HIGH-RESOLUTION N$_2$ CARS MEASUREMENTS OF PRESSURE, TEMPERATURE, AND DENSITY USING A MODELESS DYE LASER

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Abstract

In this study, high-resolution N$_2$ CARS measurements have been made using a modeless dye laser as the Stokes beam source to reduce the presence of mode noise. Along with this modification to the CARS technique, a new spectra fitting procedure was developed to avoid a starting-point bias in the least-squares fitting results. Time-averaged and single-shot measurements of pressure were made in a static pressure vessel over the range of 0.1 to 4.0 atm to test the pressure sensitivity of the technique. In addition, the precision of single-shot measurements in the pressure vessel is indicative of the baseline pressure-fluctuation detection limit of the system. The precision uncertainty of the measurements was studied to investigate the possibility of making property fluctuation measurements in high-speed flows. Centerline measurements of pressure and temperature in an underexpanded jet ($M_j = 1.85$) were also used to determine the performance of the technique in a compressible flowfield. Improvements in accuracy for time-averaged and single-shot mean measurements and increased precision were found for pressure levels above 1.0 atm. For the subatmospheric pressure levels that are important in high-speed flows, the results indicated that the current method is incapable of making fluctuation measurements due to limited precision. Nevertheless, the increased precision above 1.0 atm indicates that fluctuation measurements may be possible with further modifications.

Introduction

As the demand for improved performance of high-speed missiles, projectiles, and aircraft increases, so does the requirement for extensive knowledge of the thermodynamic and kinematic properties of compressible flowfields. For the projectile and missile designer, the base drag$^1$ and infrared plume signature$^2$ are important design criteria that are dependent on near-wake properties. Similarly, in aircraft design, structural fatigue due to acoustic fluctuations presents one of many issues to be dealt with.$^3$ In addition, other important practical applications, such as supersonic combustion, gas dynamic lasers, and metal deposition, depend on an in-depth understanding of compressible flows.$^4$ Due to compressibility effects in these flows, probe-based measurements are limited in their accuracy by interference effects. Therefore, advances in nonintrusive, laser-based diagnostics are required to assist in the design and implementation of the applications discussed above.

This paper presents the development and application of an innovative, broadband coherent anti-Stokes Raman scattering (CARS) technique that has the capability to obtain mean and fluctuating pressure, temperature, density, and velocity measurements in a compressible flow. A brief discussion of this CARS technique is presented here, whereas a more thorough review of the theory can be found in the extensive reviews that exist in the literature.$^5$–$^8$ The particular method employed here probes the first vibrational Raman transition ($v = 0 \rightarrow 1$) of diatomic nitrogen found in the flowfield through a third-order,

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nonlinear wave-mixing process. An energy level diagram of the interaction is displayed in Figure 1. Two pump beams ($\nu_1$ and $\nu_2$) and a Stokes beam ($\nu_3$) are focused and overlapped in the probe volume, where the signal is generated. The source for the Stokes beam is broadband, allowing for multiple transitions to be probed simultaneously and for instantaneous, or single-shot, measurements to be made. Pressure and temperature are determined from the spectral shape of the signal, while density and velocity are calculated from an equation of state and an energy equation, respectively. For this study, commercially available software known as CARSFIT is employed to least-squares fit the experimental spectra to theoretical spectra.\(^9\)

Because the process relies on molecules already present in the flow, there is no need for tracer molecules or particles, such as required by fluorescence techniques. Thus, this laser-based method is noninvasive and nonperturbing. The coherent nature of the signal provides a high signal level and signal-to-noise ratio (SNR). With the use of the folded-BOXCARS phase-matching geometry,\(^5\) the signal is spatially separated from the input beams. This phase-matching geometry also allows for user-specified spatial resolution (i.e., size) of the probe volume.

Additional benefits of the CARS process make the technique very attractive. With the use of pulsed lasers, the CARS signal is formed on a time scale of the order of nanoseconds. Therefore, along with the aforementioned spatial resolution characteristics, the CARS process provides excellent temporal resolution as well. Due to the relatively high SNR, the CARS process also provides the ability to probe areas of low molecular number densities.\(^10\) These benefits outweigh the complex implementation of the CARS method itself.

