New Diagnostic Techniques in Engine Combustion Research

D. L. Hartley and T. M. Dyer

Combustion Research Facility
Sandia National Laboratories, Livermore, CA 94550

ABSTRACT

The application of advanced diagnostics and computer analysis to the study of combustion processes in IC engines has been a major element of the Combustion Research Facility program for a decade. Working closely with industry and universities, a series of research objectives related to critical engine combustion problems has been defined, and these objectives have dictated an evolution of experimental and computational capabilities that form our efforts.

A significant element in our experimental program is the optically-ported research engine designed for access by our diagnostics, and with sufficiently simplified geometrical design to be modeled by the computer analysts. Several of these engines are used with different diagnostic systems for studying the important combustion issues. Laser Doppler velocimetry is used for flow field velocity and turbulence measurement; Rayleigh scattering is used for density measurement; spontaneous Raman scattering is used for major species concentration and average temperature measurement; and coherent anti-Stokes Raman spectroscopy is used primarily for instantaneous temperature measurement. Several new techniques involving laser-induced fluorescence and planar imaging, as well as coupling to high speed physical sampling and flow visualization are also being studied to expand our ability to fully understand the combustion details. This paper reviews the status of these experimental efforts, and how they fit into our overall combustion programs.

INTRODUCTION

The continuing and growing need for detailed understanding of the combustion process in IC engines has been a major motivator behind the adoption of advanced measurement methods in engineering. The confrontation with the clean air crisis in the 1960's placed demands on designers and equipment manufacturers to fully understand the emission characteristics of engines; this lead to the general adoption and further sophistication of techniques to measure small quantities of specific pollutants, NOx, CO and unburned hydrocarbons, in the exhaust system. However, these techniques did not have to be rapid response nor space-resolved, but they did, to a large degree, advance the understanding of the spectroscopic character of these molecules. Chemiluminesence, light absorption and, to a lesser degree, light scattering became important tools for the designer to better understand his product. Not surprisingly then, as the laser also made its practical debut in the 1960's and 70's, those researchers who fought the limits of accuracy of older methods found the laser an irresistable lever to further advance their diagnostic capabilities. As the energy crisis hit in the early '70's, this new capability was called upon to provide the designer with further needed details of the combustion process in order to fine-tune novel combustion schemes that promised higher efficiency.

The Combustion Research Facility (CRF) was conceived in that era, and was created with the intent of developing the most advanced diagnostic systems possible for combustion applications, with a special emphasis on combustion in engines. The formula for the program was developed a decade ago and is true today: half of the research dedicated to fundamentals in diagnostics and combustion, half of the research dedicated to applications of those tools to problems in practical combustors. Although funding for research at the CRF comes from several offices of the Department of Energy, the original formula for operation is maintained and the synergism strenghtens the overall progress. Fundamental studies (soot formation, turbulent reacting flow, nitrogen chemistry, spectroscopy) feed directly and immediately into the applied programs (engines, coal); and the applied programs are strongly coupled to industry through working groups that had their origins 10 years ago. Feedback from the working groups provides further guidance for the fundamental programs as well as the applied programs. This system has worked very well to date, and we endeavor to maintain this technical structure.

The evolution of computer modeling has also played a major role in setting goals for the diagnosticians. As large mainframe computers now have the capacity to manipulate complex, multidimensional computer models of combustion, the pressure exists for the diagnostician to validate (or disprove) these sophisticated models. To do so requires yet more information on temporal and spatial variations of several parameters. New methods of simultaneous space and parameter detection have therefore been created--many to apply to engines.

The engine combustion aspect of the CRF has benefited from playing such a central role in the CRF development, and from having several key staff apply our resources to the implementation of new engine combustion diagnostics. Recent reports (1-3) have discussed various aspects of this program, with particular emphasis on diagnostic achievements by our engine combustion team. This paper reviews the history of that team, and brings the reader up to date on its current status. We will first review the methods developed to measure certain important parameters in engines (velocity, concentration and temperature), and then we review new methods of complex diagnostics, multidimensional or multiparameters, to achieve yet another level of understanding of combustion.

VELOCITY AND TURBULENCE MEASUREMENTS

The fluid dynamic state of the fuel-air mixture at the time of ignition is one of the dominant factors controlling the combustion process. It is impossible to fully understand engine combustion without measuring the fluid properties and how they evolve during the intake, compression and postcombustion phases. The power of the new diagnostic techniques is in their ability to characterize the mixture motion including global flow characteristics, mean velocity, turbulence intensity, and turbulence scales.

