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Modelling and Simulation of Radio-Frequency Inductively Coupled Plasma Torch at Low Pressure

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***Abstract*— A numerical model of radio-frequency (RF) discharge is developed to simulate the electromagnetic field, fluid flow and heat transfer in an inductively coupled plasma torch working at low pressure for argon plasma. This model will be of fundamental importance in the design of the plasma magnetic control system. Electric and magnetic fields inside the discharge chamber are evaluated by solving a magnetic vector potential equation. To start with, the equations of the ideal magneto-hydrodynamics theory will be presented describing the basic behaviour of magnetically confined plasma and equations are discretized with finite element method in cylindrical coordinates. The discharge chamber is assumed to be axially symmetric and the plasma is treated as a compressible gas. Plasma generation due to ionization is added to the continuity equation. Magnetic vector potential equation is solved for the electromagnetic fields. A strong dependence of the plasma properties on the discharge conditions and the gas temperature is obtained.**

Key words: Argon plasma, low pressure ICP torch, RF generator.

I. INTRODUCTION

Inductively coupled plasmas (ICPs) are used in a wide range of industrial applications such as semiconductor processing, high purity silica synthesis, Nano-powder synthesis, spectrochemical analysis or recent developments in the silica purification process for photovoltaic applications [1]. Numerical modelling is a useful tool to understand phenomena in plasmas. The first one dimensional models were developed in the late 1960 with the aim to calculate the radial temperature profiles [2]. A gas is injected in a swirling, annular way into a heat-resistant quartz tube surrounded by an inductor the plasma is formed within and/or above a set. A radio-frequency electric current runs through the inductor and induces a secondary current through the gas inside the tube, which heats up by means of ohmic dissipation.

During the past few decades there has been growing interest in modelling and simulation for the ICP torch of low-temperature, weakly ionized and high-density RF plasma. At present, plasma simulation is becoming the significant technology in developing new equipment and improving process control schemes in semiconductor industries [3,4]. An accurate plasma discharge model will therefore be a very helpful tool in predicting the processing procedure, designing the configuration, and even optimizing the operation parameters of plasma tools. Since the success of a given process depends directly on the plasma temperature and velocity fields in the discharge and/or in the jet, which in turn depend on the geometric and operating parameters of the system, the characterization of the torch and the knowledge of the influence of such parameters on the plasma properties are of primary importance. The numerical simulations of low-thermal plasmas tend to be unstable and require effort to stabilize the computations, which must take into account the large variations in the density and properties of the thermal plasma despite its incompressible state. So, mathematical and numerical models of the RF-ICP have advanced to a considerable degree. That's why a large effort has been devoted to the mathematical and numerical analysis of the temperature or the flow fields in the inductively-coupled RF plasma in the steady state, continuous mode.

In this ICP torch of process, the electrons receive energy from the induced magnetic field produced by a coil that generates a nominal frequency oscillation of 3MHz. The numerical simulation techniques commonly used for simulating low-temperature plasma discharge mainly include fluid dynamic, kinetic and hybrid models. Although the kinetic and hybrid models are commonly considered more precise. The fluid model is also able to maintain computational accuracy even at very low pressure.

II. DESCRIPTION OF THE MODEL

The plasma model contains 4 species, in particular Ar, Ar+, Ars and electrons. The reactions that were considered, along with references, are shown in table 1.

Reaction	Formula	Type	Δε(eV)
1	$e + Ar \rightarrow e + Ar$	Momentum	0
2	$e + Ar \rightarrow e + Ars$	Excitation	11.56
3	$e + Ar \rightarrow 2e + Ar^{+}$	Ionisation	15.80
4	$e + Ars \rightarrow e + Ar$	Super elastic	-11.56
5	$e + Ars \rightarrow 2e + Ar^{+}$	Ionisation	4.24
6	$Ars + Ars \rightarrow e + Ar + Ar^{+}$	Penning ion	0
7	$Ars + Ar \rightarrow Ar + Ar$	Quenching	0

TABLE 1.IMPORTANT COLLISION PARAMETERS IN THE ARGON DISCHARGE.

