The effect of swirl velocity on ICP torch simulation

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Abstract. In this paper numerical simulation is performed to investigate the effects of swirl velocity 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 for the standard RF-ICP torch geometry under the assumption of local thermodynamic assumption (LTE), steady and laminar flow. The argon plasma is simulated at oscillator frequency of 3.0 MHz with coil current 150 Amp. Study has been done for different swirl velocities of plasma and sheath gas. In this paper, we consider the swirl of sheath and plasma gas and reverse swirl. In reverse swirl, at the inlet, swirl is given to plasma gas in one direction and sheath gas in the opposite directions. The swirl effect has been adjudged from thermal energy transport point of view. It has been found that swirl of sheath gas increases the wall heat loss and decreases the axial temperature towards the outlet of the torch. The increased heat transfer rate along the periphery of plasma core, due to swirl velocity, increases the stability of plasma core.

1. Introduction

The RF (radio frequency) ICP (Inductively coupled plasma) system has been subject of interest for past four decades from fundamental and industrial research point of view. The main advantage of ICP is that it is electrodeless which helps in obtaining pure plasma and it has low flow velocity. Therefore it has wide range of industrial applications. Mathematical modeling has made considerable advances in predicting the flow and temperature fields in inductively coupled plasma. A comprehensive review on 2D modeling of inductively coupled plasma has been published in year 1992 by [1]. Progress in mathematical modeling led to development of turbulent flow model [2-4], and three-dimensional model using commercial code such as FLUENT® [5-6].

Swirl has long been thought to be necessary to sustain arcs in high-speed flows [7]. Takayoshi Inoue, et. al. [8] investigated the effects of swirl flow injection on the characteristics of an atmospheric ICP generator. The experiment found that the specific enthalpy increased with decreasing the swirl flow fraction. Boulos [9] has shown that the presence of swirl results in an outward displacement of the recirculation eddy in the fire-ball with a corresponding decrease of the backflow along the centerline of the torch. The effect of swirl on the corresponding temperature fields seems to be relatively much smaller. El-Hage et. al. [10] had shown that the effect of swirl in the sheath gas was found to increase the turbulence and to decrease the size of the discharge. These papers deal with swirl effect in plasma flow having high gas flow rates. Analytical spectroscopic and material processing
applications requires low flow rate. In this paper, we study the swirl effects on an ICP torch performance having moderate gas flow rates. Applying swirl to ICP torch are varied in four different ways, which are swirl to plasma gas flow with no swirl to sheath gas flow, swirl to sheath gas flow with no swirl to plasma gas flow, swirl to both plasma and sheath gas flow and reverse swirl. In reverse swirl, at the inlet, swirl is given to plasma gas flow in one direction and sheath gas flow in the opposite directions.

2. Plasma Simulation model.
A standard 2D Vector potential model [11] was used to perform the numerical simulation. Simulations are performed for argon plasma with the assumptions of local thermal Equilibrium, axially symmetric, optically thin and laminar flow with negligible viscous dissipation. The Governing equations used are as follows:

Continuity equation:
\[ \frac{\partial (\rho v_z)}{\partial z} + \frac{1}{r} \frac{\partial (\rho v_r)}{\partial r} = 0 \]  

Momentum equation:
\[ \rho \left( \frac{\partial v_z}{\partial z} v_z + \frac{\partial v_z}{\partial r} v_r \right) = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial z} \left[ \mu \left( \frac{\partial v_z}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left[ \mu \left( \frac{\partial v_r}{\partial z} + \frac{\partial v_z}{\partial r} \right) \right] + F_z \right] \] 

\[ \rho \left( \frac{\partial v_r}{\partial r} v_r + \frac{\partial v_r}{\partial z} v_z \right) = -\frac{\partial p}{\partial r} + \frac{\partial}{\partial r} \left[ \mu \left( \frac{\partial v_r}{\partial r} \right) + \frac{\partial}{\partial z} \left[ \mu \left( \frac{\partial v_z}{\partial r} + \frac{\partial v_z}{\partial r} \right) \right] + \frac{2\mu}{r} \left( \frac{\partial v_r}{\partial r} \right) - \frac{v_r}{r} \right] + \frac{\rho v_\theta}{r} + F_r \] 