The development of CARS for measurements in high-speed flows has been ongoing at the University of Illinois for several years. The work started with dual-pump CARS\(^11\) measurements of pressure and temperature.\(^12\) This method probed the vibrational and pure rotational transitions of diatomic nitrogen in a stagnant gas cell and along the centerline of an underexpanded jet. The technique provided accurate time-averaged pressure results above 1 atm, as well as accurate mean and instantaneous temperature results throughout the range of 100 – 300 K. Unfortunately, the method performed poorly for time-averaged pressure measurements below 1 atm and for instantaneous pressure measurements below 3 atm. For instantaneous pressure measurements, the standard deviation was reported at approximately 10% of the mean for 3 atm, dropping to 4% at 18 atm. This baseline noise level prohibits the technique’s use for obtaining meaningful pressure fluctuation measurements in many applications.

In light of these results, modifications to the dual-pump CARS technique were made in order to increase pressure sensitivity at lower pressure and to investigate the ability of the method to obtain accurate, instantaneous, single-shot measurements.\(^10\) Instead of probing both pure rotational and vibrational resonances of diatomic nitrogen, the modified technique focused on vibrational resonances. Whereas in the previous study the CARS signal spanned a range between 40 and 100 cm\(^{-1}\), the modified CARS measurements only spanned 10 cm\(^{-1}\). Using a relay lens system to magnify the CARS signal spectrally, this new, high-resolution technique was able to resolve the CARS signal to within 0.10 cm\(^{-1}\), allowing pressure and temperature sensitivity of the diatomic nitrogen Q-branch ($\nu = 0 \rightarrow 1$) to be investigated. As before, the method was tested in a stagnant gas cell and throughout the flowfield of an underexpanded jet. The results from the gas cell revealed that only below 2 atm was the method capable of making accurate time-averaged and ensemble-averaged single-shot measurements of mean pressure, therefore displaying the opposite pressure sensitivity as compared to the previous dual-pump method. The high-resolution technique also provided accurate mean pressure and temperature measurements in the underexpanded jet flowfield. Most notably, the method displayed the ability to generate usable single-shot signal levels at high spatial resolution even at low molecular number densities.

One goal of this modified technique was to provide the ability to measure fluctuating thermodynamic properties in compressible shear flows.\(^13\) While the technique could provide single-shot measurements with accurate mean values, the ensemble-averaged fluctuations were not accurate. From the gas-cell experiment, the baseline noise level over the 0.1 to 5.0 atm range examined was approximately 12% of the mean value on average. These artificial fluctuations (precision uncertainty), which dominated the results, were attributed to mode-noise contributions from the conventional broadband dye laser (BDL) that was used as the source for the Stokes beam.\(^14\) An in-depth discussion of mode noise and its effects on the CARS method can be found in the work of Greenhalgh and Whittley.\(^15\)

Therefore, this study examines modifications to the high-resolution CARS method to extend its capabilities to measure mean and fluctuating thermodynamic and kinematic properties. To reduce the
effects of mode noise, a modeless broadband dye laser (MDL), based on the design of Ewart,\textsuperscript{16} has been implemented as the new source for the Stokes beam. The capabilities of the method were benchmarked in two, well-defined experiments. First, the pressure-sensitivity and capability to make fluctuating pressure measurements were assessed in a gas cell. Then, measurements were obtained along the centerline of an underexpanded jet flowfield. The results of these investigations were used to determine the accuracy and precision of the new CARS method.

**Experimental Facilities and Equipment**

The facilities and equipment described herein are located in the Gas Dynamics Laboratory at the University of Illinois at Urbana-Champaign. A top view of the CARS system can be seen in Figure 2. On the right-hand side of the figure is the Q-switched, injection-seeded, Nd:YAG laser (Continuum Powerlite 8010). This laser provides approximately 900 mJ of energy per pulse at a wavelength of 532 nm and a repetition rate of 10 Hz. The beam is turned such that it passes through a quarter wave plate and a Glan polarizer; these two optics comprise the power attenuation control for the rest of the CARS system. Following this, the beam is directed around the translation system, which will be discussed later. A beamsplitter separates 20% of the beam to provide the pump beams in the CARS process ($\nu_{p1}$ and $\nu_{p2}$ in Figure 1). The pump beam is then traversed over a distance in space to delay its arrival at the probe volume such that it is coincident in time with the Stokes beam. This is the reason for the winding path in the upper left-hand corner of the figure. Shortly before the beam is directed to the probe volume, it is split equally to form the two necessary pump beams.

