

# Influence of sheath gas flow rate in Ar induction thermal plasma with Ti powder injection on the plasma temperature by numerical calculation

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**Abstract.** Numerical calculation was conducted to study the gas flow fields and temperature distribution in Ar inductively couple thermal plasma (ICTP) with titanium (Ti) powder injection. Influence of sheath gas flow rates at 90 L/min, 80 L/min and 70 L/min was investigated on the thermal plasma temperature in the torch. Results indicated that higher sheath gas flow rate raises the axial temperature and gas flow velocity in the thermal plasma

## 1 Introduction

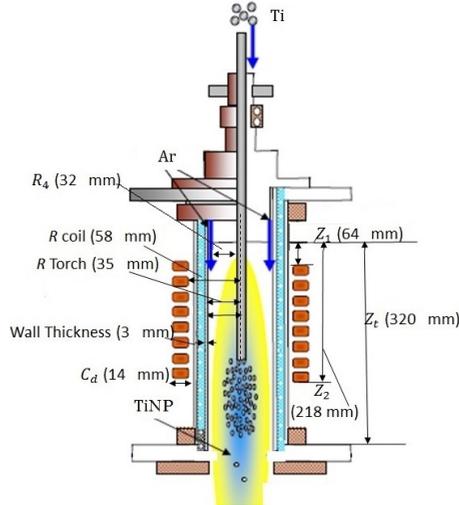
Inductively coupled thermal plasma (ICTP) in high-pressure and high-power has been widely used for different materials processing such as nanoparticle synthesis [1], thermal barrier coatings [2], fabrication of diamond films [3], surface modification [4], synthesis of fullerene [5]. The ICTP can be an adequate chemical and heat source to different materials processing with little contamination. The ICTP often have high gas temperature and high enthalpy, which can be adequate to evaporate solid feedstock in materials processing. In case of nanoparticle synthesis, the ICTP gives one-step direct processing with rapid evaporation of injected feedstock using the above high gas temperature and high enthalpy. In addition, the ICTP offers rapid cooling of evaporated materials because of high temperature gradient in the downstream portion of the ICTP. This rapid cooling of the evaporated material can enhance nucleation and produce nanoparticles.

The ICTP is usually sustained with sheath gas along the inner plasma torch. The sheath gas is used to supply the plasma gas itself and also to prevent the plasma from contacting the plasma torch from the thermal damage of the torch. It is well known that this sheath gas influence the generation of the ICTP itself, and the temperature and gas flow fields in the ICTP. However, it is not yet enough understood to study the influence of sheath gas flow rate on the temperature field in the ICTP and also on the evaporation rate of feedstock power injected into the ICTP.

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In this report, the influence of sheath gas flow rate on thermal interactions between argon (Ar) ICTP and titanium (Ti) powder injection was studied using our previously



**Fig. 1.** Configuration of Ar/Ti ICTP torch

developed numerical calculation model [6,7]. Results indicated that higher gas flow rate in the sheath gas enhances evaporation of feedstock by increased thermal plasma temperature along the axis of the plasma torch.

## 2 Configuration of inductively coupled thermal plasma torch

The configuration of the ICTP treated here is shown in Fig. 1. The plasma torch is composed of two coaxial quartz tubes with a length of 320 mm. The inner quartz tube has an internal radius of 35 mm. Around this tube, an 8 turn-coil is wound with a radius of 58 mm. To this 8 turn-coil, rf current is supplied to produce electromagnetic field inside the tube. In the tube, the ICTP is sustained by electromagnetic field generated from the coil current. Argon is provided as a sheath gas flow along the inner quartz tube wall. The sheath gas is supplied with a swirl to avoid the plasma from contacting the inner quartz tube.

Titanium feedstock powder is assumed to be injected with Ar carrier gas through a water cooled pipe into the ICTP as shown in Fig.1. For numerical calculation of the temperature and gas flow fields in the ICTP with titanium feedstock powder, a two-dimensional cylindrical  $r - z$  cross section of this plasma torch was set as a calculation space.

