3D modeling of microwave plasma using Funer model

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Abstract: After previous microwave simulations [1] done with very hard assumptions, we improve the model by using Funer model [2] to improve prediction of plasma effects on the microwave coupling. Some parameters are still not well known and are used as adaptation parameters. An experience plan technique is used to find these parameters by comparison of experimental measurements of reflected power to simulated values. The results show quite good agreement with 4 experimental values of a real industrial example. Of course this rough comparison has to be followed by other comparisons with experimental measurements and model improvement for plasma chemistry aspects, but is a good starting point for microwave system simulation.

Keywords: EM simulation, plasma, coupling.

1. Introduction

As emphasis in our article [1] for COMSOL 2007 conference, one of the technological problems to be overcome when using microwave plasma for process or equipment R&D is the instability of the coupling between EM source and the plasma. When the antenna is not well adapted to the plasma the reflected power increase and the plasma shut down. One way to get a good power transfer is to simulate microwaves propagation in the 3D cavity and the coupling with the plasma to estimate the reflected power. An efficient model to predict the adaptation may be interesting, but this is also for us a way to check our ability to simulate microwave propagation..

The presented work use a Funer model [2] to take in account plasma effect on microwaves propagation. As previously the results are shown for an academic geometry but the study was done for an industrial application. The reflected power obtained by simulation is compared to measured reflected power for four working points with a nitrogen plasma. The sensitivities of the model to many parameters were characterized. Over all the uncertain parameters, only two have an strong effect on the results : the “gamma” parameter of Funer model and the electron – neutral collision frequency. We study the response surfaces for reflected power to these two parameters. We determine the part of the DOE in which the agreement between calculated and measured reflected powers is good for the four working points. This thin part cross the line were the collision frequency correspond to a nitrogen plasma.

In other word, only one parameter of the model is not known. And after setting this parameter we obtain a good agreement with experimental results for four working points.

2. Models

2.1 Geometry

The validation of this type of simulation was performed by comparison with an industrial case which cannot be illustrated here. The results are presented for a common simplified geometry (Figure 1). From bottom to top of the figure 1 we can see the coaxial connection, the antenna zone with stubs to adapt the antenna impedance, the plasma zone, the gas inlet and pumping.

The position of the stubs are the same as the experimental working points. Four experimental working points were simulated (see chapter methodology) corresponding to four set of position of the three stubs and to four values of the reflected power.

2.2 Electromagnetic Model

The model used is the “rwf” mode from RF module of COMSOL MULTIPHYSICS. The 3D model with harmonic propagation is solved at 2.45GHz. The permittivity and conductivity depends on electron density which is calculated by plasma model. They also depends on collision frequency of gaseous (here pure nitrogen) which depend on neutral temperature.

Then we also solve classical Navier Stokes model coupled with thermal conduction – convection to estimate temperature.

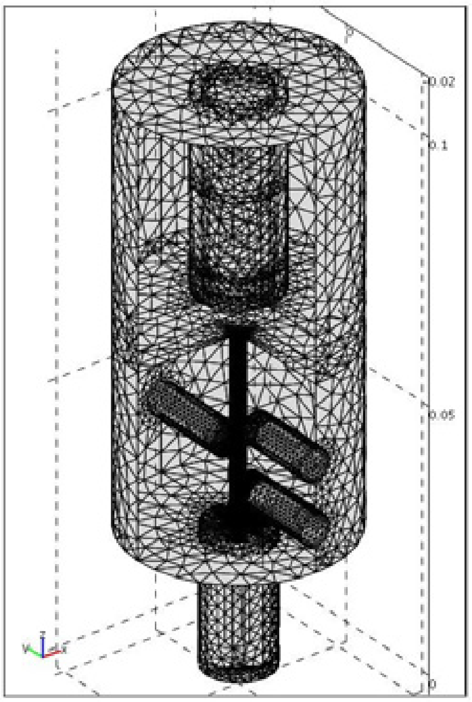

Figure 1. Mesh used for the EM simulations.

2.3 Plasma model

In the present study the electron density is solved from Funer model:

$$\nabla(-D_e \nabla n_e) = \gamma . (E - E_M) + n_{emin}$$

with :

- De the electronic diffusion,
- gamma the Funer coefficient,
- Em the smaller maintenance field
- n_{min} the minimal electronic density.

The electronic temperature is assumed to be constant, then the electron energy conservation is not solved.

2.4 Boundary conditions

The boundary used was "perfect electric conductor" everywhere except where rf power are injected. In this case, we use port conditions with a coaxial shape. Using assembled geometries and identity pair on the corresponding boundary allow easily to compute the input power and the reflected power inside the coaxial cable.

The boundary condition for the electronic density are Neumann without flux near the plasma zone, and n_{min} elsewhere.

2.5 Electromagnetic Properties

In order to obtain accurate results, we need to supply good plasma values. The permittivity relies on:

$$\epsilon_r = 1 - \frac{\omega_{pe}^2}{\nu_{eN}^2 + \omega^2} + i . \frac{\omega_{pe}^2 . \nu_{eN}}{\omega(\nu_{eN}^2 + \omega^2)}$$

where w_{pe} is the plasma frequency, w the excitation frequency, and ν_{en} the electron-neutral collision frequency, which can be approximated from experimental values.

