CO₂ and H₂ Gas Mixture Inclusion Effect on Shrinkage of Ar Induction Thermal Plasmas

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Keywords: inductively coupled thermal plasma, molecular gas mixture, plasma radius, shrinkage

1. Introduction

In thermal plasma technology, some molecular gas mixtures are used for working gases. On the other hand it is well known that SF₆ has high global warming potential. So in the circuit breaker fields, alternatives for SF₆ are being searched as an arc quenching gas from the viewpoint of an environmental issue. The CO₂ or additional gas added CO₂ is one of the candidates for such arc quenching gases. In order to investigate its fundamental properties, the inductively coupled thermal plasma technique is useful because of free from any contamination. In the present work, effect of CO₂+H₂ gas mixture inclusion was numerically investigated on high power Ar inductively coupled thermal plasmas at atmospheric pressure.

2. Calculation Condition

Simulation has been carried out solving a two-dimensional local thermodynamic equilibrium (LTE) code. Calculation was performed for the high power radio frequency ICTP system setup installed in the laboratory shown in Fig. 1. The active plasma power and input fundamental frequency were 27 kW and 450 kHz respectively. The numerical calculation was carried out using SIMPLE algorithm with uniform grid system having 66 radial and 92 axial nodes. The thermodynamic and transport properties had been derived from thermal plasma composition calculated by Gibb's energy minimization (GEM). Using the equilibrium composition, the thermodynamic properties such as mass density, enthalpy, and specific heat at constant pressure were calculated from partition function.

Fig. 1. Plasma torch configuration

Fig. 2. Variation of specific heat and thermal conductivity for different gases as a function of temperature

Also, with the equilibrium composition and collision cross section data, the transport properties including viscosity, electrical and thermal conductivity were calculated by the first order approximation of Chapman-Enskog method. Figure 2 shows the Variation of specific heat and thermal conductivity for different gases as a function of temperature. Calculation conditions are listed in Table 1. The main variable parameter was the admixture ratio of secondary gas (CO₂+H₂ gas mixture).

3. Results

It has been found that the injection of excess dissociative molecular gases shrink the plasma (salender plasma column) in radius keeping the center temperature about 9–10 kK as shown in Fig. 3. The result shows that inclusion of secondary molecular gas mixture of CO₂+H₂ causes the shrink of plasma torch and increasing the admixture ratio of molecular gas further shrinks it. It can be found easily if we define 'plasma radius' having temperature beyond 5000 K for each of the cases. The result is also compared with that of Ar-CO₂ and Ar-H₂ thermal plasma and finally a comparative study and conclusion had been made.

Table 1. Calculation conditions

Input power = 30 kW
Active plasma power = 27 kW
Pressure = 0.1 MPa (atmospheric)
Frequency = 450 kHz
Volume ratio of CO ₂ : H ₂ gas mixture: 1: 1 (50% each)
Flow rate: Case 1. Ar = 100 slpm (standard liter per minute); Case 2. Ar = 98 slpm, CO ₂ +H ₂ = 2 slpm; Case 3. Ar = 96 slpm, CO ₂ +H ₂ = 4 slpm; Case 4. Ar = 94 slpm, CO ₂ +H ₂ = 6 slpm; Case 5. Ar = 92 slpm, CO ₂ +H ₂ = 8 slpm; Case 6. Ar = 90 slpm, CO ₂ +H ₂ = 10 slpm

Fig. 3. Radial temperature distribution for all cases at axial position of $z = 155$ mm

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In the present work, effect of CO₂+H₂ gas mixture inclusion on shrinkage of plasma was numerically investigated on high power Ar inductively coupled thermal plasmas at atmospheric pressure. The gas mixture of CO₂+H₂ has many reactions in wide temperature range of 300–20000 K which may cause some performance in thermal plasmas. Simulation has been carried out solving a two-dimensional local thermodynamic equilibrium (LTE) code. The active plasma power and input fundamental frequency were fixed at 27 kW and 450 kHz respectively. The main variable parameter was the admixture ratio of secondary gas (CO₂+H₂ gas mixture) and it has been found that the injection of excess dissociative molecular gases shrink the plasma in radius keeping the center temperature about 10,000 K by investigating the plasma radius having temperature beyond 5,000 K for each of the case. The result also shows that increasing the inclusion (admixture ratio) of CO₂+H₂ molecular gas raises the plasma peak temperature. The result is also compared with that of Ar-CO₂ and Ar-H₂ thermal plasma and finally a comparative study and conclusions have been made.