## 3 Modeling and calculation of ICTP

### 3.1 Assumptions

We assumed the following conditions for the ICTP[7]: (i) Local thermodynamic equilibrium (LTE) is established in the ICTP. Thus, all the temperatures including electron temperature and heavy particle temperature are the same to one another. Boltzmann distribution is assumed to the excited state at that temperature. In addition, chemical equilibrium conditions were also set for all reactions. (ii) The optically thin assumption was adopted at wavelengths above 200 nm. (iii) Steady state, axis-symmetric and laminar flow

were assumed with no viscous dissipation. (iv) The particle-particle interactions were not considered for injected particles. (v) The mean free path of plasma components was assumed to be much smaller than the particle radius. (vi) The particle radius was assumed to be much higher than the mean free path of plasma components. (vii) In evaporation, particle always has spherical shape. (viii) The particles are heated uniformly from the around plasmas. Therefore, evaporation uniformly occurs at the particle surface. (ix) Influence of electronic charging on the particle were not considered. (x) Rocket force was neglected.

**Table 1.** Titanium powder of thermodynamic properties

Parameter	Unit	Value
Injection load	g/min	0.5
Mass density	kg/m <sup>3</sup>	4506
Melting temperature	K	1953
Boiling temperature	K	3535
Latent heat for melting	J/kg	391000
Latent heat for evaporation	J/kg	8294000
Specific heat of solid	J/(kg.K)	528
Specific heat of liquid	J/(kg.K)	700
Thermal conductivity	W/(m.K)	14
Emissivity of particle source	(-)	0.4

### 3.2 Numerical calculation condition

In this calculation, the operating frequency for the rf coil current was fixed at 450kHz. The pressure condition was set at 300 Torr (=40 kPa) inside the plasma torch. The input power was set at 40 kW. Sheath gas flow rate was set to three values of 90 L/min, 80L/min, and 70 L/min. To this ICTP, titanium feedstock powder is injected through a water-cooled pipe inserted on the torch axis from the plasma torch head. The injected titanium feedstock powder has a mean diameter of 2 μm and a deviation of 0.5 μm. In the calculation, 35 trajectories for feedstock particles with 7 different diameters with 5 different initial positions were assumed to be injected. The titanium feedstock feed rate was set to 0.5 g/min. In addition, transport properties and thermodynamic of argon and titanium vapor were in advance calculated as a function of temperature. For solid and liquid thermal properties of feedstock, the values were used in the literatures as indicated in Tab.1.

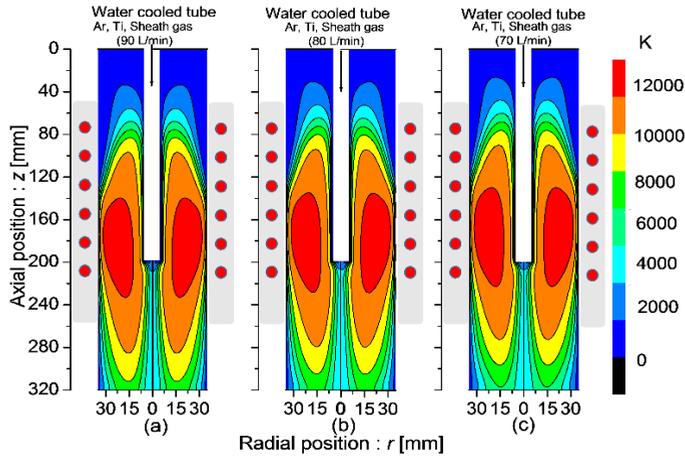
## 4 Calculation results

### 4.1 The temperature distribution of the ICTP

Figure 2(a), (b) and (c) show the temperature distribution of the ICTP with an sheath gas flow rate of 90 L/min, 80 L/min and 70 L/min, respectively. In case of Fig.2(a) with a sheath gas rate of 90 L/min, the ICTP has high temperature area about 11000 K in wide region around radial positions of 10 mm < r < 30 mm and axial positions 140<z<235mm. In this high temperature area, the rf eddy current flows inside the ICTP to heat it. At a sheath gas flow rate of 80 L/min as shown in Fig.2(b), the high temperature area at temperatures above 11000 K becomes smaller around radial positions of 9 mm < r < 29 mm and axial positions of 135 mm < z < 225 mm than that in Fig.2(a). Furthermore, lower sheath gas flow rate at 70 L/min case as indicated in Fig.2(c) presents a further smaller high temperature area at temperatures above 11000 K around radial positions of 15mm<r<28mm and axial positions of 130 mm < z < 220 mm. This means that the high temperature area is shifted to upstream with decreasing sheath gas flow rate. This is due to reduced gas flow

