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14. ABSTRACT

The Mechanical Engineering Department at Vanderbilt University obtained a high pulse energy Nd-YAG laser, together with a dye laser and frequency doubling/mixing system. This laser system provides the light sources necessary for nonintrusive, unseeded velocimetry of low temperature air flows, with applications to base flows and high speed flows around projectiles. The laser system also provides high pulse energy light for visible Raman scattering measurements in rich, hydrocarbon-fueled flames. The visible wavelength and high pulse energy allow strong, interference-free Raman signals to be obtained in flame regions where fluorescence interference precludes application of the UV Raman scattering technique.

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FINAL REPORT

GRANT F49620-99-1-0120

DURIP99 Neodymium-YAG Laser System for Combustion Scalar Flux Measurements

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FINAL REPORT: GRANT F49620-99-1-0120

DURIP99 Neodymium-YAG Laser System for Combustion Scalar Flux Measurements

List of equipment items obtained under grant

Name	Manufacturer	Cost
Model 9010 Powerlite Q-switched Nd-YAG laser with frequency doubling and mixing crystals.	Continuum, Inc.	$105,792
Model ND6000 high energy nanosecond dye laser, and Model UVT/UVX doubling and mixing crystal system for tunable, pulsed, ultraviolet light.	Continuum, Inc.	$47,189
Optics set for ultraviolet laser system.	Lambda-Physik	$10,360
Etalon monitoring system for ultraviolet laser.	CVI Laser Corporation	$2,460
Model VH3648W-OPT-25 laser optics table.	Newport Corporation	$2,381
Model 44701, 3 inch diameter, 6 inch focal length Raman signal collection lens.	JML Optical Industries, Inc.	$2,250
Computer system for gas mass flowmeter control for Raman sytem.	Gateway 2000	$3,301

All items were obtained with 17% cost matching provided by Vanderbilt School of Engineeing.

Concise summaries of current and future research projects using DURIP equipment

Hydroxyl tagging velocimetry for low temperature applications

At Vanderbilt University, a new nonintrusive, laser-based velocimetry technique, Hydroxyl Tagging Velocimetry (HTV) has been developed for high temperature flows.[1] This technique involves "writing" a line of OH in a moving gas stream by photodissociating the vibrationally-excited H_2O present in high temperature combustion flows. The line of OH is superimposed upon the ambient OH present. The line of "superequilibrium" OH is convected downstream and after an appropriate delay time a second laser pulse causes the OH in the moving flowfield to fluoresce, giving an image of the displaced superequilibrium OH line. The original and displaced positions of the OH line, together with the known delay time for the displaced image, can be used to determine velocity.

The HTV technique was originally developed to be complementary to another flow tagging technique, Ozone Tagging Velocimetry (OTV),[2] that uses two narrowband, tunable excimer lasers, hence a 248 nm KrF excimer laser is used for the "read" laser in high temperature HTV work. The KrF excimer laser accesses only relatively weak (3,0) vibrational transitions for the (A-X) OH band which are relatively weak compared to the (1,0) or (0,0) transitions that are normally used for OH fluorescence spectroscopy. Because of the weakness of the OH lines pumped by the KrF laser, only high temperature flows have been successfully probed, because these flows have significant populations of vibrationally-excited H_2O, which have 193 nm photodissociation cross sections two or more orders of magnitude higher than ground vibrational state H_2O.[1] The ArF excimer laser used as the "writing" laser for either HTV or OTV has a 193 nm output wavelength.

By substituting the dye laser/ frequency doubler system (obtained from this DURIP award) for the KrF excimer laser, the HTV technique has been demostrated to be applicable to low temperature flowfields.[3,4,5] Figure 1 shows a schematic of the HTV system in current use at Vanderbilt, which is similar to previous systems[1,2] except for the substitution of the new read laser. By operating the dye laser/ frequency doubler at an approximate output wavelength of 309 nm, the (0,0) band of vibrational transitions can be accessed, which are orders of magnitude stronger than the (3,0) bands. These stronger transitions make up for the relatively weak 193 nm photodissociation cross section of ground vibrational state H_2O, allowing HTV to be applied to low temperature flowfields. Figure 2 shows an HTV flow tagging grid created in a stream of room temperature air. There is a 50 μsec delay between the firing of the ArF excimer "write" laser and the dye laser/ frequency doubler "read" laser.