The remaining 80% of the initial Nd:YAG beam is used to pump the MDL. The MDL is derived from the Ewart\textsuperscript{16} design, modified to include an additional amplification stage. Rhodamine 640 perchlorate\textsuperscript{17} dissolved in methanol provides the organic dye solution used as the gain medium. The MDL emits coherent light in the range of 607 nm at approximately 25 mJ per pulse, and is the source for the Stokes beam in the CARS process ($\nu_S$ in Figure 1). The Stokes beam is then directed into the probe volume. Note that the last turn made by each of the three input beams is achieved by fixing a prism to a high-precision mirror mount (Newport 610 Series) to allow for fine tuning of the probe volume alignment. The timing of the three input beams is checked at this point in the system using a fast photodiode and oscilloscope to ensure that all beams reach the probe volume within 1 ns of each other.

The path of the beams through the translation system can be seen in Figure 3. The system is based on an earlier, successful design,\textsuperscript{18} and has a positional repeatability under 5 $\mu$m in each direction. In order to maintain beam alignment during translation, movement must occur along the path of beam propagation. For example, considering the beam propagation into the translation system as shown in Figure 2, the first stage (Parker Hannifin 424012) is required to move left-to-right. Returning attention to Figure 3, all three beams are turned 90° using one large prism attached to the first stage and directed at the next stage (Parker Hannifin 412012). The beams are then projected upwards to the initial vertical stage (Parker Hannifin 404300) with a prism attached to the second stage. Once on the initial vertical stage, the beams are focused at the probe volume using a 250 mm focal length lens. The beams, including the newly formed CARS signal, are collimated using another 250 mm lens attached to an identical vertical stage. Using two independent vertical stages allows for a test section to be placed between them. Once the system is aligned, the motion of the two vertical stages is coupled so that they move simultaneously. Beyond the measurement volume, the three input beams are discarded into beam dumps, as they are no longer needed. The CARS signal follows a path similar to the input beams as it leaves the translation system; however, in this case specially designed mirrors (CVI TLM2-475) are substituted for the prisms.

The CARS signal is then directed to the 1.25 m spectrometer (SPEx 1250M); see Figure 2. A 100 mm lens focuses the CARS signal onto the entrance slit. The spectrometer design is based on a single-pass Czerny-Turner configuration\textsuperscript{19} using a 3600 groove/mm holographic grating. This configuration provides a theoretical resolution of $\Delta \omega \approx 0.09$ cm$^{-1}$. At the exit of the spectrometer, a relay lens pair disperses the signal onto the CCD (Roper Scientific NTE/2500PB). The CCD is a 2500 x 600 pixel, 16 bit array that provides on average one count for every 3.5 incident photons. The relay lens pair consists of 28 mm and 210 mm focal length Nikon camera lenses focused at infinity, resulting in a magnification factor of 7.5. The image of the CARS signal is captured and binned on the CCD chip to provide the CARS spectra that will be analyzed. In these experiments, two types of spectra were obtained: time-averaged and single-shot. The term “time-averaged” is used here to indicate that the CCD camera was exposed for ten laser shots (one second) before the spectrum was read out. On the
other hand, “single-shot” spectra correspond to the CCD camera being exposed to only one laser shot. Therefore, single-shot spectra represent essentially instantaneous measurements for the pulsed lasers used here.

An optically-accessible gas chamber was modified for use in this study. As seen in Figure 4, air, argon, and propane can occupy the gas cell. Air is used to provide constant pressure levels in benchmarking the CARS technique. Because they contain no resonant transitions in the frequency range being probed, argon and propane are utilized to obtain nonresonant signals. Argon is also employed in the propane line as a nonoxidizing purge gas. The vent is connected to the building exhaust. To avoid surpassing the maximum operating pressure of the chamber (estimated at 250 psi), a 100 psi check valve was installed in the system. In addition to pressurizing the test gases, the cell can be evacuated using a vacuum pump. This allows subatmospheric pressure levels to be investigated with the CARS system. Pressure is tested gases, the cell can be evacuated using a vacuum pump. This allows subatmospheric pressure levels to be investigated with the CARS system. Pressure is monitored independently of the CARS measurements by using digital pressure transducers: a 1000 torr absolute transducer (MKS 722A13TCE2FK) for subatmospheric studies, and a 5000 torr absolute transducer (MKS 722A53TCE2FK) for above-atmospheric studies. Both transducers are accurate to 0.5% of the pressure reading.

