About the influences of gas composition and generator frequency on the formation conditions and parameters of vortex tube in the RF inductively coupled plasma

Yu M Grishin, L. Miao*

Bauman Moscow State Technical University, 2-ya Baumanskaya str., bld. 5, 1, Moscow, 105005, Russia

*E-mail: miaolongbmstu@gmail.com

Abstract. The results of numerical simulation of plasma flow in the channel of technological radio frequency inductively coupled plasma (RF–ICP) with three coils are presented. The generator frequency is varied from 1.76 to 13.56 MHz. The pure argon or Ar/H₂ mixture are considered as the working gas. The volume fraction of hydrogen in Ar/H₂ mixture is varied from 0 to 10%. The distributions of gas-dynamic parameters of plasma flow are calculated. It is shown that when the amplitude of discharge current exceeds a critical value (depends on volume fraction of hydrogen), the states of plasma flow transform from potential to vortical patterns, in which a toroidal vortex is found in front of the inductor zone. The dependencies of critical current on the generator frequency and volume fraction of hydrogen are established. The influences of generator frequency, volume fraction and discharge current on the intensity and coordinate of vortex tube are determined.

1. Introduction

At present in connection with the development of new technologies for the production of ultrapure substances [1-5], nanopowders [6-9], the interests in the inductively coupled plasma (ICP) are steadily increasing. The basic gas–dynamic parameters of plasma (velocity and temperature) are determined by the flow features in the inductor zone of ICP (exothermic zone). Results [10-12] indicate that there is a specific vortex in front of this zone under high discharge current. This leads to a change of plasma flow state and violates the heating and evaporation processes of the solid particles in high temperature zone. Since those solid particles may be slow down by the reversed flow (vortex) and then bypass the high temperature zone without efficient heating and evaporation.

The implementation of plasma technology requires the use of ICP under different plasma power, generator frequency and within various working gases, which may lead to significantly differences in the parameters of vortex tube. However, until now there is practically no systematic information about the formation conditions and parameters of vortex flow in ICP channel.

The aim of present work is to investigate the features of pure argon or Ar/H₂ plasma flow in the ICP channel, find the conditions of forming vortex and determine the parameters of plasma flow under different volume fraction of hydrogen.

2. Physical and mathematical model.
Figure 1 shows a sketch of the ICP with axial gases supplies and three inductor coils to be modeled. The flow rates of transporting, central and sheath gases are correspondingly set as $Q_1=0.5\text{ L/min} \ (R_1=3.7\text{ mm}, \delta_1=2\text{ mm}, \ Z_1=50\text{ mm}), \ Q_2=3.4L/min \text{ and } Q_3=35.4L/min$. The length of external quartz tube is $Z_4=400\text{ mm}$ with an internal radius $R_3=25\text{ mm}$ and wall thickness $\delta_3=3.5\text{ mm}$. The peripheral annual channel have a length $Z_3=50\text{ mm}$ and width $R_3-R_2-\delta_2=2.2\text{ mm}$. Three copper coils with the same coil diameter $d_{\text{coil}}=6\text{ mm}$ and loop radius $R_4=33\text{ mm}$ are evenly distributed. The first coil is located at $Z_{in}=63\text{ mm}$. The distance between the first and last coils is $l_{in}=Z_{inl}-Z_{inf}=60\text{ mm}$. The amplitude of discharge current $J_{\text{coil}}$ and generator frequency $\omega$ are varied respectively in the range of 60-300 A and 1.76-13.56 MHz.

In present calculations the spiral inductor is assumed as three cylindrically symmetric parallel coils. The flows of transporting, central and sheath gases at the inlets are azimuthally symmetrical and stationary. Under the fulfillments of these assumptions the electromagnetic and gas dynamic equations can be written under 2D – model in the cylindrical coordinate $(r, z)$ system. Besides that, it is calculated that plasma flow in the ICP channels is laminar and subsonic with average $Re$ number $Re<1000$.

The gas dynamic parameters of plasma flow are calculated on the basis of plasma dynamic system equations. The effect of electromagnetic forces, Joule heating and radiation losses in the gas dynamics equations have been taken into account. The electromagnetic filed were calculated using Maxwell equations [12, 13].

