The effect of various coil parameters on ICP torch simulation

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Abstract In this paper numerical simulation is performed to investigate the effects of coil parameters on the characteristics of argon discharges in 2D axi-symmetric inductively coupled plasma (ICP) torch working at atmospheric pressure. Simulations were carried out using an indigenously developed CFD code in FORTRAN for ICP torch. The code uses the standard RF-ICP torch geometry to solve continuity, momentum, energy and vector potential equations under the assumption of LTE, steady and laminar flow. Using ICP torch argon plasma is simulated at oscillator frequency of 3.0 MHz with coil current 152 Amp. The coil parameters such as number of turns of the coil (Nc), spacing between the turns of the coil (Lc), radius of coil turn (Rc), axial variation of first coil position (Pc) and non uniform spacing of the coil turn, are varied to study their effect on temperature and flow fields in ICP torch. The results indicate that increase in number of turns of the coil increase total power dissipated into discharge almost linearly. The spacing between turns of the coil drastically affects the flow pattern and the total power dissipated into discharge. Increase in radius of the coil turn decreases the maximum energy dissipation rate and hence affects the temperature field. The axial variation of coil position affects the flow field. Wall temperature profile plays an important role in deciding the practical suitability of a particular coil configuration. It has been shown that temperature and flow fields can be controlled by changing various coil parameters and one can design an ICP torch system suitable for a particular process application.

1. Introduction
In 1961, Reed [1] reported first time that a stable atmospheric pressure discharge can be produced by inductively heating a gas with RF power sources. Since past four decades RF (radio frequency) ICP (Inductively coupled plasma) system has been subject of interest for both industrial applications and basic understanding of plasma discharge. The main advantages of ICP are that it is electrodeless which helps in obtaining contamination free plasmas, have low flow velocity and large volume of plasma. Due to this it has wide range of industrial applications in powder spheroidization, spectrochemical analysis, sintering, spray coating of ceramic and metallic powders, synthesis of ultra fine powders of advanced materials, nano particle synthesis, etc.

To calculate the flow and temperature fields in inductively coupled plasma mathematical modeling has made considerable advances. Various models have been developed in last three decades such as one dimensional model [2-4], two dimensional model with 1D electromagnetic equation [5-8], two-dimensional vector potential model [9]. A comprehensive review on 2D modeling of inductively coupled plasma has been published in year 1992 by Mostaghimi and Boulos [10]. Progress in
mathematical modeling and advent of high speed computers led to development of turbulent flow model [11-13], and three-dimensional model using commercial code such as FLUENT© [14-15]. In most of these models conventional coil geometry has been assumed.

A parametric study of the flow and temperature fields in RF- ICP was reported by Boulos [16], considering variation of central gas flow rate, sheath gas flow rate, input power and plasma gas which is either argon or nitrogen. Nishiyama et. al. [17] using 2D axisymmetric turbulent model reported that the temperature and flow fields of the RF-ICP can be controlled by injecting a secondary gas (helium). Bernadi et. al.[18] performed 3D simulations to study the effect of different coil geometries such as conventional helicoidal, planar and double-stage configurations on flow, power dissipated and temperature field in inductively coupled plasma discharge. The physical behavior of a torch with elliptical crossection has also been analyzed. Xue, et. al. [19] proposed a novel 2D model to study the influence of coil angle on temperatures and flow field. The results indicated that the influence of coil angle on temperature and flow field does not have noticeable change. Mckelliget and El-Kaddah [20] proposed a 2-D ICP model, to study how the various coil geometries influence the velocity, temperature distribution and reaction kinetics on thermal deposition of silicon tetrachloride to silicon. Different coil geometries such as conventional coil, modified conventional coil where the coils were not equidistant, a planar coil and a levitation coil has been considered for analysis. The underlying investigation was done to control the location of the reaction zone and reduce silicon deposition on wall of the torch.

Although the effect of various coil geometries on plasma discharge has been studied, a comprehensive parametric study has not been reported taking the effect of various coil parameters on ICP flow, temperature field, power dissipation distribution and wall temperature profile. In this paper, the coil parameters are varied to have a comprehensive parametric study of plasma discharge using ICP torch. The coil parameters have been varied are such as number of turns of the coil (Nc), spacing between the turns of the coil (Lc), Radius of coil turn (Rc), axial variation of first coil position (Pc) and non uniform spacing of the coil turn.