The underexpanded jet facility can be seen in Figure 5. It is similar in design to previous investigations. Dry, high-pressure air is supplied to the horizontally mounted inlet pipe at approximately 120 psig. A 4 in. control valve (Fisher EK-14/40) mounted far upstream and a 1 in. ball valve at the start of the inlet pipe are employed to control the stagnation pressure. The stagnation pressure and temperature are monitored using the 5000 torr transducer described above and a hermetically sealed thermistor (Omega ON-920-4007), respectively. The nozzle exit is 10 mm in diameter, and the nozzle diameter contracts linearly from the inner pipe diameter of 19.3 mm to the exit. The area reduction, which occurs over 101.6 mm, results in an angle of contraction of 2.61°. The jet can be operated over a fully expanded jet Mach number \((M_j)\) range up to \(\sim 2\). In the present work, the jet was operated at a nozzle pressure ratio \((NPR = P_o/P_{amb})\) of 6.17, which corresponds to \(M_j = 1.85\).

**Spectra Fitting Procedure**

When analyzing data for the pressure vessel, the final answer is known \textit{a priori} from the transducer measurements. However, in the flowfield investigations, the pressure and temperature measured are not known before the spectra are fit. This can present a problem, as CARSFIT requires an initial value for all variables. If an individual spectrum is of poor quality or the specified initial values of the fit are too far from the true conditions, CARSFIT may return the initial values as an indication that a fit could not be made. Therefore, a procedure was developed to determine if the returned values were an accurate prediction of pressure and temperature or if the spectrum should be discarded. This eliminates the chance of a starting-point bias. The procedure was then tested on the pressure vessel data to determine its effectiveness.

The process begins by initially discarding any spectra that saturated a CCD pixel or contained a low integrated signal intensity. The remaining spectra are fit starting from three unique points. If two of the three fitting results are within a preset percentage of each other, the spectrum with the lowest chi-squared, goodness-of-fit value is kept, regardless of the prediction of temperature or pressure. However, if all three fitting results are separated by more than this preset percentage, the spectrum is discarded. For the pressure vessel, for which only pressure is allowed to float, each spectrum was started at 70%, 100%, and 130% of the transducer-measured pressure and was kept if two of the results were within 10% of each other. In the case of a flowfield where both pressure and temperature are allowed to float, then both pressure and temperature must simultaneously pass this criterion for the spectrum to be kept.

Using 70% and 130% starting points for comparison considerably relaxes the required accuracy in estimating the conditions at the probe volume for use as initial values in the spectra fitting procedure. However, this advantage in turn brought about the concern that CARSFIT may not be capable of starting this far from the true condition and still be able to return an accurate prediction. Hence, a test was performed on a small set of time-averaged pressure vessel spectra for which 70% and 130% starting points were used, as well as 90% and 110% starting points for comparison. As seen in Figure 6, the mean pressure levels resulting from both sets of starting values are in excellent agreement. In addition, Figure 7 shows the relatively good agreement between the standard deviations of the time-averaged ensembles for each case. These results verify the integrity of the newly developed spectra fitting procedure and lend considerable confidence to measurements obtained with this method.
Pressure Vessel Results

The current results represent 100 time-averaged and 500 single-shot measurements made in the gas cell at 25 pressure levels in the range from 0.1 to 4.0 atm. Figure 8 displays time-averaged CARS spectra obtained in the gas cell at 0.1, 0.5, 1.0, 2.0, 3.0, and 4.0 atm and 292 K along with the theoretical results from CARSFIT. For reference, each spectrum is labeled with the transducer pressure, $P_{\text{TRAN}}$, and the predicted CARSFIT pressure, $P_{\text{CARS}}$. As CARSFIT compares the square root of intensity in the least-squares fitting process, all subsequent results will be plotted as such.

All spectra in Figure 8 display excellent agreement between data and theory. Not only are the peak intensities of each transition generally closely matched by the theory, but the linewidth and lineshape are as well. Of the fact is that these, and all theoretical spectra presented herein, were generated at a resolution of 0.10 cm$^{-1}$, reinforcing the high-resolution nature of the experimental spectra. Notice that the linewidths of the transitions broaden and interfere as pressure increases, denoting the competing effects of collisional broadening and collisional narrowing. It is these features that give the technique its pressure sensitivity. This sensitivity is evident, as all the spectra produced accurate predictions of the transducer pressure.