Hot-Wire Anemometry

In early 1975 Pete Witze began our first measurements examining the applicability of hot-wire anemometry for IC engine applications. These early measurements defined the nature of turbulence in engines and how it varied with engine design and operating variables.

Much of the early work focused on the development of statistical techniques for the processing of hot-wire signals recorded in a motored engine (4,5). Since engine flow processes are highly unsteady it was necessary to use ensemble-averaging procedures to define both the mean flow properties and turbulence structure. Experimental results were obtained for the mean velocity, turbulence intensity, skewness, kurtosis, probability density distribution, autocorrelation function, one-dimensional energy spectrum, and the micro- and integral-scales of turbulence. We showed that the mean velocity and turbulence intensity varied linearly with engine speed, and that the turbulence scales were a function of geometry only. These studies suggest that these turbulence quantities were statistically well-behaved, which was the first indication that engine flow processes could likely be handled using previously developed classical models of turbulence.

Laser Velocimetry

During the late 1970's laser Doppler velocimetry (LDV) was developed to a high state of maturity so that it could be used in a variety of engine configurations. We found that the commercially available dual-beam backscatter optical configurations with a counter-type signal processor performed most satisfactorily. Several papers were published recording the development and the first applications of LDV to motored engines and to the simulated engine combustion environments of a combustion bomb.

The hot-wire anemometry work culminated in papers (6,7) critically comparing it with the newly developed nonintrusive laser Doppler velocimetry technique. Hot-wire and LDV measurements were taken in a motored high-swirl engine and compared to assess the validity of hot-wire measurements. The overall conclusion of the study was that LDV is far superior to hot-wire anemometry for engine applications for several reasons: (a) inherent accuracy, (b) ability to resolve a single velocity component and direction, (c) wide dynamic range, (d) capability to obtain measurements during combustion, and (e) nonintrusive nature. Regardless of the complexity and degree of turbulence in the flow, LDV was shown to have the potential to identify and accurately measure individual components of mean velocity and turbulence intensity.

Witze also performed an extensive investigation (7) of the procedure used to account for the sensitivity of the hot wire to changes in the gas temperature. The results showed that for the optimum conditions of known flow direction, low turbulence level, and low compression ratio, the hot-wire anemometer provided useful mean velocity results. Accurate hot-wire turbulence intensity measurements were possible only for the intake and exhaust strokes. One important advantage of the hot-wire is that it has a continuous analog output which is important in measuring turbulent time scales to infer length scales--parameters recently identified as major factors controlling the flame shape and burn duration in the engine.

In addition to these motored engine measurements, we examined the decay of turbulent fluid motion in our constant volume combustion bomb and made the first measurements during the combustion process (8). This combustion bomb, designed and fabricated by Volkswagen Research and loaned to Sandia as part of a cooperative program, closely simulates the combustion process near top dead center (TDC) in a conventional automotive spark-ignition engine. The thin, cylindrical combustion chamber has pyrex windows on each end. A highly-swirling methane-air mixture was introduced into an initially evacuated chamber through a tangentially-directed valve in the side of the cylinder. Time-resolved mean velocity measurements were made in both the pre- and postcombustion gases.

Milestone on Fluid Motion in IC Engines

By the early 1980's a significant experimental data base had been established for the noncombusting fluid motion in several engine and engine simulator configurations. A parallel development effort in the area of large-scale multidimensional simulations of the engine air motion, fuel sprays, and engine combustion processes was beginning to show promising initial results. The research community felt the time was right to document the progress made with these two emerging technologies. A milestone report (9) was prepared by Peter Witze, who edited the contributions of many researchers working primarily under the Department of Energy sponsored Engine Combustion Technology project. This report summarized the capabilities of multidimensional computer models developed by the project to predict the behavior of turbulent air motion in engine environments.

Computed results were compared directly with experimental data in six different areas of importance to IC engines: 1) induction-generated ring-vortex structures; 2) piston-induced vortex roll-up; 3) behavior of turbulence during combustion; 4) decay of swirling flow during compression in a simplified engine; 5) decay of swirling flow in the constant volume combustion bomb; and 6) exhaust-pipe flow. The computational procedures used included vortex dynamics, rapid distortion theory, and finite difference models employing two-equation and subgrid-scale turbulence models. A summary of the comparisons between the measurements and computations of the decay of swirling flow in an engine is shown in Fig. 1. Although the capability did not then exist to predict the air motion in an engine from its geometric configuration alone, the results showed that many flow field subprocesses could be predicted given well-specified initial and boundary conditions.