convection transport by decreasing gas flow rate. In addition, the high temperature area is shrunk in axial direction with decreasing gas flow rate. These features can be seen for mid-temperature area of 6000-6500 K.

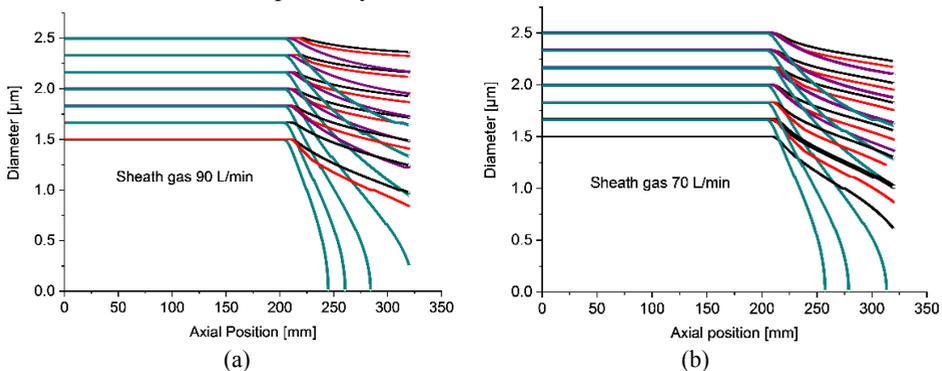
On the axis of the torch, the temperature is higher at higher gas flow rate of 90L/min than at lower gas flow rate of 70 L/min. This may be because at higher gas flow rate of 90 L/min, the high temperature area is present near the center axis by strong gas flow around the torch wall. That stronger gas flow make the high temperature plasma present near the axis. This higher temperature around the axis is related to the evaporation rate of feedstock as described later.



**Fig. 2.** The temperature distribution of Ar and Ti powder injection with sheath gas flow rate at 90L/min, 80 L/min, 70 L/min.

## 4.2 Titanium feedstock particle evaporation

In this temperature fields of the ICTP, titanium feedstock particles were assumed to be injected. Figure 3 indicates variation in diameters of 15 particles with 5 different initial diameters injected from 3 different initial positions into the sheath gas as a function of axial position. Figure 3(a) and 3(b) corresponds to the results for sheath gas flow rates of 90L/min and 70 L/min, respectively.



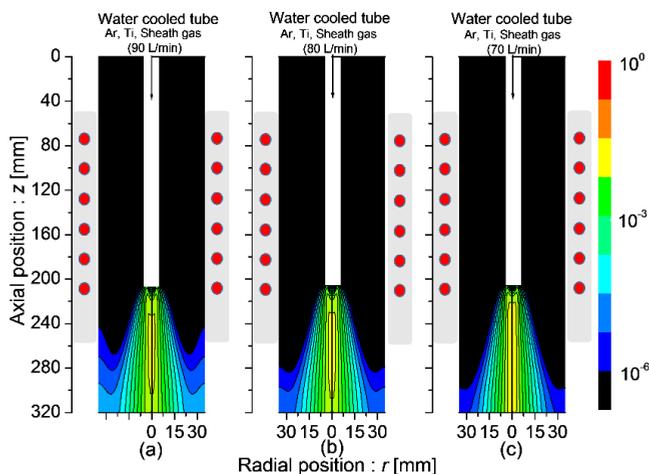
**Fig. 3.** Diameter variation of titanium particles injected for 35 kinds with 5 different initial positions and different 7 initial diameters as a function of axial position in argon ICTPs with sheath gas flow rate at 90 L/min (a) and 70 L/min (b).

