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Technical Notes

Comprehensive Flow Characterization in a 110-Kilowatt Inductively-Coupled-Plasma Heater

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I. Introduction

ELECTRICALLY heated wind tunnels are widely used as one of the ground-test facilities to evaluate the performance of thermal protection system (TPS) materials for atmospheric reentry vehicles. Recent interests in TPS development may be focused on accurate assessment of heat generation due to chemical reactions on the gas–surface interface, such as catalytic recombination on the surface, and oxidation and nitridation of the TPS material. To accurately assess the contributions of such processes to the net heat transfer rate, it is necessary to obtain detailed information about the flow properties such as temperature and concentration of the atomic species when TPS materials are tested.

In the past studies [1,2], in an attempt to measure the thermochemical properties of the test flow in a 110-kW inductively-coupled-plasma (ICP) heater at the Aerospace Research Center, Japan Aerospace Exploration Agency [3], emission spectroscopy associated with the line-by-line spectrum analysis was conducted by using the radiation code SPRADIAN2 [2]. The temperature and the chemical composition in the test flow were successfully determined under the representative operating conditions. More recently, the nitridation rate coefficient for the carbon surface was measured in the nitrogen test flow using the ICP heater [4,5]. In this experiment, to eliminate atomic oxygen remaining in the test section as an impurity, the ambient gas in the test section was replaced with pure nitrogen before ignition of the ICP heater. The experimental results indicated successful reduction of atomic oxygen by the gas replacement; however, its effectiveness has not been quantitatively assessed yet.

In this study, following the preceding studies, comprehensive flow characterization in a wide range of the operating conditions is conducted for future use in thermal protection materials testing and evaluation. A new imaging optical system is introduced to obtain emission spectra with less optical aberration in a wider wavelength range than before. The presence and source of impurities in the test flow are discussed more elaborately. Finally, effectiveness of the gas replacement on reduction of impurities is quantitatively assessed by obtaining the radial distribution of the impurities in the core flow of the test section.

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II. Experimental and Numerical Procedures

The experimental setup is schematically illustrated in Fig. 1. The experimental procedure used in this study is the same as that developed in the past study [2] except that the optical system is replaced with a new mirror system consisting of an offaxis parabolic mirror and a flat mirror to eliminate optical aberration. The ICP heater was operated at 70, 90, and 110 kW, with nitrogen and air as the working gas at the flow rate of 2.0 g/s, which are the standard operating conditions offered to users. The ambient pressure in the test section was maintained at 10 kPa during the operation. The optical system was focused at the location 5 mm upstream of the stagnation point of the test piece, and emission spectroscopy was conducted without insertion of the test piece into the test flow. Radial distribution of emission spectra was obtained by the one-dimensional radial imaging spectroscopy with a 1.4 mm spatial resolution in the radial direction. The measurement system was calibrated as a whole using an Optronic Laboratories UV-40IR deuterium lamp and a 550 C standard tungsten lamp.

The radial imaging spectroscopy of the test flow was performed in the wavelength range from 230 to 900 nm. An overall spectrum was constructed from 8 individual images that covered 200–300, 300–400, 350–450, 450–500, 550–650, 650–750, 750–850, and 800–900 nm wavelength ranges, respectively. A series of spectroscopies from the short to long wavelength ranges was repeated 5 times to produce an averaged spectrum. In general, because the test flow is stable, deviations of the individual spectrum from the averaged one remain less than 3% over the entire wavelength range. Finally, the radial distribution of the emission intensity was obtained by the inverse Abel conversion.

Temperature and chemical concentration were deduced from the observed emission intensity by the spectrum fitting method, using the line-by-line radiation code SPRADIAN2 [2]. To reproduce a numerical spectrum for high-temperature air and nitrogen flows containing a considerable amount of impurities such as hydrogen and carbon, bound–bound, free–bound, and free–free transitions of 7 atomic species (H, C, N, O, C^+, N^+, and O^+) and 7 molecular species (N_2, O_2, N_2^+, CH, NH, OH, and CN) were taken into account (for details, see Table 1 of [2]). Because the gas in the test section is known to be closely in local thermal equilibrium [2], the numerical spectrum was computed using the equilibrium chemical composition for air and nitrogen at temperatures from 3000 to 7000 K at every 50 K. The spectral fitting criteria was set to minimize the performance function $S = \Sigma_i^N [I_i/I(\lambda_i) - 1]^2/N$, where I_i and $I(\lambda_i)$ are the measured and the calculated emission intensity at the wavelength λ_i, respectively, and N is the total number of wavelength points in the measured overall spectrum. In addition, to incorporate emission from impurities, the numerical spectrum were recomputed by changing mole fractions of the impurities until the performance function could be minimized.