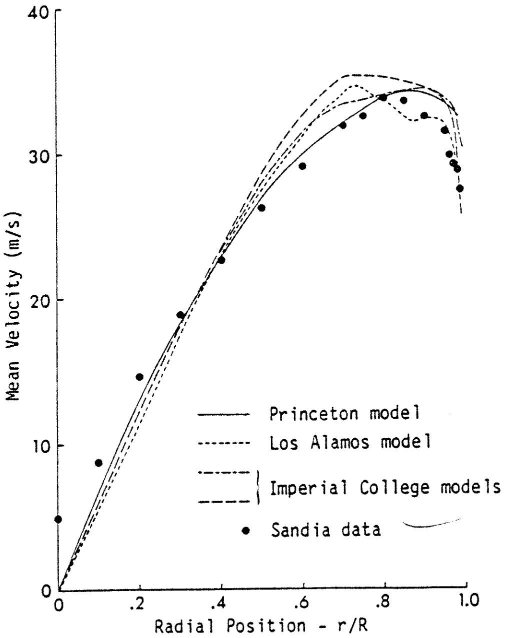

Fig. 1 Summary comparison of measured velocity profile with several calculations for swirling flow in the research engine at 1200 rpm. (from Ref. 9)

Measurements and Predictions of Precombustion Fluid Motion

During 1983 a collaboration was begun between Peter Witze, and Jay Martin and Prof. Claus Borgnakke from the University of Michigan. Some of the results of this collaboration were the comparisons of measured and predicted fluid motion in our optical research engine.

In the first study published (10), LDV results were presented for the mean velocity and turbulence intensity measured in the engine. The compression of complex bulk motions created during induction produced turbulence as the piston approached TDC. The turbulence field was shown to be isotropic but nonhomogeneous. A zero-dimensional computer simulation developed by Borgnakke based on an averaged k-ϵ model adequately predicted the measured pressure histories when the turbulence results determined from the motored tests were used to establish initial conditions for the combustion model.

Conditionally Sampled LDV

As interest grew in extending these capabilities beyond precombustion fluid motion to that during the combustion event, the techniques had to be refined to deal with variations in flame conditions. The cyclic variability of the engine combustion process stimulated the application of conditional sampling techniques for two reasons: (a) to provide a logical framework for sorting data into groups with similar characteristics, and (b) to use these groupings to investigate cause-and-effect relationships. Conditional sampling requires multiple measurements of pressure, flame position, and other properties at every velocity realization. These simultaneous measurements make it possible to postprocess the data in search of strong correlations. By judicious selection of the sampling criteria, Witze proposed (11) that one is able to test the validity of certain cause-and-effect relationships that may prove to have importance in resolving the issue of turbulence and combustion interactions.

In an initial study using these techniques (12), LDV measurements were made in the homogeneous-charge engine, igniting at the side wall of the cylindrical combustion chamber. The fluid motion in the direction of flame propagation was measured at the center of the chamber. An ionization probe simultaneously identified the time of flame arrival at the velocimeter probe volume. Phase-averaged measurements recorded from many engine cycles were conditionally sampled according to flame arrival time. The data, shown in Fig. 2, indicate an increase in the unburned gas turbulence from compression, and strongly suggest that cyclic variation in burn duration is caused by cyclic variation in the bulk turbulence intensity ahead of the flame.

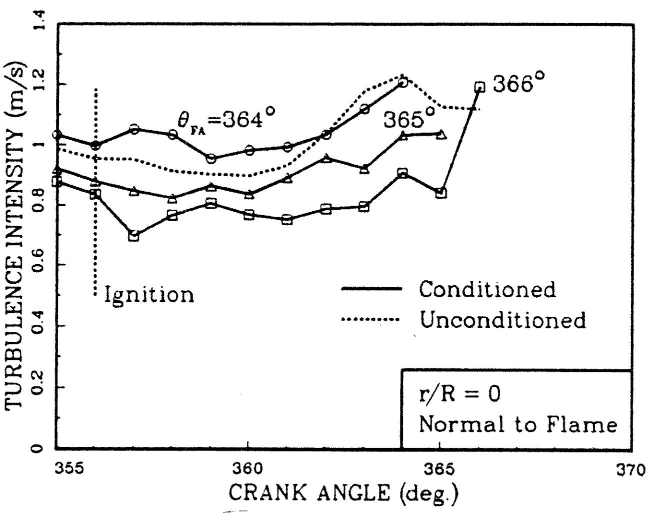

Fig. 2 Conditional sampling of the unburned gas velocities based on time of flame arrival reveals that a correlation exists between the flame velocity and the turbulence intensity ahead of the flame. (from Ref. 12)

