuum environment, having a conductivity due to free charges (electrons), i.e.For plasma:

$$\varepsilon_{rp} = 1 - \frac{\omega_p^2}{\omega^2\left(1 - \frac{j\nu}{\omega}\right)} . \quad (7)$$

$$\sigma_p = \frac{n_e e^2}{m_e(\nu + j\omega)} . \quad (8)$$

$$\mu_1 = 1 . \quad (9)$$

With:
$\omega = 2.\pi.\nu_{HF}$ and ν_{HF} =2.45GHz the microwave excitation frequency,

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}} . \quad (10)$$

is the plasma frequency (e and m_e are the electron charge and mass, respectively), and ν the electron-neutral collision frequency.

To propagate microwaves in a medium, its permittivity must be positive. For plasma, this implies that its frequency must be lower than the excitation frequency, which yields a critical (minimum) electron density (at 2.45 GHz) of :

$$n_c = \frac{\varepsilon_0 m_e \omega^2}{e^2} = 7.4 \times 10^{10}\,cm^{-3} . \quad (11)$$

III. NUMERICAL MODEL

A. Torch Geometry

The plasma is created at the outlet of the nozzle that terminates a coaxial waveguide (Fig. 1). The gas flows inside the inner metallic tube of the coaxial structure, where a TEM mode propagates, and the electromagnetic field couples to the plasma at the nozzle's exit, where the gas exhausts [2].

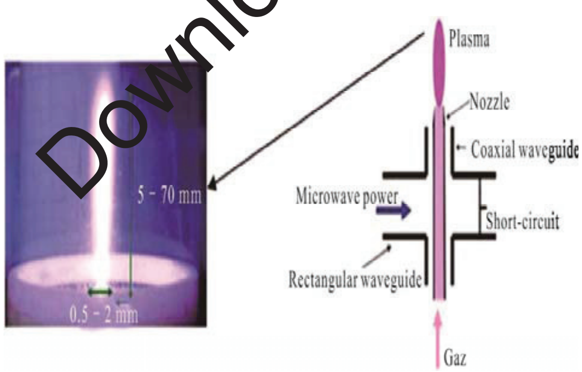


Figure 1. TIA design

The plasma was simulated in 2D axisymmetrical geometry. Fig. 1 represents the computational domain adopted.

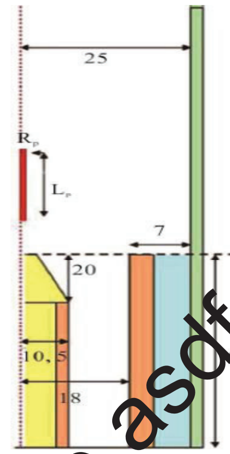


Figure 2. Computational domain

This figure adopted to solve the EM, showing the waveguide (brown), torch (yellow), the dielectric tube (green), Teflon (blue) and plasma (red). All dimensions are in millimeters and the diagram is not to scale. The plasma is located 1 mm above the nozzle.

So, the configuration of our system includes:

- Plasma ;
- Vacuum ;
- Quartz ;
- Metal waveguides (brass) ;
- Parts of Teflon.

The EM module uses the "rwf" mode from the Radio Frequency Module of COMSOL Multiphysics, which is solved at 2.45 GHz.

B. Boundary Conditions

The boundary conditions for the waveguide and the torch correspond to those of a perfect electric conductor, except for the input plane (P.E.) where the microwave power is supplied. At this boundary, a port condition for a rectangular mode TE10 is imposed. Moreover, this configuration is surrounded by typical PML Cartesian type regions, where scattering boundary conditions were assumed.

Below we will explain the various types of boundaries of the configuration under study and the corresponding conditions imposed to E_r and/or E_z [5-6].

- Symmetry boundary conditions (r = 0). The axial symmetry requires at the axis a homogeneous Neumann condition;

$$\frac{\partial E_z}{\partial r} = 0 . \quad (12)$$

- Perfect Electrical Conductors (PEC) boundary conditions. For metallic boundaries we assume that the E field component parallel to the surface is zero which demands for a homogeneous Dirichlet boundary conditions. For example at the inner conductor of the coaxial waveguide the condition reads ;

$$E_z = 0 \,. \qquad (13)$$

- Propagation boundary condition (PBC) for axial propagation. A homogeneous mixed boundary is used at the top-boundary positions.

$$\frac{\partial E_r}{\partial z} + i\beta E_r = 0 \,. \qquad (14)$$

Here β is the wave number of the wave. With this axial PBC, we assume that the EM energy leaves the domain in axial direction with a wave in the TM_{01} circular waveguide mode with wave number $\beta = \sqrt{k_0^2 - (p_{01}/R)^2}$, in which R is the radius of the circular waveguide, k the wave number of the medium, while p_{01} = 2.405 is the first zero of the Bessel function J_0 of first kind.

