PLIF thermometry in shock tunnel flows using a Raman-shifted tunable excimer laser

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Received 5 June 1996 / Accepted 8 February 1998

Abstract. Planar laser-induced fluorescence is performed in a free-piston shock tunnel by using a Raman-shifted tunable excimer laser to excite nitric oxide molecules in the flow. Two different flowfields are examined to test the difficulties associated with applying the technique to shock tunnels: the bluff body flow produced by a 25 mm diameter cylinder; and the oblique shock and expansion fan produced by a 35° half-angle wedge. For the cylinder, the maximum flow enthalpy was limited to 4.1 MJ kg⁻¹ due to high flow luminosity which is produced by metallic contaminants in the flow. A reflective filter is used to reduce the influence of flow luminosity making these measurements feasible. Freestream temperature measurements are in excellent agreement with those predicted from numerical flow calculations. Large uncertainties were observed for the high-temperature post-shock results. Several higher enthalpy shots (14 MJ kg⁻¹) were also performed with the wedge and showed an insignificant amount of contaminant emission.

Key words: Planar laser-induced fluorescence (PLIF), Shock tunnel, Nitric oxide, Temperature measurements, Tunable excimer laser

1 Introduction

Free-piston shock tunnels are used to simulate conditions encountered by aerospace vehicles during atmospheric re-entry and high speed flight. These ground-based facilities offer a less expensive means of testing compared to inflight measurements. The experimental data obtained from these facilities is often used to validate computer codes used in computational fluid dynamics (CFD) (Boyce et al. 1994; Houwing et al. 1996). The validated codes then provide a means for confidently predicting inflight behaviour and aid in vehicle design and performance evaluation.

In the past, many optical techniques have been used for flow visualisation in shock tunnels and to complement surface pressure and heat transfer measurements. Schlieren, shadowgraph and interferometry have been used extensively to provide two-dimensional measurements with high temporal resolution. However, they can only provide an integrated measurement along the line-of-sight through the flow which masks any three-dimensional behaviour in the flow. Planar laser-induced fluorescence (PLIF) has been widely used for flow visualisation and as a combustion diagnostic (Seitzman and Hanson 1993; McIntyre et al. 1997). It provides high spatial and temporal resolution, two-dimensional quantitative measurements and is chemical species specific. PLIF uses a thin sheet of laser light to excite a radiative transition in a particular chemical species in the flow. The laser sheet provides a thin (<1 mm) cross section through the flowfield and therefore PLIF can resolve three-dimensional features in flows unlike the aforementioned line-of-sight techniques. The short duration of the laser pulse and resulting fluorescence gives PLIF the ability to freeze the motion of hypersonic flows which makes it particularly applicable to shock tunnels.

For supersonic flows, PLIF has been used to measure rotational temperatures (Palmer et al. 1992; McMillin et al. 1993; Palmer and Hanson 1995), vibrational temperatures (McMillin et al. 1992; Palmer and Hanson 1993), velocity (Paul et al. 1989), pressure (Lemoine et al. 1995) and mole fraction (Abbitt et al. 1991).

Tunable excimer lasers have been used for combustion diagnostics and flow visualisation (Andresen et al. 1990; Ketterle et al. 1992). However, due to their limited tuning ranges (typically 1 nm) they have not been as widely employed as frequency-doubled dye laser systems. By Raman-shifting the output of a tunable excimer laser it is possible to substantially increase the flexibility and tunability of the laser system (Dreier et al. 1992). In particular, by Raman-shifting the 248 nm output of a tunable KrF excimer laser in H₂, we can produce tunable narrowband radiation between 224.8 and 225.7 nm.
coincides with the $A^2\Sigma^+ \leftarrow X^2\Pi(0,0)$ absorption band of nitric oxide (NO). NO is a species of particular interest since it is present in heated-air flows and is a pollutant species from combustion flows.

The main aim of the work presented here is to determine whether PLIF can be applied quantitatively to free-piston shock tunnels and to ascertain the important parameters that need to be considered. We also examine the effectiveness of using a Raman-shifted tunable excimer laser.

2 PLIF measurement theory

In a typical PLIF experiment, a laser is tuned to an optically-allowed electronic resonance of a particular molecular species. The molecules in a particular rotational-vibrational level $v',J'$ of the lower electronic state (typically the ground state) are excited to a rotational-vibrational level $v'',J''$ in an excited electronic state. Molecules in the excited level $v'',J''$ can then emit radiation (fluorescence) which is collected by a detector (typically a two-dimensional CCD camera). Molecules may also undergo collisions with other molecules or atoms which cause a transfer of population out of the laser coupled state $v'',J''$ to nearby rotational levels. This is known as rotational-energy transfer (RET). These collisionally-excited nearby rotational levels also fluoresce resulting in a broadband fluorescence signal. Similarly, there may also be vibrational-energy transfer (VET) from the excited vibrational level. Other collisions may cause some of the molecules in the excited state to be de-excited non-radiatively (collisional quenching) which produces a corresponding decrease in the total amount of fluorescence signal.

