2. Governing equations

A schematic illustration of the RF-ICP torch is shown in figure 1. The inlet portion has three nozzles for carrier gas, plasma gas and sheath gas respectively. An RF-ICP is produced and maintained in the torch by the RF induction coils (3-13.56 MHz, 8 kW). The seed materials are prevaporized and injected into the plasma gas through the nozzle 2.

The plasma model is proposed on the following assumptions:

- steady, laminar and 2D axisymmetric flow and temperature fields
- 2D axisymmetric induced electromagnetic fields with negligible displacement currents
- negligible viscous dissipation and gravitational forces
- Local thermal equilibrium
- optically thin
- two-body collision ionization and three-body recombination
- diffusion of ions and electrons is ambipolar diffusion

The governing equations of continuity, momentum, energy, plasma species and induced electromagnetic fields are as follows:

Continuity

\[ \nabla \cdot (\rho \mathbf{u}) = 0 \]  \hspace{1cm} (1)

where \( \mathbf{u} \) is the time-averaged velocity, \( \rho \) is the density

Momentum

\[ \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \mathbf{\tau} + \mathbf{F} \]  \hspace{1cm} (2)

where \( p \) is the pressure, \( \mathbf{\tau} \) is the viscous stress tensor. \( \mathbf{F} \) is the Lorentz force vector which has the time-averaged axial and radial components \( F_a \) and \( F_r \), as follows respectively.
\[ F_r = -\frac{1}{2} \sigma \text{Re}(E_x B_z) \quad (3) \]
\[ F_r = \frac{1}{2} \sigma \text{Re}(E_x \overline{B_z}) \quad (4) \]

where \( \sigma \) is the electrical conductivity, \( E_x \) is the azimuthal component of the induced electric field, \( B_r \) and \( B_z \) are the radial and axial components of the induced magnetic flux density respectively; symbol \( \overline{\cdot} \) denotes the complex conjugate.

**Energy**

\[ \nabla \cdot (\rho \mathbf{u}) = \nabla \cdot \left( \frac{k}{C_p} \nabla h \right) + Q_r - Q_s \quad (5) \]

where \( h, C_p, k \) and \( Q_r \) are the enthalpy, the specific heat at constant pressure, the thermal conductivity and the radiation loss respectively; Joule heating \( Q_s \) is written as

\[ Q_s = \frac{1}{2} \sigma E_x \overline{E_z} \quad (6) \]

**Species**

\[ \nabla \cdot (n_{e, r} u) = \nabla \cdot (D_{e, r} \nabla n_{e, r}) + \dot{n}_{e, r} \quad (7) \]
\[ \nabla \cdot (n_{seed, r} u) = \nabla \cdot (D_{seed, r} \nabla n_{seed, r}) + \dot{n}_{seed, r} \quad (8) \]
\[ \nabla \cdot (n_{seed, r} u) = \nabla \cdot (D_{seed, r} \nabla n_{seed, r}) + \dot{n}_{seed, r} \quad (9) \]

where \( n \) is the number density of each species, \( \dot{n} \) is the net production of each species, \( D \) is the diffusion coefficient, the subscripts \( e \) and \( seed \) denote electron and seed atom such as potassium and cesium respectively. Since the net production is determined by the balance between ionization and recombination, it can be written as

\[ Ar + e = Ar^+ + e + e \]
\[ \dot{n}_{e, r} = k_{ion, e} n_{Ar} n_e - k_{rec, e} n_{Ar^+} n_e \quad (10) \]
\[ seed + e = seed^+ + e + e \]
\[ \dot{n}_{seed, r} = k_{ion, seed} n_{seed} n_e - k_{rec, seed} n_{seed^+} n_e \quad (11) \]
\[ \dot{n}_{seed, r} = k_{ion, seed} n_{seed} n_e - k_{rec, seed} n_{seed^+} n_e \quad (12) \]

where \( k_{ion} \) and \( k_{rec} \) are the ionization and recombination coefficient respectively, subscript \( e \) denotes electron. Since plasma is electrically neutral, the electron number density is written as

\[ n_e = n_{Ar^+} + n_{seed^+} \quad (13) \]