C. *Physical Proprieties*

The values of permittivity, permeability and conductivity of the various media used by the model are given in Table I

TABLE I. PHYSICAL PROPRIETIES

	ε_r	μ_r	σ (S.m^{-1})
Vacuum	1	1	0
Laiton	1	1	$1{,}57\times10^{7}$
Teflon	2.8	1	10^{-22}
Quartz	3.8	1	10^{-22}
Plasma	1	1	σ_p

IV. RESULTS AND DISCUSSION

Fig. 3 represents the computational domain adopted, where is discretized using a 2D triangular mesh.

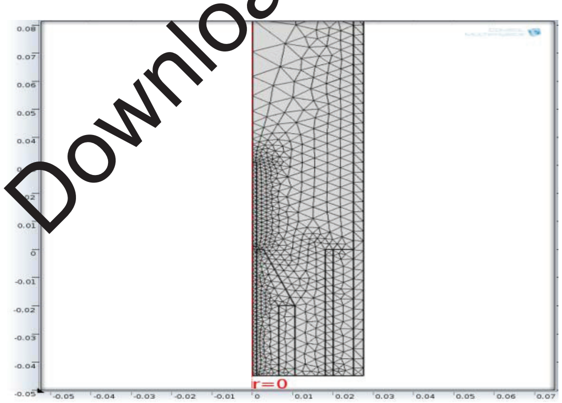


Figure 3. Triangular mesh used in our simulations

The mesh is refined at the outlet of the nozzle in and around the plasma. The number of cells was chosen to minimize the computation time without the results are not changed too. It is here in the order of 2773 elements.

A. *Calculation without Plasma*

Fig. 4 shows the distribution of the norm of the electric field in the computational domain. The incident microwave power is 500 W. The delivered frequency is 2.45 GHz.

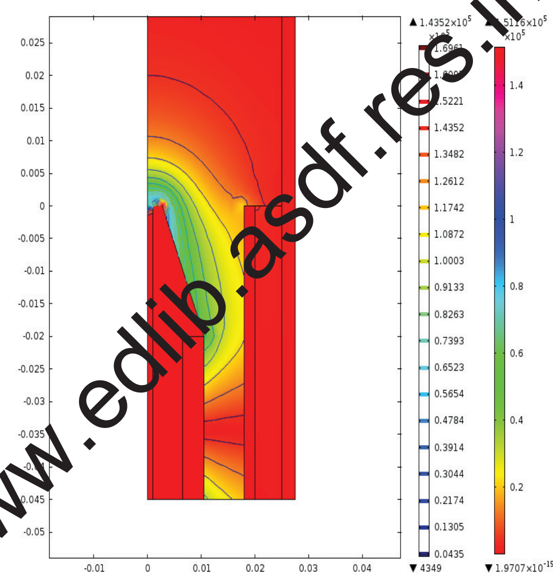


Figure 4. Distribution of the norm of the electric field

Fig. 4 shows the distribution of the electric field around the nozzle.