By using the dye laser/frequency doubler obtained from this DURIP funding, the HTV technique has been demonstrated for low temperature, unseeed, velocimetry applications. This type of application includes non-reacting base flows for high speed projectiles, or low temperature hypersonic external or internal flows.

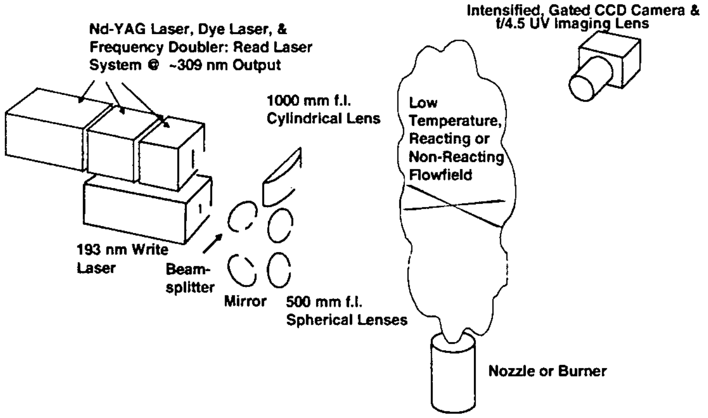


Fig. 1. Schematic of low temperature HTV system, showing replacement of KrF "read" laser of previous systems[1] with YAG laser/dye laser/ frequency doubler "read" laser system.

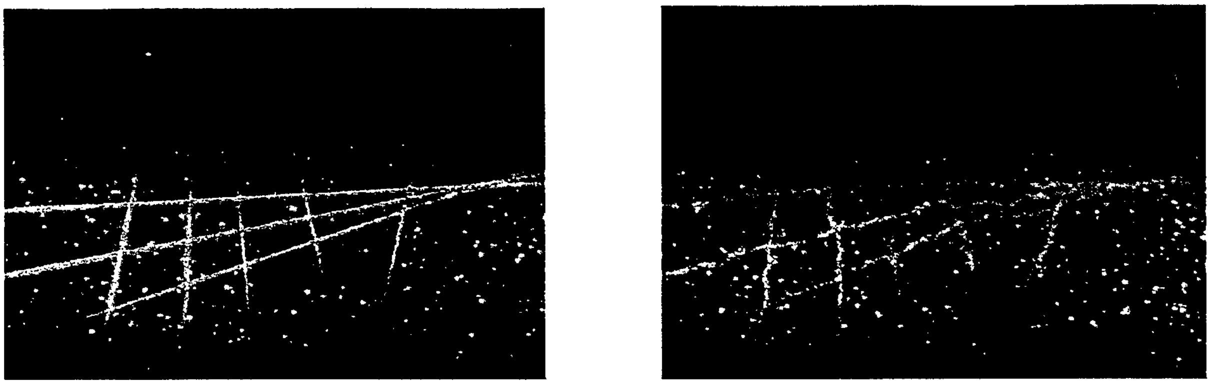


Fig. 2. Hydroxyl tagging images obtained in a room temperature air flow (flow moving from lower right to upper left). Write laser: ArF excimer @193 nm. Read Laser: doubled dye @ 309 nm. Left image for 0 µsec delay time between write and read laser. Right image for 50 µsec delay time.

References

1. Wehrmeyer, J. A., L. A. Ribarov, D. A. Oguss, and R. W. Pitz. 1999. "Flame Flow Tagging Velocimetry with 193 nm H_2O Photodissociation." *Applied Optics* 38: 6912-6917.

2. Ribarov, L. A., J. A. Wehrmeyer, F. Batliwala, and R. W. Pitz. 1999. "Ozone Tagging Velocimetry Using Narrowband Excimer Lasers." *AIAA Journal* 37: 708-714.

3. Ribarov, L. A., Wehrmeyer, J. A., and Pitz, R. W. "Hydroxyl Tagging Velocimetry for Low Temperature Gas Flows." manuscript in preparation for submittal to *Applied Physics B.*

4. Ribarov, L. A., Wehrmeyer, J. A., and Pitz, R. W. 2000. "Molecular Flow Tagging for Low and High Temperature Flowfields." Poster #644 to be presented at the Optical Society of America Annual Meeting, Providence, Rhode Island, October 22-26.