Keywords: inductively coupled thermal plasma, molecular gas mixture, plasma radius, shrinkage

1. Introduction

Nowadays, a great attention has been paid to mixed gas inductively coupled thermal plasmas (ICTP) for their bright prospect especially in surface modification, material processing and investigation of steady and transient quenching property of molecular gases. It has distinctive feature of high energy density, chemical reactivity and variable transport properties. For example, Ar+N₂+CO₂ are tried to adapt to thermal plasma treatment for improving anode electrode performance in Li battery⁽¹⁾.

On the other hand, it is well known that SF₆ is used as an arc quenching medium in the high voltage circuit breaker. SF₆ gas has the attractive arc quenching property ever found among almost all gases. There seems to have mainly two reasons behind it. Firstly, high thermal conductivity of SF₆ at low temperature (around 2000 K) makes the thermal plasma column slender shape which leads the plasma to have fast dynamic response in changing its conductance. Secondly, SF₆ and its products have high electron attachment cross sections that cause a decrease in electron density and thus the plasma temperature⁽²⁾. However, SF₆ has high global warming potential. So in the circuit breaker fields, alternatives for SF₆ are being searched as an arc quenching gas from the viewpoint of an environmental issue. The CO₂ or additional gas added CO₂ is one of the candidates for such arc quenching gases. CO₂ has a low global warming potential (GWP) as compared with SF₆ (1/23900 times). Moreover H₂ is environmentally benign and easily available in nature. Concerning about the

air pollution and global warming, H₂ is considered as one of the arc quenching medium because of its high thermal conductivity. Thus CO₂+H₂ gas inclusion effect was investigated in this paper for fundamental study. In addition, CO₂+H₂ gas mixture is also related with polymer ablation vapor such as POM and PMMA used for dielectric insulation because these materials contain only C, H and O atoms. The polymer ablation is one of the key technique for low-voltage circuit breakers. We have studied plasma quenching efficiency of gas using inductively coupled thermal plasma (ICTP) technique. The ICTP technique has some advantages for fundamental and comparative study of gas-plasma interactions both in numerical and experimental approaches⁽²⁾ since it is free from any contamination. Thus CO₂+H₂ gas inclusion effect was investigated in this paper. We have studied plasma quenching efficiency of gas using ICTP technique. On the other hand, other researchers have been studying both the steady state and transient response for argon mixed with single molecular gas ICTP. For example, Nishiyama et al.⁽³⁾, Cai et al.⁽⁴⁾ and Bourg et al.⁽⁵⁾ investigated the temperature and flow field for Ar-He, Ar-O₂, Ar-N₂ and Ar-H₂ thermal plasmas in steady state. And then dynamic characteristics and also non-equilibrium analysis have been made for argon with single molecular gas⁽⁶⁾. Ar-CO₂ and Ar-H₂ radio frequency ICTP simulation has been executed already. However, Ar-CO₂-H₂ thermal plasma ICTP has not been done yet because of complexity of its transport and thermodynamic properties.

The shrinkage of thermal plasma is a very significant parameter to be considered now-a-days, especially in high power gas circuit breakers. Because, it has been found that slenderness plasma column leads to have fast dynamic behaviour in changing its conductance that causes high plasma

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quenching efficiency⁽²⁾. Generally, shrinkage of plasma means the establishment of narrower or thin thermal plasma with low radius.

In the present work, we did numerical simulation to predict differences in temperature fields and plasma shrinkage as a function of admixture ratio of secondary gas for Ar-CO₂-H₂ induction thermal plasma under local thermal equilibrium condition. Thus, we show the effect of molecular gas inclusion on plasma shrinkage phenomena, and then the controllability of plasma temperature and gas flow field by changing admixing ratio of molecular gas mixture (secondary gases) in ICTP.

