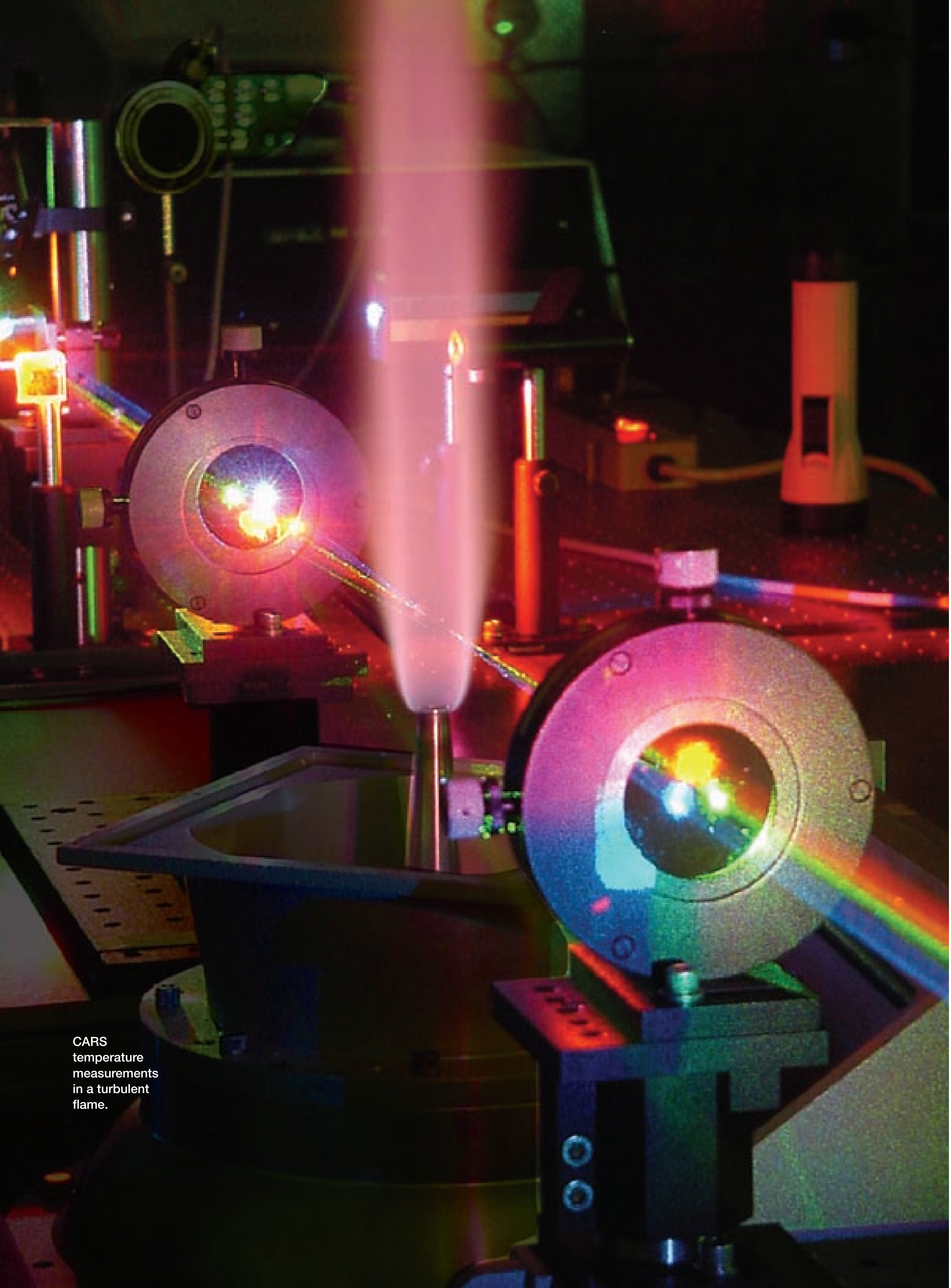


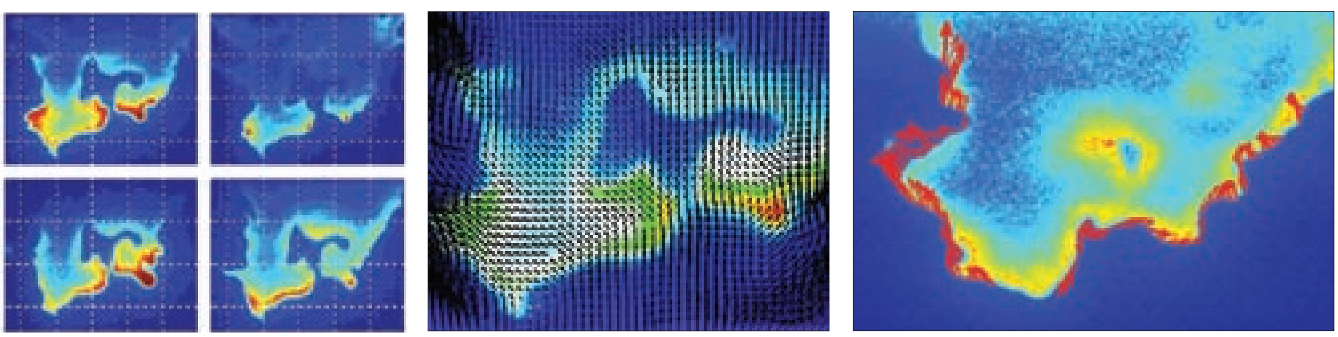
CARS temperature measurements in a turbulent flame.

Laser Diagnostics in Combustion Research

[Some Recent Advances]

Mark Linne and James Gord

Controlled combustion is among the oldest of human technologies; even the most modern combustion devices have their origins in the first half of the 20th century. Despite the long history of this technology, there is no shortage of modern challenges to tackle through combustion research. Since the 1970s, new combustion problems have continued to surface at a steady pace. This type of research has applications in emissions and noise control, combustor stability and reliability, energy efficiency, fire extinction and waste control.



(a) (b) (c)

[Rapid framing system to image dynamics of a turbulent, swirl-stabilized premixed methane air flame. This flame is related to advanced designs for gas turbine combustors, and the data have been generated for validation