Nitric Oxide Molecular Tagging Velocimetry of a Free-Flight Model in a Shock Tunnel

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Abstract

Nitric Oxide Molecular Tagging Velocimetry (NO-MTV) is used to characterize the flow around a free-flight spherical model in a free-piston reflected shock tunnel. A novel pulse-burst laser and timing arrangement enables time-resolved measurements at 20 kHz for 3 ms, which captures the steady state flow and tunnel start/stop transients. A 3 km/s and 5 km/s condition will be explored to evaluate changes in wake structure as a function of freestream velocity.

1 Introduction

Velocimetry measurements in hypersonic, hypervelocity impulse facilities are important for facility characterization, physical discovery, and simulation validation. The high-speed and low-density flow in these facilities preclude use of particle-velocity methods due to particle lag/slip effects. Instead, molecular tracer methods are used. Additionally, methods which do not seed additional tracer molecules into the flow are preferred to prevent alteration of thermochemistry. In reflected shock tunnels, nitric oxide (NO) naturally forms in the stagnation chamber and in local regions of the flow due to shock heating, and persists via chemical freezing throughout the flow. This makes NO an ideal in-situ molecule to probe for diagnostic purposes.

Laser-induced fluorescence (LIF) of NO has been exploited for velocimetry via Doppler-shift and molecular-tagging velocimetry (MTV) techniques. Examples of the former are the works of Hiller and Hanson (1988), Paul et al. (1989), Danehy et al. (2001), Hruschka et al. (2010), and Le Page et al. (2020). These require intensity calibrations for laser sheet intensity variation, saturation, and background emission suppression. Further, these methods require a flow to be steady and repeatable so images from different runs can be analyzed together, a challenge for impulse facilites. A recent implementation by Rodrigues et al. (2023) used a pulse-burst laser at 100 kHz to reduce the repeatability requirements, but still requires intensity corrections.

MTV does not require intensity corrections nor compilation of results from multiple independent shots. Example implementations include Danehy et al. (2003), Bathel et al. (2011), Inman et al. (2013), and de Souza Matos et al. (2020). In each, a low-repetition-rate Nd:YAG-pumped laser was used together with various single-delay and multi-delay imaging schemes. These methods are capable of making a single velocity measurement in a shot of an impulse facility, but are unable to capture transient flow effects.

This work applies a pulse-burst laser with an optical parametric oscillator (OPO) and high-speed imaging to perform NO MTV throughout the run duration of an impulse facility. This allows the steady-state period to be ascertained for correct comparisons to numerical simulation. An example measurement is shown of flow around a free-flight sphere model. In section 2 the flow facility, model, and optical configuration is explained. In section 3 fluorescence delay, freestream and wake velocity measurements are shown.

2 Approach

2.1 Flow Facility and Model

Measurements were performed in the Sandia Hypersonic Shock Tunnel (HST), a free-piston facility capable of producing hypersonic environments at speeds from 3-5 km/s. Further details regarding the facility and condition design can be found in [Lynch et al.](2022).

The model used in this test was a 50.8-mm diameter 440C stainless-steel sphere. The sphere was held above the nozzle exit prior to the test using an electromagnet (McMaster 5698K116). The free-piston launch mechanism of the shock tunnel was highly repeatable, with delay from valve actuation approximately 280 ms +/- 5 ms. The delay from electromagnet actuation to the sphere dropping to the center of the test section was 380 ms +/- 1 ms. Thus the sphere was released prior to firing the shock tunnel, reaching approximately the centerline of the nozzle with an accuracy of approximately +/- 5 mm as the flow began. During the approximately 1 ms of flow time, the sphere continued to drop 1 mm. Under the nozzle, a catch bin was placed to keep the sphere from hitting the optical window. This bin had a slit allowing passage of the laser lines, and a slope to roll the sphere out of the field of view after the run for reference imaging after the shot.