The low signal level seen in Figure 8(a) for 0.1 atm is a cause for concern, as the intensity will drop to approximately one-tenth of this value for single-shot spectra. As the experimental setup closely resembles a previous setup$^{10}$ in all ways aside from the MDL, which is used in place of a conventional BDL, the MDL is considered the most probable cause for this low signal level. While the total average power out of the MDL is 30% lower than previous experiments with the BDL,$^{10}$ this does not completely account for the drop in signal level. The low signal level is most likely attributed to the decrease in spatial beam quality and transverse electromagnetic (TEM) mode structure provided by the MDL as compared to the previous BDL, which employed an oscillator cavity. This decline in beam quality lowers the efficiency at which the CARS signal is generated in the nonlinear wave-mixing process. It was hoped during this study that this decrease in signal strength would be more than offset by the reduction of mode noise in single-shot spectra.

A comparison of the time-averaged CARS-predicted pressure and transducer pressure over the entire range is shown in Figure 9(a), with Figure 9(b) displaying the subatmospheric portion of the results. Included in this figure are the results of a previous study,$^{13}$ which is used as a comparison for the current technique. Here, and in all plots, the uncertainty bars denote the standard deviation of the pressure levels obtained from the ensemble of spectra at each pressure level. Above 1.0 atm, the current results compare very well with the transducer values with an accuracy slightly better than for the previous study. The deviation between the CARS and transducer values seen at 3.4 atm is considered to be an isolated incident associated with a temporary loss in single-mode operation of the Nd:YAG laser that was not immediately noticed. As is seen in Figure 9(b), the accuracy of the technique decreases for pressure levels below 1.0 atm, with CARS values that are consistently below the transducer values. This decrease in accuracy is the direct result of the decrease in signal level at these lower molecular number density levels. This discrepancy is unfortunate, as the results for pressure levels above 1.0 atm indicate that the inclusion of the MDL in the system improves the accuracy of the technique.

As a preliminary study of the precision of the technique, the standard deviations presented as uncertainty bars in the previous figure are plotted in Figure 10 and compared to previous results.$^{13}$ Because these are standard deviations of time-averaged spectra, they cannot be considered as an indication of the precision uncertainty of the method. However, it is promising that the modified method with the MDL produces similar standard deviation results for pressure levels above 1.0 atm. Once again, the data point at 3.4 atm is considered anomalous and its increased standard deviation not indicative of the method’s performance. The increase in standard deviation below 1.0 atm compared to the previous results is not unexpected, as it is believed that the previous measurements were affected by the starting-point bias discussed earlier. Additionally, the decrease in signal strength degrades current system performance at low pressure.

Figure 11 presents the number of spectra that were kept at each pressure level using the new spectra fitting procedure described earlier. The dropoff seen at low and high pressure levels is expected. At low pressure, the low signal strength produces spectra that cannot be fit by CARSFIT. The effects of collisional broadening at high pressure reduce the sensitivity of the technique, and this change in spectral behavior also reduces the number of spectra that can be fit. Aside from those effects and the obvious problem discussed previously at 3.4 atm, nearly all of the time-averaged spectra obtained were able to be fit.
from at least two different starting points with best-fit pressure values falling within a prescribed tolerance. Not only were these spectra able to be fit, but in addition, each data set provided accurate mean values, as seen in Figure 9. This result confirms the ability of the technique to provide accurate predictions when the actual conditions at the probe volume are not known.

Example spectra from the single-shot measurements in the pressure vessel are shown in Figure 12 at the same pressure levels as in Figure 8. As expected from the time-averaged spectra at 0.1 atm, low signal levels are evident in Figure 12(a). Even with the low signal strength, the single-shot spectra generally match closely with the theoretical spectra from CARSFIT, except at the lowest pressure level of 0.1 atm. The mean pressure results from the single-shot spectra are presented in Figure 13. For comparison, the results of the previous study are again included. As seen with the mean time-averaged results, the accuracy of the technique is improved compared to the previous experiments for pressure levels above 1.0 atm. Figure 13(b) focuses on the subatmospheric pressure levels, where the trend for the time-averaged measurements is again exhibited by the single-shot results. In particular, the accuracy of the mean single-shot measurements is generally poorer than that of the previous experiments with most of the CARS pressure levels below the transducer values. As discussed above, the current technique suffers from low signal levels in this region, which is the cause of the errors in predicted pressure.

