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journal or publication title	Thin Solid Films
volume	518
number	3
page range	943-951
year	2009-12-30
URL	http://hdl.handle.net/2297/23880

doi: 10.1016/j.tsf.2009.07.185

Observation of non-chemical equilibrium effect on Ar-CO₂-H₂ thermal plasma model by changing pressure

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Abstract. The authors developed a two-dimensional one-temperature chemical non-equilibrium (1T-NCE) model of Ar-CO₂-H₂ inductively coupled thermal plasmas (ICTP) to investigate the effect of pressure variation. The basic concept of one-temperature model is the assumption and treatment of same energy conservation equation for electrons and heavy particles. The energy conservation equations consider reaction heat effects and energy transfer among the species produced as well as enthalpy flow resulting from diffusion. Assuming twenty two (22) different particles in this model and by solving mass conservation equations for each particle, considering diffusion, convection and net production terms resulting from hundred and ninety eight (198) chemical reactions,

chemical non-equilibrium effects were taken into account. Transport and thermodynamic properties of Ar-CO₂-H₂ thermal plasmas were self-consistently calculated using the first order approximation of the Chapman-Enskog method. Finally results obtained at atmospheric pressure (760 torr) and at reduced pressure (500, 300 torr) were compared with results from one temperature chemical equilibrium (1T-CE) model. And of course, this comparison supported discussion of chemical non-equilibrium effects in the inductively coupled thermal plasmas (ICTP).

Keywords: 1T-NCE, 1T-CE, ICTP, chemically non-equilibrium, plasma shrinkage, diffusion

1. Introduction

Now-a-days, the distinctive features of high energy density and chemical reactivity [1] of reactive molecular gas seeded inductively coupled thermal plasmas (ICTP) let researchers be inspired to try it in a numerous applications like water purification, surface treatment, waste treatment [2] and other fundamental investigation of molecular gas kinetics. The ICTP technique has some advantages for fundamental and comparative study of gas-plasma interactions both in numerical and experimental approaches [3] since it is free from any contamination. Moreover, in recent days researchers have found some attributes of plasma extinguishing capability and plasma shrinkage in case of molecular gas injection

[4, 5].

In addition, for the last couple of decades researchers have shown particular interests in applications of non-equilibrium plasma for the problems of plasma assisted ignition and plasma assisted combustion of hydrocarbon fuels [6, 7] due to the fact that an electrical discharge's properties strongly depend on the conditions of excitation, flow parameters and characteristics of supplying electromagnetic power. It has been reported that combustion rate can be enhanced limiting combustion temperature to a much lower value with plasma assistance [8] which might be a great achievement for comparatively safer operation as combustion can be achieved at lower temperature.

It is very important to obtain a clear view and explanation of particle composition, reactions, temperature fields, gas kinetics and the electromagnetic field inside ICTP not only for plasma assisted combustion but also for circuit breakers, power sectors, material processing and other applications. Numerical modeling of ICTP has been performing a great job for this purpose. To study and understand the transport phenomena of mass, momentum and energy as well as temperature field and gas kinetics, the LTE model may be sufficient enough but to investigate about the chemical field and particle composition of thermal plasma more precisely, numerical calculation assuming chemically non equilibrium (NCE) model would be necessary.

This paper proposes a two-dimensional one-temperature chemically non-equilibrium

model (1T-NCE) for Ar-CO₂-H₂ ICTP and this is the first step for multiple gas mixture as a secondary gas together with Ar and 198 chemical reactions (forward and backward) taken into account. The reason of choosing CO₂-H₂ gas mixture is that it could be an ideal example of C-H-O system (combustion gas). Moreover, this gas mixture has been tried to adopt in circuit breaker application as a quenching gas in place of SF₆. First of all, the 1T-NCE model and the governing equations are explained. Secondly, the calculation outputs such as temperature field and mass fraction distributions are demonstrated. Thirdly, the Ar-CO₂-H₂ ICTP simulation is carried out using two different models i.e., the present one-temperature chemically non-equilibrium (1T-NCE) model and a one-temperature chemically equilibrium (1T-CE) model [3]. For detailed examination of chemical non-equilibrium effects, 1T-NCE calculations under three different pressures were done because it is thought to believe that non-chemical equilibrium affects more at reduced pressure than under normal pressure. Finally, the authors present a comparative study of results obtained by two different models and the effects of thermal and chemical non-equilibrium in the Ar-CO₂-H₂ ICTP are discussed.