For electrons, a Maxwellian distribution is assumed. This is an appropriate assumption while the electron energy is lower than 15 eV at low pressures. The symbols "Ar+"," Ars", and "e" denotes positive ions, metastable atoms and electrons respectively. The neutrals atoms, refer to metastable atom to this model, are not of electric charge, and they are completely unaffected by the electromagnetic force.

A. Domain Equations

The simulations were performed by argon plasma with the assumptions of axial symmetry, optically negligible viscous dissipation. The governing equations used are as follows:

1) Electromagnetic equations

In solving electromagnetic field equations could be used the Maxwell's equations ,in the case of two-dimensional axisymmetric ICP model, where these have been reduced in the form of the magnetic vector (A), and thus the distribution of the electromagnetic field is obtained :

$$(j\omega\sigma - \omega^2\epsilon_0\epsilon_r)A + \nabla \times H - \sigma v \times B = J_e \qquad (1)$$

$$B = \nabla \times \mathrm{A} \qquad (2)$$

$$\nabla.\mathrm{D} = \rho_v \qquad (3)$$

$$E = -\nabla \mathrm{V} \qquad (4)$$

The plasma model solves the continuity equations for electrons ions, and excited species in the form:

$$\frac{dn_e}{dt} + \nabla.\Gamma_e = R_e(u.\nabla)n_e \qquad (5)$$

$$\frac{dn_e}{dt} + \nabla.\Gamma_e + E.\Gamma_e = S_{en} - (u.\nabla)n_e + \frac{Q+Q_{gen}}{q} \qquad (6)$$

Where: $n_e$is the electron density, $\Gamma_e$is the electron flux, u is the flow velocity (considered the same for all species).

2) Flow field equations

The single-phase fluid flow model in the laminar regime governed by the Navier-Stokes equation:

$$\rho(u.\nabla)\mathrm{u} = \nabla.\left[-\rho \mathrm{I} + \mu(\nabla \mathrm{u} + (\nabla \mathrm{u})^T) - \frac{2}{3}\mu(\nabla.\mathrm{u})\mathrm{I}\right] + \mathrm{F} \qquad (7)$$

$$\nabla.(\rho \mathrm{u}) = 0 \qquad (8)$$

3) Temperature equation

The Heat Transfer in Fluid node adds the heat equation for convective and conductive heat transfer in fluids. The heat equation takes the form:

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p \mathrm{u}.\nabla \mathrm{T} = \nabla.(\mathrm{k}\nabla \mathrm{T}) + \mathrm{Q} + Q_{vh} + W_p \qquad (9)$$

Where: k is the thermal conductivity, $C_p\rho$ is the volume mass.

B. Torch geometry

The scheme of plasma torch used is shown in Fig. 1. A summary of the dimensions of the torch and the operating conditions are given in Table 2. The gas used was pure argon at a pressure of 1Torr.

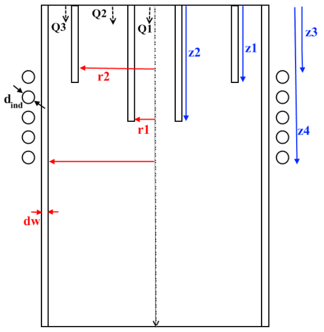
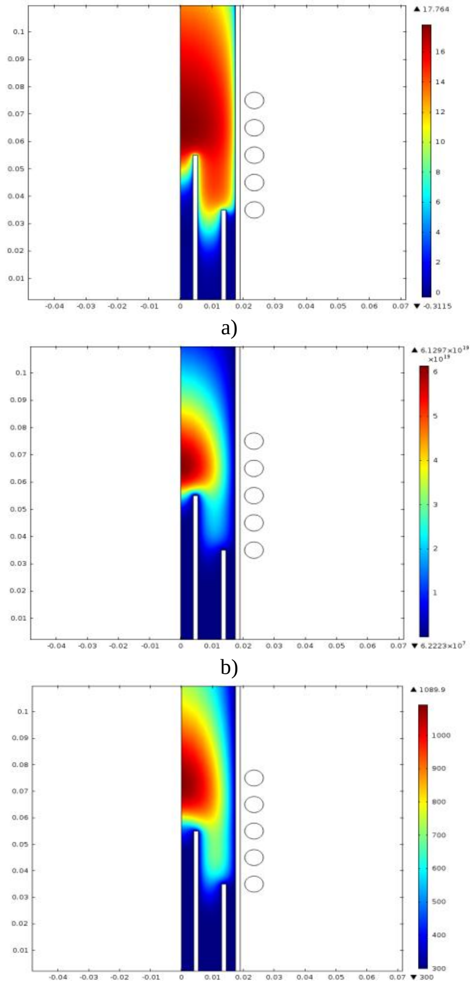