Figure 14 displays the precision of the technique by plotting the standard deviations of the single-shot measurements for the corresponding pressure level. In comparison to the previous study, the increased accuracy of the technique above 1.0 atm is complemented by a small but discernible increase in precision as well. The subatmospheric trend seen in the standard deviation of the time-averaged results is also duplicated by the single-shot data. While the previous technique displayed better precision in this region, it is believed that those results may have been influenced by starting-point bias, as reported above. As a final note, the number of spectra kept from the ensemble of 500 single-shot spectra at each pressure level is presented in Figure 15. As the technique loses pressure sensitivity as pressure increases, there is a dropoff in the number of spectra kept above 2.0 atm, similar to the trend seen in the time-averaged measurements. Still, the large number of spectra kept confirms the ability of the technique to provide spectra that can be fit independently of the initial value for the least-squares fitting process.

Regardless of the reason for decreased precision of the single-shot measurements below 1.0 atm, these results would indicate that meaningful fluctuation measurements may not be obtainable in a supersonic flowfield with this technique. In typical supersonic flowfields, regions of low pressure are often accompanied by low to moderate temperature. While this may correspond to low molecular number density depending on the specific pressure and temperature, previous experiments have shown improved performance of the CARS technique at the low temperatures encountered in an underexpanded jet. This improved performance is due to the increased signal strength encountered at low temperatures. This experience provides the motivation to attempt the underexpanded jet measurements described in the following section.

**Underexpanded Jet Results**

The pertinent flow features of an underexpanded jet are sketched in Figure 16. For a jet to be underexpanded, the exit pressure of the nozzle must be greater than that of the ambient surroundings. This mismatch causes a Prandtl-Meyer expansion fan to form at the lip of the nozzle. These expansion waves propagate across the flow and reflect from the constant-pressure jet boundary as compression waves, which in turn coalesce to form the intercepting shock (or “barrel” shock) that is attached to the nozzle lip. The core flow is accelerated to supersonic speeds by the expansion fan and travels downstream to a point where the intercepting shock would cross the centerline. Here, the flow will be recompressed. If the exit pressure is great enough (NPR > 3), the simple crossing (i.e., regular reflection) of the intercepting shock along the centerline will no longer provide sufficient pressure rise, and a minimally-curved normal shock, or Mach disk, forms. Instead of crossing (reflecting) at the centerline, the intercepting shock now attaches to the edge of the Mach disk, where the reflecting shock forms and propagates downstream to the constant-pressure boundary. The triple point is the intersection of the intercepting shock, reflecting shock, and Mach disk, and is the starting point for the slip line or inner shear layer. The inner shear layer complements the outer shear layer, which resides along the constant-pressure boundary. As the reflecting shock reflects from the outer shear layer, a new series of expansion waves form. The expansion waves are the start of a semi-duplication of the first series of flow features at the nozzle exit that result in a new shock cell. The shock train that forms from this repeating shock cell pattern continues downstream
until the pressure mismatch is dissipated by viscosity. As in the subsonic case, the outer and inner shear layers will grow until they close off the jet core region, and the jet becomes fully turbulent.

In this investigation, 50 time-averaged and 250 single-shot spectra were obtained at nine locations along the centerline from the jet exit to just beyond the Mach disk. Figure 17 displays time-averaged spectra at centerline positions corresponding to the jet exit, halfway to the Mach disk, just upstream of, and just downstream of the Mach disk \((z/d_j = 0.019, 0.870, 1.508, \text{ and } 1.579)\) along with the fitted theoretical spectra. Included in the plots are the CARSFIT \((P_{\text{CARS}} \text{ and } T_{\text{CARS}})\) and CFD\(^{20}\) \((P_{\text{CFD}} \text{ and } T_{\text{CFD}})\) predictions of pressure and temperature for comparison. As with the pressure vessel results, the experimental spectra exhibit the same spectral behavior as the theoretical spectra. Special attention is drawn to the differences between Figures 17(c) and 17(d), where the large differences in thermodynamic conditions upstream and downstream of the Mach disk are readily apparent in the spectra. These spectra display the sensitivity of the technique to these differing thermodynamic conditions. Moreover, for all of the spectra, there is a close correlation between the CFD and experimental predictions of temperature and pressure, with pressure predictions marginally outperforming temperature predictions. The increased discrepancy in temperature and pressure predictions seen in Figures 17(c) and 17(d) can be accounted for by considering the unsteady position of the Mach disk, which will add to experimental error in these locations, along with the inability of the CFD to accurately capture the shock location.