In numerical calculations the working gas is either pure argon or Ar/H$_2$ mixture with a variation of hydrogen volume fraction $\alpha$ from 0 to 10%. The thermophysical parameters and electrical conductivity of plasma are obtained in the approximation of local thermodynamic equilibrium (LTE) from calculated data [11, 12, 14].

At the inlets ($z=0$) the temperature and the axial velocities of the transporting, central and sheath gases (in corresponding with $Q_1$, $Q_2$ and $Q_3$) are set constant. The velocities of gases at the walls are zero. The gas temperature on the inner surface of external quartz wall is equal to 400 K. At the outlet ($Z_4=400\text{ mm}$) the pressure is set constant $p = 10^5\text{ Pa}$. The boundary conditions for the Maxwell equations are given as in accordance with [12].

The numerical solutions of plasma dynamic and Maxwell equations are based on the finite volume method in ANSYS CFX. The meshes in the calculating regions are built by ANSYS ICEM CFD package using HEXA_8 hexagonal structural blocks.
3. Results and Discussion

The main reason for the arose of vortex tube in front of inductor zone is due to the formation of high pressure zone [15, 16] near the axis of ICP torch, which is connected with the radial component of electromagnetic force of induced current in the plasma.

It is found that when the relative pressure is above a certain value, the working gas flows into the high pressure zone and forms a toroidal vortex around the cross section of first coil (Figure 2). The value and distribution of plasma pressure are determined by the discharge current $J_{\text{coil}}$.

It is found that there is a critical current $J_{\text{cr}}$, which separates the states of plasma flow into potential (subcritical, $J_{\text{coil}} \leq J_{\text{cr}}$) and vortical (supercritical, $J_{\text{coil}} \geq J_{\text{cr}}$) regimes.

![Figure 2](image-url)

**Figure 2.** The streamlines (colored lines), temperature contour $T = 8000 \text{ K}$ (dashed lines) and relative pressure contour $\Delta p = 6 \text{ Pa}$ (solid lines) under $J_{\text{coil}} = 170 \text{ A}$: $\alpha = 0\%$ – upper half-plane; $\alpha = 5\%$ – lower half-plane.

As calculations shown, the critical current for ICP with three coils depends on the properties of working gas and generator frequency under the given dimension parameters and mass flow rate of working gas.

The position and shape (axial cross section) of vortex tube in supercritical regime are demonstrated by the distribution of spatial velocity, which are shown in Figure 2 (color lines). When pure argon is used as working gas, the critical current $J_{\text{cr}}$ (under $\omega=3 \text{ MHz}$) is found at 90–100 A. The axial cross section of vortex tube have an ellipsoidal shape. The vortex center locates at the left side of the first coil.

However, the use of Ar/H$_2$ mixtures as working gas leads to a change in the heat-gas dynamic parameters of plasma flow. Since the Ar/H$_2$ mixtures are characterized by lower electrical conductivity, higher heat capacity and thermal conductivity [14] compared to the pure argon plasma.

It is found that at the same discharge current $J_{\text{coil}}$ the Joule heating zone and its volumetric energy $q_o$ are reduced in the Ar/H$_2$ plasma in comparison to that in the pure argon plasma. As can be seen in Figure 2, this leads to a decrease of plasma zone (the dashed lines of temperature contours $T = 8000 \text{ K}$ are reduced) and maximum plasma temperature. Note that, with the increase of volume fraction $\alpha$ the distribution of temperature in the plasma zone becomes more homogeneous because of higher thermal conductivity. What's more, the transitions of plasma flow states from potential to vortical regimes are observed at higher discharge current. As a result, the dependence of critical discharge current $J_{\text{cr}}$ on the volume fraction of hydrogen $\alpha$ (under $\omega =3 \text{ MHz}$) could be approximated by the linear function $J_{\text{cr}} \approx 100 + 10\alpha(\%)$, A.

