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Technical Notes

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Generation of Highly Dissociated Oxygen Flows Using a Constrictor-Type Arc Heater

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Nomenclature

C_p	=	specific heat at constant pressure, J/kg K
h_{chem}	=	chemical potential, MJ/kg
h_0	=	total specific enthalpy, MJ/kg
M	=	Mach number
p_0	=	total pressure, Pa
R	=	gas constant, J/kg K
r	=	radial position, mm
T	=	translational temperature, K
T_0	=	total temperature, K
T'	=	variable of integration
u	=	flow velocity, m/s
γ	=	ratio of specific heat
ν_0	=	center absorption frequency, GHz

I. Introduction

In developing thermal protection systems (TPS) for reentry vehicles, a constrictor-type arc heater is widely used to simulate such high enthalpy flows because it has a simple and rugged structure and long operational time; moreover, it requires little maintenance after several hours' operation [1,2]. Recently, atomic oxygen has been found to play important roles through heat-flux enhancement by catalytic effects and active–passive oxidation of TPS surfaces [3,4].

Figure 1a shows that, in constrictor-type arc heaters, oxygen is usually injected at the constrictor part to prevent the cathode's oxidation, whereas an inert gas such as argon or nitrogen is supplied from the cathode base. In our previous studies, number density distributions of atomic oxygen in argon–oxygen flows generated by constrictor-type arc heaters were evaluated using laser absorption spectroscopy (LAS) and CFD analysis [5,6]. Results showed that oxygen was insufficiently mixed with argon and then only slightly dissociated in the constrictor region. Although the oxygen was mixed gradually in the plume, the dissociation rate was quite low because of the low temperature after nozzle expansion, engendering the low degree of dissociation in oxygen.

Figure 1b shows that for the enhancement of oxygen dissociation, a hollow cathode arc heater was developed to supply oxygen through the cathode tip into the high temperature cathode-jet region [7]. Consequently, the degree of dissociation in oxygen increased. However, severe cathode erosion up to 1.5×10^{-3} g/s limited the operation time to less than 20 min.

Next, we tested a premixed gas injection of oxygen and argon from the cathode base. As a cathode material, zirconium was used instead of conventional thoriated tungsten to reduce cathode erosion. Zirconium reacts with oxygen and forms an oxide ceramic (zirconia) layer on the cathode surface. This zirconia has a high melting point of 3000 K and lower vapor pressure than oxide tungsten [8,9]. In this study, the erosion rate of the zirconium cathode was measured. In addition to the degree of dissociation in oxygen, the specific enthalpy was evaluated using LAS.

II. Experimental Apparatus

The zirconium cathode arc heater is shown in Fig. 1c. Because the thermal conductivity of zirconium is one-tenth that of tungsten, the length from the cathode tip to the water-cooled copper socket was designed to be as short as 4 mm; the cathode tip was flattened to prevent the cathode from melting. Before the operation, the zirconium cathode was exposed in the arc-heater plume for 30 min to produce an oxide coating.

In LAS, the translational temperature T and the flow velocity u were deduced from an absorption line of ArI at the center frequency of ν_0 (=842.46 nm). Figure 1 shows that the probe laser beam was scanned at the plane 10 mm downstream of the nozzle exit with the incident angle of 75 deg to the flow; the Doppler shift and the broadening width were measured simultaneously. A glow discharge tube was used as a stationary plasma source to calibrate the frequency of the shift. Other details of the LAS principle and the measurement system are described in [5,10].

III. Results

Operation conditions are listed in Table 1. Although the oxide ceramic layer is nonconductive at room temperature, discharge was initiated successfully using a 5 kV high voltage igniter and sustained stably because electric conductivity of the layer increases with temperature. The cathode mass loss was measured after three hours of continuous operation. Consequently, the time-averaged erosion rate was estimated as 1.7×10^{-5} g/s, which corresponds to the cathode surface erosion speed of 0.27 mm/h. The erosion rate increased drastically, to as much as 4.1×10^{-4} g/s, when the discharge current was increased to 50 A.