The mean results from the time-averaged spectra at all centerline locations examined are compared to previous measurements\(^{13}\) and the CFD results\(^{20}\) in Figure 18. Clearly, there is a substantial improvement in agreement between the CARS measurements and CFD results for pressure levels above 1.0 atm. This result is expected from the pressure vessel measurements. There is a small but consistent discrepancy between the CFD and experimental mean temperature results upstream of the Mach disk, with the CARS results always being lower. There are two possible reasons for this offset. First, the stagnation temperature in the current experiment \((290 \text{ K})\) was slightly lower than for the previous study \((296 \text{ K})\). Second, the previous nozzle used a contraction angle of \(4.1^\circ\), almost twice the current angle, thus providing slightly different flow conditions at the jet exit. Overall, though, the current time-averaged measurements match well with the CFD predictions from the jet exit through the Mach disk.

The standard deviation of the time-averaged measurements is shown in Figure 19, along with those from the comparison study.\(^{13}\) There is a noticeable increase in standard deviation in both pressure and temperature as compared to the previous work. The most plausible explanation for this increase is due to the low signal strength of the current technique. Adding another variable to the least-squares fitting process further exposes the low signal strength problem of this method. This is again demonstrated in Figure 20, where the number of spectra kept drops severely in the region of low molecular number density just upstream of the Mach disk. Note that the number of spectra fit is included in this plot, as some of the spectra were discarded before fitting because of saturated pixels or low signal conditions.

Turning to the single-shot centerline results, Figure 21 shows sample spectra at the same locations as in Figure 17 for the time-averaged measurements. Aside from a slight increase in noise level, all the spectra exhibit the same excellent agreement between data and theory that was seen in the time-averaged spectra. In addition, the predicted pressure and temperature levels agree relatively well with the CFD values, with the discrepancy in temperature and pressure predictions in Figures 21(c) and 21(d) likely occurring for the same reasons as discussed with respect to the time-averaged spectra in Figure 17. Ensemble-averaged pressure and temperature values from the single-shot data set at all centerline locations examined are presented in Figure 22, which includes the previous results\(^{13}\) and CFD predictions\(^{20}\) for comparison. The current technique again displays better accuracy at high pressure and good agreement with the CFD results through the first Mach disk. For temperature, a similar offset of the CARS measurements below the CFD predictions as was seen in the time-averaged results exists.

The standard deviation of the current and previous\(^{13}\) single-shot measurements, which is representative of the precision of the method, is plotted in Figure 23. Because there is low turbulence intensity along the centerline of the jet before the Mach disk, the standard deviation results here should represent the baseline detection limit of fluctuations nearly exactly. As expected from the time-averaged results, the technique displays an increase in standard deviation as compared to the previous technique, most likely due to the decreased signal strength of the current method. This increase indicates that fluctuation measurements will most likely not be possible in the shear layer of the underexpanded jet using this technique, as the baseline detection limit is above the fluctuation level expected therein.
Conclusions

Reviewing the pressure vessel results, an improvement in accuracy of time-averaged and single-shot mean measurements was shown as compared to previous work for pressure levels above 1.0 atm. This result demonstrates the benefit of employing the MDL. Decreased performance for subatmospheric pressure levels was attributed mainly to the low signal strength at these conditions. Standard deviations of the time-averaged results were similar to previous results above 1.0 atm, and marginally higher below this level. A decrease in standard deviations for the single-shot spectra was shown above atmospheric pressure, representing increased precision resulting from the use of the MDL. Below 1.0 atm, the single-shot standard deviations increased as compared to previous results. Both time-averaged and single-shot CARS spectra displayed excellent spectral behavior, allowing for good agreement between theoretical and experimental spectra.

Mean time-averaged and single-shot results from the centerline traverse of an underexpanded jet displayed excellent agreement with CFD results, especially for pressure levels above 1.0 atm. Slight offsets in mean temperature were observed and explained. Experimental spectra from the centerline traverse provided good predictions of pressure, with a minor decrease in agreement in temperature as compared to previous results. Increases in standard deviations for both temperature and pressure occurred in the time-averaged and single-shot measurements, which is most likely indicative of low signal strength.

