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ADP012108

TITLE: Experimental and Computational Characterization of Combustion Phenomena

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TITLE: Army Research Office and Air Force Office of Scientific Research. Contractors' Meeting in Chemical Propulsion [2001] Held in the University of Southern California on June 18-19, 2001

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ADP012092 thru ADP012132

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EXPERIMENTAL AND COMPUTATIONAL CHARACTERIZATION OF COMBUSTION PHENOMENA

AFOSR Task No. 93PR02COR

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SUMMARY/OVERVIEW:

Propulsion systems represent a substantial fraction of the cost, weight, and complexity of Air Force aircraft, spacecraft, and other weapon-system platforms. The vast majority of these propulsion systems are powered through combustion of fuel; therefore, the detailed study of combustion has emerged as a highly relevant and important field of endeavor. Much of the work performed by today's combustion scientists and engineers is devoted to the tasks of improving propulsion-system performance while simultaneously reducing pollutant emissions. Increasing the affordability, maintainability, and reliability of these critical propulsion systems is a major driver of activity as well. This research effort is designed to forward the scientific investigation of combustion phenomena through an integrated program of fundamental combustion studies, both experimental and computational, supported by parallel efforts to develop, demonstrate, and apply advanced techniques in laser-based/optical diagnostics and modeling and simulation. These technical approaches are applied to explore a host of fundamental combustion phenomena, including turbulent mixing, turbulence-chemistry interactions, combustion chemistry and kinetics (particularly as they apply to the formation of particulate emissions), ignition, and two-phase flow characteristics.

TECHNICAL DISCUSSION:

Providing enabling propulsion-system solutions for Air-Force applications is the primary motivator for this research effort. While improved performance can be described quantitatively in many terms (*e.g.*, specific fuel consumption, thrust-to-weight ratio, etc.), it often involves efforts to increase heat release during the combustion process. Improvements may be achieved as well by reducing the length and/or weight of the combustor through informed design decisions. Engine emissions that might adversely impact the environment and the military signature of Air-Force systems must be reduced while striving to improve performance. Judicious design and control of the combustor can significantly impact the affordability, maintainability, and reliability of the propulsion system by extending the useful life of engine components or by permitting the incorporation of less-expensive materials in combustor construction, for example. Pursuing these goals requires a thorough understanding of the fundamental physics and chemistry of combustion processes.

While this AFOSR-funded program involves numerous ongoing investigations designed to address these goals, just a few recent advances are described in this abstract. Specific activities cited include continuing development of terahertz-radiation ("T-ray") systems for combustion studies in the far infrared and exploration of vortex-flame interactions with emphasis on application to the design and development of vortex-based ignition schemes.

Far-Infrared Measurements with Terahertz Radiation. Terahertz radiation falls energetically between the far-infrared and microwave spectral regions. While some basic spectroscopy has been achieved at terahertz frequencies in the past using evacuated far-infrared instruments or microwave devices, this region remains a largely "undiscovered" spectral territory dominated by molecular rotational transitions; however, that territory is being rapidly developed as an explosion of new terahertz-radiation research is fueled by the availability of coherent sources and time-gated detection techniques.^{1,2}

There exist numerous potential advantages of T-ray technology over combustion measurements in the visible and ultraviolet regions of the spectrum. Many species of interest do not possess electronic transitions suitable for detection using techniques such as laser-induced fluorescence; however, many molecules of interest do possess suitable rotational transitions in the terahertz region. As compared to the ultraviolet and the visible, effects due to scattering, optical thickness, and beam steering are typically reduced in the far-infrared due to the wavelength dependence of scattering cross sections and the characteristics of the real and imaginary components of the wavelength-dependent refractive index. Indeed, combustor flowfields that are nearly opaque in the visible region of the spectrum may transmit sufficient terahertz radiation from a coherent source to permit detection and analysis. Our preliminary studies reveal that soot and liquid fuels (JP-8 and JP-8+100 aviation fuels, for example) are largely transparent in the terahertz spectral region. These observations suggest the possible utility of T-ray technology in real-world combustors that exhibit high pressures, significant optical depth, fuel droplets and sprays, and potentially substantial soot loadings.