2. Plasma Simulation model
A standard 2D Vector potential model [21] has been used to perform the numerical simulation. Simulations are performed for argon plasma with the assumptions of Local thermal Equilibrium, axial symmetry, optically thin plasma and laminar flow with negligible viscous dissipation. The Governing equations used are as follows:

Continuity equation:

$$\frac{\partial (\rho v_z)}{\partial z} + \frac{1}{r} \frac{\partial (\rho rv_r)}{\partial r} = 0$$  \hspace{1cm} (1)

Momentum equation:

$$\rho \left[ \frac{\partial v_z}{\partial z} + \frac{\partial v_r}{\partial r} \right] = - \frac{\partial p}{\partial z} + \frac{1}{r} \frac{\partial}{\partial r} \left[ \mu \left( 2 \frac{\partial v_z}{\partial z} \right) + \frac{\partial}{\partial r} \left( \mu \frac{\partial v_r}{\partial r} + \frac{\partial v_z}{\partial z} \right) \right] + F_z$$  \hspace{1cm} (2)

$$\rho \left[ \frac{\partial v_r}{\partial r} \right] = - \frac{\partial p}{\partial r} + \frac{\partial}{\partial r} \left[ \mu \left( 2 \frac{\partial v_r}{\partial r} \right) + \frac{\partial}{\partial r} \left( \mu \frac{\partial v_r}{\partial r} + \frac{\partial v_z}{\partial z} \right) \right] + 2 \mu \left[ \frac{\partial v_r}{\partial r} \right] + F_r$$  \hspace{1cm} (3)

Energy equation:

$$\rho \left[ \frac{\partial h}{\partial r} v_r + \frac{\partial h}{\partial z} v_z \right] = \frac{\partial}{\partial z} \left( \frac{\lambda}{c_p} \frac{\partial h}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{\lambda}{c_p} \frac{\partial h}{\partial r} \right) + U_p - U_R$$  \hspace{1cm} (4)
Vector potential equation:

\[
\frac{\partial^2 A_R}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial A_R}{\partial r} \right) - \frac{A_R}{r^2} + \mu_0 \omega \sigma A_I = 0
\]  

(5)

\[
\frac{\partial^2 A_I}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial A_I}{\partial r} \right) - \frac{A_I}{r^2} - \mu_0 \omega \sigma A_R = 0
\]  

(6)

\[A_\theta = A_R + i A_I\]  

(7)

Where \( r \) is the distance in radial direction and \( z \) is the distance in axial direction, \( v_z \) is the axial velocity and \( v_r \) is the radial component of velocity; \( \rho, \mu, \lambda, \sigma \) and \( c_p \) are the density, viscosity, thermal conductivity, electrical conductivity and specific heat at constant pressure, respectively; \( h \) is the enthalpy, \( p \) is pressure, \( \mu_0 \) is the permeability of free space, \( \omega = 2\pi f \) and \( f \) is the oscillator frequency, \( U_p \) and \( U_R \) are the local energy dissipation rate and volumetric radiation heat losses respectively. \( A_R \) and \( A_I \) are real and imaginary components of vector potential \( A_\theta \). \( F_r \) and \( F_z \) are the radial and axial body force acting on plasma gas in the discharge region.

\[F_r = \frac{1}{2} \mu_0 \sigma \text{Real} \left[ E_\theta H^*_z \right]\]  

(8)

\[F_z = -\frac{1}{2} \mu_0 \sigma \text{Real} \left[ E_\theta H^*_r \right]\]  

(9)

\[U_p = \frac{1}{2} \sigma \left[ E_\theta E^*_\theta \right]\]  

(10)

The corresponding electrical field intensity in azimuthal direction, \( E_\theta \), the axial and radial components of the magnetic field, \( H_z \) and \( H_r \), can be calculated as follows

\[E_\theta = -i \omega A_\theta\]  

(11)

\[\mu_0 H_z = \frac{1}{r} \frac{\partial}{\partial r} \left( r A_\theta \right)\]  

(12)

\[\mu_0 H_r = -\frac{\partial}{\partial z} (A_\theta)\]  

(13)

The total RF discharge power dissipated into plasma is denoted by \( P_{diss} \) and \( P_{coil} \) is power supplied to the coil. \( V' \) is total discharge volume.

\[P_{diss} = \int_V U_p dv'\]  

(14)

\[P_{coil} = \frac{1}{2} \pi f \mu_0 \int_{V'} (H^2_r + H^2_z) dv'\]  

(15)

Conversion efficiency is calculated as

\[\eta_c = \frac{P_{diss}}{P_{coil}} \times 100\]  

(16)
Boundary conditions:
The boundary conditions for the conservation equations of inductively coupled plasma are as follows:

- **Inlet conditions** \((z = 0)\):
  \[
  v_z = \begin{cases} 
  Q_1/\pi r_1^2 & r < r_1 \\
  0 & r_1 \leq r \leq r_2 \\
  Q_2/\pi (r_2^2 - r_1^2) & r_2 \leq r \leq r_3 \\
  Q_3/\pi (R_0^2 - r_3^2) & r_3 \leq r \leq R_0 
  \end{cases} 
  \tag{17}
  \]

- **Centerline** \((r = 0)\):
  \[
  \frac{\partial v_z}{\partial z} = \frac{\partial h}{\partial z} = A_r = A_i = 0 
  \tag{21}
  \]

- **Wall** \((r = R_0)\):
  \[
  v_z = v_r = 0 
  \tag{22}
  \]

\[
\dot{T} = 300K 
\tag{19}
\]

\[
\frac{\partial A_r}{\partial z} = \frac{\partial A_i}{\partial z} = 0 
\tag{20}
\]

\[
\lambda \frac{\partial T}{\partial r} = \frac{\lambda_w}{\delta_w} (T_s - T_w) 
\tag{23}
\]

\[
A_r = \frac{\mu_0 I}{2\pi} \sqrt{\frac{R_c}{R_0}} \sum_{i=1}^{\text{coil}} G(k_i) + \frac{\mu_0 \omega_C V_r}{2\pi} \sum_{p=1}^{\text{p}} \sqrt{\frac{r_p}{R_0}} \sigma_p A_{r,p} S_p G(k_p) 
\tag{24}
\]

\[
A_i = -\frac{\mu_0 \omega_C V_r}{2\pi} \sum_{p=1}^{\text{p}} \sqrt{\frac{r_p}{R_0}} \sigma_p A_{r,p} S_p G(k_p) 
\tag{25}
\]

where \(G(k) = \frac{(2 - k^2)K(k) - 2E(k)}{k} \)

\[
k_p^2 = \frac{4R_0^2r_p}{(r_p + R_0)^2 + (z_b - z_p)^2}, \quad k_i^2 = \frac{4R_0^2R_i}{(R_i + R_0)^2 + (z_i - z_b)^2} 
\tag{27}
\]

\(Q_1, Q_2, Q_3\) is the flow rate of carrier, plasma and sheath gas. \(r_1\) is the inner radius of injection tube, \(r_2\) is the outer radius of injection tube, \(r_3\) is the radius of intermediate tube and \(R_0\) is the inner radius of the torch as shown in figure1. \(T\) is the temperature and \(K(k) and E(k)\) are complete elliptic integrals[22]. The vector potential at each point depends on the current carrying region of space. So vector potential is determined by superposition of the coil and plasma effects. So in \(A_r\) at wall boundary the first summation extends over the number of coils and the second one extends over the current carrying region of the discharge as shown in equation (24). Here \(R_0\) is the radius of the confinement tube; \(R_c\) is the radius of the coil and \(r_p\) and \(S_p\) is the radius and crosssection of the p\textsuperscript{th}
control volume. $R_i$ is the radius of the $i$th coil, $z_i$ is the height of the $i$th coil, $z_b$ is the height of the boundary and $\sigma_p$ is the electrical conductivity at the $p$th control volume. $\lambda_w$ is the thermal conductivity of the quartz confinement tube ($\lambda_w = 1.047 \text{ W/mK}$), $\delta_w$ is the tube wall thickness, $d_c$ is the coil tube diameter, $I$ is the coil current, $T_i$ is inside surface temperature of quartz tube and $T_w$ is the external (wall) surface temperature of quartz tube (350 K).

- Exit

\[
\frac{\partial (\rho v_z)}{\partial z} = \frac{\partial v_r}{\partial z} = \frac{\partial h}{\partial z} = \frac{\partial A_R}{\partial z} = \frac{\partial A_I}{\partial z} = 0
\]  

3. Numerical Procedure

A 2D CFD code is developed to perform simulation of argon plasma at atmospheric pressure. Computations are performed with same torch dimension that was used by Boulos [21]. The governing equations are solved using control volume techniques with co-located variable arrangement. SIMPLE pressure-velocity correction with momentum interpolation for cell face velocity is used for pressure-velocity coupling [23, 24]. 25 × 50 control volumes in radial and axial directions respectively are used for simulation. For stable computation, under-relaxation factors are used for all dependent variables as well as for all physical parameters. Under-relaxation factors are also used for momentum source terms and temperature source term. Strongly Implicit Procedure (SIP) is used for inner iteration to solve linear algebraic equations [23]. Central difference scheme is used for diffusion terms and hybrid scheme (central difference and upwind difference) is used for convective terms. Data required for transport and thermodynamic properties of argon plasma are taken from reference [25, 26].