2. Simulation Details

2.1 Assumption and Governing Equations In the present work, the plasma is under LTE condition, assumed to be optically thin so that light absorption can be neglected. Two-dimensional, laminar, steady and axisymmetric plasma flow has been considered and also viscous dissipation is negligible.

Electron temperature is assumed to be equal to that of heavy particles. Under the assumptions mentioned above, the present model is derived from conservation equations along with two-dimensional vector potential form of Maxwell's equation. The governing equations are as follows:

Mass conservation

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

Momentum conservation

Axial momentum

$$\begin{aligned} & \frac{\partial(\rho u)}{\partial z} + \frac{1}{r} \frac{\partial(\rho r v)}{\partial r} \\ &= -\frac{\partial p}{\partial z} + 2 \frac{\partial}{\partial z} \left(\eta \frac{\partial u}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left[\eta r \left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial z} \right) \right] + F_z \end{aligned} \quad (2)$$

Radial momentum

$$\begin{aligned} & \frac{\partial(\rho v)}{\partial z} + \frac{1}{r} \frac{\partial(\rho r v)}{\partial r} \\ &= -\frac{\partial p}{\partial r} + \frac{\partial}{\partial z} \left[\eta \left(\frac{\partial v}{\partial z} + \frac{\partial u}{\partial r} \right) \right] + \frac{2}{r} \frac{\partial}{\partial r} \left[\eta r \left(\frac{\partial v}{\partial r} \right) \right] + F_r \end{aligned} \quad (3)$$

Tangential (swirl) momentum

$$\begin{aligned} & \frac{\partial(\rho w)}{\partial z} + \frac{1}{r} \frac{\partial(\rho r w)}{\partial r} \\ &= \frac{\partial}{\partial z} \left(\eta \frac{\partial w}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(\eta r \frac{\partial w}{\partial r} \right) - \frac{\rho v w}{r} - \frac{1}{r} \frac{\partial(\eta w)}{\partial r} + \eta \frac{\partial}{\partial r} \left(\frac{w}{r} \right) \end{aligned} \quad (4)$$

Energy conservation

$$\begin{aligned} & \frac{\partial(\rho u h)}{\partial z} + \frac{1}{r} \frac{\partial(\rho r v h)}{\partial r} \\ &= \frac{\partial}{\partial z} \left(\frac{k}{C_p} \frac{\partial h}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(\frac{k}{C_p} r \frac{\partial h}{\partial r} \right) + P^o - R^o \end{aligned} \quad (5)$$

Vector potential form of Maxwell's equation

$$\dot{A}_\theta = A_R + j A_I \quad (6)$$

$$\frac{\partial^2 \dot{A}_\theta}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \dot{A}_\theta}{\partial r} \right) - \frac{\dot{A}_\theta}{r^2} = j \mu_0 \sigma \omega \dot{A}_\theta \quad (7)$$

where, u , v and w : velocity in z -axis (axial), r -axis (radial) and tangential (swirl) components in m/s; σ : electrical conductivity in S/m; k : thermal conductivity in W/m/K; ρ : density in kg/m³; C_p : specific heat in kJ/m³/K; h : enthalpy in J/kg; p : pressure in Pa; η : viscosity in Pa·s; μ_0 : permeability of vacuum in H/m; F_z and F_r : Axial and radial components of Lorentz forces respectively in N/m³; P^o : volumetric joule heating in W/m³; R^o : volumetric radiation loss in W/m³; A_θ : phasor of vector potential in A/m; ω : angular velocity in rad/s ($\omega = 2\pi f$, where f is the frequency of coil current); and j : complex operator.

