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1D Temperature Measurement of a Supersonic Air Jet with N_2 Resonantly Ionized Photoemission Thermometry

Aleksander Clark[1], Walker McCord[2], Kyle Pride[3], and Zhili Zhang[4]
Dept. of Mechanical, Aerospace, and Biomedical Engineering, University of Tennessee, Knoxville, TN 37996, USA

Capturing and understanding of the thermal effects present in supersonic flows is essential for further characterization of the flow interactions within them. A critical component of understanding is to be able to quantify the thermal gradients observed. Characterization of the temperature changes in supersonic flow has recently been demonstrated using a novel, non-intrusive technique. Resonantly ionized photoemission thermometry (RIPT) captures signals that can be directly imaged, and their intensity relationship to temperature. N_2 RIPT uses calibration studies of the temperature dependence on resonant excitation. This process liberates electrons from the N_2 molecules present resulting in the deexcitation emissions of ionized nitrogen. Demonstrated is the work associated with imaging the photoemission produced and assigning gas temperatures based on the calibration data along a 1D fluorescent line. The N_2 RIPT measurements are validated via previously established O_2 RIPT jet measurements. Capitalizing on the resonance-enhanced multi-photon ionization (REMPI) scheme of the nitrogen already present in the air, no tracers are needed for application. Also, because of the direct signal imaging of the photoemissions produced, RIPT requires less equipment and is much simpler to stage and align compared to other known techniques.

I. Nomenclature

$h\nu_{REMPI}$	=	absorbed photon by REMPI
e^-	=	free electron
$\hbar\nu_{1^-}$	=	first negative system emission
$\hbar\nu_{1^+}$	=	first positive system emission
k_B	=	Boltzmann constant
T	=	temperature
λ_n	=	excitation wavelength for nitrogen
I_{λ_n}	=	fluorescent intensity of emission
$S(J', J")$	=	averaged multi-photon transitional line strength
E_{g_n}	=	ground state energy

[1] Graduate Student, Dept. of Mechanical, Aerospace and Biomedical Engineering, University of Tennessee, AIAA Student member.
[2] Graduate Student, Dept. of Mechanical, Aerospace and Biomedical Engineering, University of Tennessee, AIAA Student member.
[3] Undergraduate Research Assistant, Dept. of Mechanical, Aerospace and Biomedical Engineering, University of Tennessee.
[4] Professor, Dept. of Mechanical, Aerospace, and Biomedical Engineering, University of Tennessee, AIAA Associate Fellow.

II. Introduction

Temperature measurements in high-speed flows have become increasingly important as diagnostic techniques are evolving. Understanding the shock-shock interactions and temperature changes within supersonic flow can help better guide developing techniques and computational simulations. Near non-intrusive diagnostic techniques are best suited for this as they introduce the least number of perturbations into the flow. Laser diagnostics is a popular approach for observing and characterizing such flows. Some temperature measurement techniques already developed provide accurate temperature measurements, such as picosecond coherent anti-Stokes Raman scattering (CARS) [1,2] but are only capable of point measurements and are extremely difficult to align. Other techniques such as toluene planar laser induced fluorescence (PLIF) [3] can capture two-dimensional temperature gradients but require a tracer or seeding agent to be fluoresced.

Capitalizing on the effects of energy deposition into flows with a pulsed nanosecond laser, N_2 RIPT can be used to measure temperature in a flow along a 1D fluorescent line. By resonantly ionizing nitrogen molecules and observing the photo-emissive intensity, a temperature can be calculated with an error of less than 5% for flows not exceeding 600 Kelvin. This robust technique uses resonance calibrations for the targeted molecule at various temperatures, thus a tracer is not needed for fluorescence. The selected calibration temperature uses just a few resonance lines plotted as a Boltzmann distribution to determine with relative accuracy the temperature profile across the fluorescent line.

An application of N_2 RIPT is used to measure the temperature of an under-expanded supersonic flow structure from a Mach 1 nozzle. The applications performed in this text show the capability of resonance with the nitrogen present in flows as to describe the temperature at different points along a line. To show variation of this technique, two different flow orientations are used, both with the same flow conditions for comparison. A supersonic flow perpendicular to the beam path is used for crossflow temperature measurements and several points along the flow path. An axisymmetric measurement is taken as the supersonic flow path is anti-parallel to the beam path for counterflow temperature measurements.

