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Numerical simulation on thermal plasma temperature field in the torch for different conditions

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Abstract. Numerical simulation was conducted to obtain the temperature and gas flow fields in inductively coupled thermal plasma (ICTP). Influence of gas composition, power supply, quenching gas, carrier gas, pressure and frequencies were investigated on thermal plasma temperature fields. Results indicated that higher oxygen fraction in gas composition makes the shrinkage of the thermal plasmas, which increases power density in local volume. Further, an increase in the quenching gas, the carrier gas and the pressure did not affect the temperature of thermal plasma. On the other hand, the temperature in thermal plasma decreased at axial position along with degradation of frequency.

1. Introduction

Inductively coupled thermal plasma (ICTP) with high power and high pressure has been widely used in different materials processing like synthesis of diamond films [1], syntheses of fullerene [2] and thermal barrier coatings [3], a chemical source and effective heat source. In the materials processing, raw material powder is injected into the thermal plasma. The injected powder is rapidly heated and then evaporated. These evaporated materials are used for materials processing such as coating, nanoparticle synthesis and so on. One feature of the ICTP is that it needs no electrode. This gives a benefit of no contaminated process compared to the arc plasma processing. From the above benefit, the ICTP is adopted to material processing like synthesis of nanopowder [4]. The ICTP processing is affected markedly by the temperature field of the ICTP.

In this work, we studied the effect of gas composition, the input power, the quenching gas, the carrier gas flow rate, the pressure and the frequency on the ICTP temperature field. Firstly, we describe the modelling of the ICTP and the assumptions. Secondly, the calculation was made for the temperature field for Ar-O\textsubscript{2} gas mixture thermal plasma at 25 kW. We studied the effect of each of physical parameters: O\textsubscript{2} percentage to Ar, the input power, the quenching gas, the carrier gas flow rate, the pressure and the frequency on the ICTP temperature field. From these results, we obtain the sensitivity from each physical parameter on the ICTP temperature fields.
Figure 1. Cross section of inductively coupled thermal plasma torch used in the numerical simulation.

2. Structure of inductively coupled thermal plasma torch

Figure 1 illustrate the structure inductively coupled thermal plasma torch and the reaction chamber used in this numerical simulation. The plasma torch comprises two coaxial quartz tubes with 330 mm in length. The inner quartz tube has a internal radius of 35 mm and an 8 turn-coil is located around the quartz tube to generate electromagnetic field. This electromagnetic field forms a inductively coupled thermal plasma inside the plasma torch. The quartz tube wall of the plasma torch is cooled with cooling water at room temperature.

From the head of the plasma torch, argon and O\textsubscript{2} gas mixture is supplied in the inner quartz tube wall with a swirl to prevent the plasma from attaching the tube wall. This gas is called the sheath gas. From the plasma torch head, a water-cooled tube is inserted for feedstock injection in case of materials processing. The feedstock is usually injected with a carrier gas. In addition, quenching gas can be injected downstream of the plasma torch in radial direction to cool down the thermal plasma.

3. Modeling

3.1 Assumptions

The thermal plasma was modelled based on the following assumptions: (i) The plasma is in local thermodynamic equilibrium; consequently, all the temperatures such as the electron temperature, heavy particle temperature, and excitation temperature are identical. In addition, the model assumes chemical equilibrium conditions for all reactions. (ii) The plasma is optically thin for wavelengths greater than 200 nm. For wavelengths of less than 200 nm, 20\% of the total emission coefficient is accounted for radiation loss to consider the effective light absorption. (iii) The flow is steady, laminar, and axisymmetric, with negligible viscous dissipation.

3.2 Governing equation for thermal plasma region

On the basis of the assumptions described above, the thermal plasma is governed by the following equations.

Mass conservation.

$$ \frac{\partial (\rho u)}{\partial z} + \frac{1}{r} \frac{\partial (r \rho v)}{\partial r} = 0 $$

Momentum conservation.

Axial:

$$ \rho u \frac{\partial u}{\partial z} + \rho v \frac{\partial u}{\partial r} = -\frac{\partial p}{\partial z} + 2 \frac{\partial}{\partial z} \left[ \eta \left( \frac{\partial u}{\partial z} + \frac{\partial v}{\partial r} \right) \right] + \frac{1}{r} \frac{\partial}{\partial r} \left[ \eta r \left( \frac{\partial u}{\partial r} + \frac{\partial v}{\partial z} \right) \right] + \mu_0 \sigma \Re \left[ \vec{E}_\theta \vec{H}_z \right] $$

