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Modeling and Simulation of Inductively Coupled Plasma (ICP)

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Abstract— — **The purpose of this paper is to present a simplified model of inductively coupled plasma (ICP). The study of the effect of parameters such as current and number of turns in the coil is simulated using Comsol Multiphysics 3.5 by applying the fluid dynamic models that are generally appropriate for the investigation of inductively coupled plasmas.**

Keywords—— ***Thermal Plasmas, Inductively Coupled Plasma (ICP), Electron Continuity Equation, Argon.***

I. Introduction

Thermal plasmas have nowadays a large range of industrial applications including: cutting, welding, spraying, waste destruction and surface treatment. Thermal plasmas are assumed to be under partial to complete local thermodynamic equilibrium (LTE) conditions. Under LTE, the plasma can be considered a conductive fluid mixture and therefore, be modeled using the magnetohydrodynamics (MHD) equations,[1]. This model shows how to use the equilibrium inductively coupled discharge interface to simulate the plasma generated in an inductively coupled plasma,[1]-[2].

The main objective of this work is to investigate: the effect of Increasing number of turns in a coil and the effect of electrical current both on the plasma temperature distribution, and the electron density of the argon plasma

II. FORMULATION OF PLASMA FLUID MODEL

The plasma fluid model developed in this work resolves electron continuity equation, electron energy equation and Poisson's equation [3]-[4]:

Electron equation::

$$\frac{\partial n_e}{\partial t} + \nabla.\Gamma_e = R_e - (u.\nabla)n_e \quad (1)$$

$$\Gamma_e = -(\mu_e.E)n_e - D_e.\nabla n_e \quad (2)$$

Electron energy density equation:

$$\frac{\partial n_\varepsilon}{\partial t} + \nabla.\Gamma_\varepsilon + E.\Gamma_e = R_\varepsilon \quad (3)$$

$$\Gamma_\varepsilon = -(\mu_\varepsilon.E)n_\varepsilon - D_\varepsilon.\nabla n_\varepsilon \quad (4)$$

Poisson's equation:

$$E = -\nabla V \quad (5)$$

Where n_e denotes the electron density (1⁄m^3), R_e is the source term (electron rate expression) in unit (1⁄(m^3.s)), U is the electronic speed vector (m/s), Γ_e is the electron flux (1/(m^2.s)), μ_e is the electron mobility (m^2/(V.s)), E is the electric field (V/m), D_e is the electron diffusivity (m^2/s), n_ε denotes the electron energy density (V/m^3), R_ε is the energy loss/gain due to inelastic collisions (V/(m^3.s)), Γ_e is the electron energy flux (1/ (m^2.s)), μ_ε is the electron energy mobility (m^2/(V.s)), D_ε is the electron energy diffusivity (m^2/s) and V is the electric potential (Volt). The following relationships hold [4] for Maxwellian electron energy distribution function:

$$D_e = \mu_e T_e \quad (6)$$

$$D_\varepsilon = \mu_\varepsilon T_e \quad (7)$$

$$\mu_\varepsilon = (\frac{5}{3})\mu_e \quad (8)$$

Te is the electron temperature (eV) depending on the mean electron energy, it is defined as:

$$\bar{\varepsilon} = \frac{n_\varepsilon}{n_e} \quad (9)$$

$$T_e = (\frac{2}{3})\bar{\varepsilon} \quad (10)$$

The electron source is defined as:

$$R_e = \sum_{j=1}^{M} x_j k_j N_n n_e \quad (11)$$

Where x_j denotes the mole fraction of the target species for reaction j, K_j is the rate coefficient for reaction j (m^3⁄s) and Nn is the total neutral number density (1⁄m^3). The energy loss is defined as:

$$R_\varepsilon = \sum_{j=1}^{M} x_j k_j N_n n_e \Delta\varepsilon_j \quad (12)$$

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Where $\Delta\varepsilon_j$ is the energy loss from reaction j(eV).The collision rate k_k is the collision frequency per unit density of electrons with gas atoms [4]:

$$k_k = y\int_0^{\infty} \varepsilon\sigma_k(\varepsilon) f(\varepsilon) d\varepsilon \qquad (13)$$