2. One-temperature modeling of Ar-CO₂-H₂ ICTP

2.1. Hypothesis

The following assumptions have been made for Ar-CO₂-H₂ ICTP for present calculation:

- (a) Maxwellian velocity distribution was assumed for all species.
- (b) All species were assumed to be in the ground state although in reality some excited particles may exist.
- (c) Axis-symmetric plasma structure had been considered.
- (d) The gas flow was laminar. Turbulence flow had been neglected.
- (e) Although the light absorption can occur in the actual ICTP, this can be omitted as optically thin plasma has been assumed.
- (f) Quasi-neutrality of charges has been considered so that the total sum of charges throughout the plasma is zero and thus all particles can move together with the gas flow.
- (g) For simplicity, thermal equilibrium or one temperature model had been assumed though this assumption does not realize near the wall region.

2.2. Selection of species

To consider dominant particles in high power density Ar-C_xH_yO_z molecular mixture plasma, equilibrium composition of Ar-C_xH_yO_z system were calculated. For this calculation, 53 chemical species, (data obtained from JANAF tables [9]) namely, CO₂, C, C⁺, HO₂, O₂, O₂⁺, CO₂⁺, CH₂O, CHO, CHO⁺, CO, CO⁺, H₂O, OH, C₂O, C₂, O, O⁺, C₂H, CH₄, CH₃, CH₂, CH, CH⁺, H₂, H₂⁺, H, H⁺, C₂H₂, Ar, Ar⁺, C₂H₄, C₃, C₄, C₅, C⁻, C₂⁻, CO₂⁻, C₃O₂, H⁻, H₂⁻, O²⁺, H₃O⁺, OH⁺, OH⁻, C₂H₄O, O⁻, O₂⁻, O₃, C²⁺, Ar²⁺, Ar³⁺, and electrons were considered. The equilibrium composition was calculated by minimization of Gibb's

free energy. The temperature range was set to 300-30000 K. Fig.1 shows Equilibrium composition of 98%Ar-1%CO₂-1%H₂ plasmas at atmospheric pressure. For Ar-CO₂-H₂ ICTP simulation, a total number of 22 dominant species were selected out of 53 species. They are (1) CO₂, (2) CO, (3) CHO, (4) CH₂O, (5) CH₄, (6) CH₃, (7) OH, (8) H₂O, (9) HO₂, (10) O₂, (11) O, (12) H₂, (13) H, (14) CO⁺, (15) CHO⁺, (16)O₂⁺, (17) O⁺, (18) H₂⁺, (19) H⁺, (20) Ar, (21) Ar⁺ and (22) electrons.

2.3.1 Selection of reactions

Among the 22 species, there are numerous reactions taking place. From literatures [10-21], totally 198 reactions were taken into account for a two-dimensional thermo-fluid dynamics modeling summarized in Tab.1. These reactions include dissociation, recombination or association and ionization reactions. Reactions 29, 30, 33-37, 43-47, 50-52 include electrons, which may be related to the electrical conductivity of plasmas. Other reactions are positive or negative heat sources and radical sources.

2.3.2 Reaction rates

For selected reactions 1-28, we estimated reaction rates or obtained them from literatures [10]. Ionization reaction rates were calculated using an electron impact ionization cross-section (data collected from National Institute of Standards and Technology [11]) on the assumption of Maxwellian velocity distribution function for electrons. Fig.2 shows some of reaction rates as a function of temperature classified as heavy particle and electron temperature dependent reactions. Reactions with the high frequency factor and low

activation energy are dominant ones especially for high temperature region. Ionization reactions of H and O have comparatively higher rates than others and especially higher than Ar.