III. Results

The optimal solutions of the numerical spectrum are compared with the measured spectrum in Figs. 2a and 2b for the nitrogen and the air test flow produced at 90 kW, respectively. In the nitrogen test flow (Fig. 2a), the spectrum is seen to mainly consist of the first positive and the Meinel system of N_2^+, and the first positive and the second positive system of N_2. Although nitrogen is used as the working gas, emission from NO is seen to be intense in the ultraviolet wavelength range, and considerable emission from OH, NH, and CN

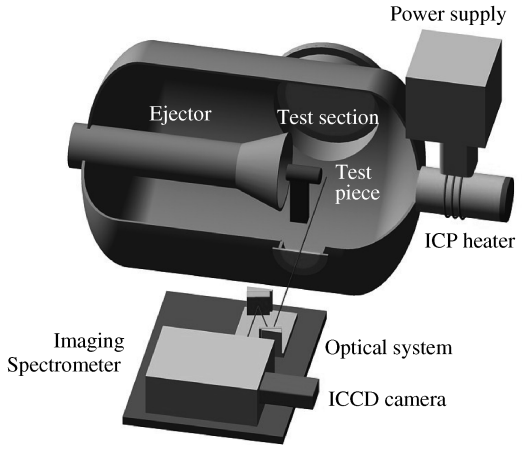

Fig. 1 Schematic view of the experimental setup (ICCD denotes the intensified charge-coupled device).

is observed as well. This is because the test section was not completely evacuated before ignition of the ICP heater, due to limited capacity of the evacuation system. In contrast, in the air test flow (Fig. 2b), the band systems of N_2 and N_2^+ are considerably reduced, whereas the band systems of NO are the most intense. In addition, the emission from CN, OH, and NH is seen to be one of the major components of the overall spectrum in short wavelengths below 400 nm. For this reason, it is necessary to accurately take into account the emission from the minor species as well as that from the major species to measure the flow properties by the spectrum fitting method.

As seen in Fig. 2, excellent agreement between the measured and the computed spectrum is obtained at the center of the test flow by assuming the temperature to be 5800 and 5600 K for the nitrogen and the air test flow, respectively. In general, agreement becomes degraded to some extent with increasing the distance from the flow center [2], although the results are not shown here. This is because the flow tends to depart from the thermochemical equilibrium with increasing the distance from the flow center, due to radial diffusion and thermal conduction.

Figure 3 illustrates the contributions of the impurities to the overall spectrum in the nitrogen test flow. The numerical spectrum based on the equilibrium composition does not completely reproduce the measured spectrum, resulting in poor accuracy in temperature determination by the spectrum fitting method. The measured spectrum can be reproduced by adding NO, NH, and CN by 0.0014, 1.7×10^{-6}, and 3.2×10^{-6} in mole fraction, respectively. In the outer region of the flow, the emission from OH becomes prominent enough to measure its mole fraction. In addition, the mole fraction of atomic oxygen can be determined by matching of the atomic line intensity at 777 nm (see Fig. 2a).

The radial distribution of temperature is summarized in Figs. 4a and 4b for the nitrogen and the air test flows, respectively. The flow enthalpy deduced from the temperature and the chemical composition is also plotted for comparison. The data are only available within a 28 mm radial distance, because the emission from the test flow is not intense enough to accurately determine the temperature beyond this limit. In the ICP heater tested in this study, an increase in the electric power not only raises the flow temperature at the center, but also increases the diameter of the high-temperature core of the test flow.