Radial:

$$ \rho u \frac{\partial v}{\partial z} + \rho v \frac{\partial v}{\partial r} = -\frac{\partial p}{\partial r} + \frac{\partial}{\partial z} \left[ \eta \left( \frac{\partial v}{\partial z} + \frac{\partial u}{\partial r} \right) \right] + \frac{2}{r} \frac{\partial}{\partial r} \left[ \eta r \frac{\partial v}{\partial r} \right] + 2 \eta \frac{v}{r^2} + \mu_0 \sigma \Re \left[ \vec{E}_\theta \vec{H}_z \right] $$


Swirl:
\[
\rho u \frac{\partial w}{\partial z} + \rho v \frac{\partial w}{\partial r} = -\frac{\partial}{\partial z} \left( \eta \frac{\partial w}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \eta \frac{\partial w}{\partial r} \right) - \frac{\rho vw}{r} - \frac{w \partial \tau_n}{\partial r} \tag{4}
\]

Energy conservation.
\[
\rho u \frac{\partial h}{\partial z} + \rho v \frac{\partial h}{\partial r} = \frac{\partial}{\partial z} \left( \lambda \frac{\partial h}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda \frac{\partial h}{\partial r} \right) + \sigma |\dot{E}_\theta|^2 - P_{rad} \tag{5}
\]

Maxwell equation.
\[
\frac{\partial^2}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial A_\theta}{\partial r} \right) - \frac{\dot{A}_\theta}{r^2} = j \mu_0 \sigma \omega \dot{A}_\theta \tag{6}
\]
\[
\dot{H}_z = j \frac{1}{\mu_0} \frac{1}{r} \frac{\partial}{\partial r} (r \dot{A}_\theta), \quad \dot{H}_r = -\frac{1}{\mu_0} \frac{\partial}{\partial z} \dot{A}_\theta \tag{7}
\]
\[
\dot{E}_\theta = -j \omega \dot{A}_\theta \tag{8}
\]

In those equations, the following pertain. \(r\): radial position, \(z\): axial position, \(u\): axial flow velocity, \(v\): radial flow velocity, \(\rho\): mass density, \(p\): pressure, \(\eta\): viscosity, \(h\): enthalpy, \(\lambda\): thermal conductivity, \(C_p\): specific heat at constant pressure, \(\sigma\): electrical conductivity, \(P_{rad}\): radiative loss, \(\mu_0\): permeability of vacuum, \(\dot{A}_\theta\): phasor of the vector potential, \(\omega\): frequency of the coil current, \(\dot{E}_\theta\): phasor of the electric field strength, \(\dot{H}_z\), \(\dot{H}_r\): phasors of axial and radial components, of the magnetic field strength, respectively, \(j\): complex factor (\(j^2 = -1\)). The magnitudes of the phasors including \(\dot{A}_\theta\), \(\dot{E}_\theta\), \(\dot{H}_z\), and \(\dot{H}_r\) are defined as the root mean square values. The asterisks in equations 2 and 3 indicate the conjugate, and a symbol \(\Re\) is the real part of the phasor.

**Table 1. Calculation condition-1**

| Condition No. | 3 (ref) | 1 | 2 | 4 |
|---------------|--------|---|---|---|
| Input power   | 25 kW  | - | 20 kW | - |
| Frequency     | 450 kHz | - | - | - |
| Pressure      | 300 torr | - | - | - |
| Total sheath gas flow rate | 120 L/min | - | - | - |
| \(\text{O}_2\) percentage to Ar | 10% | 15% | - | - |
| Carrier Ar gas flow rate | 4 L/min | - | - | - |
| Quenching flow rate | 50 L/min | - | - | 75 L/min |

**Table 2. Calculation condition-2**

| Condition No. | 3 (ref) | 5 | 6 | 7 |
|---------------|--------|---|---|---|
| Input power   | 25 kW  | - | - | - |
| Frequency     | 450 kHz | - | - | 400 kHz |
| Pressure      | 300 torr | - | 500 torr | - |
| Total sheath gas flow rate | 120 L/min | - | - | - |
| \(\text{O}_2\) percentage to Ar | 10% | - | - | - |
| Carrier Ar gas flow rate | 4 L/min | 6 L/min | - | - |
| Quenching flow rate | 50 L/min | - | - | - |

The thermodynamic such as the mass density, the enthalpy and the specific heat, and transport properties such as the thermal conductivity, the viscosity and the electrical conductivity are necessary for simulation. These were calculated in advance using the calculated equilibrium composition and the first-order approximation of Chapman-Enskog method [5].
4. Numerical calculation condition

The calculation was made for Ar-O₂ thermal plasmas. The thermal plasma temperature fields is affected by many physical parameters. Here, we studied the physical parameter effects on the thermal plasma temperature field. Table 1 summarizes the numerical calculation conditions in the present work. There are seven conditions. Condition 3 is the reference condition having the input power of 25 kW, the frequency of the coil current of 450 kHz, the pressure of 300 torr, the total gas flow rate of 120 L/min, percentage to Ar of 10%, the Ar carrier gas flow rate of 4 L/min, quenching gas flow rate of 50 L/min.

