Non-Intrusive Optical Diagnostic Methods for Flowfield Characterization

Bagher M Tabibi, Charles A. Terrell, Darrell Spraggins, Ja H. Lee

Department of Physics
Research Center for Optical Physics
Hampton University
Hampton, VA 23668

and

Leonard M. Weinstein
NASA LaRC
Hampton, VA 23681

SUMMARY/OVERVIEW

Non-intrusive optical diagnostic techniques such as Electron Beam Fluorescence (EBF), Laser-Induced Fluorescence (LIF), and Focusing Schlieren (FS) have been setup for high-speed flow characterization and large flowfield visualization, respectively. Fluorescence emission from the First Negative band of N_2^+ with the (0,0) vibration transition (at λ =391.44 nm) was obtained using the EBF technique and a quenching rate of N_2^{+*} molecules by argon gas was reported'. A very high sensitivity FS system was built and applied in the High-Speed Flow Generator (HFG) at NASA LaRC. A LIF system is available at the Advanced Propulsion Laboratory (APL) on campus and a plume exhaust velocity measurement, measuring the Doppler shift from λ = 728.7 nm of argon gas, is under way.

INTRODUCTION

Advancement of non-intrusive optical diagnostic techniques has been a major area of research since the founding of the Research Center for Optical Physics (RCOP) at Hampton University. Many non-intrusive optical techniques have been developed and successfully applied worldwide in high-speed flow facilities and other areas of research during the past two decades. Among them, Electron Beam Fluorescence (EBF), Laser-Induced Fluorescence (LIF), Rayleigh/ Raman Scattering (RRS), Coherent Anti-Raman Scattering (CARS), Laser Doppler Velocimetry[6] (LDV), and Focusing Schlieren[7] (FS) were commonly chosen by researchers because of their wide range of applications.

Our goals for the development of several non-intrusive techniques (namely EBF, LIF, and FS) at RCOP were two-fold: first, to apply these techniques in the aerodynamic wind tunnels at NASA Langley Research Center and second, to apply them in the Advanced Propulsion Laboratory (APL) (supported by a AFOSR Grant) at Hampton University. The developed FS system is already being applied in the HFG facility at NASA LaRC to visualize low-density flow in the free-jet regime.

TECHNICAL DISCUSSION

A. Electron-Beam Fluorescence

A schematic of our EBF system is shown in Figure 1. The system mainly consists of a commercially available electron gun, a stainless steel vacuum chamber, vacuum pumping system, spectroscopic system, gas supply, and focusing optics. One or two gases can be mixed and flowed into the continuously-pumped vacuum chamber until a static pressure is reached. The electron gun, maintained at a pressure of less than 104 Torr, can then be energized between 100 eV and 10 keV. The beam of electrons (between 1 and 2 mm diameter) traverses the chamber, passes through the gas at the center of the chamber, and is collected by a faraday cup, which collects the beam current. The fluorescence emission produced is then observed through an 80 mm diameter quartz window and focused, with a 150 mm quartz lens, into the entrance slit of a 0.22 m double spectrometer. The 0.22-m double spectrometer provides dispersion (with two 1200 gr/mm holographic gratings) at the exit slit where a photomultiplier tube is mounted to amplify the signal. The spectral information can then be sent to a computer where it was displayed and analyzed
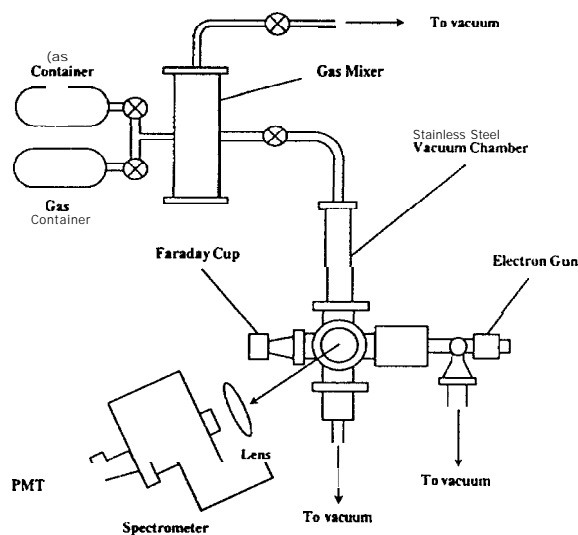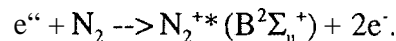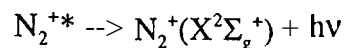

Figure 1. Diagram of the Electron Beam Fluorescence system.