of detailed models. (a) Four PLIF images of OH taken in rapid succession (400 μs time delays). (b) A simultaneous image of flow-field velocity acquired via particle image velocimetry (PIV). These data make it possible to track flame front motion (c).]

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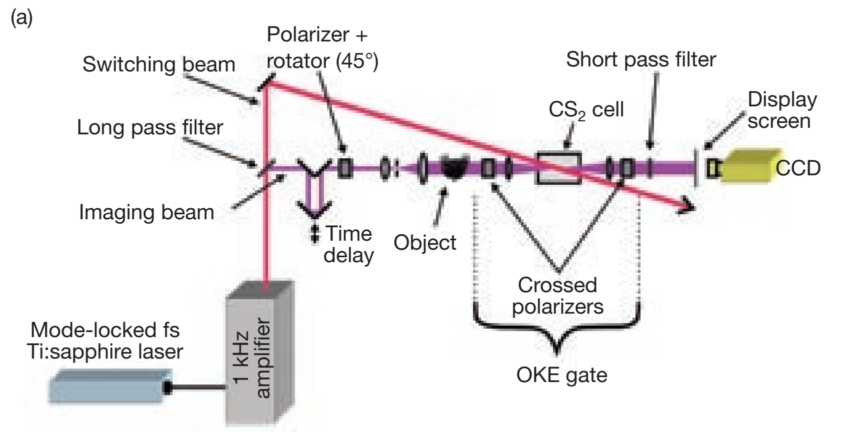
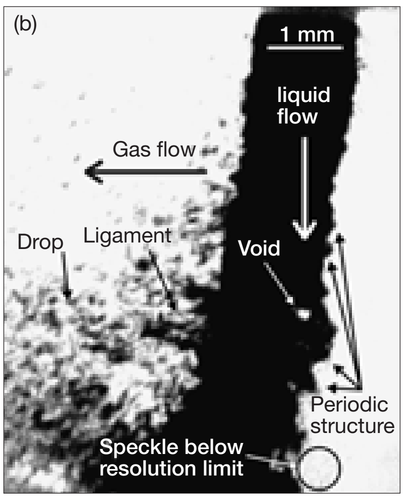
Two developments have contributed greatly to the advancement of combustion science over the past decade: advanced numerical models for combustion systems and the laser diagnostics that have made it possible to both generate and validate these models. Engineers use new model developments to design next-generation combustion systems, and then rely on optical diagnostics to investigate the new technologies. Academia, national labs and industry have worked collaboratively to nurture these new techniques and their application to practical devices, and this flow of knowledge has produced impressive results.