IV. Reduction of Impurities in Nitrogen Test Flows

The measured radial distribution of the impurities in the nitrogen test flow at 90 kW is shown in Fig. 5a. Although nitrogen was used as

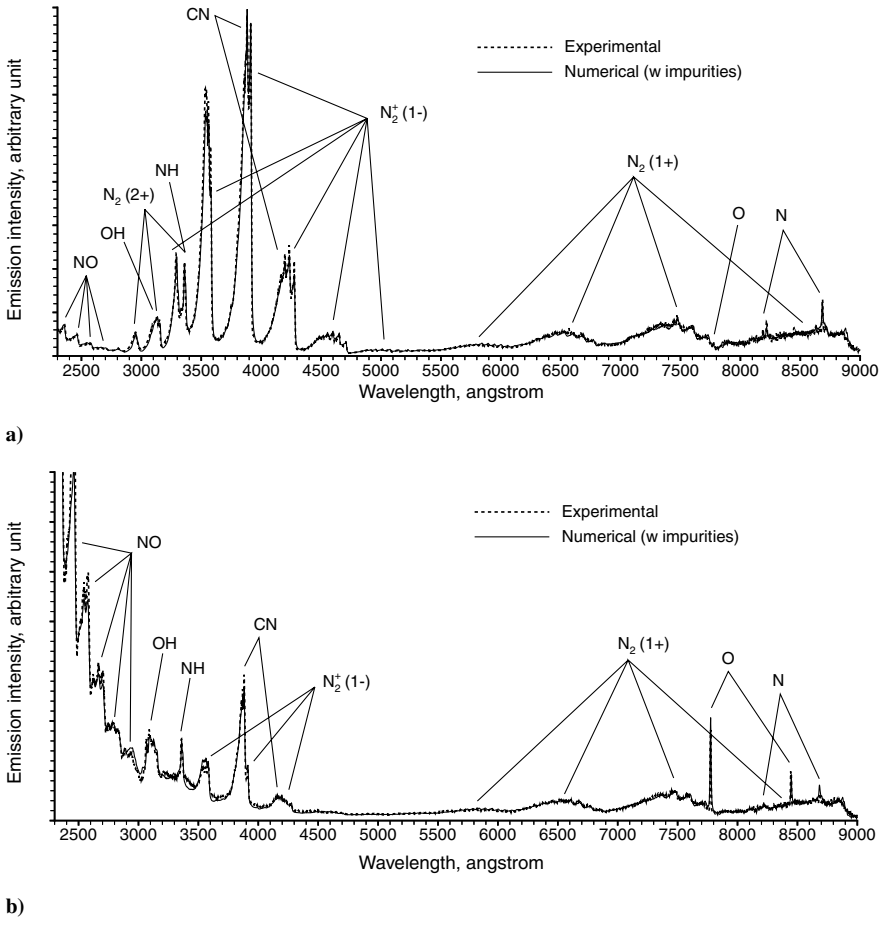

Fig. 2 Comparison between measured and calculated emission intensity at the center of a) nitrogen and b) air test flow at 90 kW; estimated temperatures are 5800 ± 100 K and 5600 ± 100 K, respectively.

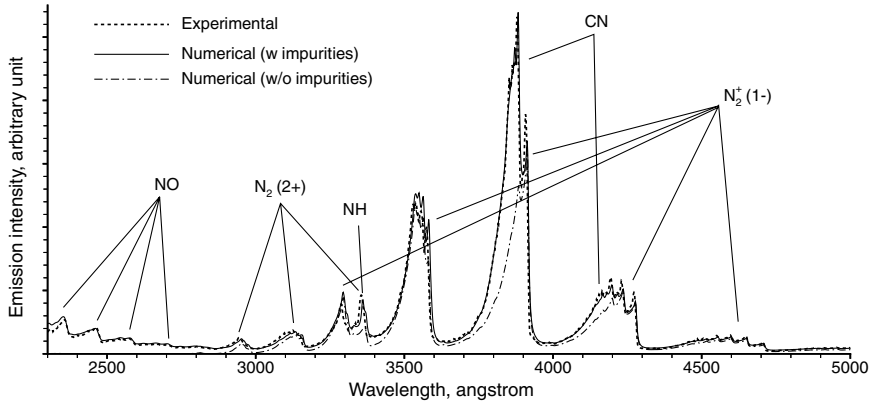

Fig. 3 Contribution of impurities to the overall spectrum at the center of nitrogen test flow produced at 90 kW.

