JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 45, No. 1, January–February 2008

Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Enthalpy Measurement of Inductively Heated Airflow

Makoto Matsui,* Kimiya Komurasaki,† and Yoshihiro Arakawa‡
University of Tokyo, Tokyo 113-8656, Japan
Andreas Knapp§ and Georg Herdrich¶
University of Stuttgart, 70550 Stuttgart, Germany
and
Monika Auweter-Kurtz**
University of Hamburg, 20146 Hamburg, Germany

DOI: 10.2514/1.34369

Nomenclature

C_p	=	specific heat at constant pressure, J/kg K
h_{chem}	=	chemical potential, MJ/kg
h_0	=	specific total enthalpy, MJ/kg
$\bar{h}_0$	=	time-averaged specific total enthalpy, MJ/kg
I	=	probe laser intensity, mW/mm^2
I_0	=	incident laser intensity, mW/mm^2
M	=	Mach number
$\dot{m}$	=	mass flow rate, g/s
P	=	input power, kW
p_{amb}	=	ambient pressure, Pa
p_{tube}	=	pressure in the discharge tube, Pa
R	=	gas constant, J/kg K
r	=	radial position, mm
T	=	translational temperature, K
T_0	=	total temperature, K
t	=	elapsed time, ms
u	=	flow velocity, m/s
γ	=	specific heat ratio
λ	=	wavelength, nm
ν	=	laser frequency, Hz
ν_0	=	center absorption frequency, Hz
ρ	=	density, kg/m^3
τ	=	fluctuation cycle, ms

Presented as Paper 4408 at the 39th AIAA Thermophysics Conference, Miami, FL, 25–28 June 2007; received 1 September 2007; revision received 24 October 2007; accepted for publication 25 October 2007.

*Japan Society for the Promotion of Science Research Fellow, Department of Aeronautics and Astronautics. Member AIAA.
†Associate Professor, Department of Advanced Energy. Member AIAA.
‡Professor, Department of Aeronautics and Astronautics. Member AIAA.
§Doctoral Student, Institut für Raumfahrtsysteme.
¶Section Lead Space Transportation, Institut für Raumfahrtsysteme. Member AIAA.
**President. Member AIAA.

I. Introduction

INDUCTIVELY coupled plasma (ICP) generators are useful tools to simulate entry and reentry conditions for the development of a thermal protection system (TPS) [1,2]. Although arc heaters are widely used to generate high-enthalpy flows, their electrode erosion has been recognized to cause flow pollution, which makes it difficult to evaluate the chemical reaction rates on the front side of TPS surfaces [3,4]. ICP generators can produce an ideal test condition for TPS tests, because they have no undesirable chemical reactions that result from the electrode erosion. Another advantage of such generators is that they can use even reactive gases such as carbon dioxide and oxygen, because of their electrodeless heating. Thereby, Mars or Venus entry conditions can be simulated using these generators.

An inductively heated plasma generator (IPG3) has been developed at the Institut für Raumfahrtsysteme at the University of Stuttgart [5,6]. Various intrusive measurements using a calorimeter, pitot probe, Mach probe, and heat flux probe have been applied to the flows [7]. Nevertheless, it is still difficult to measure the temporal variations of flow properties, which would be valuable information for the validation of intrusive measurements and further studies of TPS surface physics.

In our previous study, laser absorption spectroscopy (LAS) was applied to the pure oxygen flow generated by the IPG3, and the flow properties were successfully estimated from the absorption line of atomic oxygen at $\lambda_0 = 777.19$ nm [8]. However, in the airflows generated at the Institute of Space Technology and Aeronautics (ISTA) of the Japan Aerospace Exploration Agency (JAXA) by an ICP wind tunnel [9], the absorption signal of the same line was too small to be detected. This result is the case with arc-heater plumes. It is reported that in air plumes, no absorption signal of the line could be detected (even for one of the largest arc heaters, the Interaction Heating Facility at NASA Ames Research Center [10]), though strong absorption signals were detected in argon/oxygen plumes [11]. In this study, the LAS was applied to an airflow by the IPG3, and the temporal and time-averaged specific enthalpy and degree of dissociation in oxygen and nitrogen were estimated.