5. Pitz, R W., J. A. Wehrmeyer, L. A. Ribarov, D. A. Oguss, F. Batliwala, P. A. DeBarber, S. Deusch, and P. E. Dimotakis. 2000. "Unseeded Molecular Flow Tagging in Cold and Hot Flows Using Ozone and Hydroxyl Tagging Velocimetry," Work-In-Progress Poster #P442 to be presented at 28th International Symposium on Combustion, Combustion Institute, Edinburgh, Scotland, July 30-Aug. 4.

Publications and presentations, associated with low temperature HTV, acknowledging support from this DURIP award:

Ribarov, L. A., Wehrmeyer, J. A., and Pitz, R. W. "Hydroxyl Tagging Velocimetry for Low Temperature Gas Flows." manuscript in preparation for submittal to *Applied Physics B.*

Ribarov, L. A., Wehrmeyer, J. A., and Pitz, R. W. 2000. "Molecular Flow Tagging for Low and High Temperature Flowfields." Poster #644 to be presented at the Optical Society of America Annual Meeting, Providence, Rhode Island, October 22-26.

Pitz, R W., J. A. Wehrmeyer, L. A. Ribarov, D. A. Oguss, F. Batliwala, P. A. DeBarber, S. Deusch, and P. E. Dimotakis. 2000. "Unseeded Molecular Flow Tagging in Cold and Hot Flows Using Ozone and Hydroxyl Tagging Velocimetry," Work-In-Progress Poster #P442 to be presented at 28th International Symposium on Combustion, Combustion Institute, Edinburgh, Scotland, July 30-Aug. 4.

Visible Raman measurements in sooting and non-sooting hydrocarbon-fueled flames

A major limitation for the application of spontaneous Raman to hydrocarbon-fueled flames is the laser-induced interference created by incandescing soot particles and fluorescing soot precursors, such as polycyclic aromatic hydrocarbon (PAH) molecules. The PAH compounds typically occur in fuel pyrolysis regions, especially when the local equivalence ratio is fuel-rich. This presents a problem when probing undiluted hydrocarbon diffusion flames or partially premixed flames that have a fuel-rich reactant stream. This latter situation is of current interest because of its relationship to the combustion environment found in direct injection spark ignition (DISI) engines operating under stratified charge conditions.

A current effort at Vanderbilt University is directed at understanding the DISI combustion process, in order to both maximize the combustion efficiency and minimize the hydrocarbon emissions of the DISI engine.[6] At light load conditions the DISI engine operates in a stratified charge mode, and in this mode the fuel is directly injected into the combustion chamber during the compression stroke and hence has time to mix only with a portion of the air in the chamber. As a result a burnable mixture does not exist throughout the chamber. Instead, regions exist within the chamber where there are mixtures either too lean or too rich to ignite, or at least too lean or too rich to burn without the sustaining action provided by hot products coming from burned regions.

The interaction between reacting flows of disparate equivalence ratio can be fundamentally modeled by the interaction between two opposing (or counterflowing) jets of premixed reactants, as shown in Fig. 3, where two "top-hat" jet flows impinge upon each other. Each jet can be rich or lean, even outside of flammability limits. The opposed jet reacting flow need be experimentally probed only along the symmetry axis to provide experimental data for comparison to numerical data.

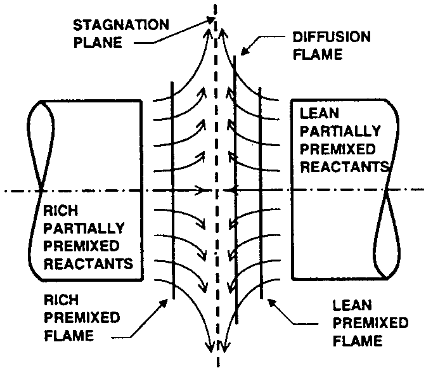


Fig. 3. Schematic of opposed jet flows of partialy-premixed reactants.

