Investigation on Application of Closed Cavity Inductively Coupled Plasma in Inlet Stealth

Han Xinmin, Zhang Wenyuan, Wei Xiaolong*, Xu Haojun and Chen Junlin

Science and Technology on Plasma Dynamics Laboratory, Air Force Engineering University, Xi’an, 710038, China

*Corresponding author’s e-mail :wei18892022001@163.com

Abstract. The design of inlet into S-shaped is a stealth method with limited effect. The ICP generated in closed quartz chamber is an effective solution to improve the stealth effect. In this paper, an inductively coupled plasma (ICP) generator with the size of 30cm×30cm×2cm which could be conformal with S-shaped inlet was designed, the discharge experiment was carried out to study the discharge configuration of air ICP and the distribution of the electron density in the core area of ICP under 100Pa and different discharge power was diagnosed with microwave interference method. On this basis, the three-dimensional electromagnetic model of inlet and the plasma generator were established and the finite-difference time-domain method was used to calculate the broad-band scattering parameter of the inlet with and without the ICP generator. The variation of radar cross section area (RCS) with the azimuth angle, electromagnetic wave frequency and discharge power of ICP was studied. The result indicated that the ICP generator could effectively improve the stealth effect of S-shaped inlet in the head direction.

1. Introduction

Inlet is the strongest and most widely scattering source of the fighter in the forward area. In general single-engine aircraft the inlet can be accounted for 40% of the forward scattering, and in the double-engine aircraft the proportion could be as high as 60% or even higher [1]. Some scholars have put forward the design scheme of the S-shaped low-scattering inlet and the corresponding electromagnetic wave absorption measurement. Through the numerical calculation and the measurement of the scaling model, the optimal design of the duct parameters in inlet could effectively restrain but couldn’t completely eliminate the cavity scattering, the scattering in the important direction (± 60 degrees around the head of aircraft) is still strong[2]. Therefore, it is necessary to adopt the technical means for further suppressing the scattering of the inlet cavity.

Inductively Coupled Plasma (ICP) is a discharge pattern which inputs the RF power to the non-resonant induction coil that delivers energy to the plasma through the inductive coupling style. In ICP discharge, the plasma density can reach to $10^{11} \sim 10^{12} \text{cm}^{-3}$ and the plasma frequency can cover the main radar wave band. The device has the advantages of simple structure, low discharge power, and the plasma parameters are easy to be controlled[3-4]. Thus ICP plasma is much potential for the plasma stealth applications. In this paper, the application of the thin-layer transmission cavity ICP in the local stealthy design of the S-shaped inlet is explored.

2. Scheme of Plasma Stealth of S-shaped Inlet
Due to the limited power provided by the aircraft's on-board conditions, it is not advisable to fully or largely cover the inlet with plasma for the stealth, but to replace the key parts locally. Figure 1 shown the application of ICP generator to achieve plasma stealth of S-shaped inlet, the overall framework of the S-shaped inlet was made of solid wood with the aluminum skin attached to the surface, and the outlet of the inlet was closed with a metal plate. In order to facilitate the processing of the ICP generator and its installation on the S-shaped pipe, the cross-section of the inlet was processed into rectangular shape. The pipeline is designed by the regular of the changing center line, which was tangentially connected with the straight one. The lower surface retains an outlet for the installation of conformal ICP generator.

![Figure 1. Details of inlet plasma stealth](image)

The inlet parameters included: a total length of 1.5m, inlet cross-section of 60 cm × 50 cm rectangle. The change of centerline and area was the key parameter in the design of S-shaped inlet, which determined the change of the inner channel profile. In reference [5], the flow field and the total pressure recovery of the S-shaped inlet were analyzed. The results shown that the inlet with the center line that changed slowly in the front and urgent in the back would have stable flow field and high total pressure. Therefore, the change law of the center line of the road was as follow:

\[
y = \Delta y \cdot \left[ -3 \cdot \left( \frac{x}{d} \right)^4 + 4 \cdot \left( \frac{x}{d} \right)^3 \right]
\]

Where \( y \) was the ordinate of the centerline, \( \Delta y \) was the longitudinal offset of the center of the inlet and outlet sections, and \( d \) was the length of the S-shaped part in the x-axis. ICP generator was installed 40cm away from the lip of the inlet which was a 0.8cm thick quartz chamber, with the coil placed under the surface of the quartz chamber.