II. Experimental Apparatus

The IPG3 comprises a Meissner-type resonant circuit as an RF oscillator. Its operational frequency can be optimized to achieve high-energy coupling efficiency for various gas species by switching the number of capacitors. In the airflows, the optimized frequency with four capacitors is 640 kHz. Figure 1 shows the image of the IPG3 plume, operation conditions, and measurement position. These conditions and position are the same as those in standard TPS tests. The details of the IPG3 are described in [5,6].

In the LAS, the translational temperature was deduced from the absorption-line broadening of atomic oxygen at $\lambda_0 = 777.19$ nm by assuming a Gauss profile. The measurement system and probe laser conditions were almost the same as those in the previous study [8,12]. Because the absorption signals in the airflow are considerably weaker than those in the oxygen flow, a 2-mm pinhole and a bandpass filter with a full-width at half-maximum of 10 nm were used in front of a photodetector to reduce the plasma emission. An etalon was used as a wave meter; its free spectral range was 0.75 GHz.

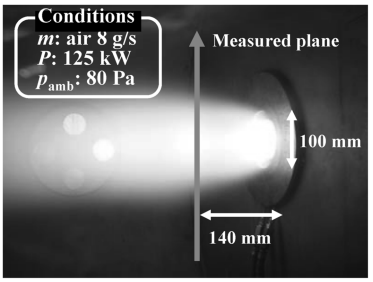

Fig. 1 IPG3 plume and operation conditions.

III. Result

Figure 2 shows the history of the absorbance $-\ell_n(I/I_0)$, along with an emission signal. The absorbance fluctuated in synchronization with the emission signal at 300 Hz. The trace is regular, and it can be categorized into two modes, as shown in Fig. 2. In both modes, the emission signal approaches zero and the plasma might be extinguished over half a cycle.

In each mode, the absorbance was extracted every 0.25 ms, as shown in Fig. 2. Here, the origin of elapsed time is set at the maximum emission signal in mode 1. Then time-synchronous absorption profiles were obtained by rearranging the absorbance according to the same elapsed time in the same mode, as shown in Fig. 3. The absorption profiles could be detected for a total of nine elapsed points in a series of modes 1 and 2, which implies that the averaged measurement time duration is 33% of a cycle.

Because the absorbance comprises path-integrated absorption coefficients, Abel inversion was applied to the detected region of $r < 6$ mm to obtain the absorption coefficients on a frequency-by-frequency basis. After curve-fitting the path-integrated absorption profiles shown in Fig. 3, the absorbance was extracted from the fitted curves every 0.4 GHz, following which the absorption profiles were reconstructed. In this study, we discuss only axial values.

Figure 4 shows the history of the translational temperature and the corresponding emission signal with the extracted points. In the measured time region, the temperature was in the range from 3100 to 3600 K.

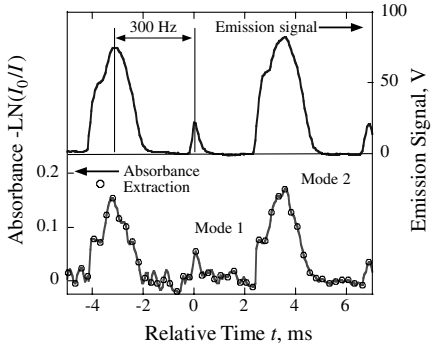

Fig. 2 Typical emission signal and absorbance with extraction points.

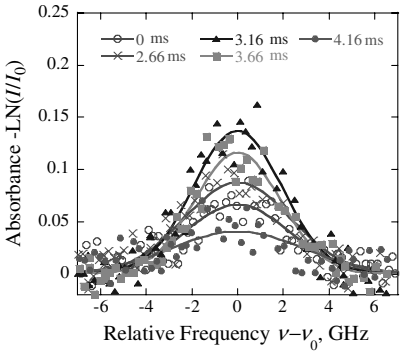

Fig. 3 Temporal variations of path-integrated absorption profiles.

IV. Discussion

The specific enthalpy and degree of dissociation in oxygen and nitrogen were estimated as follows. Unlike in a pure-oxygen condition, the air is accelerated more aerodynamically than electromagnetically [13]. Then, assuming an isentropic expansion and chemically frozen flow between the discharge tube and the plume, the total specific enthalpy is estimated as

$$h_0 = \int_0^{T_0} Cp\,\mathrm{d}T' + h_{\mathrm{chem}} = \int_0^{T} Cp\,\mathrm{d}T' + h_{\mathrm{chem}} + \frac{1}{2}u^2 \qquad (1)$$

In this study, the flow velocity was estimated from $u = M\sqrt{\gamma RT}$ using an averaged Mach number of 1.94 ± 0.14 measured by the pitot probe and the temperature by this work.