The diameters do not change at axial position from 0 to 200 nm because all the particles

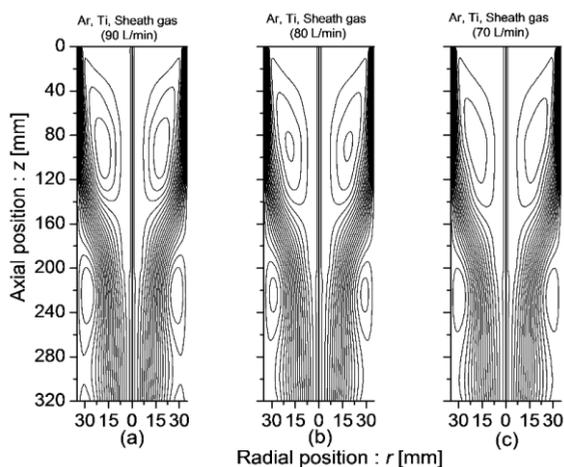
injected are present inside the water-cooled pipe. From axial position of 200 mm, the particles start flying into the ICTP, and then they are heated by the ICTP. After some fly to be heated, the Ti particles have the diameter decreased because of its evaporation. In this calculation, the particles with initial diameter of 1.5  $\mu\text{m}$  are strongly heated from the ICTP, and then the particle diameter decreases to 0.01  $\mu\text{m}$ . As shown in Fig.3(a) and (b), higher sheath gas flow rate of 90 L/min involves rapid decrease in diameter than 70 L/min. This is attributed to the higher temperature along the torch axis as indicated in the previous section. This evaporation of the feedstock particles produces titanium vapor to the ICTP, which can change the properties of the Ar ICTP.

### 4.3 Mass fraction of titanium vapor

Influence of sheath gas flow rate on titanium vapor creation in the ICTP can be seen in Fig. 4. As shown in this figure, the mass fraction of titanium (Ti) vapor is distributed from the tip of the water-cooled pipe.



**Fig. 4.** Mass fraction of Ar and Ti powder injection with sheath gas flow rate at 90 L/min, 80 L/min, 70 L/min



**Fig. 5.** Streamline of Ar and Ti powder injection with sheath gas flow rate at 90 L/min, 80 L/min, 70L/min

The injected Ti feedstock particles are injected to the ICTP through the feeding pipe. The Ti particles are evaporated during their flight to produce Ti vapor as contamination to Ar ICTP. This contaminated Ti vapor is transported by gas flow convection of Ar carrier gas and by diffusion. This Ti vapor is present downstream of the feeding pipe along the axis. Titanium vapor concentration just slowly increases with decreasing sheath gas flow rate. This is due to lower gas flow velocity along the axis, and thus the Ti vapor concentration is higher at 50 L/min of sheath gas flow rate.

Another difference in Ti vapor concentration is that Ti vapor is present around the wall at higher gas flow rate of 90 L/min. This arises from the vortex near the wall. Figure 5 shows the streamline inside the ICTP at different sheath gas flow rate at 90 L/min, 80L/min and 70 L/min. As indicated in Fig.5, increasing sheath gas flow rate gives strong vortex at the upper side of the plasma torch at axial position  $40 \text{ mm} < z < 140 \text{ mm}$ . Furthermore, another vortex present at axial position  $200 \text{ mm} < z < 280 \text{ mm}$  around the torch wall is strengthened by increasing sheath gas flow rate. Because of this vortex, the mass fraction of Ti vapor is transported to upstream direction near the torch wall around axial position  $240 \text{ mm} < z < 320 \text{ mm}$ .

## 5 Conclusion

Numerical simulation was made to study influence of sheath gas flow rate on the temperature distribution in argon (Ar) induction thermal plasma with titanium (Ti) feedstock powder. The calculated temperature distributions of argon thermal plasma and titanium feedstock powder were compared with different sheath gas flow rate at 90 L/min, 80 L/min and 70 L/min. Results indicated that higher sheath gas flow rate raises the axial temperature distribution and gas flow velocity in the thermal plasma torch.

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