2.2 Schematic and Calculational Domain

Calculation was performed for the high power radio frequency ICTP system setup installed in the laboratory. The schematic configuration with calculation space of the high power ICP system is shown in Fig. 1. The setup comprises of two basic parts namely (a) plasma torch and (b) reaction chamber. The plasma torch portion is made up with two coaxial quartz tubes of 3.0 mm thickness. Between the gaps of the tubes, cooling water at room temperature flows for efficient cooling of tube wall. The inner diameter and length of plasma torch are 70 mm and 330 mm respectively. Along the inside tube wall, Ar-CO₂-H₂ gas mixture is supplied as a sheath gas. A winding of eight turn induction coil is installed around the

Fig. 1. Plasma torch configuration and calculation space

Fig. 2. Calculational domain

Table 1. Operating conditions

Input power = 30 kW
Active plasma power = 27 kW
Pressure = 0.1 MPa (atmospheric)
Frequency = 450 kHz
Volume ratio of CO ₂ : H ₂ gas mixture: 1: 1 (50% each) at 300 K
Flow rate(Admixture ratio):
Case 1. Ar = 100 slpm (standard liter per minute)(100%Ar);
Case 2. Ar = 98 slpm, CO ₂ +H ₂ = 2 slpm(98%Ar-1%CO ₂ -1%H ₂);
Case 3. Ar = 96 slpm, CO ₂ +H ₂ = 4 slpm(96%Ar-2%CO ₂ -2%H ₂);
Case 4. Ar = 94 slpm, CO ₂ +H ₂ = 6 slpm(94%Ar-3%CO ₂ -3%H ₂);
Case 5. Ar = 92 slpm, CO ₂ +H ₂ = 8 slpm(92%Ar-4%CO ₂ -4%H ₂);
Case 6. Ar = 90 slpm, CO ₂ +H ₂ = 10 slpm(90%Ar-5%CO ₂ -5%H ₂)
(gas injection temperature is 300 K)

plasma torch. A high frequency coil current (450 kHz) with an input power of 30 kW is fed to the system to produce and sustain steady plasma inside the plasma torch.

Figure 2 shows the calculational domain where O-A-B-C-D-E-F is the calculational space inside which fluid parameters and scalar quantities were evaluated. The two-dimensional space co-ordinate are O(0, 0), A(0, 35), B(330, 35), C(330, 65), D(480, 65), E(910, 20) and F(910, 0) where the unit is in mm. The operating conditions are listed in Table 1.

The numerical calculation was carried out using SIMPLE algorithm with uniform grid system having 66 radial and 92 axial nodes.

2.3 Calculation of Composition and Gas Properties

2.3.1 Equilibrium composition of Ar-CO₂-H₂

Equilibrium composition of Ar-CO₂-H₂ thermal plasma was calculated by minimization of Gibb's free energy of a system including Ar, CO₂ and H₂. Thermo-chemical properties were taken from JANAF thermo chemical tables⁽⁷⁾. Figure 3 shows the equilibrium composition of 98%Ar-1%CO₂-1%H₂ plasma at a pressure of 0.1 MPa as an example. Around 300 K, CO₂, H₂O, CH₄, H₂ are dominant species. This means that once gas mixture of CO₂+H₂ is decomposed, it do not recover CO₂ and H₂, but become another mixture of CO₂, H₂O, CH₄ and H₂ due to minimization of energy of the system. On the other hand, increasing temperature from 300 to 1000 K, CH₄ is dissociated rapidly, and then H atoms are produced. From 1000 to 3000 K, densities of H, OH, O and O₂ increase. In 3000–9000 K, molecules are dissociated and, H is dominant species. These many species and reactions causes complex thermodynamic and transport properties of CO₂+H₂ mixture.

2.3.2 Calculation of thermodynamic and transport properties The thermodynamic and transport properties that are prerequisite for any modeling had been derived using thermal plasma composition as a function of

Fig. 3. Equilibrium composition of 98%Ar-1%CO₂-1%H₂ plasmas at atmospheric pressure Fig. 4. Specific heat per unit mass for different gases of Ar, CO₂, H₂, and CO₂-H₂ mixture as a function of temperature at atmospheric pressure