Crossflow orientation shows temperature variations at different locations along the flow path to gather data across the entire flow structure at that point. Because the RIPT measurement is a one-dimensional line, the shock interactions within the flow structure can be captured like looking at a cross section of the temperature profile across the flow region. The different locations are selected to show varying flow characteristics present in an under-expanded supersonic jet.

Counterflow orientation relies on a single measurement at the axisymmetric center of the supersonic flow. The 1D RIPT line written in the flow captures the temperature characteristics of the shock interactions directly in the center of the flow. This measurement shows the temperature variations in the direction of the flow at more flow path points than that of crossflow.

III. Theoretical Background and Results

Resonance-enhanced multiphoton ionization (REMPI) [4,5] is implemented in an N_2 (3+1) scheme to ionize the targeted flow. The nitrogen is excited to an intermediate state with three photons where collisional influence occurs from atmospheric pressure, and two additional photons are absorbed to ionize. The previous publication [6] outlines in detail the fundamental process of the RIPT technique for O_2. For coherency of this paper, some of the mechanisms in the technique will be discussed for the application of N_2.

The targeted transition is $N_2(X^1\Sigma_g^+, v=0 \rightarrow b^1\Pi_u, v=6)$ absorption band. The recombination of the electrons and nitrogen molecules results in observable fluorescent emissions. The emissions resulting are in the first negative band of $N_2^+(B^2\Sigma_u^+ - X^2\Sigma_g^+)$, specifically 390nm ($\Delta v_0; 1 \rightarrow 0$) and 430nm ($\Delta v_1; 1 \rightarrow 1$) transitions. The absorptive wavelengths were chosen from previous experiments to have the best emissions dependent on temperature.

The N_2(3+1) REMPI scheme ultimately become a N_2(3+2) scheme resulting from collisional effects at atmospheric pressures. There is an absorption of three photons into nitrogen molecule, a loss of one photon from collisional effects, then an absorption of an additional two photons to ionize the nitrogen molecule. The results in a total of five absorbed photons to ionize. The N_2 RIPT (3+2) REMPI scheme has a two-step mechanism in the ionization of N_2 as follows:

1. Photon absorption leads to electron liberation: $N_2 + 5h\nu_{REMPI} \rightarrow N_2^+ + e^-$
2. Deexcitation results in first negative or first positive emission: $N_2^+(B) \rightarrow N_2^+(X) + \hbar\nu_{1^-}$
   or $N_2^+ + e^- \rightarrow N_2(B) \rightarrow N_2(X) + \hbar\nu_{1^+}$

The targeted emission is from the first negative system due to its short lifetime and high population probability. Because compressibility factors only suggest a certain range of temperatures that the jet can be in, the two calibration temperatures chosen for this experiment were 230K and 293K. The temperature can be determined from images taken by converting the intensity to a signal and creating a linear fit among the wavelengths associated with the temperature calibration. The resulting slope is the inverse negative proportional to the signal and energy states, shown in Eq. (1).

$$-\frac{1}{k_B T} \propto \log\left(\frac{I_{\lambda_n}}{S(J', J")}\right)/E_{g_n} \tag{1}$$

Table 1 shows the selected excitation wavelengths as well as their energies to be applied to the Boltzmann distribution. The error associated with the 230K calibration temperature can be attributed to a poor SNR at low temperatures in atmospheric conditions. Applications within low pressure, thus low number density regions, are expected to have an improved SNR. For example, the experiment described in this text, or in a wind tunnel.

Table 1: N_2 Resonance Wavelengths and Calculated Temperatures.

N_2 Excitation Wavelengths (nm)				Act. Temp (K)	Meas. Temp (K)	% Error
284.71	284.73	284.75	284.80	230	242	5.22
284.71	284.88	284.94	285.03	293	292	0.34

IV. Experimental Setup

A Mach 1 supersonic nozzle was used in the experimental setup for 1D measurements of temperature in the flow. The nozzle was supplied with dry breathable air as the working fluid. A high flow regulator was set for a running pressure of approximately 45 psi gauge to achieve under-expanded flow conditions. The nozzle and conditions described were used in both crossflow and counter flow experiments. In the crossflow configuration, the nozzle jet was perpendicular to the incoming laser beam, and different locations were probed for temperature measurement. For the counter flow configuration, the nozzle jet was anti-parallel to the incoming laser beam and with a single position, the flow structure could be observed.

