Numerical simulation on high frequency discharge of chemical nonequilibrium argon inductively coupled plasma

Minghao Yu, Libin Ma *, Chuanxin Bai, and Kai Liu

School of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, Xi'an, China

*Corresponding author e-mail: 1290357101@qq.com

Abstract. This paper studied the flow field properties of the 10 kW inductively coupled plasma wind tunnel (ICPW). The results can be used for the development of the thermal material protection material for re-entry aerospace vehicles. In this paper, the ICP flow under different input powers was numerically simulated, and the flow-field characteristics in the ICP torch under different operating parameters were obtained. The results showed that when the input power is the typical working power i.e. 10 kW, the electron number density in the plasma torch reaches a maximum of 3.23 × 10^21 m^-3, and the electron temperature is also up to 0.99 eV. Besides, the velocity in the plasma torch reaches a maximum of 34.9 m/s, and the translational temperature also reaches a maximum value of 8740 K.

1. Introduction

Inductively coupled plasma (ICP) [1-4] is one of the important thermal plasma sources in the aerospace industry. Because it has uniform temperature, large arc area and no electrode pollution, so it can provide pure heat source and the working medium is not restricted. It has great application prospects in aerospace, metallurgy, chemical and other industrial fields. In addition, it is also used in the preparation of superconducting powders [5], the development of lightweight ablation resistant thermal protection materials [6] and the study of the surface nitrogenation mechanism of graphite materials [7]. As the ICP source has important application prospects, it is very necessary to study the ICP discharge characteristics in detail.

With the rapid development of computer technology, more and more research scholars have begun to work on the numerical simulation of the ICP. In the early days, Ayen[8] used the energy conservation equation and the electromagnetic field equations to solve the temperature distribution of the argon ICP under atmospheric conditions. Then, under the assumption of local thermodynamic equilibrium, Punjabi et al [9] discussed the flow characteristics of argon, nitrogen and air plasmas in a plasma torch under standard atmospheric conditions. In recent years, Munafò [10] developed a magneto-hydrodynamic (MHD) equations for simulating thermochemical non-equilibrium nitrogen ICP flow simulation. The numerical simulation techniques of ICP became increasingly better.

In this paper, we mainly talk about the effects of input powers on the discharge characteristics of 10 kW ICP wind tunnels. The results can provide theoretical basic data for the study of spacecraft thermal protection materials and other industries.
2. Theoretical background and modeling method

In this paper, we assume that ICP torch is a two-dimensional axisymmetric model. At the same time, the plasma flow velocity is low, and the Reynolds number does not reach the turbulent flow coefficient. Therefore, we assume the plasma is a laminar flow. The schematic diagram of the ICP torch is shown in Figure 1(a), and the computational mesh is shown in Figure 1(b). The total number of mesh elements is 34866. More concentrated and finer mesh is constructed around the coil area to accurately calculate the electromagnetic field distribution.

Figure 1. Schematic diagram and mesh division of inductively coupled plasma torch

The modeling process of the ICP involves the coupling of electromagnetic field equations, Navier-Stokes equations of quasi-neutral gases (including mass conservation, momentum conservation, and total energy conservation equations) and gas chemical reaction model. The electron number density and the average electron energy are calculated by solving the drift diffusion equation of the charged particles and the electron energy conservation equation. The governing equations solved in present study are as following:

2.1. Electromagnetic field equation:

\[ \nabla^2 A - i\omega \mu_0 \sigma A + \mu_0 j_{\text{coil}} = 0 \]  

(1)

Where \( A \), \( \mu_0 \), \( \sigma \) and \( j_{\text{coil}} \) are the vector potential, the magnetic permeability of free space, the electrical conductivity of the plasma and the coil current density, respectively. \( \omega \) is the angular frequency. \( f \) is the discharge frequency of the coil current.

2.2. Mass conservation equation:

\[ \nabla (\rho u) = 0 \]  

(2)

2.3. Momentum conservation equation:

\[ \nabla (\rho uu) = -\nabla p + \nabla [\mu (\nabla u + \nabla u^T)] - \frac{2}{3} \mu \nabla (u I) + (\rho g + j \times B) \]  

(3)
Where \( u, \rho, p, T, I \) and \( g \) are velocity, gas density, pressure, temperature, identity tensor, the gravitational force, respectively. The last term \( j \times B \) stands for the Lorentz force, where \( j \) and \( B \) are the current density induced in the plasma and the magnetic induction.