2.4. Governing equations and specifications for 1T-NCE Ar-CO₂-H₂ ICTP

2.4.1 Basic governing equations

On the basis of the hypothesis mentioned in the previous section, Ar-CO₂-H₂ ICTP properties and behavior can be predicted by the governing equations listed in Tab.2. In one-temperature condition, energy conservation equations for heavy particles and electrons should be considered in the same equations. Enthalpy flow caused by diffusion had been treated explicitly in the energy conservation equation. Transport properties were calculated at each position in the calculation space at each iteration step by the first-order approximation of the Chapman-Enskog method.

2.4.2 Calculation space and specifications

Calculation was performed for the high power radio frequency ICTP system setup installed in our laboratory. The schematic configuration with calculation space of the high power ICTP system is shown in Fig.3 [22, 23]. Tab.2 includes the governing equations for a non-equilibrium model. We solved mass, momentum, energy conservation equations, Maxwell equations for vector potential and also mass conservation equations for each species. Thermodynamic and transport properties were calculated at each position using

the cross-section data and the locally calculated particle composition and the temperature by the first order approximation of Chapman-Enskog method. The pressure was set to atmospheric pressure. Total sheath gas flow rate is set to 100 slpm. Input power to the plasma is fixed at 27 kW with a radio frequency of 450 kHz. The numerical calculation was carried out using SIMPLE algorithm with uniform grid system having 66 radial and 92 axial nodes.

3. Results and discussions

3.1. Temperature field

The 1T-CE model corresponds to the LTE model where chemical equilibrium is always established under one temperature condition. In this case the particle composition can be derived easily and ex ante as a function of one-temperature by the Gibb's energy minimization method or Saha's equation. If the pressure is fixed, transport and thermodynamic properties depend only on one-temperature. The 1T-NCE model, on the other hand, incorporates a chemically non-equilibrium effect considering reaction rates and convection and diffusion effects on the particle distributions. In this case, particle composition at each position is obtained through mass conservation equation of each species j , as described in equation (6) on Tab.2. Transport and thermodynamic properties, in this case, depend not only on one-temperature but also on particle composition at each

position in thermal plasmas. Thus both temperature and particle composition distributions are influenced by chemical non-equilibrium effect.

Fig.4 shows the temperature distribution of 98%Ar-1%CO₂-1%H₂ plasma at (a) 1T-CE, 760 torr (atmospheric), (b) 1T-NCE, 760 torr (atmospheric), (c) 1T-NCE, 500 torr and (d) 1T-NCE, 300 torr. The resultant maximum temperature reaches near 10000 K in this torch.

As seen, there is a smaller region with temperatures above 10000 K for 1T-NCE results compared to that for LTE result. Fig.5 shows the Radial temperature distribution of 98%Ar-1%CO₂-1%H₂ plasmas at (a)1T-CE, 760 torr (atmospheric), (b)1T-NCE, 760 torr (atmospheric), (c) 1T-NCE, 500 torr and (d) 1T-NCE, 300 torr at an axial position of 155 mm and it suggests that considering non chemical equilibrium effect in calculation causes wider plasma or relatively flatter distribution than 1T-CE mainly for taking diffusion terms into account. This is because diffusion of electrons causes planer electron density distribution and so is the electrical conductivity distribution. This relatively planer electrical conductivity distribution gives rise to scattered joule heating dissipation.

The most important fact on the observation of these figures is that decreasing the pressure causes stronger influence of non-chemical equilibrium effect. Chemically non-equilibrium effect was introduced by considering mainly diffusion, convection and net production terms resulting from 198 reactions. At reduced pressure, the magnitude of effective diffusion coefficient increases as seen from equation (7) on Tab.2 which eventually

intensifies the diffusion term in energy conservation equation.

3.2. Particle composition and chemical field

Fig.6-9 represent mass fraction distributions of Ar, Ar^+ , H^+ and electrons as an example in the same plasma for 1T-CE (atmospheric pressure), 1T-NCE (atmospheric pressure), 1T-NCE (pressure-500 torr) and 1T-NCE (pressure-300 torr) respectively. These mass fraction profiles demonstrate that ionized particles and electrons tend to accumulate at the plasma torch region that makes high temperature area electrically conductive. The profile also supports the mass action law that the degree of ionization increases at reduced pressure. Fig.10 illustrates two-dimensional mass fraction distributions for (a) O^+ , (b) CHO, (c) OH and (d) H for 1T-NCE condition (atmospheric pressure). The presence of hydroxyl radical (OH) could be indicative and possess a potential prospect in sterilization of medical equipments [24].