For a counterflow jet flowfield, where one jet is fuel rich and the other fuel lean, both within flammability limits, there can exist three separate flames, two premixed flames (one on either side of the stagnation plane), and a diffusion flame located near or at the stagnation plane, where the excess reactants left over from the premixed flames are finally consumed. This wide range of stoichiometries, for either counterflow jet, results in flames where PAH fluorescence can be an issue in obtaining reliable Raman measurements.

The Raman system shown schematically in Fig. 4 is used to probe partially-premixed flames associated with the DISI engine. This Raman system uses the high-pulse energy frequency-doubled Nd-YAG laser obtained with this DURIP award.

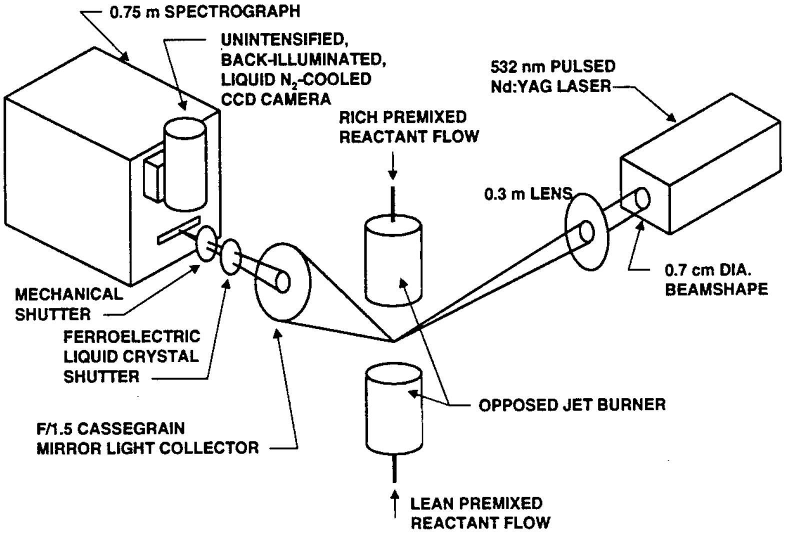
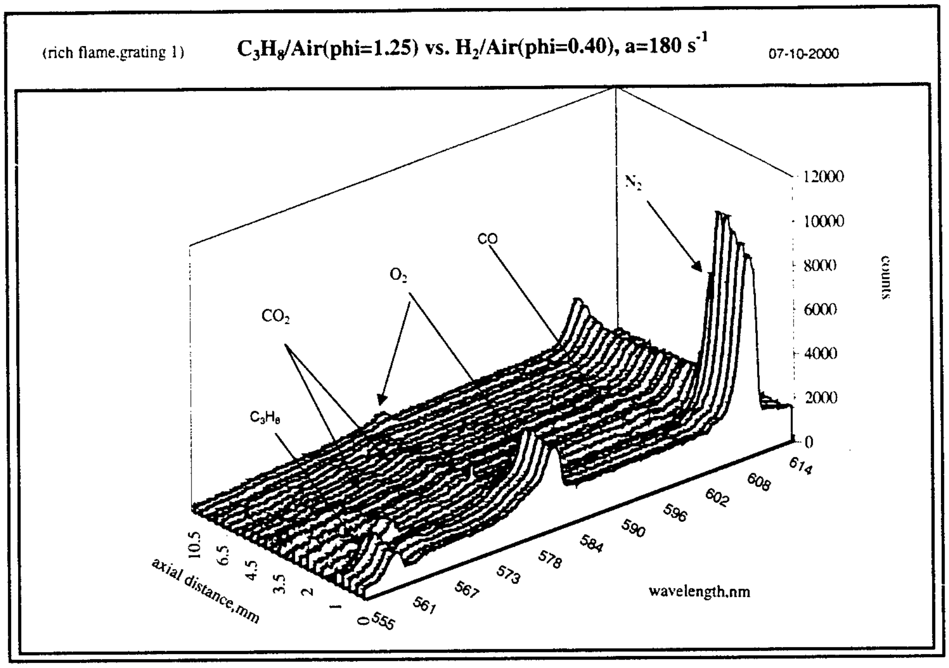


Fig. 4. Visible Raman system schematic, showing high pulse energy Nd-YAG laser.