**Figure 1.** Schematic diagram of Inductively coupled plasma torch.

ICP is operated at 3 MHz oscillator frequency and coil current of 152 Amp. The operating condition of the torch has been kept same to study the effect of various coil parameters. Schematic diagram of the torch is shown in figure 1 and the operating conditions are listed in table 1.
4. Results and Discussion.
The coil parameters that are varied are the number of turns of the coil ($N_c$), spacing between the turns of the coil ($L_c$), radius of coil turn ($R_c$), axial variation of first coil position ($P_c$) and non uniform spacing of the coil turn.

4.1. Effect of variation of number of turns of the coil ($N_c$)
In this case, the first coil position from the inlet is kept at 10 mm. The number of turn of the coil are varied from 2 to 4, keeping constant spacing between the turns ($L_c$) as 32 mm. Computational results of temperature field, as plotted in figure 2 shows that the core temperature region increases as the number of turn of the coil increases. The flow field gets affected by varying number of turns of the coil ($N_c$) as shown in figure 3.

![Figure 2. Temperature fields for the number of coil turn ($N_c$).](image)

| Dimensions | For 3MHz ICP |
|------------|--------------|
| $r_1$      | 1.70 mm      |
| $r_2$      | 3.70 mm      |
| $r_3$      | 18.8 mm      |
| $R_0$      | 25.0 mm      |
| $f$        | 3.0 MHz      |
| $Q_1$      | 1.0 lpm      |
| $Q_2$      | 3.0 lpm      |
| $Q_3$      | 21.0 lpm     |
| $δ_w$      | 2 mm         |
| $d_c$      | 5 mm         |
| $L_T$      | 150.00 mm    |
The first vortex at the inlet is present in all the three cases in flow field. These are due to high pressure (as shown in figure 4.) and strong axial body force (as indicated in figure 5) present at the inlet.

Figure 3. Flow fields for number of coil turn ($N_c$).

Figure 4. Pressure fields for variation of number of coil turn ($N_c$).
The formation of second vortex depends on the radial body force as seen in figure 3 and 6. The second vortex is formed at the end of last coil for $N_c = 3$ and $N_c = 4$ turns, this is due to the fact that negative radial body force ($F_r$) moves towards the wall.

The wall temperature profile as plotted in figure 7 shows that the maximum wall temperature for $N_c = 2$, $N_c = 3$, $N_c = 4$ is 400 K, 704 K, 1172 K respectively. $N_c = 2, 3$ are practically suitable as the wall temperature is reasonably below the melting point of quartz tube (melting point of tube is 1683 K). $N_c$
4 can also be implemented experimentally only if the wall of quartz tube is water cooled, so that the wall temperature can be reduced. Conversion efficiency, as calculated by equation (12) increases from 23% to 58% as the number of turn of the coil increases.

4.2. Effect of variation of spacing between the turn of the coil ($L_c$).

In this case, computation is performed for $L_c = 10$ mm, 25 mm and standard dimension $L_c = 32$ mm. The first coil position from inlet is kept at 10 mm for all variation of $L_c$. The Temperature field as indicated in figure 9 shows that as the spacing between turn of the coil increases the maximum temperature of the ICP decreases.

Figure 7. Wall temperature profile for variation of various coil turn ($N_c$).

Figure 8. Variation of Power dissipated and Conversion Efficiency with variation in $N_c$.

Figure 9. Temperature field for Spacing between turn of the coil ($L_c$).
Figure 10. Flow fields for Spacing between the turn of the coil (L_c).

Figure 10 shows that the recirculation region at the end of the last coil is more pronounced when the coil turn spacing (L_c) is 10 mm. and as L_c increases the recirculation (backflow) region goes on decreasing. The wall temperature profile as shown in figure 11 indicates that the wall temperature decreases as the spacing between the coil turn increases. It even shows clearly that L_c = 10 mm is not experimentally suitable as the wall temperature reaches to a value that is even higher than melting point of quartz tube. As seen in figure 12, the total power dissipated decreases from 11.5 kW to 4.6 kW as the spacing between turns increase from 10 to 35 mm. The conversion efficiency also shows a decrease from 93 % to 40 %.
4.3. Effect of variation of coil turn radius ($R_c$)

In this case, the coil radius is varied from 30 mm to 40 mm keeping the spacing between coil turn (32 mm) and first coil position (10 mm) constant. Comparison of the power dissipation field of $R_c = 30$, $R_c = 33$ and $R_c = 40$ as indicated in figure 13 shows that maximum local energy dissipation decreases as $R_c$ increases. Observing the flow fields in figure 14 indicates that the area occupied by second recirculation region decreases as $R_c$ increases and it vanishes for $R_c = 40$ mm.