A. Resonance wavelength beam generation

A Continuum nanosecond Nd:YAG laser was used to pump into a Continuum ND6000 tunable dye laser module to easily adjust the target wavelength. A combination of rhodamine 590/6G and rhodamine 610 was used to red shift the 532nm pump laser to a tunable range centered at 570nm±1nm. The output beam then entered a Continuum UVT frequency doubler to achieve the resonant wavelengths necessary to tag the flow, as described in the introduction. The Nd:YAG laser assembly used for these experiments is shown in Fig. 1.

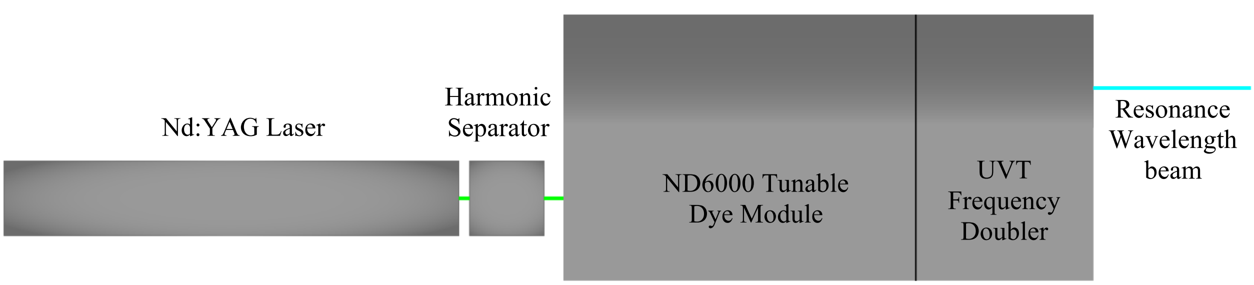

Fig. 1: A representation of the 532nm Nd:YAG pump laser, including the harmonic separator, the ND6000 tunable dye module, and the UVT frequency doubler. Beam output is the tuned resonance wavelength for performing N_2 RIPT.

B. Supersonic jet configurations

A gated intensified charge-coupled device (ICCD) camera captured the tagged flow the moment it is fluoresced by the focused laser. To achieve this, the camera and laser were synchronized with a delay generator. A bandpass filter was used in front of the camera lens to block any laser scattering that may be present in the view area. The intensified camera was set to capture 20 successive images for each of the resonance lines in all positions for cross flow and counter flow. The number of images captured was to improve the signal to noise ratio (SNR). A 200mm focal length lens was placed in the beam path and positioned to target both configurations' jet streams.

The crossflow configuration focused resonating line through the flow perpendicular to to the beam path. The camera viewed the 1D line as it fluoresced normal to the plane the jet and beam created. Counterflow focused the resonant line axisymmetric in the anti-parallel direction to the flow. The camera was positioned in the same regard as in the crossflow configuration. Figure 2 gives a simple illustration of the jet and beam path orientation as from the camera's perspective.