T-rays may also represent a solution to many optical-access and geometric constraints imposed by real-world propulsion systems. Many production combustors are not easily modified for access to detection techniques based on visible or ultraviolet radiation. Even when such modifications are possible, complicated geometries can make analysis of visible signals difficult. Advantageous transmission characteristics driving other T-ray imaging applications may be of value when performing combustion measurements. Many solid materials that are opaque in the ultraviolet, visible, or near-infrared regions of the spectrum exhibit transparent bands at frequencies near one terahertz.³ This information suggests that it may be possible to study certain "windowless" combustors without installing glass, quartz, or sapphire windows when using terahertz radiation.

To explore the potential diagnostics utility of T-ray technology while building on Grischkowsky's pioneering combustion work,^{4,5} we recently teamed with Picometrix, Inc., and

¹ M. C. Nuss and J. Orenstein, "Terahertz Time-Domain Spectroscopy," in *Millimeter and Submillimeter Wave Spectroscopy of Solids*, G. Gruner, Editor, Springer (1998).

² An excellent terahertz-radiation tutorial is available at <http://elec-engr.okstate.edu/thzlab/>, and a long list of links is available at <http://www-ece.rice.edu/~daniel/groups.html>.

³ D. M. Mittleman, M. Gupta, R. Neelamani, R. G. Baraniuk, J. V. Rudd, and M. Koch, "Recent Advances in Terahertz Imaging," *Applied Physics B*, Vol. 68, p. 1085 (1999).

⁴ R.A. Cheville and D. Grischkowsky, "Observation of Pure Rotational Absorption Spectra in the ν_2 Band of Hot H₂O in Flames," *Optics Letters*, Vol. 23, pp. 531-533 (1998).

⁵ R.A. Cheville and D. Grischkowsky, "Far Infrared, THz Time Domain Spectroscopy of Flames," *Optics Letters*, Vol. 20, pp. 1646-1648 (1995).

Innovative Scientific Solutions, Inc., to construct and demonstrate T-ray systems based on traditional delay-line schemes and asynchronous optical sampling (ASOPS).^{6,7}

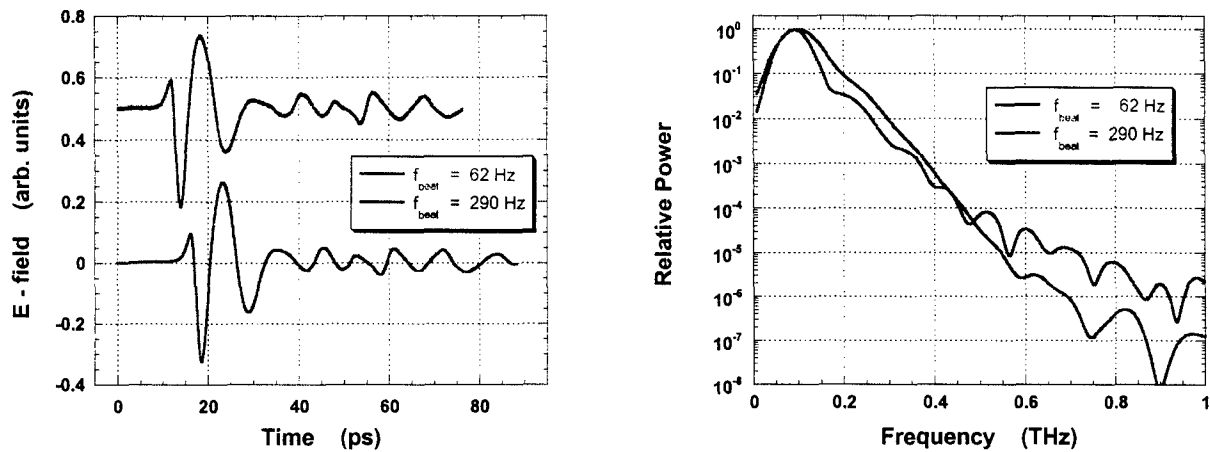


Figure 1. Time and frequency domain representations of the T-ray source spectrum.