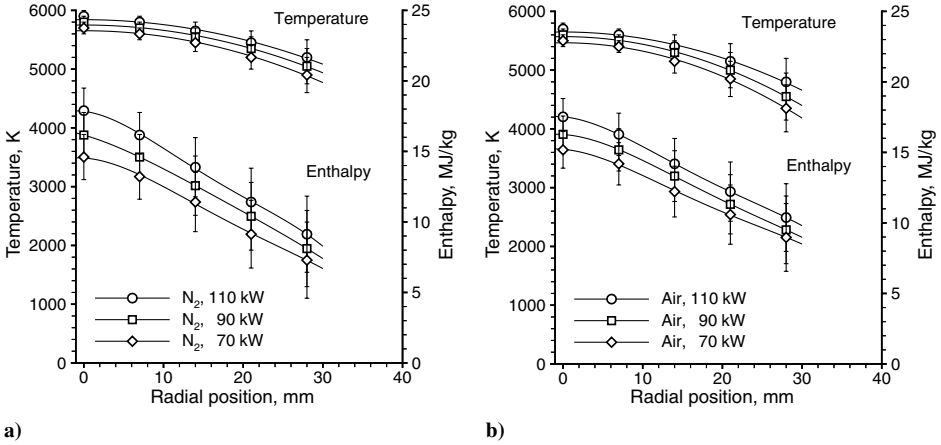

Fig. 4 Radial distribution of temperature and gas enthalpy in a) nitrogen and b) air test flows.

the working gas, the mole fraction of O and NO amounts to 2.5 and 0.14% at the flow center, respectively, and increases along with the radial position. This is because molecular oxygen remains in the ambient gas of the test section, due to insufficient evacuation of the test section before ignition of the ICP heater. Likewise, the mole fraction of OH increases along with the radial position, whereas that of NH and CN conversely decreases. When the nitrogen test flow is used in measurement of the nitridation rate coefficient for the carbon surface [4,5], the presence of atomic oxygen is considered to brings about serious errors in the measured nitridation rate, because the oxidation rate is expected to be much higher than the nitridation rate. In [6], the effects of remaining oxygen are assessed by the computational-fluid-dynamic calculation coupled with the analysis of the graphite thermochemical behavior. The results suggest that the influence of oxidation on the measured recession rate is negligible when atomic oxygen remaining in the nitrogen test flow is less than 1% in mole fraction.

In an attempt to reduce the contaminations in the nitrogen test flow, the ambient gas in the test section was replaced with nitrogen before ignition of the ICP heater in the following manner. The test section was first evacuated to 0.1 torr, which is the lowest pressure attainable by the evacuation system of the ICP heater, then filled with nitrogen

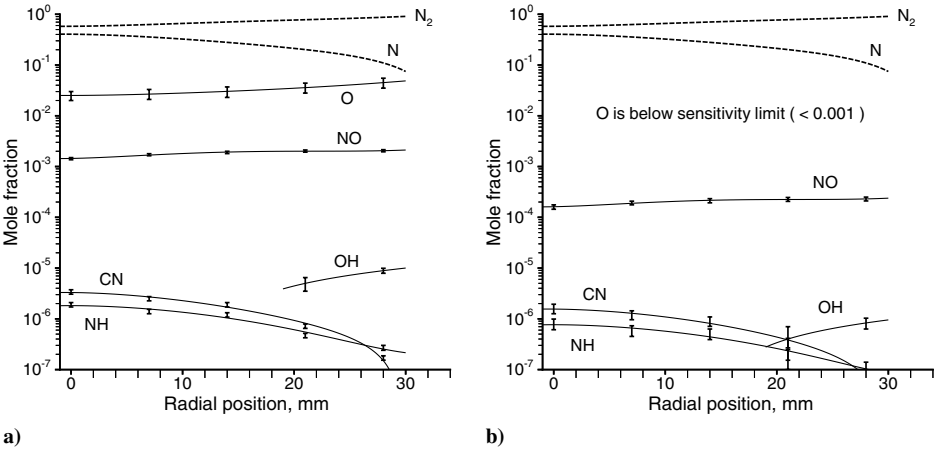

Fig. 5 Radial distribution of chemical components including impurities in nitrogen test flow produced at 90 kW: a) without replacement of the ambient gas and b) with replacement of the ambient gas with nitrogen.