Fig.11 (a), (b), (c) and (d) depict radial distributions of particle composition at an axial position of 155 mm calculated by 1T-CE (atmospheric pressure), 1T-NCE (atmospheric pressure), 1T-NCE (pressure-500 torr) and 1T-NCE (pressure-300 torr) respectively. Estimation of actual reaction rates and consideration of convection and diffusion terms markedly affect the particle distributions. CO_2 and H_2 molecules are dissociated into CO, O, H and other atoms at the plasma torch. Ionizations for various particles also occur at the high temperature plasma region though electrons are mainly produced by Ar ionization.

Near the torch wall, many kinds of molecules such as CH_2O , H_2O and H_2 are produced by association of atoms. At reduced pressure particle distributions become relatively flatter and presence of ambipolar diffusion seems to be stronger that sweeps the electrons and H^+ ions close to the wall. For comparison, at the region of $r < 20$ mm, it has been found for NCE model that number density of CO_2 is much higher than that of CE model which suggests that NCE model considers much lower dissociation of CO_2 . On the other hand, association of atoms such as CH_4 is much higher in CE model near the wall.

3.3. Comparison with experimental results

Experiment was performed for the same ICTP system setup. 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, pure Ar and Ar- CO_2 - H_2 gas mixture is supplied as a sheath gas. A winding of eight turn induction coil is installed around the plasma torch.

The observation position is adjusted to 10 mm below the coil end on the central axis. The light radiated from the observation point was transmitted through an optical filter, camera lens, a mirror, and an optical fiber bundle to the slit of a monochromator. A one-dimensional multi channel detector was installed at the focal plane of the

monochromator to measure the light intensities at the range of 100 nm simultaneously with a resolution of 0.3 nm.

Fig.12 illustrates the photograph taken by high speed digital video camera and radial distributions of radiation intensity at 10 mm below the coil end. The figure suggests that inclusion of CO₂ and H₂ mixture into pure Ar causes the plasma shrinkage due to the fact that CO₂ and H₂ mixture has relatively higher specific heat and thermal conductivity [5] than that of Ar which results better convection and conduction of heat from plasma core to peripheral region.

4. Conclusions

Estimation of dominant particles and reactions were made for chemically non-equilibrium modeling of Ar- C_xH_yO_z plasma for high power density plasma-assisted combustion system. This report of numerical modeling of Ar thermal plasma with C_xH_yO_z molecular gas system will play an undoubtedly important role in predicting the plasma assisted combustion process field where chemically non-equilibrium effect has been taken into account.

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Tab.1. Reactions taken into account