Laser diagnostics for flowfield velocity, temperature and species concentrations are critical to combustion research because, if performed properly, they do not disturb the fluid mechanics, heat and mass transfer or chemistry of a flame. These diagnostics can be performed within a very small sample volume (on the order of hundreds of microns) to provide multi-species, multidimensional single point statistics, or in a two- or three-dimensional imaging format—whichever is best matched to the modeling approach used.

This article describes a few recent advances in laser diagnostics that are making it possible to take this field to the next level.

[The Ballistic Imaging System]





(a) This ballistic imaging system is used at the Lund Institute of Technology and Wright Patterson Air Force Base. It uses very mild spatial filtering, together with polarization and time gating to create single-shot ballistic images with spatial resolution on the order of 20 to 40 μm. [From M. Paciaroni and M. Linne, Appl. Opt. **43** (26), 5100-9 (2004).]

(b) An example of a ballistic image of a spray in a cross flow of gas. This configuration is typically used for lean premixed pre-vaporized injectors for low NOx gas turbine engines, or for aircraft afterburner systems. While the portion of the jet facing the gas flow has been observable in the past, the wake region has not, and this region strongly affects mixing of fuel and air. [From M. Linne et al., Appl. Opt., in press (2005).]

Ballistic imaging for the liquid fuels

Liquid fuels are commonly used in combustion systems because they have very high energy density. In order to use the fuel effectively, however, it must be dispersed into the air stream using a spray. Models for liquid-fueled combustion systems thus require a sub-model for spray breakup and vaporization. This has been a weak link in the modeling process because spray breakup is not understood well enough to generate a fully generic and portable breakup model.

The principal missing component has been an understanding of what happens to the liquid portion of the jet near the centerline, just at the location where it exits into the air (called the "near field" of the spray). This problem has persisted because most atomizing fuel sprays have a very dense cloud of small droplets shrouding the near field, and this cloud appears opaque when normal imaging techniques are used.

However, various forms of ballistic imaging that were initially developed to image biological tissue can be adapted to the problem of imaging inside the near field of a spray. This requires an instrument that can segregate minimally scattered photons from multiply scattered photons, so that an image can be prepared using the minimally scattered light. For spray studies, it is also necessary to do this within one camera frame (10 µs) because of the transient nature of sprays.

Minimally scattered light has several signatures that can be used to distinguish it from multiply scattered light: It is nearly collinear with the input beam, first to exit, and the input polarization and coherence are preserved.

Researchers at the Lund Institute of Technology and the Air Force Research Labs have recently demonstrated that two images taken in rapid succession can be correlated to provide an image of the velocities of the features at the liquid/gas interface and of the droplets.

Commercially available lasers and cameras make it possible to do this twice in rapid succession, thus enabling image acceleration of these same features. Because the density of the liquid phase can be considered constant, such an image provides a two-dimensional map of the force vectors acting to tear the liquid core apart. This development can determine unambiguously the processes by which the near field breaks up.

Rapid-frame imaging

Techniques such as laser Rayleigh scattering and laser-induced fluorescence are commonly used in a two-dimensional format by spreading the excitation beam into a sheet and imaging at 90° using an intensified camera. This technique produces images of temperature and species concentration that have provided critical insight into model development.

Recently, researchers from the Lund Institute of Technology and the Technical University of Darmstadt have applied a rapid framing system to image dynamics of a turbulent flame (results will be published soon). The system consists of a pulse-burst Nd:YAG laser that generates eight pulses with variable time separation down to 7 µs between pulses. The beams are frequency doubled and then used to pump a set of four dye lasers.