The EBF system was calibrated with N_2 gas to evaluate its sensitivity and reliability for application to high-speed aerodynamic flowfields. Among many channels of electron-N_2 collisional kinetics, excited molecular nitrogen ions, N_2^{+*}, are mainly produced in the reaction

$$e^{\text{``}} + N_2 \text{ --> } N_2^{+*}(B^2\Sigma_u^+) + 2e^-.$$

This is followed by the emission of fluorescence in the First Negative band,

$$N_2^{+*} \text{ --> } N_2^+(X^2\Sigma_g^+) + h\nu$$

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with the (0,0) vibrational transition (at $\lambda = 391.44$ nm) being the most intense feature and considered to be a sensitive probe for N_2 concentration.

Figure 2 shows some of our preliminary experimental results. Figure 2a is a typical emission spectrum of N_2^+ emission in the First Negative band between 320 and 500 nm. We were also able to determine the quenching rate of N_2^+ emission (at $\lambda = 391.44$ nm) by argon in order to shed some light **on** the radiative properties of hypersonic aerospace vehicle bow-shock layers (see Figure 2b). We calculated a quenching rate, k , in the order of 10^{16} cm^{3}mol^{-1}s^{-1}. This is two orders of magnitude higher than we anticipated (k_n is typically less than 4.5 x 10''' cm^3 mol^{-1} s''' for N_2^+ + Ar). The source of our error is being investigated.
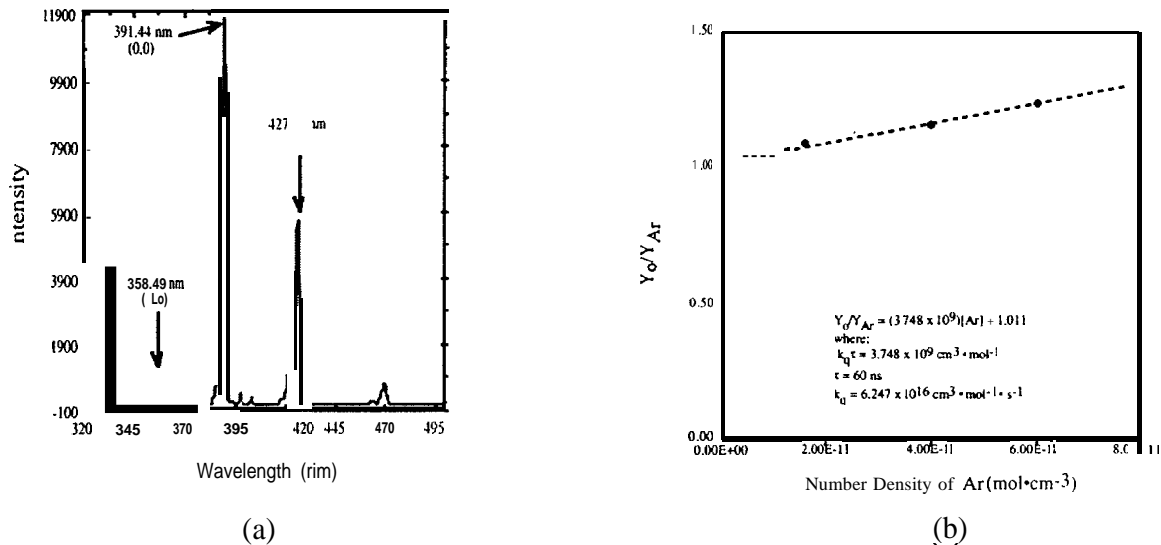
Figure 2. (a) Typical fluorescence emission spectrum of N_2^+ First Negative Band. (b) Curve of N_2^+ emission (at $\lambda = 391.44$ nm) quenching by argon.

B. Focusing Schlieren

The Focusing Schlieren technique has several advantages for flow visualization because it produces a natural, easily-interpretable image of refractive-index-gradient fields. This low-cost technique also has focusing capability, and high sensitivity. Figure 3 shows a layout of the optical components of a small-field, high-sensitivity Focusing Schlieren system. This system consists of a source grid and a cut-off grid (located on opposite sides of the flowfield), a light source, a Fresnel lens, an image lens, and an intensified CCD camera. Refraction of the collimated light beam in the flow region moves the image of the source relative to the knife edge, which results in a change in the brightness at the image of the test section.
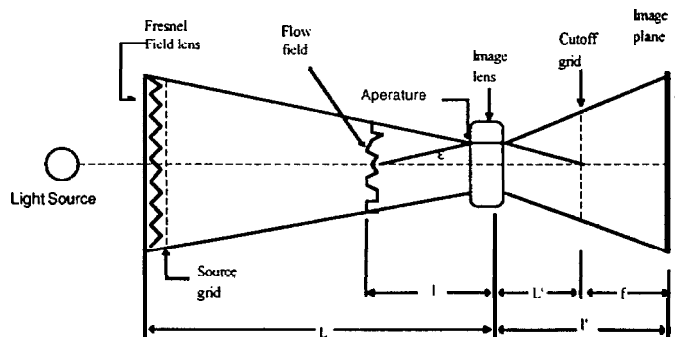
Figure 3. Layout of optical components of a small-field, high-sensitivity Focusing Schlieren system.