Time-domain terahertz signals and the corresponding T-ray source spectra obtained by Fourier transformation are depicted in Fig. 1. These data were acquired at ASOPS beat frequencies of 62 and 290 Hz. (The ASOPS beat frequency describes the rate at which the optical delay is swept through the full free temporal range defined by the nominal laser repetition rate. In this case, the delay between the pulses is swept from zero to twelve nanoseconds at the rates identified above.) These signals were acquired for T-ray transmission through room air. Transmission and absorption spectra obtained in room air and a hydrogen-fueled Hencken flame are depicted in Fig. 2. These data reveal water's strong terahertz absorption features. Extensive signal averaging over the course of many seconds was required to achieve the signals depicted in these figures. Since this signal averaging impacts data-acquisition rates, ongoing efforts are devoted to improving sensitivity and system bandwidth. Continuing combustion experiments and efforts aimed at exploring transmission through various ceramics are underway as well.

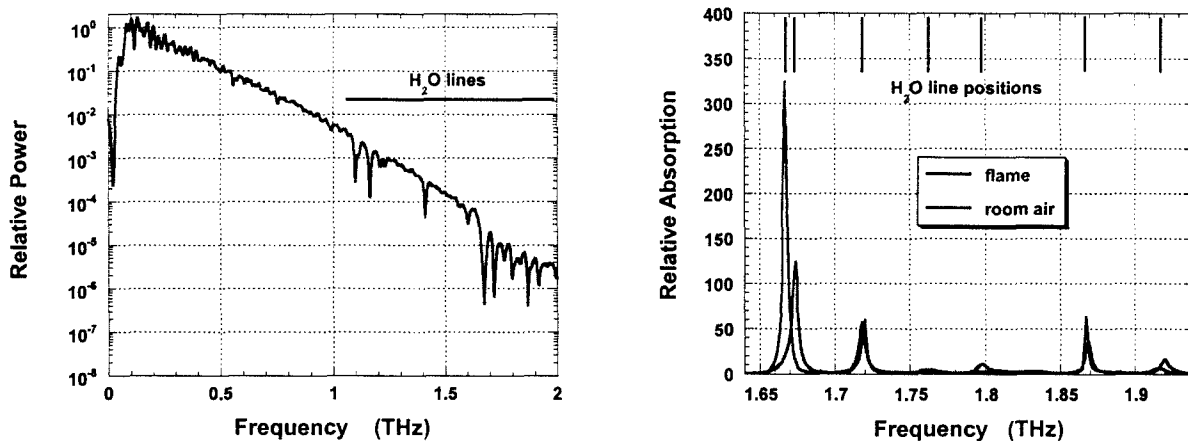


Figure 2. Terahertz spectra obtained in room air and in a hydrogen-fueled Hencken flame.

⁶ G. J. Fiechtner, G. B. King, and N. M. Laurendeau, "Quantitative Concentration Measurements of Atomic Sodium in an Atmospheric Hydrocarbon Flame with Asynchronous Optical Sampling," *Applied Optics*, Vol. 34, p. 1117, (1995).

Combustion in Impulsively Initiated Vortex Rings. Preliminary studies of reacting, premixed vortex rings have shown that flame propagation is highly sensitive to ignition timing, equivalence ratio, and vortex strength. During this investigation, a variety of divergent phenomena have been observed, including interior/exterior flame propagation, vortex-induced flame bridging across the jet column, annular extinction, flame-induced wrinkling, and the formation of unburned pockets. We have used planar laser-induced fluorescence of acetone, CH, and OH to study the non-reacting, reacting, and post-flame regions, respectively. Particle-image velocimetry has been used to measure the corresponding hydrodynamic conditions and establish input parameters required for direct numerical simulation. The flowfield includes well-characterized vortex rings of premixed methane and air generated at the exit of an axisymmetric nozzle using a solenoid-driven piston. Ignition is initiated at various phases of vortex development and propagation. PLIF data are being acquired for comparison with corresponding numerical simulations achieved with UNICORN, a time-dependent computational fluid dynamics code with chemistry. Time-resolved PLIF image sequences revealing the impact of post-actuation spark timing on vortex combustion are captured in Fig. 3. Similar parametric studies have been achieved to explore the impacts of equivalence ratio and vortex strength (as determined by piston stroke length) on combustion of the vortex.