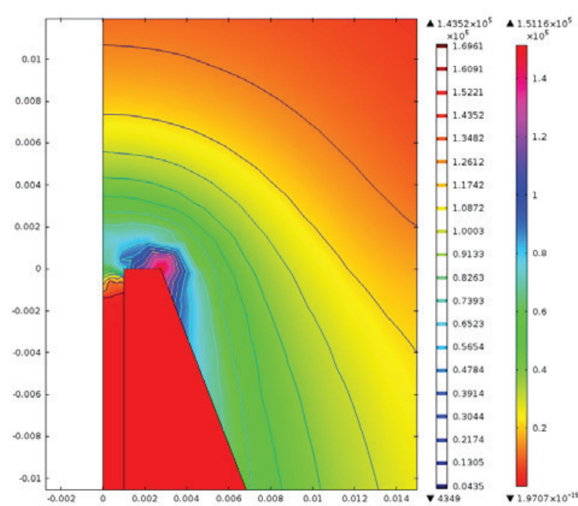
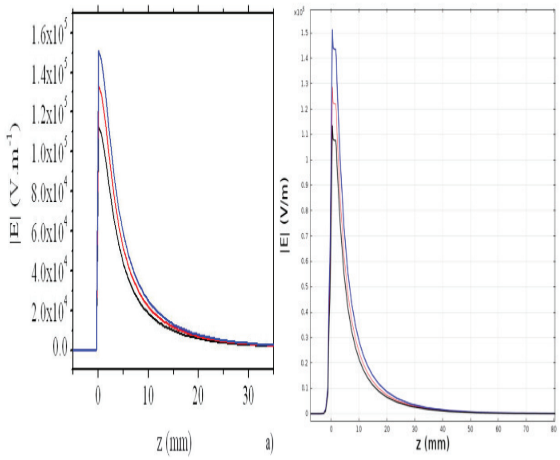


Figure 5. Distribution of the electric field around the nozzle

Here, we are interested on electromagnetic calculations without plasma, in order to get the field distribution to confirm that the maximum field is located at the nozzle. We Note that |E| decreases away from the nozzle.

In Fig. 6, we represent the norm of the electric field |E| on the axis (r = 0) for different incident microwave power.



(a) (b)

Figure 6. Norm of electric field |E| on the axis (r = 0 mm) for powers of 500 W (black curve), 700 W (red curve) and 900 W (blue curve). The frequency delivered is 2.45 GHz. (a) obtain with our calculations, (b) Obtain by [3]

We constate that the field increases with the initial microwave power. Else, Our simulation results are consistent with other author [3].

B. *Calculation with Plasma*

Now, we interest to the influence of plasma on the electromagnetic properties of the system. The microwave field interacts with the plasma by the input parameters: the permittivity and conductivity associated with the electron density of the plasma frequency and electron-neutral collision.

Fig. 4 shows the distribution of the norm of the electric field in the computational domain. The incident microwave power is 500 W. The delivered frequency is 2.45 GHz.

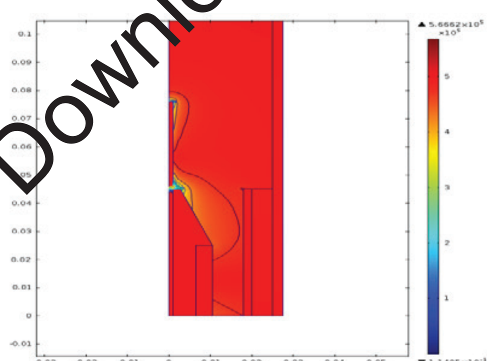


Figure 7. Distribution of the norm of the electric field

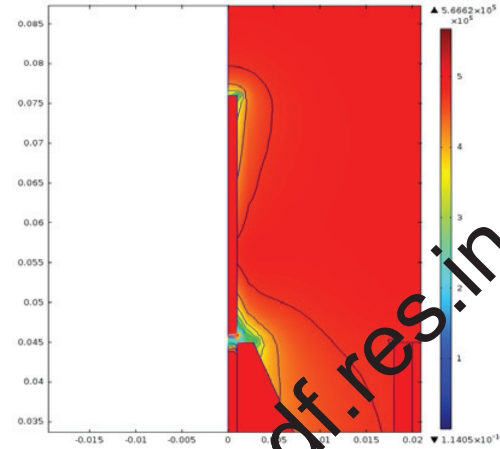


Figure 8. Distribution of the electric field around the nozzle

We constate at the distribution of |E| for the configuration in Fig. 7 Microwaves propagate in the plasma edge. The plasma acts as a propagation medium. This is possible because our electron densities are higher than the critical density. Else, by comparing Fig. 4 (without plasma) and Fig. 7 (with plasma), we observe that the first figure, the field propagation stops at the nozzle with radiation above. In Fig.8 , the progagation continues until the end of the plasma. it forms an extension of the coaxial structure.

V. Conclusion

The paper was aimed at an overview of the most important in a two-dimensional axisymmetric model of the microwave plasma was developed and used.

We have developed a 2D numerical simulation tool that solves Maxwell's equations for an axis-symmetric TM mode, by considering a frequency description. The tool was successfully used to calculate the EM field distribution with a coaxial wave guide, and a cylindrical plasma reactor operated by an AIT.

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