The output of the dye lasers is then combined into a single beam using polarization and doubling schemes, and that beam is formed into a sheet. This tunable system has been used to pump ultraviolet transitions in the OH molecule (the A ← X electronic transition), and the image is acquired using a Hadland camera consisting of eight intensified arrays that are arranged in a Gatling gun configuration. This makes it possible to acquire eight OH planar laser-induced fluorescence (PLIF) images at the same speed as the laser system. (See figure on p. 31.)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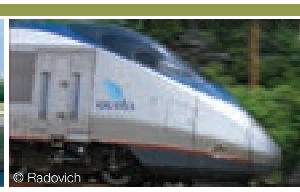
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[Combustion Research: Past Successes, Future Challenges]

Worldwide, spending for combustion research has been small compared with other areas of applied scientific research. Yet this work has led to some major success stories. Thanks to combustion research, for example, automobile engines operate at greater efficiency than ever before. Emissions have been reduced to just a few percent compared to 1966 levels (depending on the pollutant), according to 1998 data from NARSTO—a collaborative North American organization for studying ozone behavior.

A report from the Environmental Protection Agency indicates that average gas mileage does not accurately reflect these efficiency improvements because larger vehicles are more popular than they were when the U.S. Clean Air Act was passed. All the same, large SUVs lumber as far on a gallon of gas today as much smaller cars did in 1975. Similar advancements have been achieved in other combustion-based industries.

At the same time that emissions requirements are holding or tightening, energy supply issues are gaining importance. These are both critical issues, but they present a looming problem: It is difficult to find ways for engines to simultaneously burn more efficiently and reduce emissions across the board. Often these needs compete with one other. Moreover, each type of engine has its own set of limitations.

As just one example, traditional heavy-duty diesel engines are relatively efficient, and, because of this, they also produce low CO_2 emissions on a per-kW basis. Yet in the United States these same engines are required to reduce the emission of soot tenfold between now and 2010. Currently, the only options available for achieving that goal is costly and high-maintenance after-treatment devices. Engine manufacturers and owners agree that a better solution is needed.

In every projected scenario, combustion is anticipated to be the main form of chemical energy conversion for decades to come. Other technologies require more time to implement and more capital expenditure.

Electric power production or transportation may not seem as glamorous as the new fields of nano-science or bio-technology. Yet they are fundamental to modern society: Combustion research is what can enable electric power to remain available at the wall plug, and for people to have access to efficient, reliable forms of transportation with minimal environmental impact.

Although significant progress has been made, researchers have not yet achieved all of their goals because combustion is a highly complex and difficult problem. This area of research is in a genuinely exciting phase as new discoveries and advancements make new technologies possible.

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CARS spectroscopy of nitrogen using a dye laser

Picosecond Coherent Anti-Stokes Raman Scattering (CARS) has the potential to improve temperature and species measurement accuracy by reducing or eliminating the nonresonant contribution to the signal. Researchers at Wright-Patterson Air Force Base have recently demonstrated picosecond CARS spectroscopy of nitrogen using a 145-ps pump beam and a 115-ps Stokes beam.

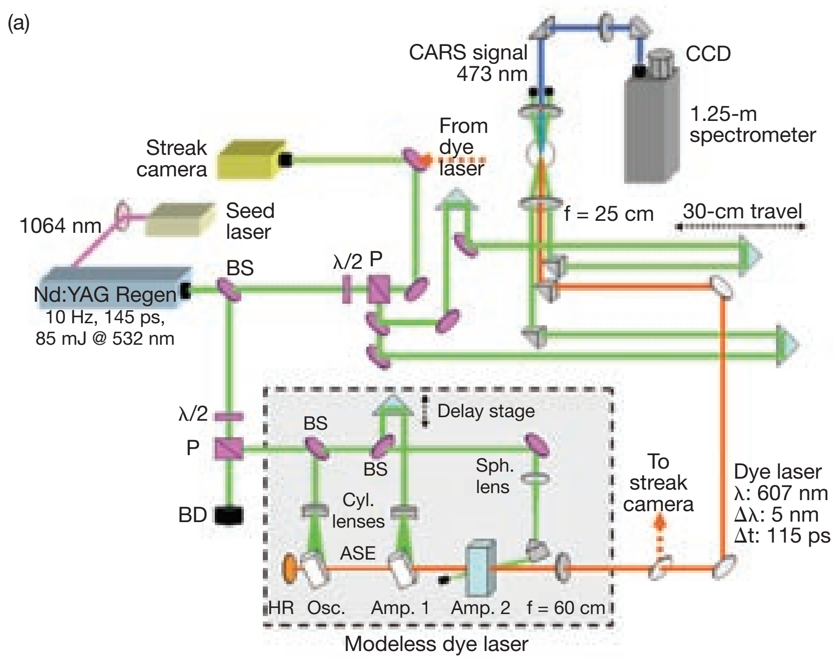
The broadband picosecond Stokes beam (at roughly 607 nm with a full width half maximum of 5 nm) is generated by pumping a modeless dye laser with a nearly transform-limited, 532-nm pump beam from a Nd:YAG regenerative amplifier. This broadband dye laser enables single-shot thermometry in unsteady flows, in contrast with scanning CARS using picosecond optical-parametric-amplifier-based, distributed-feedback or synchronously pumped dye-laser systems (see schematic diagram at left).