Reactions		
(1) $\text{H}+\text{HO}_2\rightarrow\text{H}_2+\text{O}_2$	(20) $\text{CH}_3+\text{OH}\rightarrow\text{CH}_2\text{O}+\text{H}_2$	(38) $\text{H}_2+\text{O}_2\rightarrow 2\text{OH}$
(2) $\text{H}+\text{HO}_2\rightarrow 2\text{HO}$	(21) $\text{CH}_2\text{O}+\text{H}\rightarrow\text{CHO}+\text{H}_2$	(39) $\text{CO}+\text{O}_2\rightarrow\text{CO}_2+\text{O}$
(3) $\text{H}+\text{HO}_2\rightarrow\text{H}_2\text{O}+\text{O}$	(22) $\text{CH}_2\text{O}+\text{O}\rightarrow\text{CHO}+\text{OH}$	(40) $\text{CO}+\text{HO}_2\rightarrow\text{CO}_2+\text{OH}$
(4) $\text{O}+\text{H}_2\rightarrow\text{HO}+\text{H}$	(23) $\text{CH}_2\text{O}+\text{OH}\rightarrow\text{CHO}+\text{H}_2\text{O}$	(41) $2\text{CH}_4+\text{O}_2\rightarrow 2\text{CO}+4\text{H}_2$
(5) $\text{O}+\text{HO}_2\rightarrow\text{HO}+\text{O}_2$	(24) $\text{CHO}+\text{O}\rightarrow\text{CO}+\text{OH}$	(42) $\text{H}_2+\text{H}\rightarrow \text{H}+\text{H}+\text{H}$
(6) $\text{HO}+\text{H}_2\rightarrow\text{H}_2\text{O}+\text{H}$	(25) $\text{CHO}+\text{H}\rightarrow\text{CO}+\text{H}_2$	(43) $\text{H}+\text{e}\rightarrow \text{H}^++\text{e}+\text{e}$
(7) $\text{HO}+\text{HO}\rightarrow\text{H}_2\text{O}+\text{O}$	(26) $\text{CHO}+\text{OH}\rightarrow\text{CO}+\text{H}_2\text{O}$	(44) $\text{H}_2^++\text{H}_2+\text{e}\rightarrow \text{H}_2+\text{H}_2$
(8) $\text{HO}+\text{HO}_2\rightarrow\text{H}_2\text{O}+\text{O}_2$	(27) $\text{CHO}+\text{M}\rightarrow\text{CO}+\text{H}+\text{M}$	(45) $\text{H}^++\text{H}_2+\text{e}\rightarrow \text{H}_2+\text{H}$
(9) $\text{O}+\text{CH}_3\rightarrow\text{HCHO}+\text{H}$	(28) $\text{CO}+\text{O}+\text{M}\rightarrow\text{CO}_2+\text{M}$	(46) $\text{H}+\text{H}_2^++\text{e}\rightarrow \text{H}_2+\text{H}$
(10) $\text{O}+\text{CH}_4\rightarrow\text{HO}+\text{CH}_3$	* 'M' means all the heavy particles considered;	(47) $\text{H}^++\text{H}+\text{e}\rightarrow\text{H}+\text{H}$
(11) $\text{HO}+\text{CH}_4\rightarrow\text{H}_2\text{O}+\text{CH}_3$	(29) $\text{Ar}^++\text{e}+\text{e}\rightarrow\text{Ar}+\text{e}$	(48) $\text{CH}_3+\text{H}\rightarrow\text{CH}_4$
(12) $\text{HO}+\text{CO}\rightarrow\text{H}+\text{CO}_2$	(30) $\text{Ar}+\text{Ar}\rightarrow\text{Ar}^++\text{e}+\text{Ar}$	(49) $\text{CH}_4+\text{O}_2\rightarrow\text{CH}_3+\text{HO}_2$
(13) $\text{CHO}+\text{O}_2\rightarrow\text{CO}+\text{HO}_2$	(31) $\text{O}_2+\text{O}_2\rightarrow \text{O}+\text{O}+\text{O}_2$	(50) $\text{H}_2+\text{e}\rightarrow\text{H}_2^++\text{e}+\text{e}$
(14) $\text{H}+\text{O}_2\rightarrow\text{OH}+\text{O}$	(32) $\text{O}_2+\text{O}\rightarrow \text{O}+\text{O}+\text{O}$	(51) $\text{CHO}+\text{e}\rightarrow\text{CHO}^++\text{e}+\text{e}$
(15) $\text{H}+\text{H}+\text{H}_2\rightarrow\text{H}_2+\text{H}_2$	(33) $\text{O}_2^++\text{O}\rightarrow \text{O}_2+\text{O}^+$	(52) $\text{CO}+\text{e}\rightarrow\text{CO}^++\text{e}+\text{e}$
(16) $\text{H}+\text{H}+\text{O}_2\rightarrow\text{H}_2+\text{O}_2$	(34) $\text{O}+\text{O}\rightarrow \text{O}_2^++\text{e}$	(53) $\text{O}+\text{O}+\text{N}\rightarrow \text{O}_2+\text{N}$
(17) $\text{H}+\text{H}+\text{H}_2\text{O}\rightarrow\text{H}_2+\text{H}_2\text{O}$	(35) $\text{O}+\text{e}\rightarrow \text{O}^++\text{e}+\text{e}$	* 'N' stands for Ar, Ar ⁺ , CO ₂ , CO and H ₂
(18) $\text{CH}_4+\text{H}\rightarrow\text{CH}_3+\text{H}_2$	(36) $\text{O}_2+\text{e}\rightarrow \text{O}+\text{O}+\text{e}$	
(19) $\text{CH}_3+\text{O}_2\rightarrow\text{CH}_2\text{O}+\text{OH}$	(37) $\text{O}_2+\text{e}\rightarrow \text{O}_2^++\text{e}+\text{e}$	