Because the total pressure measured in the discharge tube was as high as 11 kPa, the chemical composition in the tube was calculated by assuming thermochemical equilibrium. In the calculation, the following 11 chemical species were considered: N_2, O_2, N, O, NO, N_2^+, O_2^+, N^+, O^+, NO^+, and e^-. Their equilibrium constants were obtained from [14]. In addition, the specific heat at a constant pressure, the gas constant, and the specific heat ratio were computed as the sum of the contributions of all species. Figure 5 shows the calculated mole fraction and specific enthalpy as a function of the total temperature. The deduced total temperature was approximately in the range from 5200 to 6700 K.

Figure 6 shows the history of specific total enthalpy and degree of dissociation in oxygen and nitrogen. Here, the time axis is the same as that in Fig. 4. The maximum specific total enthalpy is 30.3 MJ/kg. Although oxygen was almost completely dissociated, the degree of dissociation in nitrogen was approximately 50%. In such a condition, the degree of dissociation in nitrogen is very sensitive to the temperature variation. Therefore, even a 5% error in the translational temperature, which is the lowest in this measurement, causes a 30% error in the degree of dissociation in nitrogen and a corresponding 20% error in the total specific enthalpy.

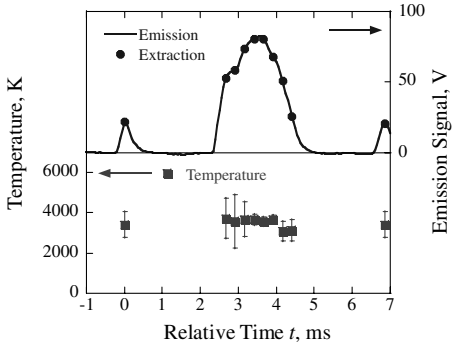

Fig. 4 History of translational temperature and emission signal.

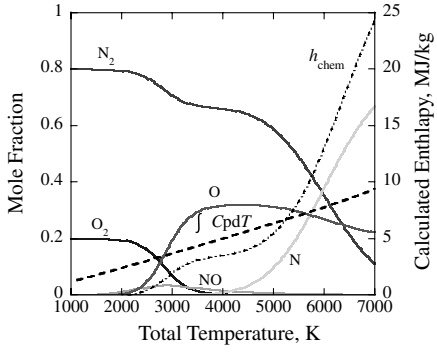

Fig. 5 Calculated enthalpy and mole fractions using the thermochemical equilibrium assumptions, $p_{\mathrm{tube}} = 11$ kPa.

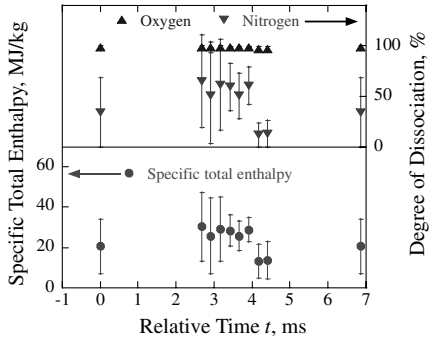

Fig. 6 History of estimated total enthalpy and degree of dissociation in oxygen and nitrogen.

The time-averaged specific total enthalpy is defined as

$$\bar{h}_0 = \frac{\int_0^\tau h_0(t)\rho(t)u(t)\,\mathrm{d}t}{\int_0^\tau \rho(t)u(t)\,\mathrm{d}t} = \int_0^\tau h_0(t)p_{\mathrm{amb}}\sqrt{\frac{\gamma(t)}{R(t)T(t)}}\,\mathrm{d}t \Big/ \int_0^\tau p_{\mathrm{amb}}\sqrt{\frac{\gamma(t)}{R(t)T(t)}}\,\mathrm{d}t \qquad (2)$$

Here, the equation of state $p_{\mathrm{amb}} = \rho RT$ is used under the assumption that the pressure in the plume is identical to the ambient pressure. Assuming a room temperature of 300 K in the extinguished region, the time-averaged specific total enthalpy was estimated as 6.86 ± 3.4 MJ/kg. However, this value might be underestimated, because the gas temperature in the extinguished region would be higher than the room temperature, due to heat conduction. In addition, a low temperature in the extinguished region has a greater influence on the averaging, because the weight of the integrand in Eq. (2) is inversely proportional to the square root of the temperature. Then the averaging was applied to the emission region, which corresponds to the measured time duration of the cycle. The estimated enthalpy and degree of dissociation in oxygen and nitrogen were 23.5 ± 11.4 MJ/kg and 98 and 44%, respectively.