Figure (b) at left illustrates normalized broadband CARS spectra of nitrogen in a C_2H_4-air diffusion flame stabilized over a flat-flame burner, resulting in effective suppression of nonresonant background. Further, a time-resolved study at room temperature indicates that the magnitude of the nonresonant signals from Ar, CO_2, and O_2 are decreased by more than three orders of magnitude when the probe beam is delayed by about 110 ps; by contrast, the resonant N_2 CARS signal is reduced by only a factor of three.

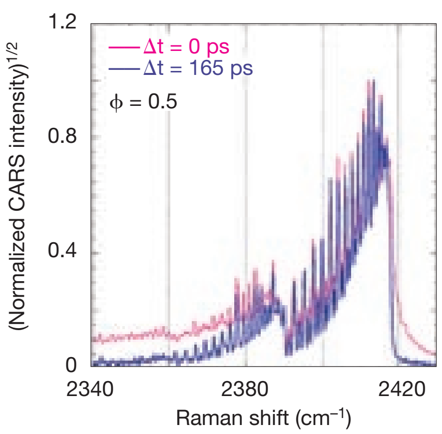
Through an appropriate selection of pump-probe time delay, the performance of CARS thermometry could be significantly enhanced in high-pressure, liquid-fueled combustors of practical interest—which have significant quantities of species with high nonresonant susceptibility.

[Broadband Picosecond CARS System]

(a)



(b)



(a) Schematic diagram of a broadband picosecond CARS system.

(b) Normalized broadband CARS spectra of nitrogen in a C_2H_4-air flame showing nonresonant background suppression for a probe-beam delay of 165 ps.