Energy equation:
\[ \rho \left( \frac{\partial h}{\partial r} v_r + \frac{\partial h}{\partial z} v_z \right) = \frac{\partial}{\partial z} \left( \lambda \frac{\partial h}{c_p} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{\mu}{r} \frac{\partial v_\theta}{\partial r} \right) - \frac{v_\theta}{r} \left( \rho v_r + \frac{\mu}{r} + \frac{\mu}{r} \right) - \frac{U_p - U_r}{r} \]

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

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

\[ A_\theta = A_R + iA_I \]
volumetric radiation heat losses respectively. $A_R$ and $A_I$ are real and imaginary components of vector potential $A$. $F_r, F_z$ are the radial and axial body force acting on plasma gas in the discharge region.

\[ F_r = \frac{1}{2} \mu_0 \sigma \text{Real} \left[ E_\theta H_z^* \right] \]  \hspace{1cm} (9)

\[ F_z = -\frac{1}{2} \mu_0 \sigma \text{Real} \left[ E_\theta H_r^* \right] \]  \hspace{1cm} (10)

\[ U_p = \frac{1}{2} \sigma \left[ E_\theta E_\theta^* \right] \]  \hspace{1cm} (11)

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

\[ E_\theta = -io A_\theta \]  \hspace{1cm} (12)

\[ \mu_0 H_z = \frac{1}{r} \frac{\partial}{\partial r} (rA_\theta) \]  \hspace{1cm} (13)

\[ \mu_0 H_r = -\frac{\partial}{\partial z} (A_\theta) \]  \hspace{1cm} (14)

The total RF discharge power dissipated into plasma is denoted by $P_{\text{diss}}$ and $\nu'$ is total discharge volume.

\[ P_{\text{diss}} = \int_{\nu'} U_p dv' \]  \hspace{1cm} (15)

**Boundary conditions:**

The boundary conditions for the conservation equations of inductively coupled plasma are as follows:

- Inlet conditions ($z = 0$):

\[ \nu_z = \begin{cases} Q_1 / \pi r_1^2 & r < r_1 \\ 0 & r_1 \leq r \leq r_2 \\ Q_2 / \pi (r_3^2 - r_2^2) & r_2 \leq r \leq r_3 \\ Q_3 / \pi (R_0^2 - r_3^2) & r_3 \leq r \leq R_0 \end{cases} \]  \hspace{1cm} (16)

\[ \nu_r = 0 \]  \hspace{1cm} (17)

\[ \nu_\theta = wR_0 \]  \hspace{1cm} (18)

\[ T = T_i = 350 \text{K} \]  \hspace{1cm} (19)

\[ \frac{\partial A_R}{\partial z} = \frac{\partial A_I}{\partial z} = 0 \]  \hspace{1cm} (20)

- Centerline ($r = 0$):

\[ \frac{\partial \nu_z}{\partial r} = \nu_r = \nu_\theta = \frac{\partial h}{\partial r} = A_R = A_I = 0 \]  \hspace{1cm} (21)
• Wall \((r = R_0)\)

\[
\nu_z = \nu_r = \nu_0 = 0
\]

\[
\begin{align*}
\lambda \frac{\partial T}{\partial r} &= \frac{\lambda_w}{\partial_w} (T_s - T_w) \\
A_R &= \frac{\mu_0 I}{2\pi} \sqrt{R_c \sum_{i=1}^{out} G(k_i)} + \frac{\mu_0 \omega_o C_V}{2\pi} \sum_{p=1}^{R_0} \frac{r_p}{R_0} \sigma_p A_{i,R_p} S_p G(k_p) \\
A_i &= -\frac{\mu_0 \omega_o C_V}{2\pi} \sum_{p=1}^{R_0} \frac{r_p}{R_0} \sigma_p A_{i,R_p} S_p G(k_p)
\end{align*}
\]

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

\[
k_p^2 = \frac{4R_0r_p}{(r_p + R_0)^2 + (z_b - z_p)^2}, \quad k_i^2 = \frac{4R_i R_0}{(R_i + R_0)^2 + (z_i - z_b)^2}
\]

\(w\) is swirl angular velocity, \(Q_1, Q_2, Q_3\) 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 \(R\) is the inner radius of the torch as shown in figure 1. \(K(k)\) and \(E(k)\) are complete elliptic integrals[12]. 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 \(A_g\) 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 cross-section of the \(p^{th}\) control volume. \(R_i\) is the radius of \(i^{th}\) coil, \(z_j\) is the height of the \(i^{th}\) coil, \(z_p\) is the height of the boundary and \(\sigma_p\) is the electrical conductivity at \(p^{th}\) 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, \(T_s\) is inside surface temperature of quartz tube and \(T_w\) is the external (wall) surface temperature of quartz tube(350 K).