Tab.2. Governing equations for one-temperature chemically non-equilibrium model

<p>Mass conservation:</p> $\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial z} + \frac{1}{r} \frac{\partial(r \rho v)}{\partial r} = 0 \quad (1)$	$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(u \rho w)}{\partial z} + \frac{1}{r} \frac{\partial(r v \rho w)}{\partial r} = \frac{\partial}{\partial z} \left(\frac{\partial w}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(\eta r \frac{\partial w}{\partial r} \right) - \frac{\rho v w}{r} - \frac{w}{r} \frac{\partial}{\partial r} (r \eta) \quad (4)$
<p>Momentum conservation:</p> $\begin{aligned} \frac{\partial(\rho u)}{\partial t} + \frac{\partial(u \rho u)}{\partial z} + \frac{1}{r} \frac{\partial(r v \rho u)}{\partial r} = \\ - \frac{\partial p}{\partial z} + 2 \frac{\partial}{\partial z} \left(\eta \frac{\partial u}{\partial z} \right) \\ + \frac{1}{r} \frac{\partial}{\partial r} \left[\eta r \left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial z} \right) \right] + \mu_0 \sigma \Re [\dot{E}_\theta \dot{H}_r] \end{aligned} \quad (2)$	<p>Translational energy conservation equation:</p> $\begin{aligned} \frac{\partial(\rho h)}{\partial t} + \frac{\partial(u \rho h)}{\partial z} + \frac{1}{r} \frac{\partial(r v \rho h)}{\partial r} = \frac{\partial}{\partial z} \left(\lambda^tr \frac{\partial T}{\partial z} \right) \\ + \frac{1}{r} \frac{\partial}{\partial r} \left(r \lambda^tr \frac{\partial T}{\partial r} \right) + \sum_j \left[\frac{\partial}{\partial z} \left(\rho D_j h_j \frac{\partial Y_j}{\partial z} \right) + \right. \\ \left. + \frac{1}{r} \frac{\partial}{\partial r} \left(r \rho D_j h_j \frac{\partial Y_j}{\partial r} \right) \right] + \sigma E_\theta E_\theta^* - P_{rad} - \sum_{l=1}^L \Delta Q_l \end{aligned} \quad (5)$
$\begin{aligned} \frac{\partial(\rho v)}{\partial t} + \frac{\partial(u \rho v)}{\partial z} + \frac{1}{r} \frac{\partial(r v \rho v)}{\partial r} = \\ - \frac{\partial p}{\partial r} + \frac{\partial}{\partial z} \left[\eta \left(\frac{\partial v}{\partial z} + \frac{\partial u}{\partial r} \right) \right] \\ + \frac{2}{r} \frac{\partial}{\partial r} \left(\eta r \frac{\partial v}{\partial r} \right) - 2 \eta \frac{v}{r^2} + \mu_0 \sigma \Re [\dot{E}_\theta \dot{H}_r] \end{aligned} \quad (3)$	<p>Mass conservation of species j:</p> $\begin{aligned} \frac{\partial(\rho Y_j)}{\partial t} + \frac{\partial(u \rho Y_j)}{\partial z} + \frac{1}{r} \frac{\partial(r v \rho Y_j)}{\partial r} \\ = \frac{\partial}{\partial z} \left(\rho D_j \frac{\partial Y_j}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \rho D_j \frac{\partial Y_j}{\partial r} \right) \\ + m_j \sum_{\ell=1}^L (\beta_{j\ell}^r - \beta_{j\ell}^f) \left(\alpha_\ell^f \prod_{i=1}^N n_i^{\beta_{i\ell}^f} - \alpha_\ell^r \prod_{i=1}^N n_i^{\beta_{i\ell}^r} \right) \end{aligned} \quad (6)$ <p>Effective diffusion coefficient of heavy particle:</p> $D_j' = \frac{1 - Y_j}{\sum_{k \neq j} \frac{x_k p \Delta Q_{kj}^{(1)}}{\kappa T}} \quad (7)$