Fig. 1. Torch geometry

d_0 =0.0982 m	d_c =0.03m	d_{ind}=0.006 m	d_w=0.0015 m
Z_1=0.035 m	Z_2 =0.055 m	Z_3=0.032 m	Z_4 =0.078 m
Q_1=1.74×10^{-3} Kgs^{-1}	Q_2 =1.74×$10^{-3}$$Kgs^{-1}$	Q_3=$10^{-4}$$Kgs^{-1}$	

TABLE 2. PRINCIPAL DIMENSIONS OF THE TORCH

The numerical simulation is carried out by using the finite element method based on COMSOL software. The modelling results are presented with the models described in [5].

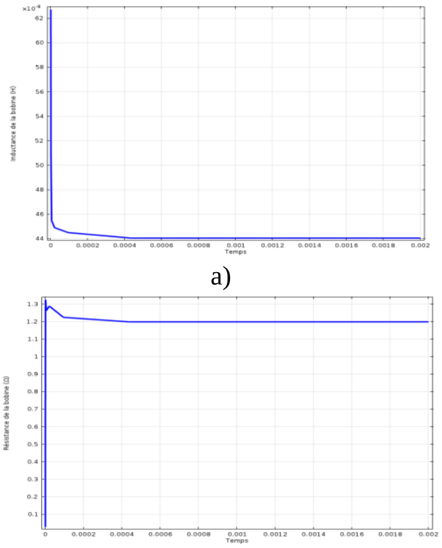


a)

b)

c)

Fig. 2. ICP torch a) electric potential, b) electronic density and c) the temperature



a)

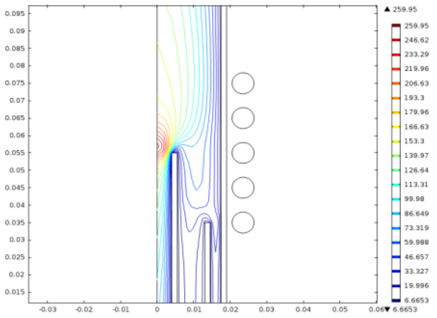
a)

Fig. 3. ICP coil: a) inductance and b) resistance.

Fig 2 and Fig 3 shows the distributions of: the ICP torch electric potential, electron density the torch temperature, ICP coil inductance and ICP coil resistance repartition is represented on the Fig 2 and Fig 3.

The discharge inductance consists of two components, the geometrical (or magnetic) inductance, due to the discharge current path and the electron inertia inductance (L_e) which follows from the complex nature of plasma conductivity [6,7]. The plasma resistance is very difficult to know accurately because it depends on both the characteristics of the generator electric circuit (R_{self}), composition and the diameter of plasma (R_{plasma}), diameter and number of turns of the inductor ($R_{inductor}$), and the resistance of the applicator (quartz tube) (R_{wall}). The study of the variation (R) as a function of all electrical parameters of the circuit shows that this value is between 0.1 and 1 Ohm [6].

The fig 4 illustrates some mechanical characteristics of the ICPT such as the velocity contours and the Lorentz forces on the gas flow.