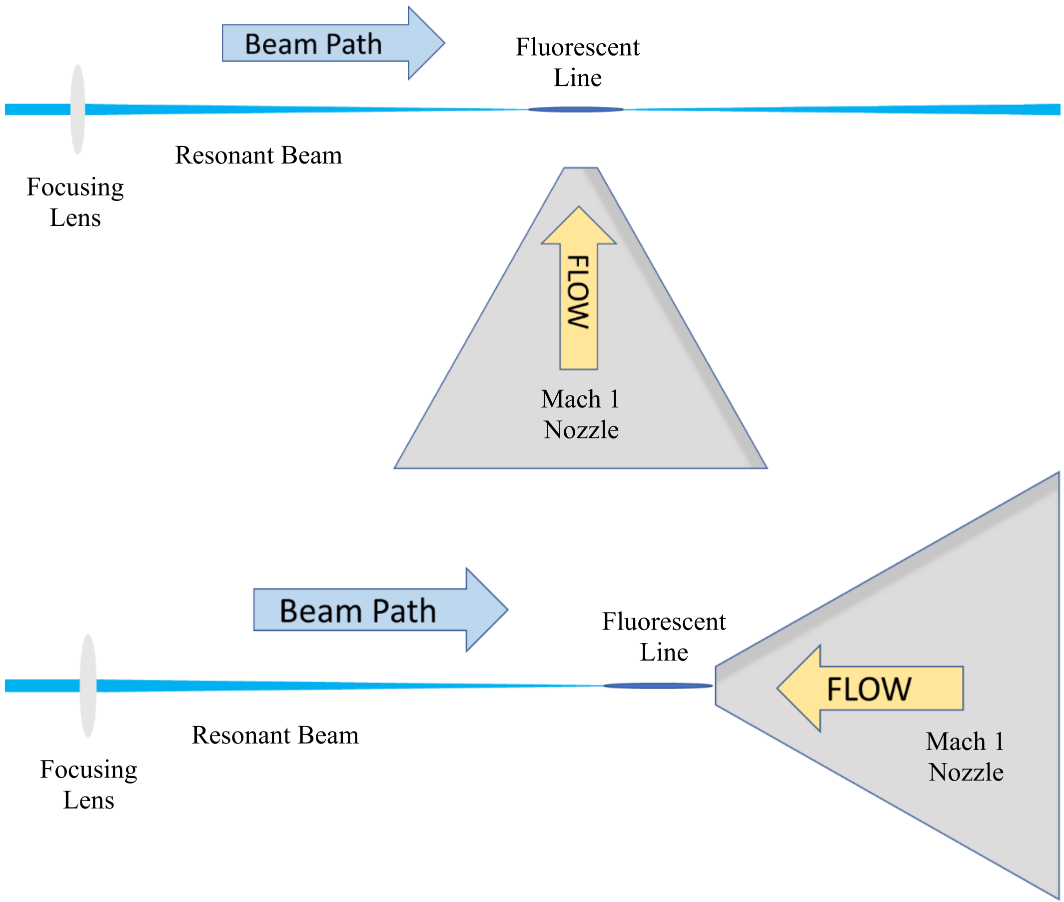

Fig. 2 Focused resonant beam path to nozzle and jet flow for crossflow (a) and counterflow (b) from the camera perspective.

V. Results and Discussion

The post processing of the images is done on a pixel-by-pixel basis, assigning intensity values to each. The images are cropped to a region of interest (ROI) to eliminate background and artifacts that may have been captured during the experiment. The ROI intensity is then binned and averaged along the beam path axis and a signal is calculated using Eq 1. A Boltzmann distribution is plotted for each of the points in the binned ROI for the four resonance wavelengths determined by previous calibration data and outlined previously in this text. The negative of the slope of the distribution yields the temperature along the path of the fluorescent line produced by the beam, which is also described by Eq (4).

A. Crossflow

The crossflow data points were gathered at 6 points of interest in the flow to capture the temperature effects on different flow structures. Also noted, there is a Gaussian profile that exists within the focal region of the beam path. As the Boltzmann distribution is applied to the relative intensities of the selected resonant lines and their given points along the path, there is no need to ratio the quiescent and flow conditions. This also implies that density changes within the flow region do not affect the temperature measurement. A final temperature profile for all the probed positions is shown in Fig. 3, as well as their nondimensionalized positions from the nozzle exit. The Mach 1 nozzle exit is 0.125 inches in diameter.

