JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 23, No. 1, January–March 2009

Technical Notes

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Inductively Heated Air Plasma Flow Characterization with Laser-Induced Fluorescence Measurements

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DOI: 10.2514/1.38114

I. Introduction

THERMAL protection systems for Earth reentry maneuvers are currently being qualified by means of plasma wind tunnels. The latter generate high enthalpy air plasma flows as expected for the reentry missions [1,2]. The progress in the development of future thermal protection systems (TPS) as, for example, toward the development of reusable systems, inherently depends on the understanding of the material behavior [2]. Here, especially the catalycity of the selected TPS material is of significant influence. To investigate the catalytic behavior, a stationary pure high enthalpy airflow is needed. Conventional arcjets contaminate the air plasma flow with electrode erosion products similar to copper or tungsten possibly leading to a change in the catalytic material's behavior during the TPS qualification process. Hence, electrodeless inductively heated plasma generators are advantageous for material investigations as well as for investigations with respect to the impurities of the plasma flow of conventional plasma wind tunnels.

In this paper, results of laser-induced fluorescence (LIF) measurements of atomic oxygen in an inductively heated air plasma flow are presented. The experimental and theoretical approaches are described in detail in previous publications [3,4]. The measurements presented in this paper are the first results of an extension of the setup to air plasma conditions. The measurements are of particular importance for comparison and validation of future flight experiments as, for example, the pyrometric heat flux experiment (PHLUX) on the European experimental reentry test bed (EXPERT) [5].

The excitation is performed using a pulsed laser system and the fluorescence is detected using a photomultiplier and a fast oscilloscope as well as gated integrators. Oxygen atoms in the ground electronic state are excited via the $3p^3P_{2,1,0} \leftarrow 2p^3P_2$ two-photon transition at about 225 nm. The resulting fluorescence is measured using the $3p^3P_{2,1,0} \rightarrow 3s^3S_1^0$ transition at 844.5 nm.

II. Experimental Setup

The facility used for the present investigation is the inductively heated plasma wind-tunnel PWK3 (see Fig. 1). It consists of a vacuum vessel 2 m in diameter and 2.5 m in length. Optical accesses on both sides of the vacuum chamber are provided to measure and observe the plasma flow. The plasma generator is installed in the forward end cap. On the rear end cap of the vacuum chamber, the vacuum system is connected [6].

The plasma is generated inside a thin quartz tube by a high-frequency current applied to the induction coil around the tube. The coil has 5.5 turns. Together with four capacitors, the coil builds a resonant circuit operating at a frequency of 640 kHz. The maximum electric power is 375 kW. The generator is voltage controlled. The water cooling system surrounds both the quartz tube and the induction coil. The working fluid air is fed into the quartz tube on one side using a tangential injection. For high enthalpy air plasma conditions, an additional air injection ring is inserted in the injection head. This protects the quartz tube from locally being overheated. The alternating current in the coil induces an electric field in the tube which in turn initiates an electric discharge in the gas. The produced plasma finally expands into the vacuum chamber. The adjustable parameters are mass flow $\dot{m}$, ambient pressure in the vacuum chamber p_a as well as anode voltage U_A of the power supplying triode. In the present case, all measurements have been carried out at minimum ambient pressure of $p_a = 80$ Pa and a constant air mass flow of $\dot{m} = 8$ g/s. Special emphasis lies on an anode voltage of $U_A = 7800$ V corresponding to an electric power at the anode of $P_A = 125$ kW. This condition is typically used as a reference condition for the development and qualification of the mentioned flight experiments. Finally, the measurement results also depend on the distance of the measurement location from the generator exit. All measurements were performed at an axial distance of 140 mm. This location was chosen due to constraints of optical access to the vacuum chamber.

The laser system is mounted on top of the vacuum chamber. It consists of a pulsed excimer gas laser used with XeCl emitting at 308 nm (Lambda Physik CompEX 205). With a dye laser (Lambda Physik Scanmate 2E) and a beta barium borate (BBO) crystal for frequency doubling, laser radiation at 225 nm is attained with a maximum output of about 1 mJ per pulse. The laser beam is adjusted to the measurement location on the plasma jet axis in the center of the vacuum chamber by three prisms and a focusing lens system.

The laser-induced fluorescence is detected at right angles to the laser and the flow direction. A gated photomultiplier tube (PMT Hamamatsu R636-10) is used. Two achromatic lenses image the fluorescence plane onto the detector. In front of the entrance slit, an interference filter with a relatively narrow width of 10 nm is used to separate the fluorescence from the background emission of the plasma. Data acquisition is realized using state of the art equipment consisting of Boxcar integrators (Stanford Research Systems SR250) and a LabView code.