In subsequent studies (13,14), LDV measurements of the mean velocity component in the direction of flame propagation were shown to agree well with a computer simulation of the induced velocities generated by the volume expansion of the burned gases. Mean velocities measured parallel and normal to the flame surface were shown to be complex with strong mean motions, and anisotropic and nonhomogeneous turbulence. Conditional sampling on the time of flame arrival at the LDV probe volume revealed a cyclic-variation bias error in the turbulence component normal to the flame. The turbulence field ahead of the flame appeared to be enhanced by compression, with the component normal to the flame increased twice as much as the parallel component. This finding was later confirmed (15) by measurements in an engine configuration where special care was taken to achieve a high level of uniformity and isotropy over the entire chamber at the time of ignition.

CONCENTRATION AND TEMPERATURE MEASUREMENTS

In situ measurements of gas mixture concentrations and temperatures inside the engine combustion chamber have been the most elusive data sought by the engine designer. With increased interest in direct-injection stratified-charge (DISC), axially-stratified, and direct-injection diesel engines, a more complete understanding is required of the fuel injection process consisting of atomization, vaporization, and mixing with the surrounding air. We know from hard experience that even subtle design changes affecting these processes can result in dramatic changes in the engine performance and emissions. The stratified mixture combustion process within the chamber, while holding the key for highly efficient, multifuel, low emission engines, has been the most problematic for the designers to optimize because of the many competing processes and the lack of in-cylinder concentration distribution measurements.

In a similar vein, emissions of NOx, CO, unburned hydrocarbons, and particulates are strongly controlled by chemical kinetics and are thus highly sensitive to combustion chamber temperatures. The control of NOx has proven to be the most problematic regulation facing the automotive industry because the NOx control strategies generally have a deleterious effect on HC, CO, and particulate emissions, in addition to fuel economy and performance. Understanding the trade-off between these many parameters as well as the kinetics of autoignition leading to engine knock have suggested that detailed measurements of in-cylinder temperatures are also essential.

Initial Spontaneous Raman Measurements

In the mid-1970's Bob Setchell undertook a pioneering investigation to examine the experimental feasibility of obtaining Raman scattering measurements within a firing engine (16). The specific objectives of this investigation were to establish the sensitivity of Raman for measurements of local precombustion fuel-air ratios for stratified-charge engine designs, and to examine emission and laser-induced spectral backgrounds in the postflame gases. A single-cylinder, L-head engine was modified with quartz and sapphire windows to permit optical access for the incident laser beams and the scattered signal.

This study was the first to demonstrate that vibrational Raman scattering was a sufficiently sensitive technique to provide useful species concentration measurements in gas-phase fuel-air mixtures. A typical spectra obtained with the Raman technique is shown in Fig. 3. The precombustion concentrations of propane, oxygen, and nitrogen are readily quantified from the data. This initial feasibility study performed during 1976 sparked the future work of Sheridan Johnston in using a continuous wave (cw) laser to probe precombustion fuel mixing processes, and the studies by Ray Smith in using a pulsed laser for single-shot temperature and concentrations during the combustion event.

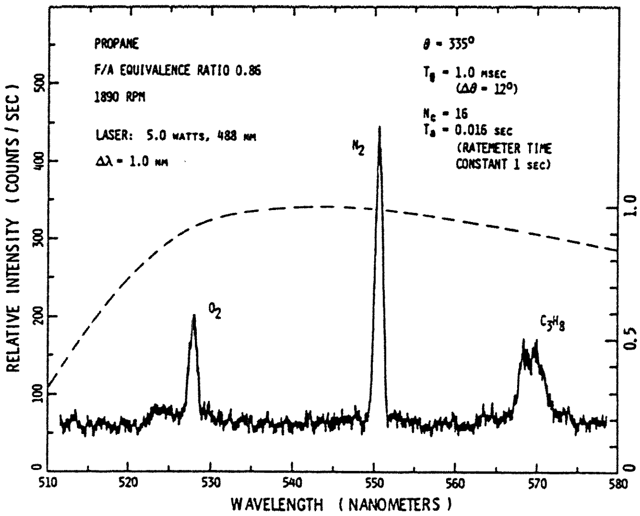

Fig. 3 Spontaneous Raman has been used to measure ensemble-averaged fuel-air concentrations prior to ignition in a lean-burn engine. (from Ref. 16)

Precombustion Fuel-Air Distribution

By the late 1970's, we had designed and fabricated several nominally-identical optical research engines that were to prove to be in future years a laboratory standard for our facility. There were a variety of laser diagnostic techniques applied to this engine.