### 3. Air ICP Discharge and Its Electronic Density Diagnosis

To study the effect of ICP on the electromagnetic scattering characteristics of the inlet, the specific form and parameter distribution of air ICP discharge need to be obtained. So the experiment of ICP discharge and electronic density diagnosis were carried out, as shown in Figure 2.

![Figure 2. ICP Discharge Systems and Diagnostic Systems](image)
ICP discharge system was mainly composed of RF power and RF matching, mosquito coils radio frequency antenna, vacuum system and the quartz chamber. The quartz cavity was made by integral welding technology. The thickness of the quartz was 0.8cm and the inner size of the cavity was 20cm × 20cm × 2cm. The upper surface of the quartz cavity had a certain curvature to conform to the key part of the S-shaped inlet. The frequency of the RF power source (MSY-1) was 13.56MHz. The matching power was adjusted by the automatic matching circuit (SP-1) to minimize the reflected power. The planar-coil RF antenna made of copper pipe with inner and outer diameter of 6mm and 8mm respectively was positioned under the bottom of quartz cavity. The diameter of RF antenna was 19.2cm and three laps around. In order to ensure the RF antenna working stably for enough time, the copper pipe with a cooling water system was provided.

Diagnosis system was mainly composed of a vector network analyzer (Anritsu-37347C) and a pair of horn antenna, the working frequency \( f = 12 \text{GHz} \), the polarized mode was vertical linear polarization and the horn antenna was symmetrically fixed on the left and right sides of the quartz chamber, with 0.3m away from the cavity, the receiving antenna was placed on the back side of the semi-open absorbing black-box. In this experiment, electron density \( n_e \) was measured by the microwave transmission interference method.

Air ICP discharge process was divided into two typical stages. The first phase was E-mode discharge. At 100Pa pressure, when the discharge power increases to about 80W, the thin plasma was generated in the quartz chamber under the capacitive high voltage of the stainless steel interface and high voltage between the coils. The electron density was low and almost uniformly filled the entire cavity, not suitable for aircraft stealth [6].

As shown in Figure 3, when the RF power increased to 300W, the brightness increased in a hopping mode, and the ICP exhibited a stable ring shape. In the presence of negative ions in air ICP, an electronegative core region with large electron density and even distribution was formed in the central region of the discharge, surrounded by an electropositive edge halo around its periphery [7]. As shown in Figure 3, with the increasing of power, the width and brightness of the ICP ring region both increased significantly.

![Figure 3](image-url)  
**Figure 3.** The shape and structure of plasma changed versus and input power

The vector network analyzer was used to record the phase shift of the microwave through the plasma [8]. The electron density in the electronegative core region was high and uniform, while the electron density in the edge halo decay fast, the phase shift \( \Delta \phi \) measured by the vector analyzer was mainly caused by the electron density in core region, the phase shift caused by the edge halo was negligible, so the electron density \( n_e \) in the electronegative core region could be expressed as [9]:

\[
  n_e = \frac{2 \varepsilon_0 m_e c \omega}{e^2 l} \Delta \phi
\]

where \( \varepsilon_0 \) was the dielectric constant in vacuum, \( m_e \) was the electron mass, \( c \) was the velocity of light in vacuum, \( \omega \) is the angular frequency of the microwave, \( e \) is the individual electron charge and \( l \) is the width of the plasma ring.