Figure 2 shows measured absorption profiles after the Abel inversion. The absorption profiles near the plume centerline exhibit larger absorption and shift than those near the plume edge. The values of T and u were deduced, respectively, from measured

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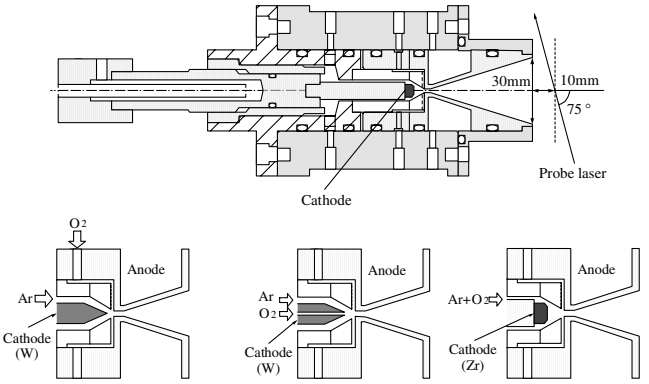


a) Conventional injection b) Hollow injection c) Pre-mixed injection

Fig. 1 Cross-sectional view of the constrictor-type arc heater and gas injection methods: a) conventional injection, b) hollow injection, and c) zirconium cathode with premixed gas injection.

broadening width of the profile and the shift [11]. Figure 3 shows their distributions along with their respective Mach numbers $M = u/\sqrt{\gamma RT}$. Here, γ and R, respectively, denote the ratios of specific heat and gas constant. Although u at the edge of the plume was subsonic, it might be an underestimation because the radial velocity component near the edge would not be negligible.

IV. Discussion

The specific enthalpy and degree of dissociation in oxygen were estimated as follows. Assuming an isentropic expansion and chemically frozen flow through the nozzle, the total specific enthalpy h_0 is conserved, which fact is expressed as

$$h_0 = \int_0^{T_0} C_p \, dT' + h_{\text{chem}} = \int_0^{T} C_p \, dT' + h_{\text{chem}} + \tfrac{1}{2}u^2 \qquad (1)$$

Here, C_p and T_0, and h_{chem}, respectively, signify the specific heat at constant pressure, the total temperature, and the chemical potential. The latter, h_{chem}, is constant under the chemically frozen flow assumption.

The total pressure p_0 measured in the plenum chamber by a silicon-diaphragm pressure sensor was as high as 22.4 kPa. Therefore, the chemical composition in the plenum chamber of the flow was calculated assuming thermochemical equilibrium. In that calculation, seven chemical species were considered, Ar, O_2, O, Ar^+, O_2^+, O^+, and e^-, in addition to four chemical reactions $Ar \leftrightarrow Ar^+ + e^-$, $O_2 \leftrightarrow 2O$, $O \leftrightarrow O^+ + e^-$, and $2O \leftrightarrow O_2^+ + e^-$. Their equilibrium constants were obtained from [12,13]. The volumetric gas mixture ratio of argon and oxygen and p_0 were set as identical to the operation condition. In addition, C_p was computed as the sum of the contributions of all species. Figure 4 shows the calculated mole fraction and specific enthalpy as a function of T_0.

Using Eq. (1), T_0 distribution was deduced from measured T, u. It was 6209 K on the axis and 1198 K at the plume edge. Figure 5 shows distributions of estimated degree of dissociation in oxygen and specific enthalpy. Oxygen was fully dissociated at the radial position of $r < 6$ mm. The averaged h_0 at $r < 6$ mm was 4.5 ± 0.1 MJ/kg, in which chemical potential accounted for 32%. Assuming that the pressure in the plume was identical to the back pressure in the

Table 1 Operation conditions

Parameters	Values
Current	40 A
Voltage	27 V
Argon mass flow	4.0 slm
Oxygen mass flow	0.5 slm
Ambient pressure	17.2 Pa
Plenum pressure	22.4 kPa