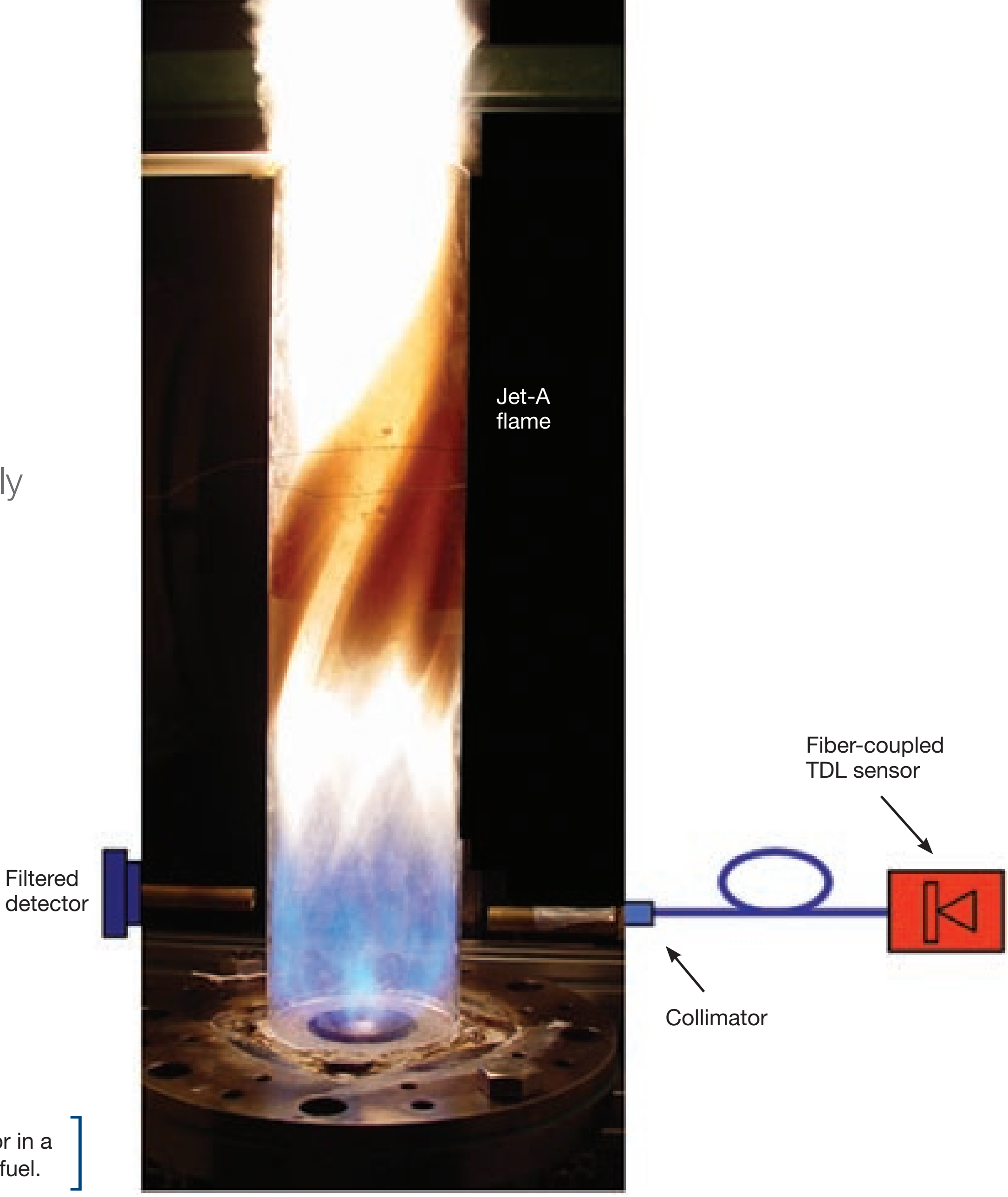
Diode-laser-based sensors for combustor control

A common approach to difficult engineering problems is to close a feedback loop. One might be tempted to follow such a strategy in an effort to achieve combustor stability, efficiency and emissions control. Unfortunately, however, flames are multi-dimensional, fast and highly nonlinear, making them extremely difficult to control.

The best alternative seems to be some form of model-based control wherein a sensor accurately determines a small number of flame parameters, and a model is used to predict flame behavior based on those measurements. Researchers can then infer a new setpoint for the fuel or air supply. Such a model would be a simplified version of existing complex codes.

Stanford researchers have recently developed a robust sensor for non-intrusive measurements of gas temperature in

“Flames are multi-dimensional, fast and highly nonlinear, making them extremely difficult to control.”



[Diode laser based sensor in a flame fired by a realistic fuel.]

combustion systems using a single diode laser for absorption measurements on two transitions of water vapor in the near-infrared. The sensor uses a fiber-coupled tunable diode laser (distributed feedback) operating near 1.4 μm and wavelength-scanned over a pair of H_2O absorption transitions (7154.354 cm^{-1} and 7153.748 cm^{-1}) for scanned-wavelength-modulation spectroscopy with second harmonic detection.

Real-time temperature can be inferred from the ratio of absorbance on the two transitions at a 2-kHz rate. This system provides temperature measurement accuracy (spatially averaged across a line of sight) of around ±10° C.

Single lasers can be used to create compact, rugged low-cost sensors that are simple to operate. The scanned-wavelength approach can minimize interference from emission and provide robust temperature measurements.

More research on laser diagnostics for combustion is under way in the United States, Europe and Asia. Many advances are driven by rapid developments in sources and detectors. This is truly an exciting time to be working in this area.

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