temperature. Using the equilibrium composition, the thermodynamic properties such as mass density, enthalpy, and specific heat at constant pressure were calculated with partition function as a function of temperature. Also, with the equilibrium composition and collision cross section data, the transport properties including viscosity, electrical and thermal conductivity were calculated as a function of temperature by the first order approximation of Chapman-Enskog method⁽⁸⁾. Figures 4 and 5 show the variation of specific heat and thermal conductivity of Ar, CO₂, CO₂-H₂ mixture of different ratios and H₂ respectively as a function of temperature. Figure 4 shows that there are inherent peaks in specific heat around 4000 K, 7000 K and 15000 K for CO₂ and CO₂+H₂ gas mixture with one extra peak around 1000 K for CO₂-H₂ only. This is due to the dissociation/formation of H₂O and CH₄. For H₂, the peaks are around 4000 K and 15000 K. At these temperatures, dissociation and ionization reactions are taken place and majority of energy is spent to dissociate and ionize the particles. H₂ has a very large specific heat per unit mass at the mentioned temperatures as compared to others. Thermal conductivity as shown in Fig. 5 also shows the similar nature to specific heat in terms of periodic peaks.

2.4 Boundary Conditions As referred to Fig. 2, for

Fig. 5. Thermal conductivity for different gases of Ar, CO₂, H₂, and CO₂-H₂ mixture as a function of temperature at atmospheric pressure

the details of necessary boundary conditions readers are referred to Ref. (6).

For O-F line, we set derivatives of physical parameters such as axial gas velocity, swirl gas velocity and enthalpy while radial gas velocity and vector potential would be zero. For walls OA, AB, and B-C-D-E, we set gas velocities as zero and the temperature is calculated considering heat transfer from the wall. Vector potentials are calculated at GA, GC, DH and HF and around the coil. We set vector potential to be zero for metallic walls OA, B-C-D-E.

3. Calculational Results and Discussions

3.1 Gas Flow Field Figure 6 shows the obtained streamlines that indicate the profile of gas flow fields. The gas flows tangentially to the streamlines.

The streamlines are drawn at an interval of $10^{-3} \text{ kg m}^{-2} \text{ s}^{-1}$ for the stream function. Here, only three figures out of six cases are outlined as examples. The gas is injected as sheath gas along the internal wall of the quartz tube. Along $z = 100 \text{ mm}$, the gas flow is bent to the radial direction due to the Lorentz force produced as an interaction between magnetic field of the coil current and eddy current inside the thermal plasma. Increasing admixture ratios of CO₂ and H₂ gas mixture to Ar cause more bending of gas flow to the radial direction.

3.2 Temperature Field Figure 7 demonstrates the iso-contour of temperature field for only the three cases already shown in streamline figures. Investigation of the plasma torch region shows that plasma shrinks as the admixture ratio of CO₂-H₂ increases. This phenomenon can be observed more clearly in Fig. 8 showing the radial distribution of temperature at axial position of $z = 155 \text{ mm}$. If we can define "thermal plasma radius" as the radius of high temperature region above 5000 K at the axial position of 155 mm, we can see the plasma shrinkage effect of CO₂-H₂ gas mixture inclusion on Ar ICTP. Figure 9 shows the thermal plasma radius, R , of 5000 K as a function of CO₂-H₂ admixture ratio to Ar. Then we see that increasing CO₂-H₂ admixture ratio decreases the thermal plasma radius R . The thermal plasma radius decreases with CO₂+H₂ admixture ratio with decaying rate of 1 mm/%. This can be shown from figure 8 that the decaying rate is $0.99 (\approx 1) \text{ mm}/\% [(29.1 - 19.2) \text{ mm}/(10 - 0)\%]$.

Fig. 6. Streamlines for gas flow field in 100%Ar, 96%Ar-2%CO₂-2%H₂ and 90%Ar-5%CO₂-5%H₂ plasmas

Fig. 7. Temperature field in 100%Ar, 96%Ar-2%CO₂-2%H₂ and 90%Ar-5%CO₂-5%H₂ plasmas

From Figs. 7 and 8, we found increased maximum temperature of Ar thermal plasma. Figure 10 shows the maximum temperature for all cases. The peak temperature inside the thermal plasma is the highest for the maximum admixing ratio of secondary gas (10 slpm).