III. Theory

The translational temperature is determined from the linewidth of the measured absorption profile. In the case of two-photon transitions, the linewidth due to temporal Doppler broadening $\Delta\lambda_{temp}$ depends on the instrumental linewidth $\Delta\lambda_{instr}$ and the total (measured) linewidth $\Delta\lambda_{tot}$. Marx et al. [7] had shown that in the case of two-photon excitation processes, the temporal broadening is

Received 17 April 2008; revision received 20 August 2008; accepted for publication 24 September 2008.

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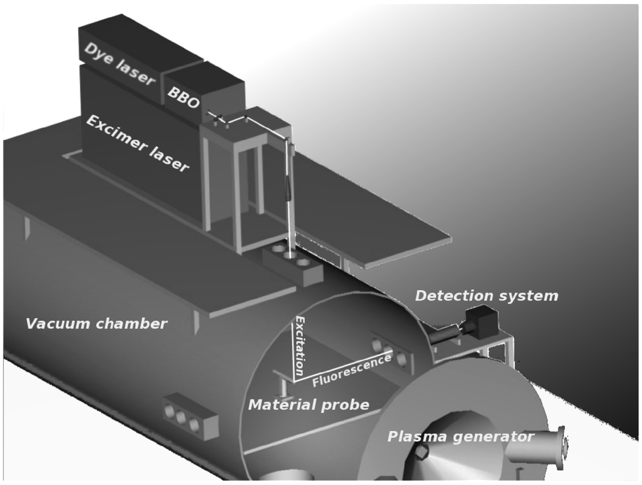

Fig. 1 Setup for laser-induced fluorescence measurements at the plasma wind-tunnel facility.

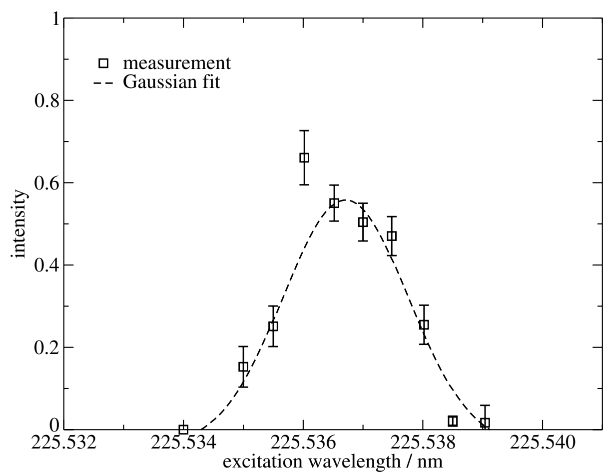

Fig. 2 LIF signal as a function of the laser wavelength ($\dot{m} = 8$ g/s, $p_A = 80$ Pa, and $U_A = 7800$ V).

$$\Delta\lambda_{\text{temp}} = \sqrt{\Delta\lambda_{\text{tot}}^2 - 2\Delta\lambda_{\text{instr}}^2} \tag{1}$$

The translational temperature is then derived using

$$\Delta\lambda_{\text{temp}} = \sqrt{\frac{8\ \ln(2) N_A k T}{M_O c^2}}\lambda_0 \tag{2}$$

the commonly known equation for thermal Doppler broadening. The line center is denoted with λ_0; all other parameters are chosen according to the conventional physical meaning.

The measured linewidth is the sum of different line broadening effects. Because of the low ambient pressure, pressure (Stark) broadening is negligible [8]. However, the line broadening due to the used experimental equipment needs to be accounted for. Two-photon LIF measurements on xenon at approximately the same absorption wavelength at room temperature and an ambient pressure of $p_a = 75$ Pa had been used to measure the instrumental linewidth to $\Delta\lambda_{\text{instr}} = 0.567$ pm [4].

IV. Results

Figure 2 shows the result of one excitation scan over the atomic absorption line. It seems that the fourth data point is an outlier. The only reason can be a coincidently high laser excitation process. Each LIF experiment was performed as a wavelength scan at constant plasma generator conditions. The average of 10 pulses is taken, whereas a standard deviation of about 5% has been measured. The temperatures are estimated from a Gaussian fit to the measured data points (see Fig. 2).