Where $Y = (\frac{2q}{m_e})^{1/2}$ in unit$(C/kg)^{1/2}$; m_e is the mass of the electron (kg), ε is the energy (eV), σ_k is the collision cross section, and $f(\varepsilon)$ is the electron energy distribution function (EEDF)

III. PLASMA CHEMISTRY

Argon is one of the simplest mechanisms to implement at low pressures. The electronically excited states can be lumped into a single species which results in a chemical mechanism consisting of only 3 species and 7 reactions:

Table 1
Table of collisions and reactions modeled [5]

Formula	**Type**	**Δε(eV)**
e+Ar=>e+Ar	Elastic	0
e+Ar=>e+Ars	Excitation	11.5
e+Ars=>e+Ar	Superelastic	-11.5
e+Ar=>2e+Ar+	Ionization	15.8
e+Ars=>2e+Ar+	Ionization	4.24
Ars+Ars=>e+Ar+Ar+	Penning ionization	_
Ars+Ar=>Ar+Ar	Metastable quenching	_

IV. DESCRIPTION OF THE MODEL

The reactor geometry is simply a cylindrical glass tube with a 4 turn coil wrapped around it. Gas flows in from the bottom and exits out of the top. The gas is heated through elastic and inelastic collisions. The inelastic collisions are responsible for the bulk of the gas heating. A fixed power of 700 W is applied to the coil.

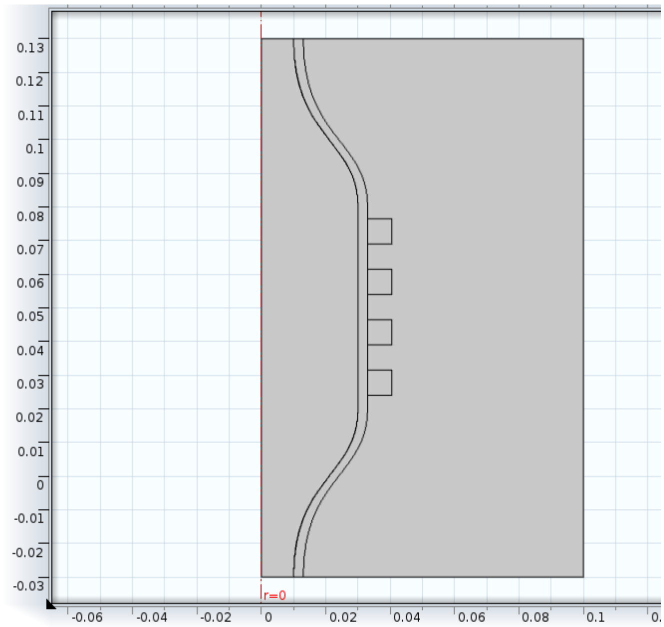

Figure 1: Schematic of the ICP reactor. Flow enters from the base and leaves out the top.

V. RESULTS AND DISCUSSION

Figure 2, and Figure 3 respectively shows the plasma temperature distribution, and velocity magnitude of the argon plasma after 0.01 s.
Figure 4 displays the electron density after 0.01 s

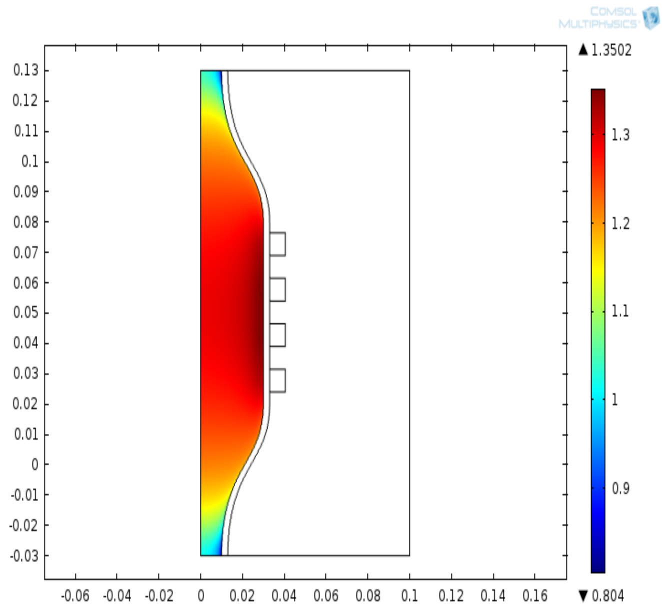

Figure 2: Plot of the electron temperature inside the plasma source.

