

Technical Notes

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

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DOI: 10.2514/1.43275

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.

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 (N₂, O₂, N₂⁺, 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 $S = \sum_i^N [I_i/I(\lambda_i) - 1]^2/N$, 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 N₂⁺, and the first positive and the second positive system of N₂. 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

Presented as Paper 1254 at the 46th AIAA Aerospace Science Meeting and Exhibit, Reno, NV, 7–10 January 2008; received 16 January 2009; revision received 27 April 2009; accepted for publication 6 May 2009. Copyright © 2009 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved. Copies of this paper may be made for personal or internal use, on condition that the copier pay the \$10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0887-8722/09 and \$10.00 in correspondence with the CCC.

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