2.4. The total energy equation for solving the heavy particles’ average temperature \( T \) is expressed as follows:

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \nabla T = \nabla (k \nabla T) + P_j - Q_r
\]  

\[
P_j = \frac{1}{2} \sigma \omega^2 AA^* \]

Where \( C_p \) is the specific heat at constant pressure, \( k \) is the thermal conductivity, \( P_j \) and \( Q_r \) are the Joule heating and the radiation energy loss, respectively.

2.5. Drift diffusion equation:

\[
\frac{\partial n_g}{\partial t} + \nabla (Y n_g \mu_g E - D_g \nabla n_g) + (u \nabla) n_g = R_g.
\]

\[
Y = \begin{cases} 
-1 & g = e^- \\
+1 & g = Ar^+
\end{cases}
\]

Where \( n_g \) is the density of particle \( g \) (\( g = Ar^+ \) for cation, and \( g = e^- \) for electrons), \( u \) and \( R_g \) are velocity and the source term. \( D_g, \mu_g \) and \( E \) are the diffusivity, the mobility and the electric field, respectively. The chemical reaction kinetics model used to solve the above particle number density is shown in Table 1.

2.6. Electron energy equation:

\[
\frac{\partial (n_e \varepsilon)}{\partial t} + \nabla (\Gamma_e \varepsilon) + \Gamma_e E = R_e.
\]

Where \( \varepsilon \) is the electron mean energy. \( \Gamma_e \) is the total electron energy flux. \( \Gamma_e E \) and \( R_e \) is Joule heating and the electron energy loss, respectively.

| Reaction number \( r \) | Reactions | Rate coefficient | Reaction energy \( \varepsilon_r \) (eV) |
|-------------------------|-----------|----------------|----------------------------------|
| 1 | \( e + Ar \rightarrow e + Ar \) | \( k_{el} \) | - |
| 2 | \( e + Ar \rightarrow e + Ar^* \) | \( k_{es} \) | 11.56 |
| 3 | \( e + Ar^* \rightarrow e + Ar \) | \( k_{sc} \) | -11.56 |
| 4 | \( e + Ar \rightarrow 2e + Ar^* \) | \( k_i \) | 15.6 |
| 5 | \( e + Ar^* \rightarrow 2e + Ar^* \) | \( k_{si} \) | 4.14 |
| 6 | \( Ar^* + Ar^* \rightarrow Ar + e + Ar^* \) | \( k_{mp} = 6.2 \times 10^{-10} \) | - |
| 7 | \( Ar + Ar^* \rightarrow Ar + Ar \) | \( k_{zp} = 3 \times 10^{-15} \) | - |

In the following numerical simulation, we use argon as the working gas to analyze the influence of different coil powers on the flow field of argon ICP. At the inlet of the torch, the setting temperature of the gas is 300K, and the gas mass flow rate is set to 0.065 g/s. The total input power is set to 10 kW.
Moreover, the working pressure is set to 4000 Pa. In the numerical calculation, we use the finite element method to discretize the governing equations and the electromagnetic field equations.

3. Results and discussion

Figure 2 shows the electron density distribution of the ICP torch under different coil powers. It can be seen from the figure that the maximum value of electron density in the ICP torch is distributed on the plasma torch center line downstream of the coil. And the maximum values are $2.73 \times 10^{21}$ $1 / m^3$, $3.23 \times 10^{21}$ $1 / m^3$ and $3.71 \times 10^{21}$ $1 / m^3$, respectively. In addition, it can be seen that as the power of the discharge coil increases, the maximum electron number density in the ICP torch gradually increases. The reason is that the ionization degree in the plasma torch gradually increases as the coil power increases. This leads to an increase in the electron number density.

![Number density distribution in the ICP torch under different discharge coil powers](image)

**Figure 2** Number density distribution in the ICP torch under different discharge coil powers

Figure 3 shows the electron temperature comparison on the ICP torch center line under different coil powers. It can be seen from the figure that the maximum temperature of the electrons appears near the wall of the quartz tube at the downstream of the plasma coil section, and the highest electron temperature is about 0.99 eV (the coil power is 10 kW). Besides, it can be seen that as the power of the discharge coil increases, the electron temperature on the center line of the plasma torch also increases. The reason is that as the coil power increases, more deposition power can be absorbed by the gas in the plasma torch, and then electrons can get with more energy.

![Comparison of electron temperature on the ICP torch center line under different coil](image)

**Figure 3** Comparison of electron temperature on the ICP torch center line under different coil
Figure 4 shows the comparison of gas velocity on the ICP torch center line at different coil powers. It can be seen from the figure, the maximum gas velocity in the ICP torch is 34.9 m/s (the coil power is 10 kW). At the same time, it can be seen that as the coil power increases, the velocity on the center line of the ICP torch begins to change at about 40 mm from the axial position. The larger the coil power is, the faster the speed is. The differences are greatest at 142 mm in the axial position, and this is also the position where the gas velocity is fastest.