The conductivity are:

$$\sigma = \frac{\epsilon_0 . \omega_{pe}^2 . \nu_{eN}}{\nu_{eN}^2 + \omega^2} + i . \frac{\epsilon_0 . \omega_{pe}^2 . \omega}{\nu_{eN}^2 + \omega^2}$$

The microwave will propagate if the permittivity is positive, i.e if the plasma frequency is lower than the excitation frequency. In the other case, plasma will act as a conductor. The critical electronic density, for a 2,45GHz microwave will be:

$$n_{ec} = \frac{\epsilon_0 m_e \omega^2}{q_e^2} = 7,4.10^{16} (m^{-3})$$

3. Methodology

The parameters which are not known data are gamma, Em, nmin three parameters of the Funer model. To reduce these unknowns and check this approach precision, we compare the reflected power calculated by the model to measurements. We use a DOE (Design Of Experiments) technique [3] to check the parameters influence and find an optimum by comparison to four experimental working points. The collision frequency can be roughly estimated for nitrogen but we prefer to include it in the DOE works.

In a first step we use a DOE for all not well known parameters: Em, n_{min} , gamma, and $\nu_{en.}$ and we find that the sensibility to Em and n_{min} is very small. Then we perform a precise DOE on the four working points to find the optimum values of gamma (from Funer model) and $\nu_{en.}$.

4. Results

The whole model (EM + plasma + fluid + thermic) was solved for every points of the numerical DOE. The presented results correspond to the optimum point which is :

- gamma = 10^{23}.
- $\nu_{en.}= 10^{10}$

obtained from comparison with the four working points.

The comparison between experiments and calculation for these for working points and for the optimum parameters is given on figure 2. The input power were the same for the four cases as for the four experimental working points. The four reflected power, obtained with the same stub positions

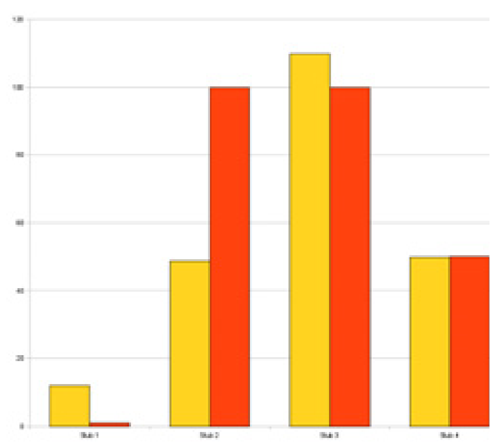

Figure 2. Compared reflected power from measure on industrial equipment and simulation for the model including Funer model for electron conservation, for four working points

We see on the figure 3 the electron density in a plane crossing the plasma zone. The nitrogen gas come from the upper side flow through the plasma zone (yellow part with high electron density) and then flow out all around across some holes. The microwave antenna is in the bottom of the figure.

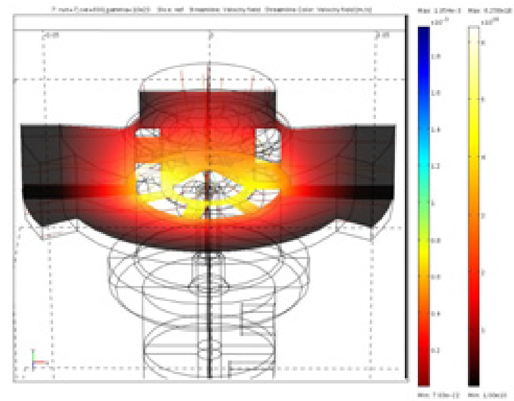

Figure 3. Electron density in the plasma zone for the optimum parameters. The yellow area correspond to the plasma with a maximum density of 6.26e18 m^{-3}.

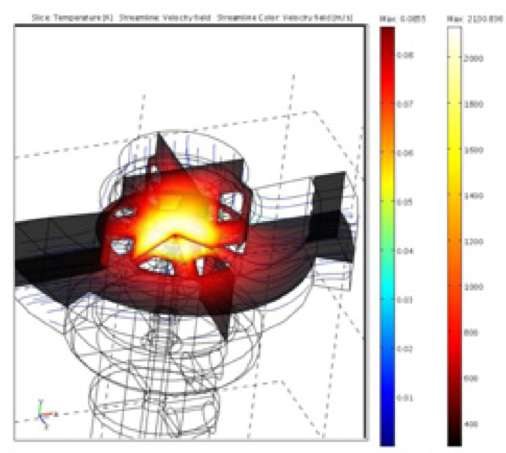

Figure 4. Neutral temperature (K) for the optimum parameters.

The figure 4 show the neutral temperature of the gas flow around the plasma zone. This temperature has a influence on the results because of the dependency of the collision frequency to it.

6. Conclusions

The adaptation cavity of an industrial nitrogen plasma equipment has been simulated in 3D using COMSOL MULTIPHYSICS RF module coupled with Funer model. The Funer model gamma parameter and the collision frequency have been settled by a DOE technique from measurements of the reflected power for four experimental working points. The results show a good fitting between simulated and measured reflected power, and the optimum electron neutral collision frequency corresponds well to nitrogen value. with optimum parameters and measurements.

This approach may be use for cavity design or tuning prediction, but work point of the plasma has to be known. It may be tested for more complex plasma chemistry. A coupling with derive diffusion models is also under development but has to be compared to experimental data.

7. References

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