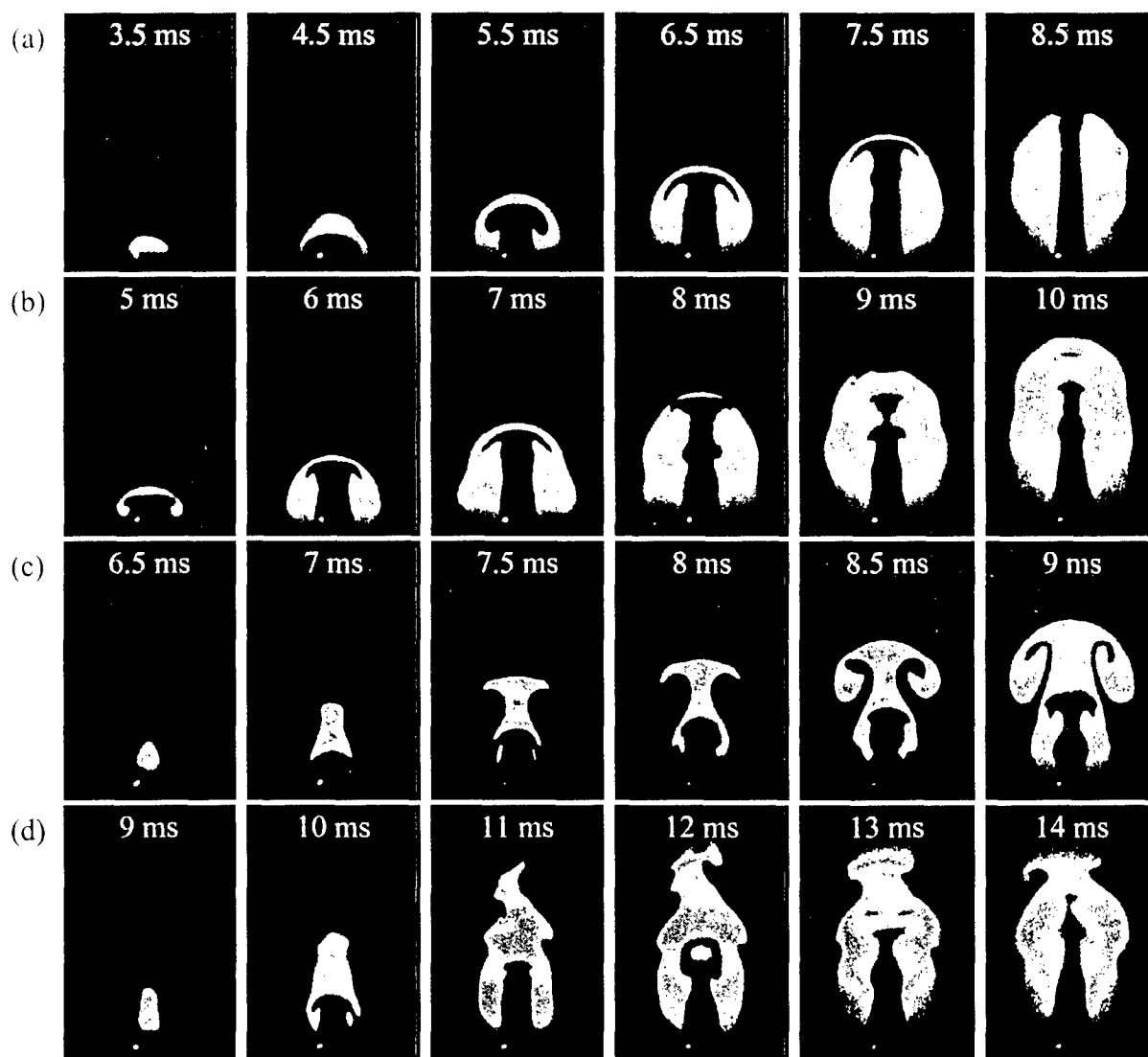


Figure 3. OH PLIF image sequence for spark timings of (a) 2.5 ms, (b) 4 ms, (c) 6 ms, and (d) 8 ms after piston actuation. Equivalence ratio is 1.0 and piston stroke is 3.3 mm.