If a CCD camera is used to record the fluorescence, then the fluorescence signal (photons s$^{-1}$) collected by a single pixel is given by

$$S_l = (N_{\text{abs}} f_T V) (B I g) \phi \eta,$$

where $N_{\text{abs}}$ is the number density (cm$^{-3}$) of absorbing species; $f_T$ is the fractional population of the lower rotational level, which for local thermodynamic equilibrium is a function of the temperature $T$ (K); $V$ is the volume (cm$^3$) imaged onto a single pixel; $B$ is the Einstein stimulated absorption coefficient (cm$^2$ J$^{-1}$ cm$^{-1}$); $I$ is the laser pulse intensity (W cm$^{-2}$); $g$ is the overlap integral (1/cm$^{-1}$) between the laser spectral profile $g_L$ and the absorption line profile $g_a$; $\eta$ is the optical collection efficiency of the imaging system; $\phi$ is the fluorescence yield and is given by

$$\phi = \left[A_{\text{eff}} (A_{\text{total}} + Q]\right],$$

where $A_{\text{eff}}$ is the effective spontaneous emission rate (s$^{-1}$) for the collected fluorescence, $A_{\text{total}}$ is the sum of spontaneous emission rates (s$^{-1}$) for all possible radiative transitions from the excited level, and $Q$ is the collisional quenching rate (s$^{-1}$). $A_{\text{eff}}$ represents the way that $A_{\text{total}}$ is modified by spectrally selective elements in the detection chain (ie. filters, camera quantum efficiency). Therefore the effective emission rate is given by (Allen et al. 1993)

$$A_{\text{eff}} = \sum_{\nu'} T_{\lambda_{\nu'}} A_{\nu'\nu'},$$

where $T_{\lambda_{\nu'}}$ is the spectral transmission function for the detection system and the summation is over all vibrational bands of the lower electronic state.

The overlap integral $g$ is given by (Gross et al. 1987)

$$g = \int_0^{+\infty} g_L(\nu, \nu_L, \Delta \nu_L) g_a(\nu, \nu_a, \Delta \nu_a) d\nu,$$

where $\nu_L$ is the laser frequency, $\nu_a$ is the absorption line frequency, $\Delta \nu_L$ is the absorption linewidth and $\Delta \nu_a$ is the laser linewidth. The integrals of $g_L$ and $g_a$ over all frequencies are normalized to 1.

When there is local thermodynamic equilibrium between the rotational levels, the fractional population $f_T$ is related to the temperature $T$ by

$$f_T \propto (2J'' + 1) \exp[-\varepsilon/kT],$$

where $\varepsilon$ is the energy of the lower rotational level, $J''$ is its rotational quantum number and $k$ is Boltzmann’s constant. Local thermodynamic equilibrium is a valid assumption for the shock tunnel flows examined here since collisional processes are more dominant than radiative.

The first term in parentheses in Eq. (1) represents the number of molecules which are in the lower rotational level of the absorption transition. The product $B I g$ is the laser-stimulated absorption rate (s$^{-1}$), and so the first two terms combined gives the number of absorption transitions per second. The final term, $\phi \eta$, represents the fraction of those molecules that absorbed a laser photon that lead to a fluorescence photon being emitted and detected. Equation (1) assumes that the exciting laser pulse is weak and that there is no radiation trapping (absorption of fluorescence photons as they leave the test environment).

2.1 NO thermometry

The scheme employed for the current work involves excitation of NO through the $A^2\Sigma^+ \leftarrow X^2\Pi(0,0)$ band near 225 nm. Fluorescence is then collected from several vibrational bands at higher wavelengths, away from the excitation wavelength (see Fig. 1). Detection at the excitation wavelength is avoided to prevent contributions to the signal from laser scatter. Furthermore, fluorescence transitions ending in the least-populated vibrational bands ($v'' \geq 1$) are preferred to reduce the influence of radiative trapping. When broadband fluorescence detection is employed, fluorescence is collected from all the rotational levels populated by collisions and not just the laser-coupled level (Seitzman and Hanson 1993). This has two advantages. Firstly, collecting all the fluorescence gives higher signal strengths. Secondly, most modern lasers have a high degree of polarisation which can make the fluorescence