It is clear that the maximum temperature is not located in the center of the torch but is a bit far from the center.

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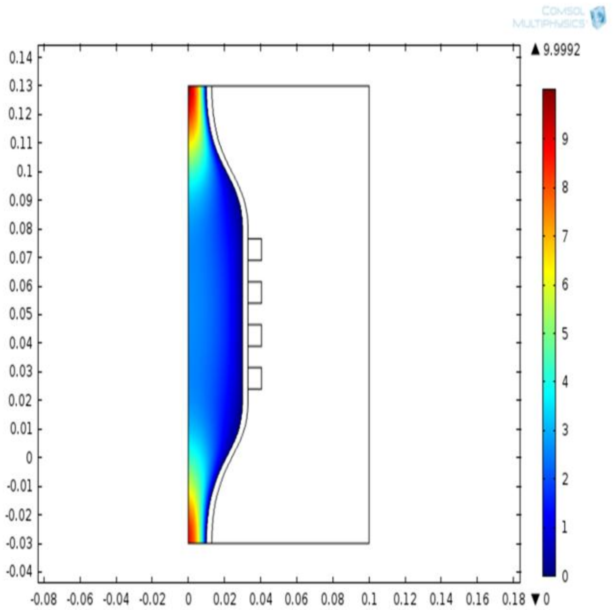


Figure 3 : Plot of the velocity field.

According to the visualization of the distribution of the velocity over time (figs above), it is noted that the movement of gas in the discharge is directed downstream (exit) in the plasma and is directed upstream (entrance) in the axial region

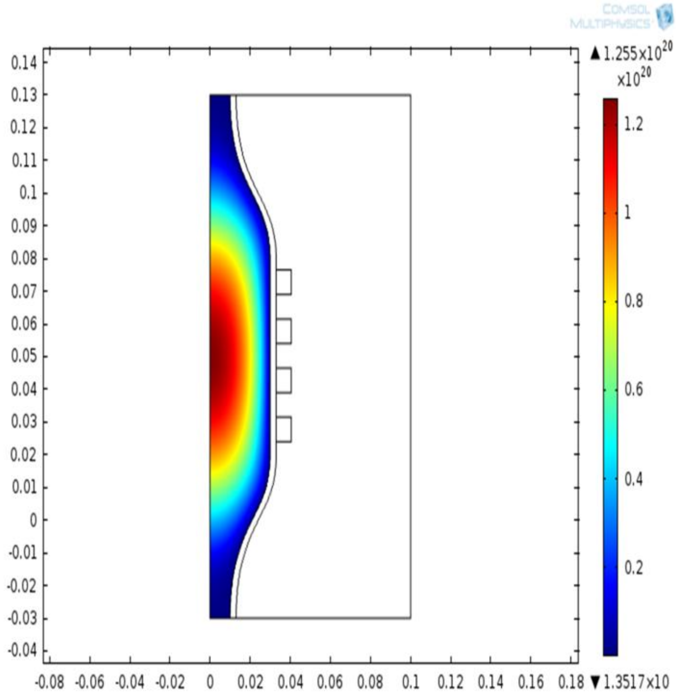
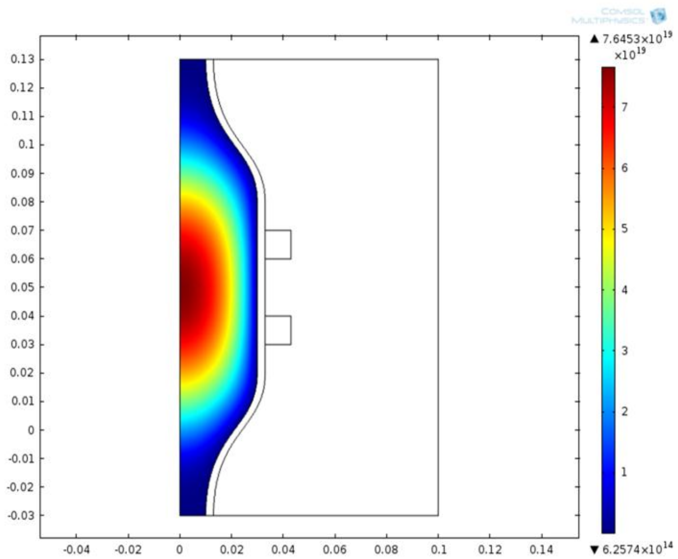