where t : time (s), r : radial position (m), z : axial position (m), u : axial flow velocity (m/s), v : radial flow velocity (m/s), ρ : mass density (kg/m³), p : pressure (Pa), η : viscosity (Pa.s), h : whole enthalpy (J/kg), h_j : enthalpy of species j (J/kg), T : temperature (K), λ^tr : translational thermal conductivity, σ : electrical conductivity (s/m), P_{rad} : radiation loss (w/m³), D_j' : effective diffusion coefficient of particle j (m²/s), x_j : mole fraction of species j , n_j : number density of species j (m⁻³), Y_j : mass fraction of species j , m_j : mass of species j (kg), $\alpha_\ell^f, \alpha_\ell^r$: rate coefficients of forward and backward reaction ℓ , $\beta_{j\ell}^f, \beta_{j\ell}^r$: stoichiometric number of species j in forward and backward reaction ℓ , μ_0 : permeability of vacuum (h/m), κ : Boltzmann constant (J/k), $\dot{E}_\theta$: electric field strength (v/m), $\dot{H}_r$: radial magnetic field strength (a/m), ΔQ_l : reaction heat per unit volume and time (J/s/m³), N : total number of species, L : total number of reactions

Fig.1. Equilibrium composition of 98%Ar-1%CO₂-1%H₂ plasmas

Fig.2 Variation of some reaction rates with temperature, (a) heavy particle temperature dependent and (b) electron temperature dependent reactions

Fig.3 Plasma torch configuration

Fig.4 Two-dimensional temperature distribution of 98% Ar-1% CO₂-1% H₂ plasmas at (a) 1T-CE, 760 torr (atmospheric), (b) 1T-NCE, 760 torr (atmospheric), (c) 1T-NCE, 500 torr and (d) 1T-NCE, 300 torr

Fig.5 Radial temperature distribution of 98% Ar-1% CO₂-1% H₂ plasmas at (a) 1T-CE, 760 torr (atmospheric), (b) 1T-NCE, 760 torr (atmospheric), (c) 1T-NCE, 500 torr and (d) 1T-NCE, 300 torr at an axial position of 155 mm

Fig.6 Two-dimensional mass fraction distributions for (a) Ar, (b) Ar⁺, (c) H⁺ and (d) electron for 1T-CE condition at atmospheric pressure

Fig.7 Two-dimensional mass fraction distributions for (a) Ar, (b) Ar⁺, (c) H⁺ and (d) electron for 1T-NCE condition at atmospheric pressure

Fig.8 Two-dimensional mass fraction distributions for (a) Ar, (b) Ar⁺, (c) H⁺ and (d) electron for 1T-NCE condition at reduced pressure (500 torr)

Fig.9 Two-dimensional mass fraction distributions for (a) Ar, (b) Ar⁺, (c) H⁺ and (d) electron for 1T-NCE condition at reduced pressure (300 torr)

Fig.10 Two-dimensional mass fraction distributions for (a) O⁺, (b) CHO, (c) OH and (d) H for 1T-NCE condition at atmospheric pressure

Fig.11 Radial distributions of particle composition at an axial position of 155 mm for (a) 1T-CE (atmospheric pressure), (b) 1T-NCE (atmospheric pressure), (c) 1T-NCE (pressure-500 torr) and (d) 1T-NCE (pressure-300 torr)

Fig.12 (a) Snapshots taken from high speed video camera for (I) Ar-100slpm and (II) 98% Ar-1% CO₂-1% H₂, (b) Radial distribution of radiation intensity at 10 mm below the coil end