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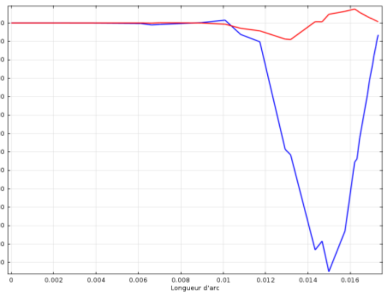


b)

Fig. 4. a) Velocity contours and, b) Lorentz force contributions.

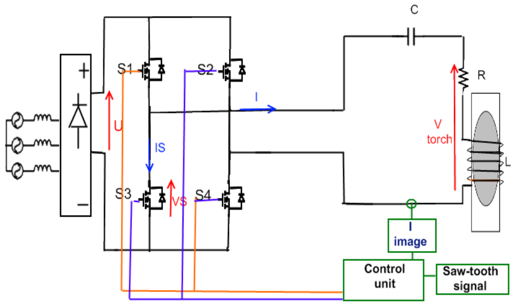


Fig. 5. Principle and configuration of plasma generator

The operating principle of a low-temperature plasma generator is given by fig 5, such a high-frequency power supply connected between its high-frequency output terminal and a series-resonant load. The discharging conditions of the low-temperature plasma are strongly affected by gas pressure and flow speed, temperature, and so on.

Before the plasma flames up, a low-voltage and large-current rating is required for the high-frequency power supply, while a high-voltage and medium-current rating is needed to sustain the generated plasma during the discharge. The plasma is considered as a non-linear electrical object in a macro time scale; that is, its impedance averaged during the RF cycle is the function of the power delivered to the plasma. [8]

To define the resonant frequency, the characteristic: impedance versus frequency is on the Fig 6. It’s improving exactly this frequency (3MHz) corresponding to the smaller value of impedance the phase of impedance is zero (the load is purely resistive).

III. LOAD ANALYSIS

The load of the ICP torch and excitation coil can be modeled by a series combination of the equivalent resistance R and inductance L [9]. These parameters depend on several variables, including the shape of the excitation coil, the distance between the torch and the coil, the temperature generated by the torch, its electrical conductivity and magnetic permeability, and the applied frequency. Indeed, the load seen by the RF source is purely inductive with low resistance. Requires compensation by a capacitor selected according to the property of the resonant frequency, which is utilized to minimize the resonance electric stress on semiconductor switches. Consequently, the resonant frequency is: $f_0 = 1/2\pi\sqrt{LC}$. This allows in particular a natural switching operation beyond the resonant frequency, therefore the use of transistor switches (MOSFETs) while minimizing the harmonics of the output signal. In which the impedance Z is given by:

$$Z = R\big(1 + j(\omega_c/\omega_r - \omega_r/\omega_c)\big) \tag{10}$$

Where: ω_c : The switching pulse.
ω_r : The resonance pulsation.
As: $\omega_c = \omega_r$: the impedance Z becomes purely resistive.

If one introduces the factor of quality:

$$Q = L\omega_r/R = 1/RC\omega_r \tag{11}$$

Then:

$$Z = |Z|\angle\Phi_i \tag{12}$$

And:

$$\Phi_i = tan(\omega_c/\omega_r - \omega_r/\omega_c) \tag{13}$$

The voltage across the load is shaped slots frequency f that can be associated with pulsation $\omega = 2\pi f$. The current response to this will be that much closer to the sine wave (quasi-sine) thatω is close ω_r. The Fourier series decomposition of the input voltage, V_1 brings up the fundamental, makes to the fundamental V_f appear as:

$$V_f(t) = (4V_1/\pi|Z|)\sin(\omega t) \tag{14}$$

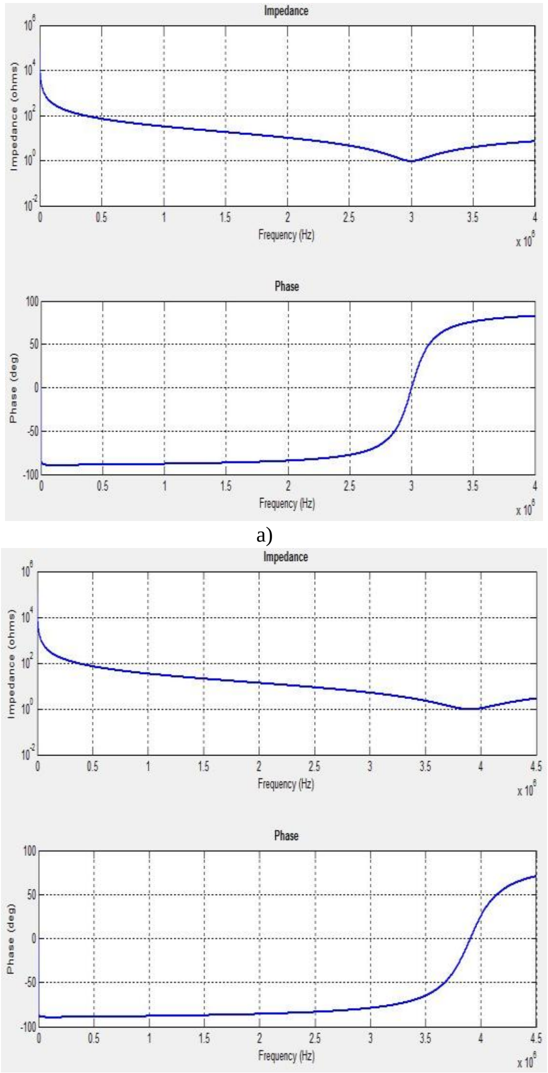
For: $0 \le \omega t \le 2\pi$
The current that it corresponds is:

$$I_f(t) = (4V_1/\pi|Z|)\sin(\omega t - \Phi) \tag{15}$$

Once it is accepted that resonant converters are suited for high frequency operation, the next challenge is implementing a control strategy that meets the requirements of the application without degrading the merits of the converter. As illustrated on the figure 3 a), the inductance value was drop from 627.10-^{9} Henry, before the ICPT flames up, to 440.10-^{9} Henry, after the ICPT flames up, to define the resonant frequency; the characteristic: impedance versus frequency is on the Fig.5. It's improving exactly this frequency corresponding to the smaller value of impedance the phase of impedance is zero (the load is purely resistive). So, one can find 3MHz from the first point (627.10-^{9} Henry) Fig 6.a), and fig 6.b) corresponds to the final point (440.10-^{9} Henry).

The schematics of plasma generator, the voltage and current waveforms in the load circuit (RLC) are shown on the Fig.7. Both the discharge current and voltage are predominantly sinusoidal. Therefore one applied a voltage of 400V in the shape of gap (shifted gate control); one recovers a quasi-sinusoidal voltage, across the coil L, nearly to 4kV (as improved on the Fig.8) sufficiently high.

So, the accelerated electrons give rise to the ionization collisions. The current flowing through the transfer circuit is very intense in order to generate the magnetic field in demand to excite the plasma and assure a high plasma power (Fig.8). Simulation results of the current waveforms through the chopper (MOSFETs) circuit shown in Fig 9, so the commutations are so smooth.

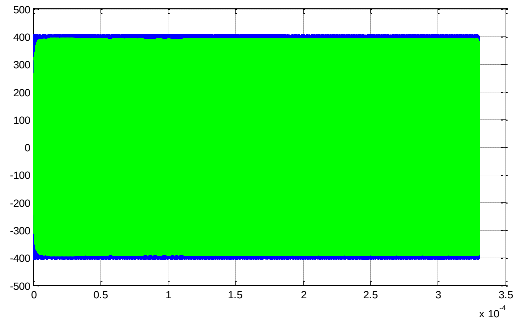


a)

b)

Fig.6. Variation of impedance and impedance phase according to the frequency

The results in Fig 10, improve that the active power consumed by the torch but the reactive power was null due to the resonant mode (that means that the load was purely resistive). And the reactive power noted on the beginning of the curve is due to the impedance variations.