Figure 4 shows the spatial distribution of ICP electron density at different discharge powers. When
the power was increased from 300W to 500W, the $n_e$ of the electronegative core region increased from $2.73 \times 10^{11} \text{cm}^{-3}$ to $4.01 \times 10^{11} \text{cm}^{-3}$. The increase of $n_e$ was approximately proportional to the power because increased power would cause more intense electron-neutral particle collision thus much more electron would be generated.

![Figure 4.](image)

**Figure 4.** The $n_e$ distribution of ICP varied from power versus radius in 100Pa.

4. **Introduction Calculation of RCS**

4.1 *Description of calculation*

According to the shape and size of the S-shaped inlet and the annular plasma, the three-dimensional model was established in CATIA, as shown in Figure 5. The electron density in the edge halo decay fast and its effect on the stealth of inlet could be ignored, so only the electronegative core region of ICP was considered. The RCS numerical simulation was carried out by using Remcom's XFDTD electromagnetic simulation software. This software calculated the electromagnetic field based on the finite difference time domain method (FDTD) which directly discredited the Maxwell equations in time and space, alternately sampling the electric field and the magnetic field, so that the process can completely simulate the electromagnetic wave with time [10].

![Figure 5.](image)

**Figure 5.** The three-dimensional model of S-shaped inlet

Process-related electromagnetic parameters of the simulation were set as follows:

The inlet and the RF antenna were set as good conductors. The plasma was set as a Drude medium and its relative permittivity can be expressed as:

$$
\varepsilon_p = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + j \omega \tau_0}
$$

(3)

Where $\varepsilon_{\infty}$ is the relative dielectric constant of the plasma when the collision frequency approaches infinity whose value was 1 for the plasma, $\varepsilon_s$ was the static relative permittivity: $\varepsilon_s = 1 - \left(\frac{\omega_p}{\nu_m}\right)^2$, $\tau_0$ was the relaxation time: $\tau_0 = 1/\nu_m$, and the value of the plasma conductivity $\sigma$ could be define as:
\[ \sigma = \varepsilon_0 \omega_p^2 / \nu_m. \]

The plasma oscillation frequency \( \omega_p \) and the plasma collision frequency \( \nu_m \) could be obtained from the electron density \( n_e \) of the plasma [11-12]:

\[ \omega_p = \sqrt{(n_e e^2) / (\varepsilon_0 m_e)} \]  
\[ \nu_m = 6.3 \times 10^{-3} n_m \frac{T}{300} \]

where \( n_m \) was the density of neutral particle which was decided by the gas state equation:

\[ n_m = 2.415 \times 10^{14} P, \]  
where \( P \) was the pressure of the chamber and \( T \) was the gas temperature which was always defined as the indoor temperature: \( T=300 \text{K} \).

The RCS calculation was carried out in the azimuth ranged from -60° to 60° of the heading direction and at the direction of 0° angle of attack of the S-shaped inlet. The mesh size of the inlet duct region was 5mm and was 1mm in the plasma and RF antenna regions. The incident waves were sinusoidal plane waves, polarized in the \( \phi \phi \) direction with 1-10GHz of the frequency, and the absorption boundary was set to 7 layers of PML. The convergence criterion was that the residual decreased by -30 dB.

4.2 RCS calculation results

Figure 6 showed the RCS of the S-shaped inlet changed with the azimuth angle with/without ICP generator in different discharge power when the EM wave frequency was 5GHz. It could be seen that, without ICP generator, RCS of ±60° range in the head presented a symmetrical distribution of tens of lobes and the main lobe appeared in the vicinity of azimuth 0° with the width of about 20° and the peak value could reach up to 10dBsm. With the azimuth away from 0°, the peak value of the lobes gradually decreased.

The RCS of the S-shaped inlet could be effectively reduced by installing the ICP generator. This attenuation was more pronounced near the main lobe. When the ICP discharge power increased to 300 W, the RCS decreased by about 10dBsm at 0° azimuth angle and the width of the main lobe decay from 20° down to about 10°. As the azimuth angle deviated from 0°, the attenuation effect decreased gradually. It could be concluded that the ICP generator had a good attenuation effect on the headscatter of the inlet.