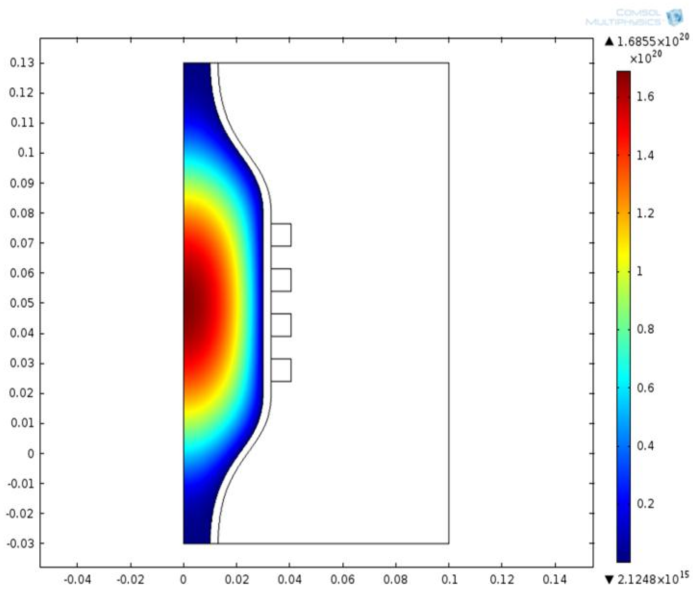
Figure 4: Surface plot of electron density inside the column.

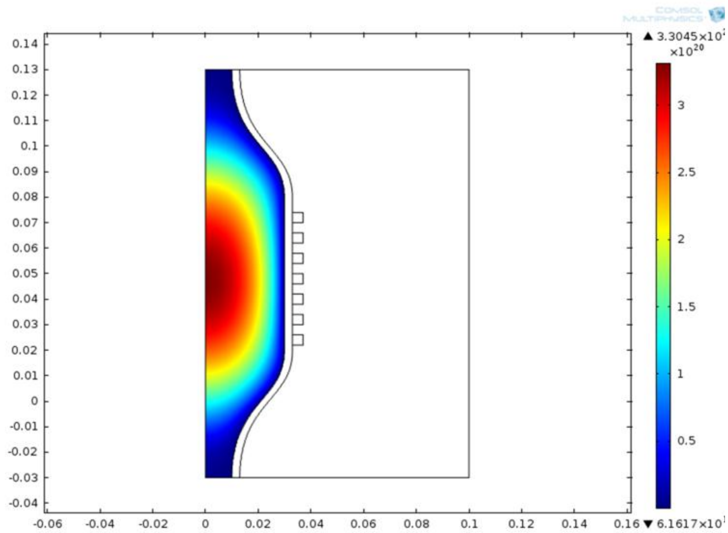
VI. INFLUENCE OF THE NUMBER OF TURNS IN THE COIL

Electron Density:

Figure 5(a, b and c), show the electron density for the different numbers of turns in the coil.