By using the high-pulse energy, visible, Nd-YAG laser, rather than a UV excimer laser, Raman measurements relatively free of PAH fluorescence can be obtained. Figure 5 shows the visible Raman spectra obtained in a reacting flowfield produced between a rich propane/air jet and lean hydrogen/air jet. Each spectrum is the result of on-chip integration of signal coming from 300 laser pulses (30 seconds @ 10 Hz). No obvious PAH fluorescence is detected in these spectra. Two sets of spectra are shown because the spectrograph grating must be moved to image all of the major species Raman signals. Similar flames examined with a UV Raman System showed significant fluorescence interference in the fuel pyrolysis zone.[7]

During the 30 sec of time integration, significant interference from cosmic rays occurs in the Raman spectrum. Because of their highly localized nature these spikes can usually be identified separately from the actual flame spectra and subtracted out, although flame spectral information at that location is lost. By using the high pulse energy Nd-YAG laser of this DURIP award, as compared to low pulse energy Nd-YAG lasers, the integration time needed for a given Raman signal strength is lessened. Less integration time reduces the number of occurrences of cosmic ray events, and increases the amount of detected Raman signal per unit of detected background luminosity.



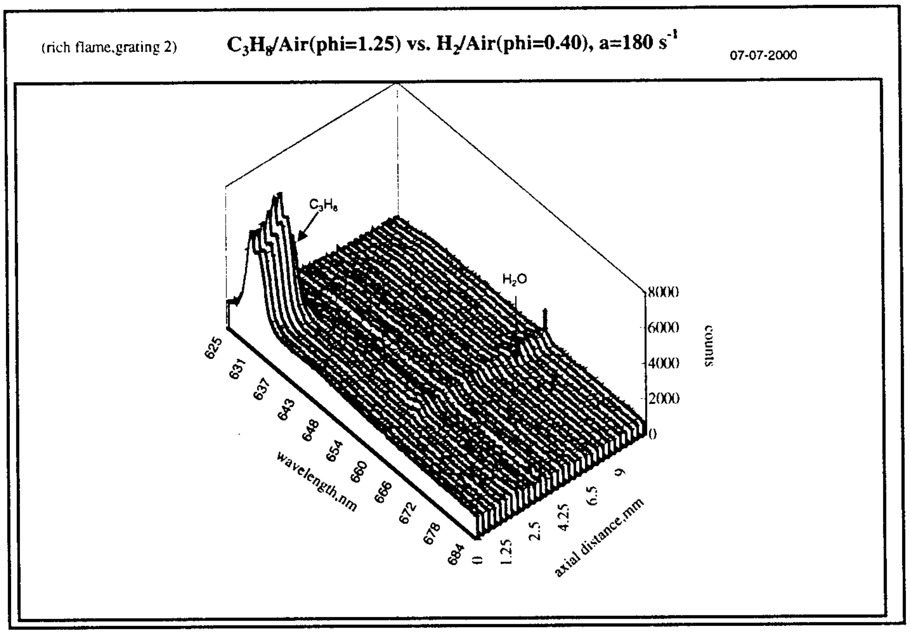


Fig. 5. Visible Raman spectra for rich propane-air reactant jet vs. lean hydrogen-air reactant jet.

References

6. Pitz, R. W., M. C. Drake, T. D. Fansler, and V. Sick. 2000. "Partially-Premixed Flames in Internal Combustion Engines." 21st Annual Combustion Research Conference, Office of Basic Energy Sciences, U. S. Department of Energy, Chantilly, Virginia, May 30-June 2, pp. 246-249.

7. Osborne, R. J., J. A. Wehrmeyer, and R. W. Pitz. 2000. "A Comparison of UV Raman and Visible Raman Techniques for Measuring Non-Sooting Partially Premixed Hydrocarbon Flames. " AIAA Paper 2000-0776 presented at the 38th Aerospace Sciences Meeting, Reno, NV, Jan. 10-13.

Publications and presentations, associated with visible Raman in hydrocarbon flames, that acknowledge DURIP support:

Wehrmeyer, J. A., Osborne, R., Mosbacher, D., Cheng, Z., and Pitz, R, 2001, "Investigation of Partially-Premixed Propane-Air Flames with Flame Curvature." Paper submitted for presentation at the 39th AIAA Aerospace Sciences Meeting, Reno, Nevada, Jan. 8-11.