2.2 Optical Arrangement

The optical setup is schematically shown in figure 1. The 355-nm output of a pulse-burst Nd:YAG laser (Spectral Energies Quasi-Modo) operated at 100-kHz pulse repetition rate pumps an OPO to generate 800-1100 µJ/pulse at 622 nm. The OPO consists of a 12-mm long type-I β-barium-borate (BBO) crystal cut at 32.8 deg and is pumped with 85 mJ/pulse of the 355 nm third-harmonic. The pump beam has a diameter of 6 mm and 8 ns duration pulses. The 622-nm OPO output and the residual 355-nm pump beam pass through a custom waveplate that aligns the polarizations for sum-frequency mixing in a second type-I BBO crystal cut at 59.1 deg. The output is tuned to 226.05 nm with a bandwidth of 15 cm⁻¹ to excite multiple rotational levels near the (0,0) bandhead of the NO \(A^2Σ - X^2Π\) system. A telescope expands the beam, then it was split by an uncoated UV-grade fused silica wedged plate into multiple beams. The plate consisted of seven wedges, each 5 mm wide, with wedge angles from -3 to 3 degrees with steps of 1 degree. A 500 mm singlet lens focuses the beams to a waist region near the facility spanwise centerline, resulting in a linear region of LIF emission that is captured using a UV-sensitive image intensifier (LaVision HS-IRO S20) coupled to a high-speed Phantom TMX 7510 monochrome camera.

Figure 1: Schematic of NO MTV diagnostic. HWP/FWP: Half/Full-wave plate; PBS: Polarizing beamsplitter; OPO: Optical parametric oscillator; BBO: Beta-Barium Borate; HR: High-reflector.
2.3 Timing Schemes

The 100 pulses generated by the pulse burst laser allowed exploration of various timing schemes, schematically depicted in figure 2. In this figure, the laser pulse train and intensifier gates are shown. The corresponding camera exposure is not shown since the effective exposure is set by the intensifier. The camera exposure is set to encompass the entirety of the intensifier gate time. The after-run reference with a single delay used a constant delay $\Delta t_1$. A reference zero-delay image sequence was taken after the run using residual NO remaining in the test section. This scheme provided the highest measurement rate with a velocity measurement for each pulse, and was easy to optimize the imaging configuration using a single intensifier gain. However, it is susceptible to bias error due to beamsteering or any movement or vibration of the optical arrangement between the test and reference captures. This scheme is a high-speed extension of the single-imaging method used by Danehy et al. (2003).

An alternative to eliminate beamsteering or motion is an in-situ reference captured during the run using a two-delay scheme. This alternates between a reference delay $\Delta t_1$ and the displaced delay $\Delta t_2$. Note, due to the limited intensifier speed of 200 kHz, it is not possible to image the same pulse using two intensifier gates. Instead, the intensifier gate alternates between pulses. The disadvantages of this scheme are that it halves the measurement rate and that the reference image at $\Delta t_1$ is much brighter than the delayed image at $\Delta t_2$ for a fixed intensifier gain and gate. This can be compensated by introducing a short negative delay for $\Delta t_1$ to reduce the overlap between the intensifier gate and the pulse. Thus, the two images can be tuned to comparable intensities to optimize the intensifier gain setting. This scheme is a high-speed extension of the sequential-imaging method used by Bathel et al. (2011).

A third method was attempted using multiple delays for each velocity measurement, which is enabled by the multiple pulses available within a burst. Conceivably, this scheme allows for variable dynamic range where the delay could be selected in postprocessing based on image intensity, or multiple delays could be combined to reduce the random error associated with the measurement. Additionally, the scheme allows in-situ characterization of the decay rate by fitting an exponential.

![Figure 2: Schematic of the three different delay timing schemes explored. Note, the time axis is not to scale. Laser pulses denoted in purple, intensifier gates shown in blue.](image-url)
2.4 Image Analysis

The zero-delay positions of the lines were determined by first averaging the after-run reference images or the in-situ reference images with a $\Delta t_1$ shift. A three-point Gaussian fit about the maximum intensity provided the sub-pixel position estimate. To further reduce random error from the zero-delay data, a second-order polynomial fit was applied to each line.

For the delayed images, an average of images acquired at $\Delta t_n$ was used to determine an initial guess for the line position. Then, the line position for each image was determined. Both analyses applied the same three-point Gaussian fit as above. The displacement was determined by subtracting the instantaneous fit position from the zero-delay polynomial fit position. The image scale of approximately 4.043 px/mm was determined using a calibration target (Edmund Optics DA020) aligned with the laser. For the after-run reference and in-situ reference cases, velocity was determined by spatial scaling with the above factor and the specified $\Delta t$. For the multi-delay scheme, a first-order least-squares polynomial fit to the displacements and spatial scaling yielded velocity.

Motion of the beam waist is tracked by repetitively sequencing the delay between the laser pulses and the intensifier gate from 0 to 200 ns in 50 ns increments. Therefore, a single velocity measurement is made for each cycle of 5 pulses yielding an effective repetition rate of 20 kHz. The total burst contains 300 pulses, yielding 60 velocity measurements over the 3 ms burst duration. The images for each cycle are processed using a Gaussian fitting routine to estimate the line center position, and a linear regression is fit to the positions.