• Exit

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

3. Numerical Procedure.

A 2D CFD code is developed to perform the simulation. Computations are performed with torch dimension used by Boulos [11]. 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 [13, 14]. \(25 \times 50\) 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.
Stone’s Implicit Method (SIP) is used for inner iteration to solve linear algebraic equations [13]. 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 [15].

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

ICP is operated with 3 MHz oscillator frequency and coil current of 150 Amp. The operating conditions of the torch are same for all coil parameters. Schematic diagram of the torch is shown in figure 1 and the operating conditions are listed in table 1.

**Table 1.** Torch Dimension and Operating conditions.

| Dimensions | For 3MHz ICP |
|------------|-------------|
| r1         | 1.70 mm     |
| r2         | 3.70 mm     |
| r3         | 18.8 mm     |
| R0         | 25.0 mm     |
| f          | 3.0 MHz     |
| Q1         | 1.0 lpm     |
| Q2         | 3.0 lpm     |
| Q3         | 21.0 lpm    |
| δw         | 2 mm        |
| d1         | 5 mm        |
| Lc         | 32 mm       |
| Ls         | 10 mm       |
| L1         | 74 mm       |
| LT         | 150.00 mm   |
4. Result and Discussion.

The Computations were carried out for argon gas at atmospheric pressure in four sets. They are swirl for sheath gas with no swirl for plasma gas, swirl for plasma gas with no swirl for sheath gas, swirl for both plasma and sheath gas in same direction and the reverse swirl.

4.1. Effect of variation of swirl of sheath gas flow

The simulations were performed for varying swirl of sheath gas with no swirl for plasma gas. The sheath gas swirl was varied from 0 to 1200 rad/s.

Figure 2 gives field plots of temperature and streamlines for different sheath gas swirl. For zero swirl of sheath gas, a big vortex is formed near to inlet, towards the symmetry line and another vortex is formed adjacent to the wall which is ahead of coil. Flow separation and flow reattachment near the wall take place and in-between the point of separation and the point of reattachment, a separation bubble is formed. As the swirl of sheath gas increases the length of separation bubble adjacent to the wall and the size of vortex at the inlet decrease as evident from the subsequent plots. Also as the swirl increases, the point of separation shifted towards the coil region. For the swirl of 1200 rad/sec, the vortex at the inlet and the separation bubble adjacent to the wall are almost vanished and thereby plasma gas flow becomes almost uniform throughout the torch. So swirl can be used as a means of making the flow uniform.

Figure 2. Field plots of temperature and streamline diagrams for different swirl for sheath gas flow (a) zero swirl velocity, (b) swirl 800 rad/sec and (c) swirl 1200 rad/sec

Figures 3a and 3b present the swirl effect on axial velocity and radial velocity along radial direction. In the large portion of the flow the axial velocity with non-zero swirl is reduced compared to that with zero-swirl. The decrease of axial velocity is the highest along the symmetry line. But near to the wall, axial velocity increases compared to zero swirl axial velocity. To maintain the conservation
of mass principle, as the axial velocity decreases in the large portion of flow, radial velocity increases throughout the radial direction. Because of higher radial velocity and a little higher axial velocity near to the wall, the tendency of flow separation decreases with swirl. So as the swirl velocity increases, the vortex size decreases.

![Figure 3.](image)

**Figure 3.** Variation of (a) axial and (b) radial velocity along radial direction at axial distance 0.07 m for different sheath swirl.