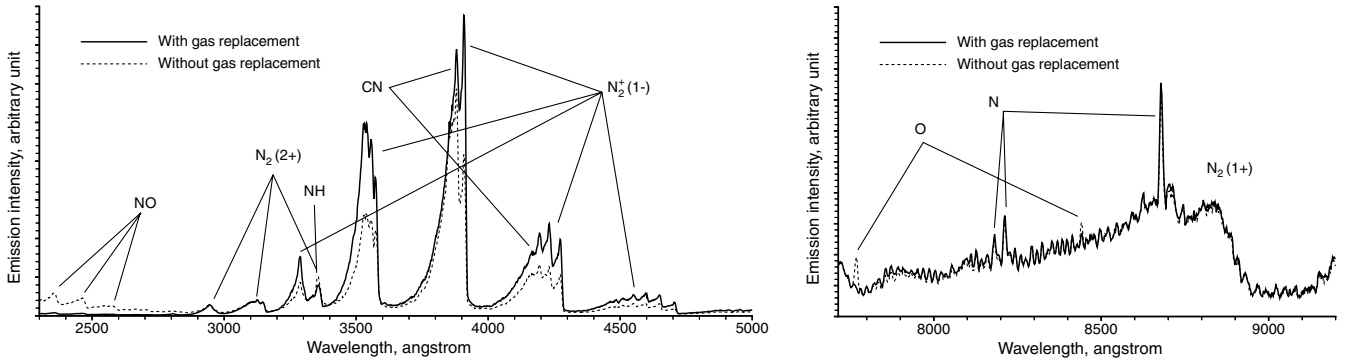

Fig. 6 Comparison between spectra obtained at 90 kW using nitrogen as the working gas with and without replacement of ambient gas with nitrogen.

up to 20 torr. This procedure was repeated 3 times, then the test section was filled with nitrogen again and the pressure was kept at 10 kPa during the ICP heater operation. In principle, the remaining gas in the test section can be attenuated by a factor of 3×10^{-8} through the preceding procedure.

In Fig. 6, comparison is made between the spectra obtained with and without the gas replacement before the heater ignition. The emission from NO, O, and NH is seen to be considerably reduced, whereas that from CN remains at the same order of magnitude. It is interesting to note that the emission from N_2^+ increases by a factor of 2 when the ambient gas is replaced with nitrogen. This implies that the reduction of the impurities has a certain influence on ionization processes in the slightly ionized plasma. Finally, the radial distribution of the impurities reduced by the gas replacement is shown in Fig. 5b for comparison. The emission from O is eliminated below the sensitivity limit of the spectroscopic system by the gas replacement, which means that the mole fraction of O is reduced below 0.1%. The mole fractions of NO and OH are reduced by a factor of 0.1. In contrast to this, the mole fractions of CN and NH are only reduced to half. This suggests that carbon comes from the contaminated wall and that hydrogen originates from the water vapor adhering to the inside wall of the test chamber, both of which are not much affected by the gas replacement before the heater ignition.

The reduction of NO by a factor of 0.1 seems to be insufficient for the gas-replacement procedure described previously. The reason for such insufficient reduction of the impurities may be attributed to backdiffusion of air from the downstream region of the ejector, because the flow is low subsonic in the entire region of the ejector and because the capacity of the evacuation system is limited. To solve this problem, the authors are currently planning to improve the facility for future investigations of the thermochemical processes on the gas–surface interface, which may require cleaner test flows with less contaminations than in the present measurement.

V. Conclusions

The one-dimensional radial imaging spectroscopy associated with the line-by-line spectrum analysis by SPRADIAN2 was conducted to offer detailed information about the test flows in a 110-kW ICP heater at the Japan Aerospace Exploration Agency's Aerospace Research Center. The radial distributions of the temperature and the species concentration including the impurities have been determined with sufficient accuracy for the nitrogen and the air test flows in a wide range of the operating conditions. The nitrogen test flows were seen to be contaminated by an unacceptable amount of O and NO due to insufficient evacuation of the test section before the heater ignition. In an attempt to eliminate O and NO from the nitrogen test flow, the ambient gas in the test section was replaced with nitrogen before the heater ignition. As a result, the concentration of O and NO was reduced by a factor of 0.1. The insufficient reduction of the flow contaminations has shown a guideline for the future improvement of the ICP heater facility.

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