![Figure 13. Local energy dissipation fields ($U_p$) for variation of radius of the coil ($R_c$).](image)

![Figure 14. Flow field for variation of radius of the coil ($R_c$).](image)
Due to power dissipation, the core temperature region decreases as $R_c$ increases as shown in figure 15. As seen from figure 16 the axial velocity profile shows peaks at $z = 53$ and $97$ mm for $R_c = 30$ and $33$ mm and there is no peaking for $R_c = 40$ mm. If this velocity profile is compared with flow field, we observe that the stream lines are having curvature at $z = 53$ and $97$ mm which could be the reason for peaking in velocity profile. The maximum axial velocity decreases as radius of the coil increases.

![Temperature field for variation of radius of the coil ($R_c$).](image1)

**Figure 15.** Temperature field for variation of radius of the coil ($R_c$).

![Axial velocity profile for various radius of the coil ($R_c$).](image2)

**Figure 16.** Axial velocity profile for various radius of the coil ($R_c$).
4.4. Effect of axial variation of first coil position \((P_c)\)

In this case as we shift the axial position of the first coil from 10 to 30 mm keeping \(L_c = 32\)mm and \(R_c = 33\)mm constant, we observe that the maximum temperature of argon plasma almost remains constant as seen in figure 17. Because the power applied or the current supplied is constant for all the variation of \(P_c\). The flow patterns as shown in figure 18 shows that the area occupied by the first recirculation region increases as first coil position \((P_c)\) increases and second recirculation region shifts downstream.

![Figure 17](image17.png)

**Figure 17.** Temperature fields for variation of first coil position \((P_c)\).

![Figure 18](image18.png)

**Figure 18.** Flow fields for various first coil positions \((P_c)\).
4.5. Effect of variation of non uniform spacing between the coil turns.

Two variation of nonuniform coil spacing were compared with standard dimension. The coil turn positions for one of the simulation are taken at 10, 58, 82 mm and for the other 10, 58, 90 mm. The temperature field as shown in figure 19 shows that there is not much difference in core temperature. According to the coil position the temperature contours get shifted. The flow fields as seen in figure 20 indicate that the second recirculation region can be avoided by using nonuniform spacing of the coil.

![Temperature field for nonuniform spacing of the coil.](image1)

**Figure 19.** Temperature field for nonuniform spacing of the coil.

![Flow field for nonuniform spacing of the coil.](image2)

**Figure 20.** Flow field for nonuniform spacing of the coil.
Figure 21 indicates that, the local energy dissipation rate at central coil position gets affected due to non-uniform spacing.

![Figure 21. The local energy dissipation due to ohmic heating at z = centre coil turn.](image)

5. Conclusion

By varying various coil parameters, the effect on flow, temperature, and conversion efficiency of inductively coupled plasma torch has been studied.

- For an ICP torch, if number of coil turn increases the total power dissipated and conversion efficiency also increases. As the number of coil turn increases the hot plasma volume increases but the wall temperature also increases. As seen from figure 7, if total power dissipation of 8 kW is desired then 4 turn coil could be used, but with water cooling quartz wall. \( N_c = 2 \) can be applicable design to gain the concentration distribution field towards the centre of torch for material synthesis as there is no second vortex in flow field.

- As spacing between the turn (\( L_c \)) increases the maximum temperature, total power dissipated and conversion efficiency of the discharge decreases. It is not practical to operate the torch with \( L_c = 10 \) mm as it has high wall temperature, which could even melt quartz tube. So depending on plasma processing requirement one has to choose optimum \( L_c \) and \( N_c \) values to design a ICP torch.

- As coil radius (\( R_c \)) increases the maximum local energy dissipation decreases. The hot plasma volume decreases as \( R_c \) increases. The flow field for \( R_c = 40 \) does not produce any second recirculation, this could be useful for material synthesis as the concentration distribution field would move towards the centre of the torch.

- Axial variation of the first coil position (\( P_c \)) does not affect the total power dissipated into the discharge. It affects the flow pattern as the \( P_c \) increases the area occupied by first vortex increases.

- Nonuniform spacing between the coils affects the flow field. The local energy dissipation rate at central coil position gets affected as the spacing between turn’s changes.
It is evident from the above results that the flow and temperature field depends on the various coil parameters. One can control and generate temperature and flow field by simply varying the coil parameters as per requirement of material processing.

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