

Molecular Tagging Using Vibrationally Excited Nitric Oxide in an Underexpanded Jet Flowfield

Andrea G. Hsu,* Ravi Srinivasan,† Rodney D. W. Bowersox,‡ and Simon W. North§
Texas A&M University, College Station, Texas 77843

DOI: 10.2514/1.39998

We report a laser diagnostic technique which relies on planar laser-induced fluorescence of vibrationally excited nitric oxide ($\text{NO}_{v=1}$) molecules produced from the 355 nm photodissociation of seeded NO_2 for molecular tagging velocimetry applications. The technique was applied toward an axisymmetric highly underexpanded jet flowfield to yield single-component (streamwise) velocity maps. Detection of the photodissociated $\text{NO}_{v=1}$ molecules would be valuable in flow environments where molecular tagging velocimetry would be highly desirable, but where there are also significant background concentrations of NO. The technique would also be valuable in high-quenching and/or low-velocity flow conditions due to the long-lived nature of the photodissociated NO molecules. Single-shot streamwise velocity uncertainties were about 5% and could be lowered by increasing signal to noise. In addition, the vibrational relaxation of NO was explored in support of a U.S. Air Force Office of Scientific Research Multidisciplinary University Research Initiative project and it was found that the vibrational decay of NO was heavily dependent on collisional vibrational relaxation with oxygen atom formed through NO_2 photodissociation.

Nomenclature

| | | |
|---------------------------|---|--|
| C_{12} | = | experimentally determined calibration constant |
| D_e | = | nozzle diameter |
| D_m | = | Mach disk diameter |
| k | = | Boltzmann constant |
| P_a | = | ambient pressure |
| P_e | = | exit pressure |
| P_o | = | stagnation pressure |
| S_f | = | fluorescence signal intensity |
| T_o | = | stagnation temperature |
| T_{vib} | = | vibrational temperature |
| w | = | primary wavelength |
| X_m | = | distance from nozzle to Mach disk |
| $\Delta E_{21\text{vib}}$ | = | energy difference between vibrational states |

I. Introduction

VELOCITY is a very important parameter in the characterization of aerodynamic flowfields. There are two approaches used to measure velocity: probe-based (intrusive) and laser-based (non-intrusive) techniques. Two widely used nonintrusive techniques relevant to this study are particle image velocimetry (PIV) and molecular tagging velocimetry (MTV). PIV and MTV are planar techniques and can therefore provide instantaneous two-component velocity maps. Both MTV and PIV require a pair of images: an initial image and a time-delayed image. The velocity is calculated by dividing the spatial displacement by the known temporal separation between the two images. PIV diagnostics require the use of seeded particles, and although these particles are small ($<1 \mu\text{m}$), they often cannot follow the flow as precisely as molecules, particularly in the region of strong shocks, as shown in [1]. In addition, the seeding of particles is undesirable in some facilities, where the particles may

clog the facility, coat optical windows, or cause damage by impinging on surfaces. MTV relies on the tagging of molecules by a “write” laser pulse, which are subsequently probed at a known time delay by a “read” laser pulse. MTV encompasses a wide range of techniques that can be applied in both gaseous and liquid flowfields and includes both line and gridded variants. Line MTV provides a single component of velocity by observing the spatial displacement of the line, whereas gridded techniques provide two components of velocity in the laser plane by observing the warping of the grid, that is, the spatial displacement of the grid intersection points. Several examples of gaseous MTV techniques are ozone tagging velocimetry (OTV), hydroxyl tagging velocimetry (HTV), Raman excitation plus laser-induced electronic fluorescence (RELIEF), nitric oxide (NO) tagging velocimetry, and NO_2 photodissociation. OTV involves the photolytic formation of ozone, which is then photodissociated to form vibrationally hot O_2 and simultaneously probed via Schumann–Runge fluorescence, as in [2]. HTV involves the photodissociation of water and followed by detection of OH by laser-induced fluorescence (LIF) [3–5]. RELIEF involves LIF probing of tagged vibrationally excited O_2 molecules, as in [6]. NO tagging velocimetry is conducted using naturally occurring NO, as in [7], by photodissociation of air [8,9], or by photodissociation of NO_2 [10,11]. In all three cases, reported studies have been limited to probing of the ground vibrational state of NO ($\text{NO}_{v=0}$) at 226 nm.

Studies in [7] have used NO tagging velocimetry where a write laser beam is used to electronically excite a line of naturally occurring NO in a hypersonic shock tube flowfield. The tagged NO decays with its fluorescence lifetime. Shortly after excitation, the tagged NO is read by imaging its fluorescence onto a short-exposure intensified charge-coupled device (ICCD) camera. A second image is obtained at a later time when the flow has experienced some spatial displacement. Based on the spatial displacement of the NO molecules, the streamwise velocity can be extracted from the data. This single laser experiment relies on conditions where the flow velocities must be sufficiently large so that the tagged NO undergoes reasonable spatial displacement within its fluorescence lifetime. In environments characterized by either low velocities or high fluorescence quenching, the time delays required for adequate spatial displacement exceed the fluorescence lifetime, decreasing signal to noise in the second image obtained and limiting the application of the technique. An alternative is the use of NO_2 photodissociation [10,11]. Instead of probing NO, which is dispersed throughout the flow, the photodissociation of NO_2 writes a column of spatially localized NO (and O atom) where the NO itself serves as the “tagged” molecules. The NO is then read at two subsequent times by two separate laser pulses via

Presented as Paper 1447 at the 47th AIAA Aerospace Sciences Meeting, including The New Horizons Forum and Aerospace Exposition, Orlando, FL, 5–8 January 2009; received 23 July 2008; revision received 10 July 2009; accepted for publication 18 July 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 0001-1452/09 and \$10.00 in correspondence with the CCC.

*Chemistry Department. Member AIAA.

†Aerospace Engineering Department. Member AIAA.

‡Aerospace Engineering Department. Associate Fellow AIAA.

§Chemistry Department.