V. Conclusions

Laser absorption spectroscopy was applied to the diagnostics of a nonstationary IPG3 airflow to obtain the temporal variations of the flow properties. Consequently, the IPG3 is found to produce a pulsed high-enthalpy flow at 300 Hz, with the averaged pulse duration equal to 33% of a cycle. The time-averaged total specific enthalpy and degree of dissociation in oxygen and nitrogen in this duration are estimated as 23.5 ± 11.4 MJ/kg and 98 and 44%, respectively.

Acknowledgments

This work was partially supported by Research Fellowships of the Japan Society for the Promotion of Science for Young Scientists, 18-09885. The authors thank Hiroki Takayanagi (University of Tokyo) for his support

References

[1] Bottin, B., Varbonaro, M., Van der Haegen, V., and Paris, S., "Predicted and Measured Capability of the VKI 1.2 MW Plasmatron Regarding Re-Entry Simulation," *Aerothermodynamics for Space Vehicles*, ESA SP-426, ESA, Paris, and European Space Research and Technology Centre, Noordwijk, The Netherlands, 1998, pp. 553–560.

[2] Gordeev, A. N., "Overview of Characteristics and Experiments in IPM Plasmatrons," *Measurement Techniques for High Enthalpy and Plasma Flows*, NATO Rept. RTO-EN-8, Neuilly-sur-Seine Cedex, France, Oct. 1999.

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

[4] 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. doi:10.1016/j.vacuum.2003.12.046

[5] Hrdrich, G., Auweter-Kurtz, M., and Kurtz, H., "New Inductively Heated Plasma Source for Reentry Simulations," *Journal of Thermophysics and Heat Transfer*, Vol. 14, No. 2, 2000, pp. 244–249.

[6] Herdrich, G., Auweter-Kurtz, M., Kurtz, H., Laux, T., and Winter, M., "Operational Behavior of Inductively Heated Plasma Source IPG3 for Entry Simulations," *Journal of Thermophysics and Heat Transfer*, Vol. 16, No. 3, 2002, pp. 440–449.

[7] Herdrich, G., and Auweter-Kurtz, M., "Development and Characterization of Inductively Heated Plasma Generator for Atmospheric Entry Simulations," AIAA Paper 04-2503, Jun. 2004.

[8] 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.

[9] Ito, T., Ishida, K., Mizuno, M., and Sumi, T., "110 kW New High Enthalpy Wind Tunnel Heated by Inductively-coupled-plasma," 12th AIAA International Space Planes and Hypersonic Systems and Technologies, AIAA Paper 2003-7023, Dec. 2003.

[10] Kim, S., "Development of Tunable Diode Laser Absorption Sensors for a Large-scale Arc-Heated-Plasma Wind Tunnel," Ph.D. Thesis, Dept. of Mechanical Engineering, Stanford Univ., Stanford, CA, 2004.

[11] Matsui, M., Ikemoto, T., Takayanagi, H., Komurasaki, K., and Arakawa, Y., "Generation of Highly Dissociated Oxygen Flows Using a Constrictor-Type Arc-Heater," *Journal of Thermophysics and Heat Transfer*, Vol. 21, No. 1, 2007, pp. 247–249. doi:10.2514/1.25404

[12] Matsui, M., Ogawa, S., Komurasaki, K., and Arakawa, Y., "Influence of Laser Intensity on Absorption Line Broadening in Laser Absorption Spectroscopy," *Journal of Applied Physics*, Vol. 100, No. 6, 2006, Paper 063102. doi:10.1063/1.2353893

[13] Herdrich, G., Petkow, D., and Auweter-Kurtz, M., "High Enthalpy, Water-Cooled and Thin-Walled ICP Sources: Characterization and MHD-Optimization," *Journal of Plasma Physics* (to be published).

[14] Gupta, 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 30000 K," NASA Rept. 1232, 1990.

I. Boyd
Associate Editor