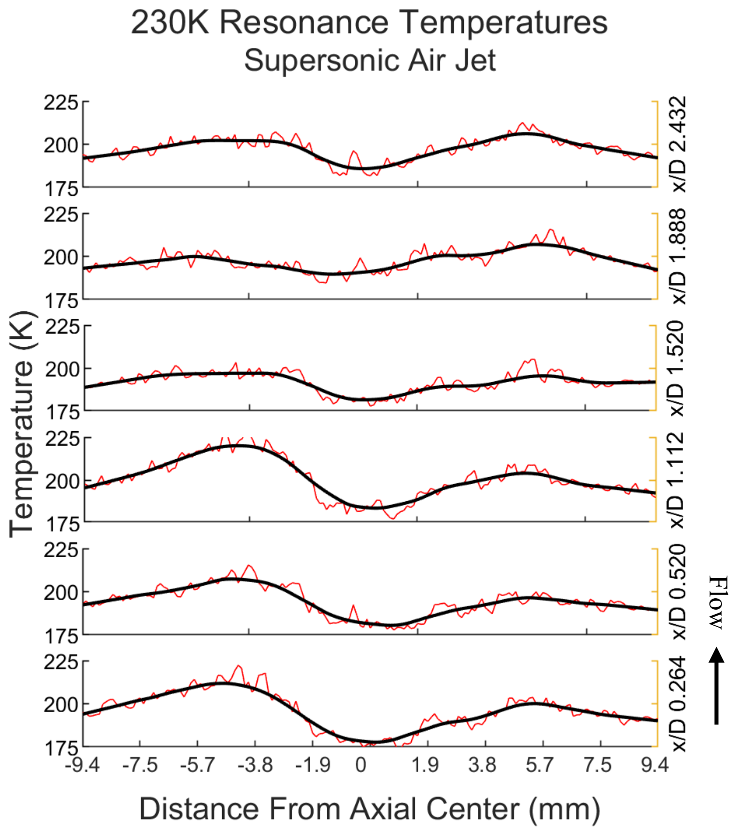

Fig. 3 Smoothed temperature profile from various locations in the crossflow experiment of a pure nitrogen jet. Temperatures calculated from 230K calibration resonance peaks.

B. Counterflow

For counter flow, the laser beam was focused near the nozzle exit anti-parallel to the fluid flow. The fluorescent line terminated just inside the exit of the nozzle to capture the most defined flow structures for analysis. Again, like with crossflow, plotting each of the 230K resonance lines at the corresponding points to get the Boltzmann distribution, the temperature can be calculated. Figure 4 shows the temperature calculation on a smoothed line. Because of the low resolution and short line fluorescent line length, only some of the shock structures are present in the temperature profile. The effects of the resolution and line length are more present here, than in crossflow because of the complexity of the structures in the anti-parallel direction. However, the temperature trend along the flow is in good agreement with theoretical values for an under-expanded jet.

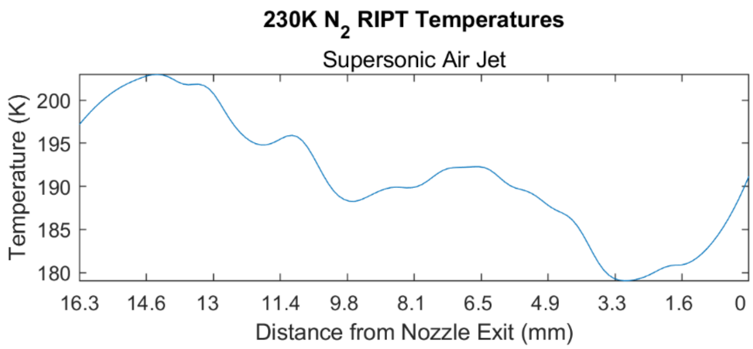

Fig. 4 Temperature profile calculated from the 230K calibration resonance wavelengths. Resonance with nitrogen present in supersonic air jet.

VI. Conclusion

Temperature measurements in supersonic flows are critical for the advancement of aerospace applications. Using the RIPT technique for N_2 in supersonic flow from a Mach 1 nozzle shows good application for non-intrusive temperature measurements that can be applied to supersonic facilities. The results from the nozzle are in good agreement with flow characterization in previous publications of the same nozzle. Temperature can be assigned to signal intensity and correlated through calibration studies done of the flow with the same equipment. The temperatures calculated from the Boltzmann distribution on a pixel-by-pixel basis trend well with theoretical data, though higher pixel density would improve the resolution of the temperature gradient captured. The RIPT technique used here shows how nitrogen can be directly excited in a supersonic jet of air or nitrogen, thus giving applicability for use in supersonic wind tunnels for a seedless non-intrusive temperature measurement.

VII. Acknowledgments

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VIII. References

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