3 Results

3.1 Fluorescence Decay Time

The multi-delay scheme allowed determination of the fluorescence lifetime, which aids in delay selection. In figure 3, example images in the hypersonic wake are shown at each delay time. The integrated intensity of each line is plotted and fit using an exponential to determine the decay time for each line. The $1/e$ fluorescence lifetime is $\approx 130$ ns throughout the wake, which is sufficiently long to track the motion of the emitting NO molecules. This lifetime is shorter than the $\approx 220$ ns reported by McDermid and Laudenslager (1982), due to the increased pressure of the current environment. Calculations performed using LIFBASE Luque and Crosley (1999) using the current conditions yielded a 120 ns lifetime, matching well to the measured values.

3.2 Freestream Velocity

The freestream velocity was measured for three different tunnel conditions using the various timing schemes. Due to saturation of the first image in the two delay, in-situ reference, runs attempting that scheme were instead processed using after-run references. This extends the earlier facility characterization work of Lynch et al. (2022) by adding multiple conditions. These freestream measurements provide a useful inflow boundary condition and uncertainty for companion simulations.

In figure 4, left, time traces of velocity for each of the runs is shown. Different symbols indicate the acquisition scheme used, and the multiple lines provide the experimental variability based on 95% confidence interval. To the right, histograms for each of the runs are shown to provide mean and standard deviation of the freestream velocity for each condition.

Apparent in the collected data is substantial run-to-run variability for data acquired using the after-run reference scheme. The variability is great enough that it is difficult to distinguish run conditions. In comparison, data acquired using the multi-delay scheme was repeatable for shots acquired at the same conditions. This indicates that the after-run reference method likely contains significant bias error due to camera motion between the run and after-run images are acquired. Unfortunately, due to saturation issues, we were unable to definitively show the removal of this bias using the two-delay in-situ scheme.

Despite the scatter in the data, trends in the time variability are consistent between runs. In 4, right, the freestream velocities are normalized by their mean values from 1.4 to 1.6 ms after trigger. For all conditions, a velocity dip is observed at the beginning of the run, which recovers and maintains relatively constant velocities from at least 1.2 ms to the end of the measurement, indicating useful test times greater than 600 $\mu$s. Similar dips during startup have been recently observed using a high-speed laser absorption technique in the T5 shock tunnel Finch et al. (2023).
For the low-enthalpy condition, measurements appear repeatable around 3 km/s, with exception run 451. The medium enthalpy condition generates approximately 4.1 km/s as measured using a multi-delay scheme, and considerably higher, between 4.5 to 5 km/s when the single-delay, after-run reference is used. Finally, the 5 km/s shot shows the widest variability, with the single-delay method returning velocities from 3.7 to 5.3 km/s. Higher velocities generated in the facility correspond to a harsher vibration environment, consistent with the scatter seen for the single-delay, after-run reference measurements.
3.3 Free-Flight Wake

The free-flight wake was measured also using the different timing schemes and for different tunnel conditions. Due to the previously mentioned bias error introduced for after-run referencing, results in this section will be shown normalized. In figure 5, left, four lines in the wake are shown for four different runs. The triggering and resulting position jitter of the sphere are low enough that the wake is captured for each shot. At present, the dynamic range of the measurement is sufficient to measure reverse velocity, but not to identify relevant differences between the 4 and 5 km/s cases. In figure 5, right, the time histories of each line and each run are shown as heatmaps. These illustrate the wake rapidly establishes, and is stable in wake size and velocity magnitude across the entire test duration. The wake at the furthest downstream position also appears axisymmetric and steady. This is consistent with these measurement locations lying within the recirculation region of the laminar, viscous near wake [Lees (1964)].

Figure 5: Free-flight wake characterization results. Left plot, average normalized velocity for four runs at 4 and 5 km/s. Dashed lines indicate initial line positions. Right plots, 2-D array of normalized velocity contours of the selected runs for lines (columns) and runs (rows). Dashed lines indicate centerline.

Conclusions

This article demonstrated NO MTV measurements around a free-flight model in a shock tunnel. A novel pulse-burst laser coupled to an optical parametric oscillator generated a high-speed train of pulses to excite NO fluorescence. This was combined with various timing schemes to capture time-resolved measurements across the impulse test duration. It was found that an in-situ reference scheme was required in order to be robust to facility vibration, while preserving dynamic range and measurement speed. Measurements were able to characterize the temporal variation of the freestream velocity, showing a characteristic velocity dip during startup across conditions. The free-flight measurements allowed the transverse extent of the wake to be measured as a function of downstream distance, and the steadiness of the wake within the test time to be verified.
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