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A Focusing Schlieren system is characterized by its sensitivity, resolution, and depth of focus[7]. The sensitivity of the system is defined by the angle of deflection normal to the knife edge. If this angle is shown by ε', the image of the source shifts by $\Delta a = \varepsilon' L'$, where a is the light source image height above the cut-off grid, and L' is the distance from the lens to the cut-off grid. This results in a change in intensity

$$\frac{AI}{I} = \frac{\Delta a}{a} = \varepsilon'(\frac{L'}{a})$$

If we use the criterion that the smallest change in brightness that can be detected is 10%, the sensitivity of the system becomes $\varepsilon' = 0.1$ (a/L'), and this quantity is defined as

$$\varepsilon'_{min} = 20626 \, (\frac{a}{L}) \, arcsec$$

Due to the non-parallel nature of the light, the sensitivity of the Focusing Schlieren is:

$$\varepsilon'_{min} = \frac{20626aL}{L'(L-l)} \, arcsec$$

where, L is the distance from the source grid to the lens and 1 is the distance from the flowfield object to the lens.

The following parameters specify the sensitivity of our system:
L = 7.6 m, L'= 1.17 m, 1 = 4.6 m, and a = 0.038 mm. Sensitivity ε'_{min} = 1.7 arcsec.

Figure 4 shows a diagram of the small-field, high brightness, and highly-sensitive Focusing Schlieren system incorporated into the High-Speed Flow Generator (HFG) at NASA LaRC. This system is able to visualize and analyze low density high-speed flows. Of particular interest is the visualization of the boundary layers associated with a continuum free jet expansion.
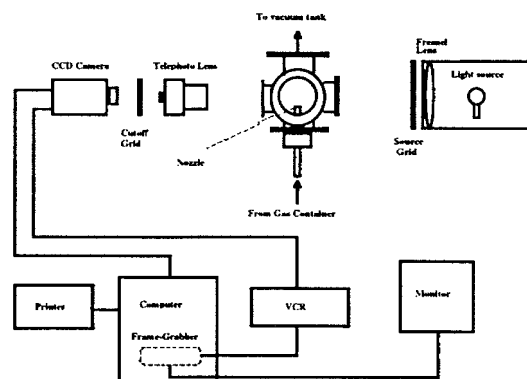

Figure 4. Diagram of the highly-sensitive Focusing Schlieren system incorporated into the High-Speed Flow Generator (HFG) at NASA LaRC.

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Figures 5a and 5b show preliminary results of the application of this system to low density

Figure 5 (a) Background-subtracted VCR picture of the HFG system with a 5.0 mm nozzle. Free-jet expansion of argon gas (at 200 psig) into a 22 micron vacuum is visualized with a highly-sensitive Focusing Schlieren system. (b) Back-ground subtracted VCR picture of the HFG system with 5.0 mm nozzle and a spherical barrier. Argon gas is flowed (at 200 psig) into a 22 micron vacuum and shock-front layers around the sphere are visualized with the Focusing Schlieren system.

C. Laser-Induced Fluorescence

Figure 6 shows the layout of LIF diagnostic of the APS, namely, the Solar Thermal-Electric Propulsion (STEP) system. A tunable dye laser (Lambda Physik, LPD 3002CES: Tuning range 332 nm - 860 nm) pumped by an excimer laser (Lambda Physik, LPX 220I CC: Computer controlled, maximum energy of 200 mJ, pulse duration of 12 ns, 60 Hz) is in place and has been tested for operation. The exhaust flow speed from the STEP is expected to reach several km per sec., providing an ideal testbed for the LIF technique. The dye laser system has produced an output of 11 mJ per pulse at 570 nm when Rhodamine 6G was used in a preliminary test run.

In order to measure the density, velocity, and temperature of the high-speed exhaust flow in the STEP system, we will use the intensity, Doppler shift, and broadening of the 728.7 nm fluorescence line of argon gas, respectively. This task is under way and the expected results will be reported later.
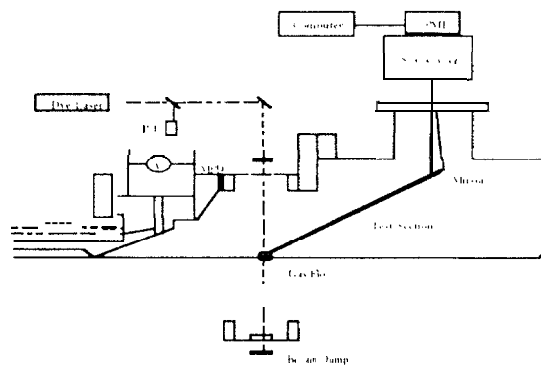

Figure 6. Layout of LIF Diagnostic of STEP system

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ACKNOWLEDGMENT

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