Sheridan Johnston focused on the application of cw laser Raman scattering to determine fuel-air distribution in the motored optical engine operating in a direct-injection stratified-charge mode (17). The primary objective of the study was to obtain point measurements of the mean, gas-phase fuel-air ratio across a diameter in the combustion chamber for a single set of engine operating parameters. A secondary objective was to obtain flow visualization records of the fuel injection and mixing processes for both liquid- and gas-phase injection.

Results of the study showed that large spatial variations in the fuel-air ratio occured in the cylinder during and after fuel injection. Figure 4 shows a three-dimensional plot of the variation of equivalence ratio across the engine bore as it evolves during the engine cycle. Near TDC, fuel-air mixing was nearly complete, but the distribution across the cylinder diameter still exhibited a region of relatively low fuel concentration.

Instantaneous Temperature and Density

As a complement to the work of Johnston, Ray Smith focused on pulsed spontaneous Raman scattering to obtain measurements of temperature and nitrogen density, and the fluctuations of these quantities in a combusting engine (18-21). This nonintrusive technique demonstrated one cubic millimeter spatial resolution and essentially instantaneous temporal resolution (10 nsec). Densities were determined by measuring the Stokes vibrational scattering of nitrogen, and the temper-

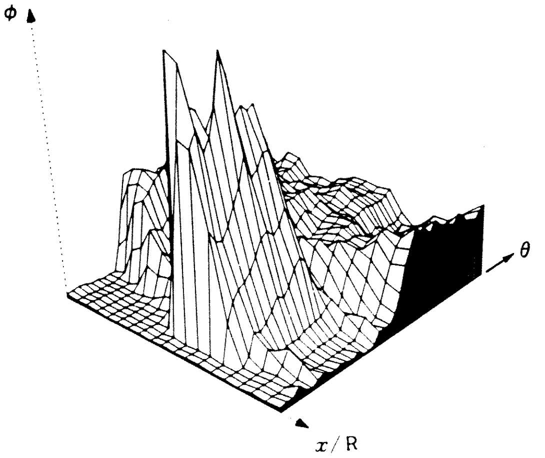

Fig. 4 Three-dimensional graphics help to show the temporal variation of fuel-air equivalence ratio measured along a diameter in a motored direct-injection stratified-charge engine. (from Ref. 17)

atures were determined by measuring the ratio of anti-Stokes to Stokes scattering. Temperatures and densities at two locations, over crank angles covering the compression and expansion strokes, for four equivalence ratios were measured. Temperature histories, shown in Fig. 5, illustrate the reduction in peak temperatures as a result of leaner equivalence ratios. These papers were significant in that they presented the first instantaneous measurements of fluctuating temperatures and density within an operating engine.

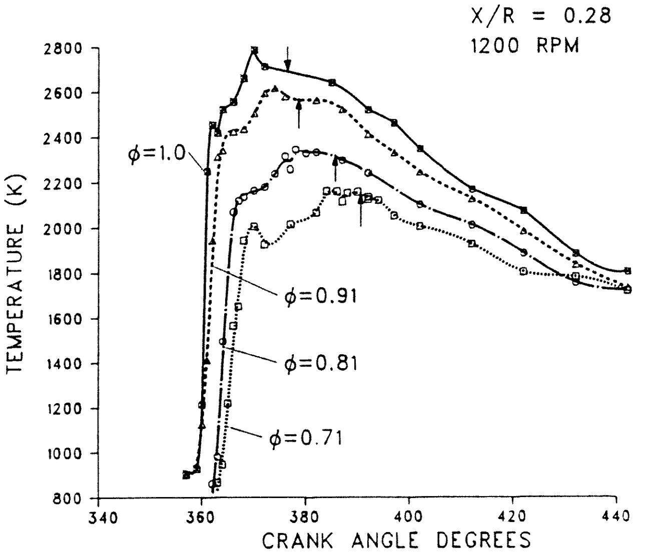

Fig. 5 Pulsed Raman measurements of temperature history show a strong dependence on equivalence ratio. Burned gas temperatures continue to rise till near the time of peak pressure indicated by the arrow. (from Ref. 20)

Raman Combined with LDV

After successfully demonstrating the capability for point measurements of temperature, concentrations, and velocities in an engine, we investigated the synergistic effects of multiple probes in identical engines to measure several parameters. In 1979 we reported the first extensive set of measurements taken in the engine operated in a direct-injection stratified-charge mode (22). The optical measurement techniques employed included cw laser Raman scattering for fuel and air concentrations, pulsed Raman for density fluctuations, high-speed cinematography for flow visualization, and LDV for velocities and turbulence intensities. More conventional data on cylinder pressure, power, and emissions levels were also given. The purpose of the study was to demonstrate the added information that could be gained by coupling the results of several different diagnostic systems.