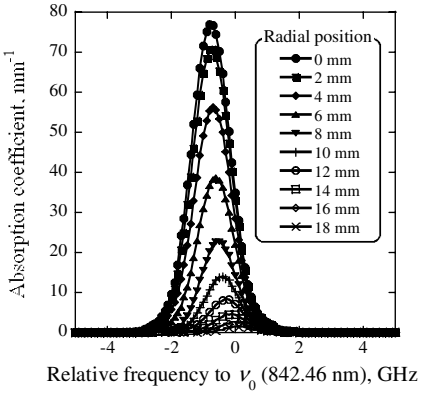
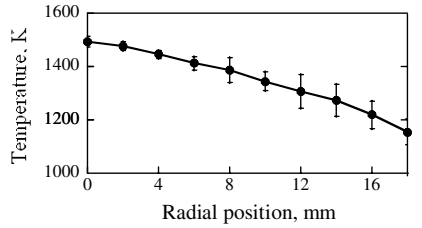
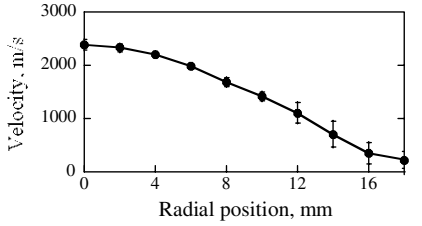


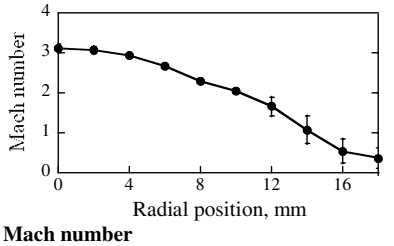
Fig. 2 Measured absorption profiles.



a) Translational temperature



b) Flow velocity



c) Mach number

Fig. 3 Measured flow properties: a) translational temperature, b) flow velocity, and c) Mach number.

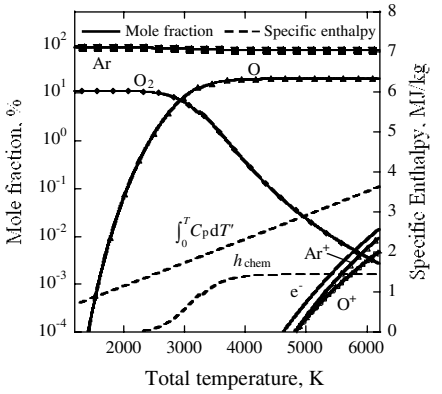


Fig. 4 Calculated specific enthalpy and mole fractions using the thermochemical equilibrium assumption, $p_0 = 22.4$ kPa, volumetric mixture ratio Ar:O_2 = 8:1.

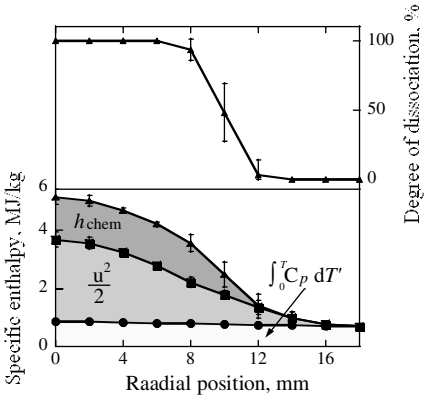


Fig. 5 Degree of dissociation in oxygen and specific enthalpy.

vacuum chamber, the averaged atomic oxygen flux was estimated as 3.1×10^{19} atom/cm^2 s, and the total plasma power was 180 W, which was 17% of the total input power.

V. Conclusion

Oxygen premixed with argon was supplied from the cathode base in the constrictor-type arc heater. To reduce cathode erosion, zirconium was used as a cathode material. Consequently, a stable discharge was maintained for more than three hours with small cathode erosion rate of 1.7×10^{-5} g/s, which corresponds to the erosion speed of the cathode surface of 0.27 mm/h.