3.3 Electrical Field Strength, Electrical Conductivity and Joule Heating Power

Figure 11 shows the iso-contours of absolute value of electrical field strength for the three cases. This figure demonstrates that electric field strength is high near the wall and maximum at the coils but nearly zero at the axis of plasma torch. It is also observed that electric field increases and penetrates more inside the plasma core as admixture ratio of CO₂-H₂ increases. High admixture

Fig. 8. Radial temperature distributions at axial position of $z = 155$ mm for 100%Ar, and Ar-CO₂-H₂ plasmas. Admixture ratio of secondary gas mixture CO₂-H₂ to Ar is taken as a parameter

Fig. 9. Thermal plasma radii defined by 5000 K for different admixture ratio of CO₂-H₂

Fig. 10. Maximum temperature in plasma for 100%Ar, and Ar-CO₂-H₂ plasmas

ratio causes high electric field strength that accelerates electrons near the wall to enhance the electron kinetic energy. As a result eddy current increases which further intensifies the Lorentz force acting on the gas mixture that causes bending

Fig. 11. Absolute value of electrical field strength (for three cases); white line shows the boundary of vacuum chamber

of gas flow to the radial direction.

Increasing admixture ratio of CO₂-H₂ causes the radial distribution of the electrical conductivity to be shrunk and become narrower to the core that is the main reason for concentrated joule heating for higher admixture ratio. CO₂-H₂ has higher specific heat per unit volume at low temperature that enhances the convection term of heat flow. This causes the shrinkage of plasma. So, the radius of electric conducting path inside plasma decreases. Also electrical conductivity increases and shrinks inside the core. As a result, current density increases that further causes increase of temperature. The eddy current also increases and the Lorentz force due to the eddy current⁽⁶⁾ also become larger that further drive the electrons and charged particles to the core of plasma.

3.4 Comparison Among Pure Ar, Ar-CO₂-H₂, Ar-CO₂ and Ar-H₂ Thermal Plasma Figure 12 demonstrates the radial temperature distribution for pure Ar, Ar-CO₂-H₂, Ar-CO₂ and Ar-H₂ thermal plasma. The admixture ratio for secondary gas in case of mixed gas plasmas was 10 slpm. In this figure also, we define the parameter of “thermal plasma radius” of the same definition stated before.

Thermal plasma radius is the highest for pure Ar plasma and decreases as we mix up molecular gas. Inclusion of CO₂ causes slight decrease of plasma radius, while inclusion of CO₂+H₂ gas mixture causes further shrink of plasma. But the mixing effect of H₂ is the most noticeable. Inclusion of H₂ causes a significant decrease of plasma radius implying a great shrink of plasma.

We can also explain these phenomena in terms of decaying rate.

The value is maximum for Ar-H₂ (1.76 mm/%) and minimum for Ar-CO₂ (0.66 mm/%) as investigated from Fig. 12.

Fig. 12. Comparison of radial temperature distribution among pure Ar, Ar-CO₂-H₂, Ar-CO₂, and Ar-H₂ plasmas

Fig. 13. Radial distribution of energy balance at an axial position of $z = 155$ mm for Ar-CO₂-H₂ thermal plasmas

Fig. 14. Radial distribution of energy balance at an axial position of $z = 155$ mm for Ar-CO₂-H₂ thermal plasmas

3.5 Power Balance Figures 13 and 14 show radial distribution of various components of power flows and joule heating at an axial position of $z = 155$ mm for only pure

Ar and Ar-CO₂-H₂ gas mixture. It is observed that an overall balance of power input and power loss is obtained that preserves the energy conservation law. For both cases, input power (in the form of electromagnetic power) by joule heating is transferred in radial direction by convection and conduction around $r = 20$ mm. Around the axis $r = 0$ mm, power is input from radial convection and then transferred by axial convection. In comparison with these two cases, Ar-CO₂-H₂ plasma has such a power transfer inner side than pure Ar plasma. Also, convection and conduction losses are higher in Ar-CO₂-H₂ plasma than pure Ar plasma.

4. Conclusions

It has been demonstrated that inclusion of secondary molecular gas causes the shrink of plasma torch. And increasing the admixture ratio of molecular gas further shrinks it. This is because it is evident that adding secondary molecular gases with pure Ar causes more chemical reactivity including ionization and dissociation reactions around the plasma temperature that greatly affects the thermodynamic and transport properties especially the specific heat and thermal conductivity of plasma gas.

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