The dependencies of axial coordinate $Z_v$ of vortex center on the discharge current (under $\omega =3 \text{ MHz}$ and various $\alpha$) are shown in Figure 3 by dashes lines. In pure argon plasma ($\alpha = 0$) $Z_v$ is practically located at the cross section of first coil ($Z_{\text{inf}}=63 \text{ mm}$) when the discharge current $J_{\text{coil}} = J_{\text{cr}} \approx 100 \text{ A}$. With the increase of discharge current $J_{\text{coil}}$ the axial coordinate of vortex center monotonous decreases to the minimum limit value $Z_{v, \text{min}} \approx 50 \text{ mm}$ (i.e. the vortex center moves left to the upstream of central gas).
The dependencies of vortex intensity $\varepsilon_p$ on the discharge current $J_{coil}$ are shown in Figure 3 by solid lines. The vortex intensity $\varepsilon_p$ is defined as in [10]: $\varepsilon_p = G_p / (G_1 + G_2)$, where $G_p$ is the backflow rate of working gas in the vortex zone, $G_1$ and $G_2$ are the mass flow rates of transporting and central gases. In all cases $\varepsilon_p$ is a monotonically increasing function of the discharge current. Under significant high discharge current $J_{coil} \geq 200 – 250$ A the intensity of vortex tube $\varepsilon_p$ becomes more than unit ($\varepsilon_p > 1$). This can be explained by that the sheath gas begins to play a role in the formation of vortex, part of its stream flows into the vortex tube. It is investigated that in the vortical regime the intensity of vortex tube in pure Ar plasma ($\alpha = 0$) is either greater or equal to that in the Ar/H$_2$ plasma ($\alpha \neq 0$) at the same discharge current. That is, the values of $\varepsilon_p$ and $Z_v$ under $\alpha = 0$ are the upper limits of the $\varepsilon_p(J_{coil})$ and $Z_v(J_{coil})$ functions under all other different compositions of Ar/H$_2$ plasma ($\alpha \neq 0$).

In order to investigate the influences of generator frequency on the features and parameters of vortex tube, the generator frequency is chosen in the range of 1.76 – 13.56 MHz. The pure argon is considered as working gas. It is found that the critical current $J_{cr}$ is a decreasing function of generator frequency and can be approximated by formula: $J_{cr} = 145\omega^{-0.35}$.

In the vortical regime the intensity of vortex is an increasing function of discharge current. It is found that under a given discharge current, the increase of generator frequency from 1 to 5 MHz leads to a significantly rise of vortex intensity. While the increase of generator frequency from 5 to 8 MHz has little influences on the vortex intensity (Fig.4, solid lines). This may be due to the changes in the distribution of magneto-hydrodynamic (MHD) forces, which are located far more away from axis under high generator frequency as a result of the “skin effect” in the discharge zone.

Besides that, the axial coordinate of vortex centre $Z_v$ also depends on the amplitude and generator frequency of discharge current, it is a decreasing function of discharge current. As can be seen that under a given amplitude of discharge current, the axial coordinate $Z_v$ increases with the decrease of discharge frequency. When the discharge current $J_{cr} \geq 200$A the vortex center almost doesn’t changes, it is located around $Z_v \approx 53$ mm (Fig.4, dashed lines).
Figure 4. The dependencies of vortex intensity $\varepsilon_v$ (solid lines) and axial coordinate of vortex center $Z_v$ (dashed lines) on the discharge current under different generator frequencies: 1 – $\omega = 1.76$ MHz; 2 – $\omega = 5.28$ MHz; 3 – $\omega = 8$ MHz.

4. Conclusions

The gas dynamic parameters of structures of plasma flow in the ICP torch are obtained. The features of the distribution of velocity and temperature fields are found in the ICP torch under the presence of toroidal vortical flow before the high temperature zone. It is established that the necessary conditions for the form of vortex tube are that the discharge current exceeds an critical value $J_{cr}$, which depends on the volume fraction of hydrogen $\alpha$ (under $\omega = 3$ MHz): $J_{cr} \approx 100 + 10\alpha(\%)$, A. The dependence of critical current (for pure Ar plasma) on generator frequency is shown by the following formula: $J_{cr} = 145\omega^{-0.35}$, A. The intensity and position of vortex tube in supercritical flow regimes are determined as a function of the discharge current $J_{coil}$, volume fraction $\alpha$ and current frequency $\omega$.

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