![Figure 4.](image)

**Figure 4.** Axial temperature for variation of swirl in sheath gas.

![Figure 5.](image)

**Figure 5.** Outlet temperature for variation of swirl in sheath gas.

Because of higher radial velocity for non-zero swirl, convection heat transfer rate in the radial direction towards the wall is also higher. Due to higher heat transfer rate in the radial direction, temperature along the symmetry line towards the outlet decreases which is evident from the figures 4.
Due to same reason as the swirl increases from 0 rad/sec to 1200 rad/sec the central temperature at the outlet decreases from 9700 K to 8000 K as shown in figure 5. Apart from this little decrease of central line temperature, the temperature field largely remains the same irrespective of swirl. Excessive swirl of sheath gas may cause excessive decrease of central line velocity and thereby may produce vortex along central line towards outlet.

From figure 6, it is observed that the peak wall temperature increases due to increase of swirl. When swirl increases from 0 rad/sec to 1200 rad/sec, the peak wall temperature rises from 897 K to 1107 K. This higher wall temperature is due to higher radial heat transfer due to swirl. Now as the radial heat transfer rate increases, the wall heat loss also increases. Figure 7 shows the energy distribution as a function of swirl in sheath gas flow. We see that wall energy loss increases steadily with swirl and thereby thermal efficiency of torch decreases. As seen radiative energy loss increases from 17 % to 25 % as the swirl in sheath gas increases afterwards becomes asymptotic. The output plasma gas energy shows a drastic decrease from 46 % to 19 % and this is compensated by heat loss to the wall which increases from 36 % to 56 %. The increased rate of heat transfer towards radially outward direction due to swirl stabilizes the plasma core. So swirl is useful to develop vortex free and stable plasma flows.

![Figure 6](image1.png)
**Figure 6.** Wall temperature profile with variation of Swirl in sheath gas

![Figure 7](image2.png)
**Figure 7.** Distribution of energy looses as a function of swirl in sheath gas

4.2. Effect of variation of swirl of plasma gas flow.
In this case we varied swirl of plasma gas flow from 0 to 1200 rad/s. As shown in figure 8 the field plots of temperature and streamline do not show much change.

4.3. Effect of swirl to plasma and sheath gas flow
We have done simulation with swirl of sheath gas as well as plasma gas as shown in figure 9. When swirl of sheath gas and swirl of plasma gas are in the same direction, then there is a high chance of formation of vortex along the central line towards the outlet. From the figure 9c, we see that at swirl 1200 rad/sec, flow is separated along the axial line at the midway cross-section of the torch.
Figure 8. Field plots of temperature and streamline diagrams for different swirl to plasma flow. (a) zero swirl velocity, (b) swirl 800 rad/sec and (c) swirl 1200 rad/sec.

Figure 9: Field plots of temperature and streamline diagrams for different swirl velocities. Here same swirl is given to both sheath gas and plasma gas. (a) zero swirl velocity, (b) swirl 800 rad/sec and (c) swirl 1200 rad/sec.
4.4. Effect of reverse swirl

In this case we have given swirl to plasma gas flow in one direction and swirl to sheath gas in opposite direction. The swirl was varied from 0 to 1200 rad/s. The temperature and streamline diagram for reverse swirl is as shown in figure 10. The heat distribution for reverse swirl gives approximately the same pattern as that of swirl given only to sheath gas flow. The main advantage of reverse swirl is the vigorous mixing of sheath gas and plasma gas which may be advantageous in some material processing applications.

![Temperature and Streamline Diagrams](image)

**Figure 10** Field plots of temperature and streamline diagrams for different reverse swirl for plasma and sheath gas flow rates. (a) zero swirl velocity both gases, (b) swirl 800 rad/sec for plasma gas flow and swirl of -800 rad/s for sheath gas flow. (c) swirl of 1200 rad/sec for plasma gas flow and swirl of -1200 rad/s for sheath gas flow.

5. Conclusions

The above discussion indicates that swirl to sheath gas flow plays an important role in the characteristics of torch. Swirl to sheath gas reduces the tendency of vortex formation, increases the wall heat transfer rate and reduces axial line temperature. Excessive swirl of sheath gas should be avoided to reduce the chance of formation of vortex in the central line of torch. Reverse swirl is good only when instant mixing of sheath gas and plasma gas is required.

The advantages of swirl depend on the application of plasma torch. Swirl is good for developing vortex free flow but at the same time increases wall heat loss. Wall heat loss decreases the thermal efficiency of plasma torch but increases the plasma core stability. Swirl also reduces the axial flow velocity which in turn increases the residence time of material particles. The increase of residence time is good in some cases but may be bad in some other cases.

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