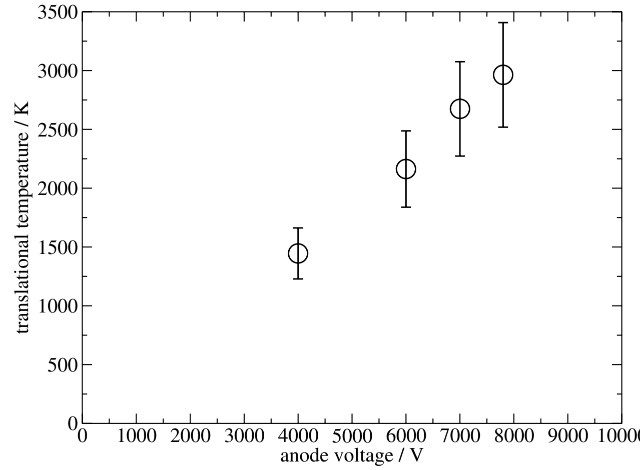

Fig. 3 Experimentally measured translational temperatures for atomic oxygen in air plasma as a function of the anode voltage of the generator ($\dot{m} = 8$ g/s, and $p_A = 80$ Pa).

Figure 3 shows the translational temperatures evaluated from the line broadening. From a sensitivity analysis of the fitting process, the accuracy is deduced to be 15%. With increasing anode voltage, that is, increasing plasma power, the temperature rises. At $U_A = 5000$ V, the facility is in a typical unsteady mode where measurements are impossible. The maximum temperature measured for the highest anode voltage at $U_A = 7800$ V is 2963 K. This is the experimental condition used as a reference for many applications as mentioned previously. Compared with the measurements using pure oxygen plasma flow, the reached temperatures presented here are comparably low, which is due to the higher mass flow rate at approximately the same discharge power [3].

Assuming thermochemical equilibrium, the mass-specific enthalpy can be deduced from the measured temperature. The enthalpy can be formulated as [9]

$$h = \tfrac{1}{2}v^2 + c_p \cdot T + h_{\text{chem}} \tag{3}$$

Applying the Rayleigh–Pitot formula for supersonic flow allows the determination of the Mach number from total pressure and ambient pressure measurements [10]. For the present reference condition where the number is $Ma = 1.94$ [11], the velocity yields

$$v = Ma \cdot \sqrt{\gamma \cdot R \cdot T} = 2393 \text{ m/s} \tag{4}$$

For the temperature region of interest and under the assumption of thermochemical equilibrium, the chemical composition can be calculated using a 7-species air model (N_2, O_2, N, O, NO, NO^+, e^-) [12].

For the reference condition, an enthalpy of $h = 13.02$ MJ/kg is reached, where the kinetic energy is $h_{\text{kin}} = 2.86$ MJ/kg. The chemical fraction derived from equilibrium chemistry is $h_{\text{chem}} = 5.02$ MJ/kg. The number density of atomic oxygen from this calculation is of the order of $n_O = \mathcal{O}(10^{20})\ 1/\text{m}^3$.

Although a thorough calibration for quantitative measurement of the LIF setup has not been performed yet, this value appears reasonable: Referring to the calibration data from the LIF measurements in pure oxygen plasma flows where the effective lifetime of the upper state is about $\tau_{\text{LT}} = 30$ ns, the detected fluorescence signal in the present case corresponds to an atomic oxygen number density of $n_O = 5 \times 10^{20}\ 1/\text{m}^3$ [4]. This value is not so far off to the equilibrium value above as calculated using the 7-species model described previously. The chemical fraction calculated from the equilibrium chemistry is $h_{\text{chem}} = 5.02$ MJ/kg. From this rough estimation of the number density, the mole fraction of atomic oxygen is derived from $p/p_O = n/n_O \cdot T/T_O$ and the assumption that $T = T_O$ as 0.26. Thus, the fraction of the chemical enthalpy due to dissociation of oxygen is 3.99 MJ/kg, that is, 80% of h_{chem}. This indicates that the dissociation of nitrogen is rather low, which in turn is reasonable with respect to the measured translational temperature of $T = 2963$ K, because the dissociation of oxygen starts above 2000 K and is completed at 4000 K, while molecular nitrogen begins to dissociate above 4000 K and is virtually completed above 9000 K. However, whether the flow really is in thermochemical equilibrium or not can only be shown by additional measurements not only of atomic oxygen but also of atomic nitrogen. A first step herein can also be to analyze the plasma flow using emission spectroscopy.

V. Conclusions

Laser-induced fluorescence measurements have been performed for the first time at inductively heated air plasma flows. From the measured signals translational temperatures have been deduced. The maximum temperature for a reference condition on the jet axis with a distance of 140 mm from the generator exit is $T = 2963 \pm 444$ K. The results presented here show the principle feasibility of LIF measurements in air plasma flows that are inductively heated. Furthermore, the estimation of the local specific enthalpy from the deduced temperature shows that the air plasma reaches an enthalpy of $h = 13.02$ MJ/kg.

Acknowledgments

The authors gratefully acknowledge the funding of this work through the Deutsche Forschungsgemeinschaft (DFG) project Au85/24-1. The authors also wish to acknowledge the help of H. Böhrk and A. Knapp.

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