This paper provided the first comprehensive set of detailed measurements made in an engine. It demonstrated the feasibility and power of a new generation of laser-based optical diagnostic techniques for providing insight into the controlling subscale processes governing engine combustion and emissions.

Combined Measurements in a Combustion Bomb

Another facility we have found useful in our combustion studies is a constant volume combustion bomb. We used the bomb to compile another comprehensive set of well-characterized experiments which could be used to validate computer models of IC engine combustion (23). Extensive variations of experimental conditions allowed the kinetics and fluid mechanics in the codes to be independently evaluated by making single parameter variations in fluid motion, equivalence ratio, temperature, and mixture density. Thermodynamic properties of the swirling, uniform precombustion mixture were characterized by measuring pressure, temperature distribution (with thermocouple probes), velocity/turbulence (with LDV) and equivalence ratio. Combustion diagnostics included pressure histories, high-speed laser shadowgraph filming, flame position determined with a laser refraction technique, and time- and space-resolved density using laser Rayleigh scattering.

Transient Fuel Concentration in the Spark Gap

As a follow-on study to the gas-phase measurements, Johnston used cw Raman scattering to measure transient, precombustion fuel-air ratios at the spark plug electrode gap in a DISC engine and correlated the data with mixture ignitability measurements (24). Figure 6 illustrates the temporal variation in equivalence ratio inside the spark gap and its effect on the rate of misfire. Lean flammability limits determined from the ignition study suggested a dual-ignition mechanism that depended on the rate of change of equivalence ratio with crank angle. Flow visualization of the stratified charge combustion revealed substantial differences in mixture burn characteristics and combustion duration as the ignition crank angle was varied. Quenching of the burning mixture was observed and its occurrence was correlated with the Raman measurements.

Raman Applications to Spray Measurements

Johnston also performed a feasibility study examining the use of spontaneous Raman for precombustion engine spray measurements (25). He inves-

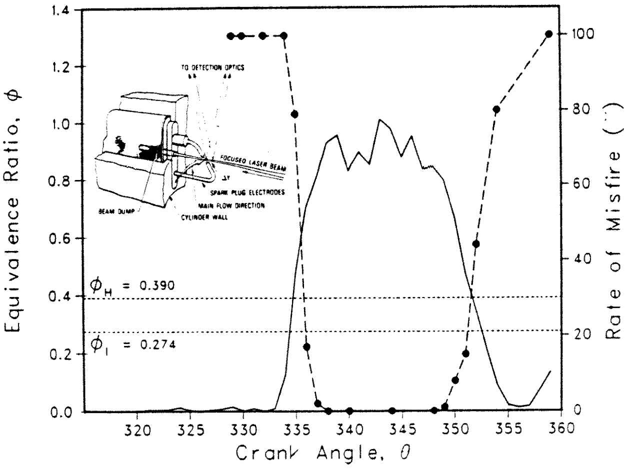

Fig. 6 The Raman measured variation in equivalence ratio within the spark gap of a DISC engine correlates with spark timing to achieve low rates of misfire. The inset shows the plug configuration and the measurement volume. (from Ref. 24)

tigated several experimental topics such as spectroscopic distinction between the liquid and vapor phase of the fuel, spray fouling of windows, laser transmission through the spray, and laser-induced background from droplet scattering. A technique for vapor temperature measurement in precombustion, vaporizing fuel sprays was developed and applied. Mie scattering was also used to complement the Raman measurements.

Results of the study indicated that vibrational Raman scattering alone could not distinguish between liquid- and vapor-phase propane fuel, at least for the spectral resolution found to be most useful in engine mixing studies. However, when combined with the Mie scattering diagnostic, it was possible to distinguish between liquid and vapor regions and to make sensible, time-averaged number density measurements in the spray boundary. Inherent limitations of the cw experiment prevented separation of fuel number density measurements obtained in two-phase flow regions into a liquid and vapor phase contribution.