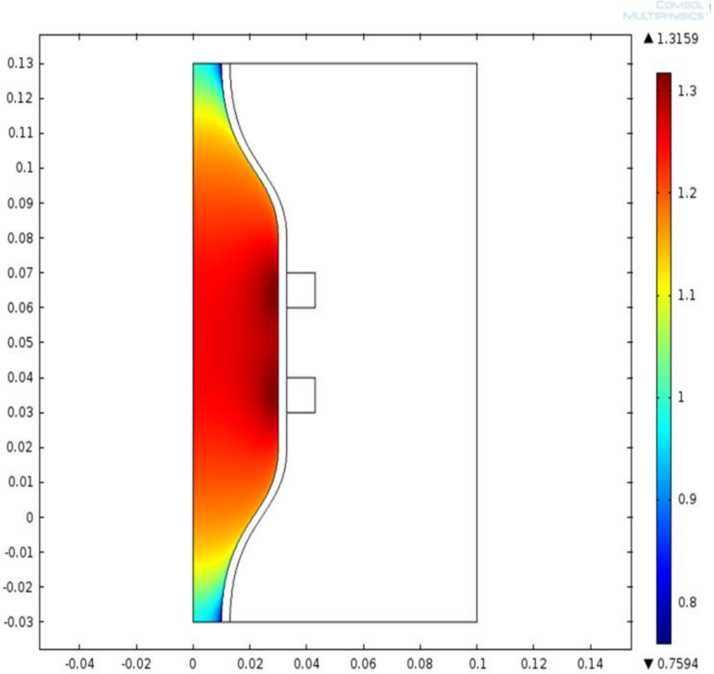
(c) : N=7Turns

Figure5: Surface plot of electron density for:: (a):N=2turns, (b)N=4 turns and (c)=7 turns

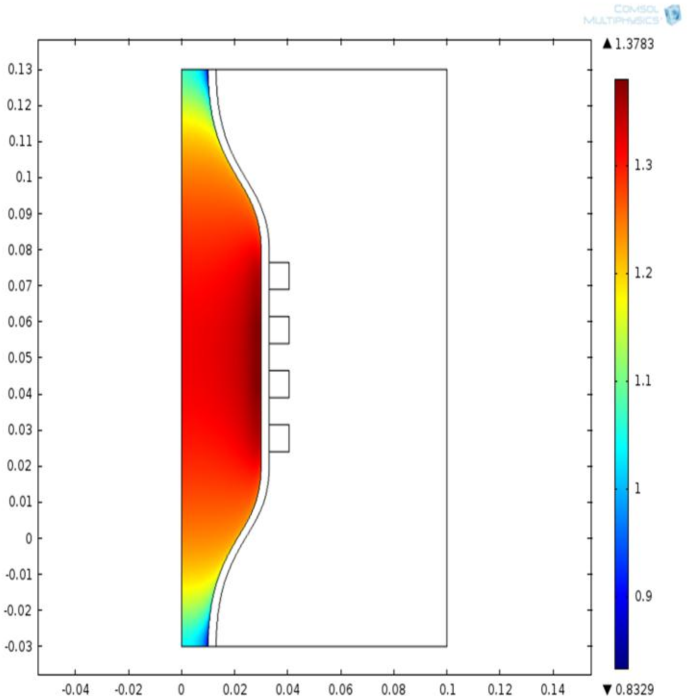
When we increase the number of turns in the coil, the electron density increases too.

Electron Temperature:

Figure 6 (a, b and c), show the electron temperature for the different numbers of turns in a coil

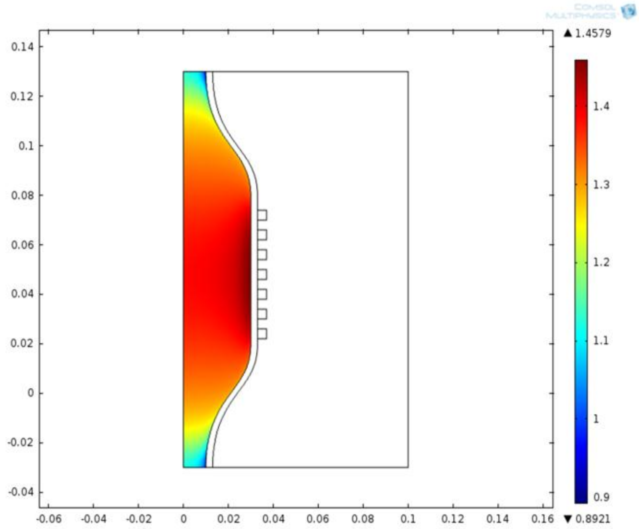


(a): N=2Turns



(b): N=4Turns

As the number of turns is increased, the plasma temperature tends to increase following the variations in the electron density.