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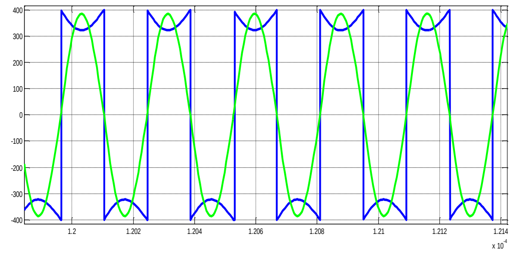
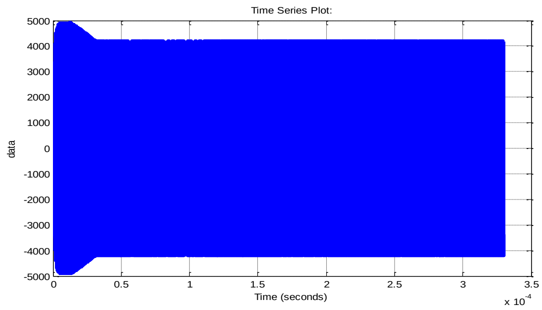


b)

Fig.7. RLC load a) current and voltage wave forms b) zoom in current and voltage wave forms.



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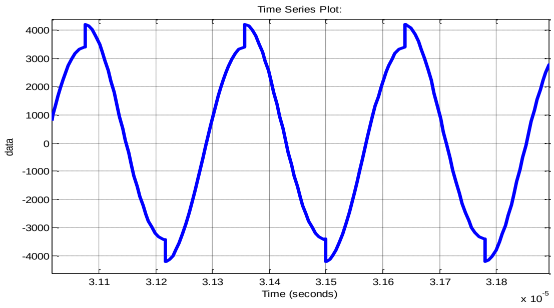

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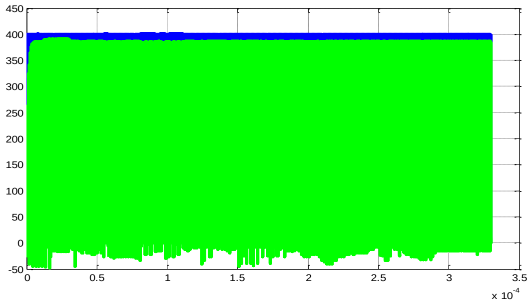
Figure 8: a) The ICP torch voltage, b) Zoom in.



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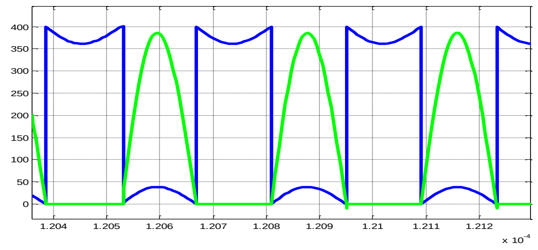

b)

Fig. 9. Switcher (MOSFET (S1)) a) voltage and current wave forms b) Zoom in.

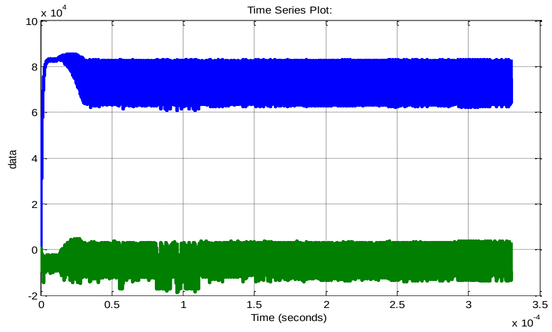

Fig.10. Active (bleu) and reactive power consumed by the load

IV. CONCLUSION

This article describes new model plasma with his party in radio frequency control for optimization. The found results clearly show the behaviour of the low pressure argon discharge in non-thermal equilibrium plasma.

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