When the discharge power of ICP increased from 300W to 400W, the attenuation effect of RCS was improved obviously, while the power increased from 400W to 500W, the attenuation effect was weakened. That’s because with the increase of power, the electron density increased, attenuation of electromagnetic waves by plasma would move to high-frequency area, and attenuation of low-frequency electromagnetic wave would be weakened [13]. So aiming at different frequency radar wave, the ICP generator should be adjusted to an appropriate discharge power to enhance the absorption.

![Figure 6. RCS of inlet versus azimuth](image-url)
Figure 7 was the RCS of S-shaped inlet changed with the frequency of electromagnetic wave when the azimuth angle was 0° with / without ICP generator of different discharge power. It could be seen that the RCS attenuation effect of the ICP generator varied with the change of discharge power, and the attenuation peak of the RCS was near the plasma frequency. When ICP discharge power rose from 300W to 500W, the attenuation of the main frequency band from 4.5-5GHz increased to 5.5-6.5GHz, the attenuation peak would also been significantly improved.

Figure 7. RCS of inlet versus frequency when the azimuth is 0°

It could be seen that the attenuation of RCS of inlet caused by ICP generator presented the characteristic of band, when the frequency of EM wave was much lower than the plasma frequency: \( \omega \ll \omega_p \), the absorption of EM wave by ICP was mainly caused by the cut-off reflection which was much limited. And when the EM wave was much higher than the plasma frequency: \( \omega >> \omega_p \), the electronic couldn’t response to the change of the EM wave thus there couldn’t be polarization phenomenon, leading to a lower attenuation effect.

5. Conclusion

The ring plasma with electron density ranging from \(2.73 \times 10^{17} \text{ m}^{-3}\) to \(4.01 \times 10^{17} \text{ m}^{-3}\) could be obtained in the experiment, the attenuation of the forward RCS of inlet could be 11-25dB caused by the plasma ring and there is an optical discharge power to maximum the attenuation the RCS of inlet at a certain frequency radar wave. When the discharge power was increased, the attenuation effect the attenuation peak region would move to the high frequency region.

References
[1] Sang Jianhua. 2013, Aircraft stealth technology, Aviation Industry Press, Beijing (in Chinese).
[2] JI Jin-zu, WU Zhe, LIU Zhanhe. 2009, JOURNAL OF XIDIAN UNIVERSITY., 4: 746(in Chinese).
[3] P.Scheubert, U.Fantz, P.Awakowicz. 2001, Journal of Applied Physics., 90: 587.
[4] Michael A. Lieberman, Allan J. Lichtenberg. 2005, Principles of Plasma Discharges and Materials Processing. John Wiley & Sons Inc, New Jersey.
[5] Lee C C, Boekicher C. 1985, AIAA-85-3073 Colorado
[6] WEI Xiao-long, XU Hao-jun, LIN Min etl. 2015, SPECTROSCOPY AND SPECTRAL ANALYSIS 36(4) (in Chinese).
[7] WEI Xiao-Long, XU Hao-Jun, LI Jian-Hai etl. 2015 Acta Phys.Sin 64:175201 (in Chinese).
[8] Heald M A, Wharton C B.1978, Plasma Diagnostics with Microwave. Krieger, New York.
[9] PeredaJA,VegasA,PrietoA 2002 IEEE Trans. Mi-crowave Theory and Techniques., 50: 1689.
[10] Ge Debiao, YAN Yubo. 2011, Finite-Difference Time-Domain Method for Electromagnetic Waves. XiDian Press, Xian(in Chinese).
[11] YUAN Zhongcai,SHI Jiaming. 2004, Nuclear Fusion and Plasma Physics., 24:157.
[12] Jin Baozi. 2004The Electromagnetic wave propagation in plasma.Science Press, Beijing(in Chinese).
[13] Lin Min, XU Haojun, WEI Xiaolong, et al. 2015, Plasma Science and Technology., 10: 847.