As indicated by LAS diagnostics, oxygen was fully dissociated in the center of plume at the radial position less than 6 mm. The atomic oxygen flux and the total specific enthalpy around the centerline were estimated, respectively, as 3.1×10^{19} atom/cm^2 s at 4.5 ± 0.1 MJ/kg.

Acknowledgments

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References

[1] Birkan, M. A., "Arcjets and Arc Heaters: An Overview of Research Status and Needs," *Journal of Propulsion and Power*, Vol. 12, No. 6, 1996, pp. 1011–1017.

[2] Auweter-Kurtz, M., Kurtz, H. L., and Laure, S., "Plasma Generators for Re-Entry Simulation," *Journal of Propulsion and Power*, Vol. 12, No. 6, 1996, pp. 1053–1061.

[3] Bykova, N. G., Vasil'evskii, S. A., Gordeev, A. N., Kolesnikov, A. F., Pershin, I. S., and Yakushin, M. I., "Determination of the Effective Probabilities of Catalytic Reactions on the Surfaces on Heat Shield Materials in Dissociated Carbon Dioxide Flows," *Fluid Dynamics*, Vol. 32, No. 6, 1997, pp. 876–886.

[4] Balat, M., Flamant, G., Male, G., and Pichelin, G., "Active to Passive Transition in the Oxidation of Silicon Carbide at High Temperature and Low Pressure in Molecular and Atomic Oxygen," *Journal of Materials Science*, Vol. 27, No. 3, 1992, pp. 697–703.

[5] Matsui, M., Takayanagi, H., Oda, Y., Komurasaki, K., and Arakawa, Y., "Performance of Arcjet-Type Atomic-Oxygen Generator by Laser Absorption Spectroscopy and CFD Analysis," *Vacuum*, Vol. 73, No. 3, 2004, pp. 341–346.

[6] Matsui, M., "Application of Laser Absorption Spectroscopy to High Enthalpy Flow Diagnostics," Ph.D. Dissertation, Department of Advanced Energy, The University of Tokyo, Mar. 2005.

[7] Matsui, M., Satoshi, O., Komurasaki, K., and Arakawa, Y., "Arc-Heater as an Atomic Oxygen Generator," AIAA Paper 2003-3903, June 2003.

[8] Marotta, A., "Zirconium Cathode Erosion Rate in a Vortex-Stabilized Air Plasma Torch," *Journal of Physics D: Applied Physics*, Vol. 27, No. 1, 1994, pp. 49–53.

[9] Nemchinsky, V. A., and Showalter, M. S., "Cathode Erosion in High-Current High-Pressure Arc," *Journal of Physics D: Applied Physics*, Vol. 36, No. 6, 2003, pp. 704–712.

[10] Matsui, M., Komurasaki, K., Herdrich, G., and Auweter-Kurtz, M., "Enthalpy Measurement in Inductively Heated Plasma Generator Flow by Laser Absorption Spectroscopy," *AIAA Journal*, Vol. 43, No. 9, 2005, pp. 2060–2064.

[11] Demtroeder, W., "Laser Spectroscopy," *Basic Concepts and Instrumentation*, 3rd ed., Springer, Berlin, 2002, pp. 68–72.

[12] Matsuzaki, R., "Quasi-One-Dimensional Aerodynamics with Chemical Vibrational and Translational Nonequilibrium," *Transactions of the Japan Society for Aeronautical and Space Sciences*, Vol. 30, No. 90, 1987, pp. 243–258.

[13] Guputa, R. N., Yos, J. M., Thompson, R. A., and Lee, K.-P., "A Review of Reaction Rates and Thermodynamic and Transport Properties for an 11-Species Air Model for Chemical and Thermal Nonequilibrium Calculations to 30,000 K," NASA RP-1232, 1990.