**Induced electromagnetic fields**

\[ \nabla^2 A - i \mu_0 \omega \sigma A = 0 \quad (14) \]
\[ E = -i \omega A \quad (15) \]
\[ B = \nabla \times A \quad (16) \]

where \( A \) is the vector potential, \( \mu_0 \) is the permeability of the free space, \( i \) is the imaginary unit, \( \omega = 2 \pi f \) is the angular frequency.
3. Thermodynamic and transport properties and boundary conditions

Viscosity, thermal conductivity, specific heat at constant pressure, diffusion coefficient, ionization coefficient and recombination coefficient may be basically expressed as functions of temperature from the database [5]. Besides the variation of the thermal conductivity caused by seeding, it is taken into account. Especially, the electrical conductivity reflects the effect of seeding and can be formulated as

\[ \sigma = e^2 n_0^2 / m_e \sqrt{8kT} \sum_i p_{i,n} Q_i \]  

(17)

where \( e \), \( m_e \), \( Q_i \), and \( k \) are the electronic charge, the electron mass, the collision cross section between an electron and a heavy particle and Boltzmann constant respectively.

The injection flow rate and the seed fraction are given at the inlet. Since the seed materials need to be prevaporized, the inlet temperature is set at 800 K. There is non-slip and heat transfer with heat conduction is considered at the wall as boundary conditions. Since both coil current and induced current in the plasma should be taken into account to determine the induced electromagnetic field, the boundary condition for the azimuthal component of the vector potential is written as

\[ A_z(r_w,z) = \frac{\mu_0 I}{2\pi} \int_{r_w}^{r_0} \sqrt{r} \sum_{i=1}^{\infty} G(k_i) + \frac{\mu_0 I}{2\pi} \int_{r_w}^{r_0} \sqrt{r} \sigma \nabla S G(k_i) \]  

(18)

where \( I \) is the coil current, \( S \) is the surface of the control volume, \( G(k_i) \) is the function of complete elliptic integrals; the subscripts \( W \) and \( C \) denote the wall and the coil respectively; \( C V \) stands for the control volume.

4. Results and discussion

Figure 2 shows a comparison of the electron number density profiles. Even by seeding a small amount of vaporized alkali metals, the electrons are distributed wider since alkali metals can be ionized early at the region of lower temperature compared with argon. The ionized region shifts to the downstream when the injection flow rate is high. The maximum region of the electron number density approaches the wall with the high applied frequency.

Figure 3 shows a comparison of the electrical conductivity profiles. The electrical conductivity in seeding alkali metals increases considerably accompanied by the increase in electrons as shown in figure 2. With the high injection flow rate, the region of high electrical conductivity becomes wider downstream. When the applied frequency is high, the maximum region...
of the electrical conductivity approaches the wall with that of the electron number density.

Figure 4 shows a comparison of the temperature profiles. The region of temperature 2000-6000 K becomes wider by seeding alkali metals. The region of high temperature becomes smaller and approaches the wall since Joule heating concentrates near the wall by the thinner skin depth with the high frequency.

Figure 5 shows a comparison of the velocity profiles. The vortices are produced near the coils due to the pinch effect by the radial Lorentz forces in Case2. The gas injection flow rate affects especially the presence of vortices near the coils. When the applied frequency increases, the vortices near the coils disappear by the decrease in the radial Lorentz force due to the skin effect.

5. Conclusion

It is investigated how its functions and thermofluid characteristics of the RF inductively coupled argon plasma are influenced and enhanced by seeding vapor potassium or cesium at
atmospheric pressure taking into account the ionization, recombination and diffusion of species. The results obtained here by numerical simulation are as follows:

1. The electrical conductivity increases by seeding alkali metals, the region of temperature 2000-6000 K becomes wider downstream and then the RF-ICP is functionalized.
2. The vortices near the coils disappear with the high injection flow rate and the region of high temperature becomes smaller and approaches the wall in the RF-ICP functionalized by seeding alkali metals.

Reference


1214