(c): N=7Turns

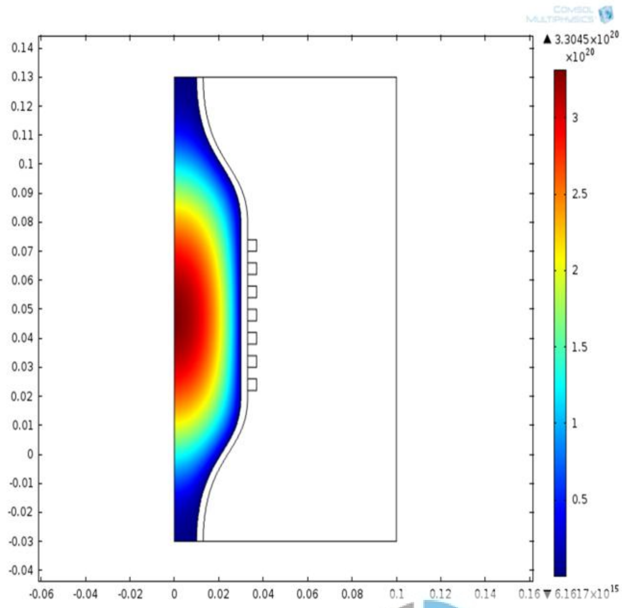
Figure6: Surface plot of the electron temperature for: (a):N=2turns, (b)N=4 turns and (c)=7 turns

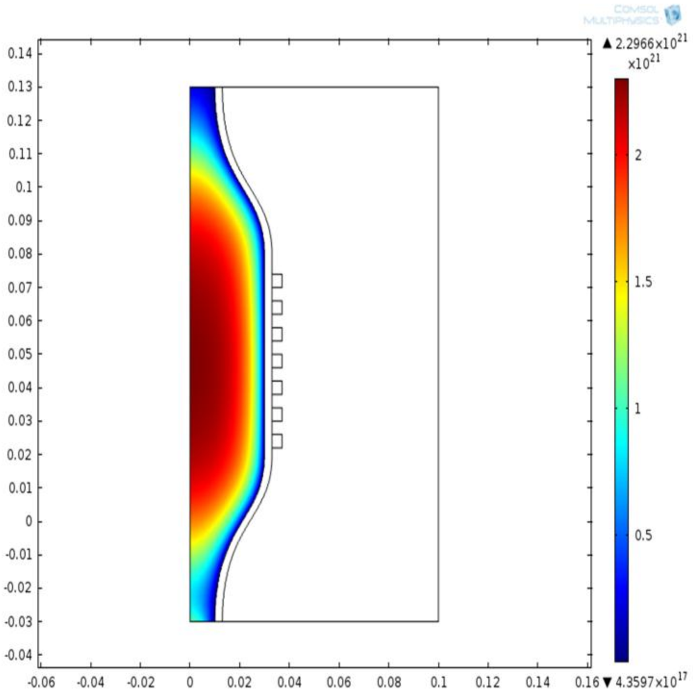
VII. INFLUENCE OF THE ELECTRICAL CURRENT INTENSITY:

Since the optimal design is obtained with 7 turns, this model is investigated with two different current intensities: I=20 A and I=200 A.

Electron Density:

Figure 7(a and b), show the electron density when the intensity of the electrical current is 20 A and 200A.