Raman and Sampling Probe Comparisons

In a cooperative effort with Dave Lancaster from the General Motors Research Laboratories, an experiment was performed to quantify probe-induced aerodynamic perturbations to in-cylinder sampling measurements in a motored engine (26). Good agreement was observed between concentration measurements obtained with a sampling probe utilizing a flame ionization detector and those obtained by laser Raman scattering at the probe tip. However, large differences were found between the Raman-measured concentration profiles obtained with and without the probe installed in the engine. These differences occurred because of probe-induced perturbations to the in-cylinder air motion that decreased the mean velocity and increased local mixing rates.

Crevice Hydrocarbon Emission Measurements

In the early 1980's major contributions were made by the engine combustion working groups toward understanding the sources of unburned hydrocarbons from homogeneous-charge engines. Unique sampling valve, laser Raman, and flow visualization were combined with a range of detailed kinetic and analytical models to validate a new interpretation of early hydrocarbon emission experiments (for more detail see Ref. 27). The new revelation was that piston ring and head gasket crevice volumes and to a lesser extent absorption and desorption by lubricating oil films and chamber deposits are the major sources of unburned hydrocarbon emissions. The previously held concept, which was based on flame quenching by the cold walls, was shown to be unimportant as a source of these emissions from homogeneous-charge engines.

Bob Green, Ray Smith and a visiting summer student, Sean Medina, undertook a study of the process of hydrocarbon emission from an engine crevice (28). Because of difficulties in obtaining measurements near the piston, a crevice volume was simulated in the operating research engine by the introduction of a small tube into the combustion chamber. This simulated crevice volume was used to determine the fate of unburned hydrocarbons that entered and were later expelled by the crevice. Shadowgraph photography and spontaneous Raman scattering were used to determine flow patterns, temperatures, and hydrocarbon concentrations 1 mm from the tube opening. Hydrocarbon species shown in Fig. 7 were first detected at the tube exit late in the expansion stroke, long after the start of outflow from the simulation volume. A flame was never observed near the tube exit. Unburned hydrocarbons exiting the tube did not undergo rapid oxidation at temperatures up to 1400 Kelvin.

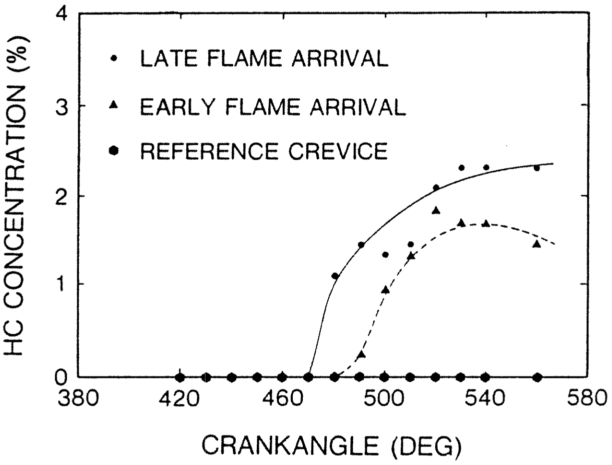

Fig. 7 Raman measurements of unburned hydrocarbons emitted from a simulated crevice volume in an engine show that they evolve late in the cycle when the measured in-cylinder temperatures are too low for complete oxidation. (from Ref. 28)

Knock Chemistry Measurements

Because of pending regulations to control anti-knock lead additives to fuel, combined with significant fuel economy benefits resulting from increased compression ratio, there is increasing interest within the research community to understand and thus control engine autoignition and knock. The approach we have taken is to develop an understanding of the chemical processes occurring in the compressively-heated end gases to guide the development of fuel additives or more effective blending strategies.

To achieve a controlled, repeatable knocking engine experiment, we modified the optical research engine to burn from the walls inward, thus trapping the end-gas region in the center of the chamber for easy optical and gas sampling investigations. Bob Green and Ray Smith used spontaneous Raman and emission spectroscopy, laser-induced fluorescence, and schlieren photography to study preflame conditions and reactions that lead to autoignition and knock (29). The intake manifold temperature and pressure were used to control the fraction of fuel autoigniting in the engine. N-butane, isobutane and propane were studied, but only n-butane and isobutane would knock within the available experimental conditions. Preflame reactions were observed that involved OH and CH radicals, and produced carbon monoxide, formaldehyde and weak blue light emission. The temperature history of the end-gas region prior to autoignition and knock was measured with spontaneous Raman scattering.