The possibility of fluctuation measurements using high-resolution $N_2$ CARS was displayed. The slight increase in precision for pressure vessel measurements above 1.0 atm confirms that the baseline fluctuation detection limit of the technique can be lowered. Unfortunately, this increased precision falls outside of the thermodynamic property range that a majority of detectors operate in. The decrease in signal strength at lower pressure levels (more representative of compressible flows) degraded system measurement precision from that seen in the previous experiment.13

In order to improve the performance of the current technique, a new source for the Stokes beam should be explored. A promising source would be a modeless dye laser based upon the design of Hahn et al.21 This laser employs Bethune dye cells as opposed to the transversely pumped dye cells in the current MDL, with a single, concentrated pass through the “oscillator” dye cell rather than four, distributed passes. As seen in a previous experiment,23 this dye laser provides low standard deviations in temperature measurements in a steady laminar flame. Another possible solution would be to incorporate two single-mode, solid-state, tunable sources into the system: one to replace the Stokes source and one to replace a pump beam, in a dual-pump CARS technique.11 With the correct choice of wavelengths for these two sources, two transitions of the nitrogen Q-branch could be probed simultaneously. This second option is less attractive, as it involves a potential decrease in pressure sensitivity by not probing the entire linewidth of both transitions, and it is also more expensive to implement. Nevertheless, using all single-mode sources for the pump and Stokes beams would provide excellent beam quality and TEM mode structure and would eliminate the possibility of mode noise.

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References


Figures

Figure 1: CARS energy-level diagram

Figure 2: Top view of CARS system
Figure 3: Translation system for CARS probe volume

Figure 4: Gas-cell facility
Figure 5: Underexpanded jet facility

Figure 6: Comparison of the mean spectra fitting procedure results using different starting points
Figure 7: Comparison of the standard deviation of the spectra fitting procedure results using different starting points.
Figure 8: Comparison of time-averaged experimental CARS and theoretical CARSFIT spectra from the pressure vessel for (a) 0.1 atm, (b) 0.5 atm, (c) 1.0 atm, (d) 2.0 atm, (e) 3.0 atm, and (f) 4.0 atm
Figure 9: Comparison of time-averaged pressure vessel results to those of Woodmansee\textsuperscript{13} (a) full range and (b) low-pressure subset
Figure 10: Comparison of time-averaged standard deviation results from the pressure vessel to those of Woodmansee\textsuperscript{13}

Figure 11: Number of time-averaged pressure vessel spectra kept out of 100 in each data set
Figure 12: Comparison of single-shot experimental CARS and theoretical CARSFIT spectra from the pressure vessel for (a) 0.1 atm, (b) 0.5 atm, (c) 1.0 atm, (d) 2.0 atm, (e) 3.0 atm, and (f) 4.0 atm
Figure 13: Comparison of mean single-shot pressure vessel results to those of Woodmansee\textsuperscript{13} (a) full range and (b) low-pressure subset.
Figure 14: Comparison of single-shot standard deviation results from the pressure vessel to those of Woodmansee\textsuperscript{13}

Figure 15: Number of single-shot pressure vessel spectra kept out of 500 in each data set
Figure 16: Underexpanded jet flowfield
Figure 17: Comparison of time-averaged experimental CARS and theoretical CARSFIT spectra along the centerline of the underexpanded jet at $z/d_j = (a) 0.019$, (b) 0.870, (c) 1.508, and (d) 1.579
Figure 18: Comparison of time-averaged centerline results to those of Woodmansee\textsuperscript{13} and CFD results (a) pressure and (b) temperature
Figure 19: Comparison of time-averaged standard deviation centerline results to those of Woodmansee\textsuperscript{13} (a) pressure and (b) temperature.
Figure 20: Number of time-averaged centerline spectra fit and kept
Figure 21: Comparison of single-shot experimental CARS and theoretical CARSFIT spectra along the centerline of the underexpanded jet at $z/d_j = (a) 0.019$, (b) 0.870, (c) 1.508, and (d) 1.579.
Figure 22: Comparison of mean single-shot centerline results to those of Woodmansee\textsuperscript{13} and CFD results (a) pressure and (b) temperature
Figure 23: Comparison of single-shot standard deviation centerline results to those of Woodmansee\textsuperscript{13} (a) pressure and (b) temperature