![Velocity comparison](image1)

(a) Velocity comparison on the torch center axis  (b) velocity contour (p=10 kW) in the torch

**Figure 4** Distributions of the gas velocity on the torch center line and in the torch

Figure 5 shows the comparison of the gas temperatures on the ICP center line at different coil powers and the temperature contour in the whole flow-field. It can be seen from the figure that the maximum gas temperature in the ICP torch is distributed on the downstream center line of the coil, and the maximum temperature is about 8740K (coil power is 10 kW). As the coil power increases, the gas temperature on the center line of the ICP torch begins to change at about 45 mm from the axial position. The greater the power is, the higher the temperature is, and the largest differences are about 150 mm at the axial position.

![Temperature comparison](image2)

(a) Temperature comparison on the torch center axis  (b) temperature contour (p=10 kW) in the torch

**Figure 5** Distributions of the flow temperature on the torch center axis and in whole torch
4. Conclusion
To sum up, this paper studied the effect of different input power on the flow characteristics of the nonequilibrium inductive plasma. The flow velocity and the temperature distributions on the center line of the ICP torch were obtained under different operating conditions. The calculation results showed that the highest electron densities in the ICP torch were $2.73 \times 10^{21}$ l/m$^3$, $3.23 \times 10^{21}$ l/m$^3$ and $3.71 \times 10^{21}$ l/m$^3$ as the powers are 7kW, 8.5kW and 10kW. The peak electronic temperatures were 0.97 eV, 0.98 eV, 0.99 eV; the maximum gas velocities were 30.4 m/s, 32.8 m/s, 34.9 m/s; and the maximum translational temperatures were 8110K, 8460K, 8740K as the coil power $P=7$kW, 8.5 kW, 10kW, respectively. The flow-field properties (e.g., the electron number density, the electron temperature, the flow velocity and the average particles' temperature) of the argon chemical non-equilibrium inductively coupled plasmas were quantitatively revealed and summarized under the typical working conditions.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (11705143), the Natural Science Basic Research Plan in Shaanxi Province of China (2018JQ1016), and the China Postdoctoral Science Foundation (2018M643814XB).

References
[1] M. Yu, Y. Takahashi, H. Kihara, et al. Thermochemical nonequilibrium 2D modeling of nitrogen inductively coupled plasma flow, Plasma Sci. Technol., 2015, 17(9): 749-760.
[2] A. Cipullo, B. Helber, F. Panerai, et al. Investigation of freestream plasma flow produced by inductively coupled plasma wind tunnel, J. Thermophys. Heat Transfer, 2014, 28(3): 381-393.
[3] D.V. Abeele, Gé, R. Degrez, Efficient computational model for inductive plasma flows, AIAA J., 2000, 38(3): 234-242.
[4] Y. Lin, Determination of copper, silver, lead and cadmium in pure gold with wide range purity by inductively coupled plasma mass spectrometry after ethyl acetate extraction, Metall. Anal., 2018, 38(3): 41-45.
[5] C. Wang, A. Inazaki, T. Shirai, et al. Effect of ambient gas and pressure on fullerene synthesis in induction thermal plasma, Thin Solid Films, 2003, 425: 41-48.
[6] H.G. Yuan, J.F. Zeng, J. Yang, et al. Research progress of high temperature thermoprotective and ablation resistant composite materials, Chem. Propellants Polym. Mater., 2006(01): 21-25+30.
[7] K. Kano, B. Uno, Surface-redox reaction mechanism of quinones adsorbed on basal-plane pyrolytic graphite electrodes, Anal. Chem., 1993, 65(8): 1088-1093.
[8] R.C. Miller, R.J. Ayen, Temperature Profiles and Energy Balances for an Inductively Coupled Plasma Torch, J. Appl. Phys., 1969, 40(13): 5260-5273.
[9] S.B. Punjabi, N.K. Joshi, H.A. Mangalvedekar, et al. A comprehensive study of different gases in inductively coupled plasma torch operating at one atmosphere, Phys. Plasmas, 2012, 19(1): 821-832.
[10] A. Munafò, S.A. Alfuhaid, J.L. Cambier, et al. A tightly coupled non-equilibrium model for inductively coupled radio-frequency plasmas, J. Appl. Phys., 2015, 118(13): 1321-984.
[11] F. Lei, X. Li, Y. Liu, et al. Simulation of a large size inductively coupled plasma generator and comparison with experimental data, AIP Adv., 2018, 8(1): 015003.