![Temperature distribution result with quenching gas injection](image)

**Figure 2.** Temperature distribution result with quenching gas injection

From the reference condition, one condition was changed to study the specified parameter on the thermal plasma temperature field. Condition 1 has different O₂ concentration of 15% to condition 3 to see the effect of O₂ concentration. Generally, high percentage of O₂ requires the excitation and dissociation energy of O₂, which leads to the higher specific heat and thermal conductivity. Condition 4 has a higher quenching gas flow of 75 L/min to study the effect of quenching gas flow. Quenching gas frequently cools the thermal plasma temperature. Effect of Ar carrier gas flow rate can be seen in condition 5 with 6 L/min by comparing with the result of condition 3. The carrier gas has low temperature, which injection to the thermal plasma affects the thermal plasma temperature markedly. Pressure is one of the important parameter to determine the thermal plasma temperature. Comparison between the results for conditions 3 and 6 may provide the partial knowledge of the pressure effect between 300 torr and 500 torr. Condition 7 has a different frequency of 400 kHz to study the effect of frequency of the coil current in comparison with condition 3. The frequency of the coil current affects the skin depth of electromagnetic field, and then influences the temperature profile.

5. Numerical result

To get the best result in thermal plasma, we compare the calculation results of gas composition, input power, quenching gas, carrier gas, pressure and frequency as shown in Figure 2. The first compare is about gas composition with condition 1 and condition 3. As we can see in Figure 2, condition 3 is better result in thermal plasma torch than condition 1.

Condition 1 Ar 85% and O₂ 15%, the temperature inside the plasma torch is 8032 K at axial
position is $z = 300$ mm and radial position is $r = 20$ mm. Furthermore, the temperature in the reaction chamber is 6484 K for axial position amount is 600 mm and radial position as much as 5 mm. Condition 3 Ar 90% and $O_2$ 10%, the temperature inside the plasma torch is 8602 K at axial position is $z = 300$ mm and radial position is $r = 20$ mm. Meanwhile, the temperature in the reaction chamber is 6932 K for axial position amount is $z = 600$ mm and radial position as much as $r = 5$ mm.

Frequency 450 KHz with condition 3, the temperature inside the plasma torch is 7788 K at axial position is $z = 300$ mm and radial position is $r = 25$ mm. Frequency 400 KHz with condition 7, the temperature inside the plasma torch is 7788 K at axial position is $z = 300$ mm and radial position is $r = 23$ mm. Meanwhile, the temperature in the reaction chamber in condition 3 and 7 are same results.

![Figure 3. Radial temperature distribution at axial position of $z = 300$ mm with quenching gas.](image1)

![Figure 4. Radial temperature distribution at axial position of $z = 400$ mm with quenching gas.](image2)

Finally, we get best of the best result in condition 3 with compare addition frequency. To compare the temperature distribution clearly in gas composition, input power, quenching gas, carrier gas, pressure and frequency, the radial temperature distributions at axial positions of $z = 300$ mm and
z = 400 mm are plotted in figure 3 and figure 4, respectively. This figure includes the curves for all condition. As indicated in this figure, the condition 3 has the temperatures about 8602 K and 5203 K (z = 300 and z = 400) at radial positions of r = 20 mm. This implies that the temperature in all condition is influenced easily to decrease by quenching gas. On the other hand, condition 6 is smaller result in thermal plasma torch in other condition with temperature about 7923K and 3621 K (z = 300 and z = 400) at r = 20 mm.

To indicate the temperature recovery characteristics in all condition, the axial temperature distributions are plotted in Figure 5. As seen in this figure, the temperature at a radial position of r = 5 mm is 300 K from z = 0 mm to z = 210 mm in all condition. z = 210 to z = 220 mm, the temperature is still 300 K due to cool argon carrier gas flow in all condition. This axial temperature recovers from z = 220 mm to z = 300 mm only to around 8500 K in all condition. On the other hand, in all condition, the temperature decrease to 5000 K up to z = 1100 mm.

6. Conclusions
In this paper, the influences of gas composition, input power, quenching gas, carrier gas, pressure and frequency on the temperature distribution in argon (Ar) induction thermal plasma with quenching gas were investigated numerically. Results indicated that addition frequency at 450 kHz significantly increase temperature at plasma torch in axial position. It means condition 3 is better than the other conditions.

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