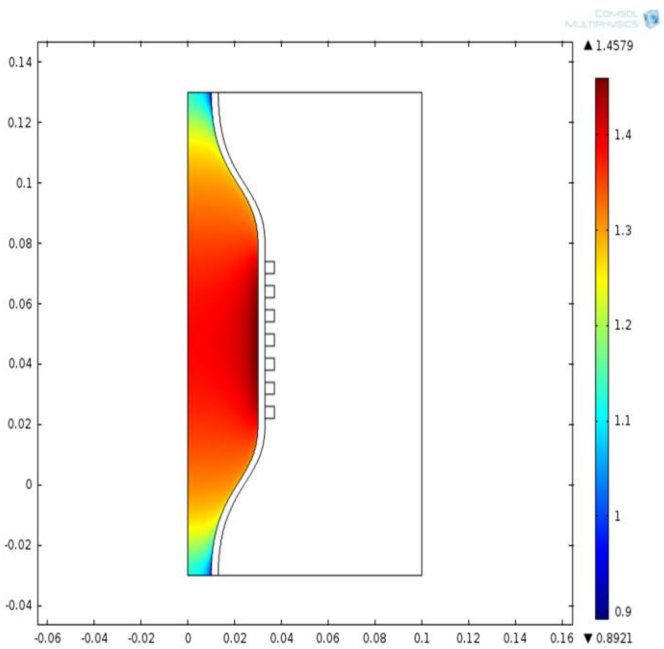
(b): I=200 A

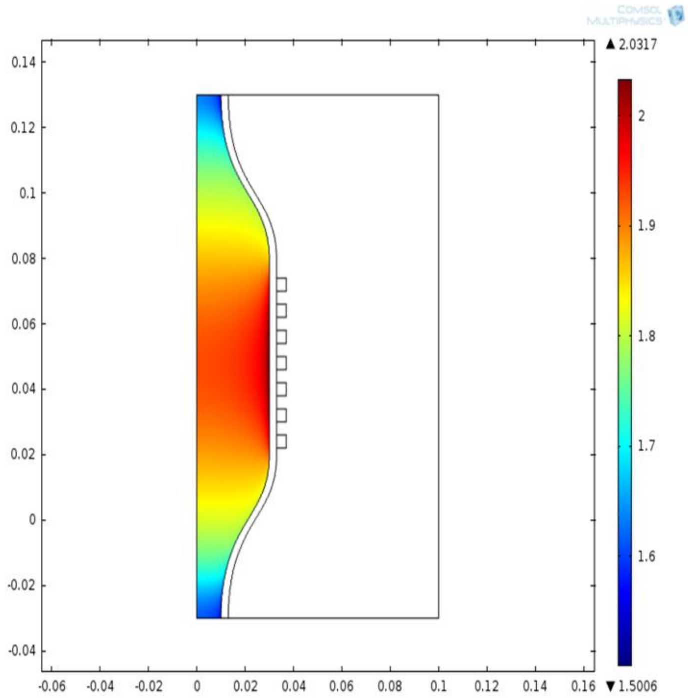
Figure7: Surface plot of electron density for: (a):I=20A and (b)I=200 A

When we increase the intensity of the electric current, the electron density increases too, so that it reaches 2.2966 $*10^{21}$ 1⁄m^3 if I=200A as compared to 3.3045 $*10^{20}$ 1⁄m^3 when I= 20 A

Electron Temperature:

Figure 8(a and b), show the electron temperature distribution when the electrical current is 20 A and 200A.





(b): I=200 A

Figure8: Surface plot of the electron temperature for: (a):I=20A and (b)I=200 A

The electron temperature reaches 2.0317 eV if I=200A whereas its value decreases to 1.4579Ev when I= 20 A

VIII. CONCLUSION

ICP is modeled as a transformer. A current is applied to the driving coil (the primary) and this induces a current in the plasma (the secondary). The plasma then induces an opposing current back in the coil, increasing its resistance. The current flowing in the plasma depends on the current applied to the coil and the reaction kinetics.

It was seen from the obtained results, that an increase in the electrical excitation induces a significant increase in the electron density of the torch.

It was clearly found that both the electron density and the plasma temperature increase with an increase in power density (number of turns in a coil and intensity of the electric current).

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