This experimental effort was complemented by a parallel study using detailed chemical kinetic modeling conducted by Charles Westbrook and Bill Pitz at the Lawrence Livermore National Laboratory. Their calculations, using a reaction scheme including over 80 species and 460 reactions for butane oxidation, correctly predicted the trends in the autoignition delay times, but computed results showed little sensitivity to low-temperature reactions.

Nick Cernansky, on sabbatical leave from Drexel University, and Bob Green have extended this work to include measurements of time-resolved species concentration prior to autoignition of the n-butane and iso-butane mixtures (30). They used a fast acting, magnetically-actuated sampling valve, on loan from the GM Research Laboratories, to collect ensemble-averaged samples that were analyzed using a gas chromatograph. Figure 8 shows the measured alkene concentration histories near TDC for knocking n-butane combustion. It is apparent from these data that the fuel has decomposed considerably prior to the onset of autoignition as a result of the compression heating by the piston motion and combustion process. In most cases, the relative product distributions of stable species were in good agreement between the Sandia experiment and the LLNL kinetic model.

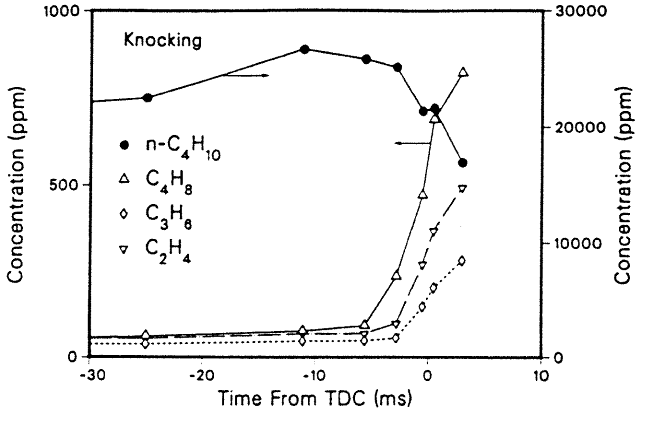

Fig. 8 Alkene species concentration prior to autoignition for knocking n-butane combustion are measured using fast-acting gas sampling with gas chromatographic analysis of the stable species. (from Ref. 30)

Initial Applications of CARS

In the early 1980's we were beginning to see promising results from our more fundamental diagnostic development activities which indicated that the nonlinear coherent anti-Stokes Raman spectroscopy (CARS) technique had great potential for in-cylinder engine measurements of temperature and major species concentrations. Under the conditions of high background luminosity found with droplet combustion or sooting, the low signal levels of spontaneous Raman are easily masked. CARS is potentially much more powerful, but equally more difficult to implement and interpret. The technique uses two lasers of different wavelengths (pump and Stokes beams) to stimulate a nonlinear interaction with the gas molecules contained in the measurement volume. A third laser beam generated by this interaction (CARS beam) is directed into a spectrometer for measurement of its intensity and spectral structure. An important feature of CARS is the coherent signal beam that allows for efficient collection with limited optical access, and the effective spatial rejection of combustion luminosity.

Working collaboratively, Larry Rahn and Sheridan Johnston were able to obtain CARS measurements of temperature from nitrogen in an operating IC engine (31). Time-averaged data were acquired during the compression and power strokes of a propane-fueled research engine operating under homogeneous-charge conditions. Temperatures from 655 K to greater than 2600 K were determined from a nonlinear least squares fit of the CARS spectra. In addition, they were able to implement polarization background suppression and in situ referencing techniques that had been successfully used in atmospheric pressure flames.

Because CARS is a nonlinear technique, errors in measured temperature result if the measurement is made from an ensemble of nonidentical engine cycles, which is the necessary approach if the CARS spectra is obtained by slowly scanning a spectrometer. For this reason, we have begun to focus our CARS-engine activities on broadband CARS techniques that use a broadband dye laser and an optical multichannel analyzer to obtain the temperature for each individual pulse of the laser. These initial studies applying broadband CARS to the knocking engine are reported in a companion paper at this Symposium by Green and Lucht (32). Working in a collaborative effort with Richard Teets, a visiting researcher from the GM Research Laboratories, they have been able to obtain temperature measurements throughout the autoignition and combustion process as shown by a typical CARS spectra in Fig. 9.

The potential of CARS for obtaining measurements in luminous, soot-laden environments, has led to a large number of research laboratories undertaking development of the technique. There are several general observations to be derived from our investigations that are guiding our continued application of the technique. First, the transient, nonrepeatable nature of the engine combustion event demands the application of single-shot broadband techniques because of the inherent errors in time-averaging nonlinear signals. Second, there is a need to develop computer-efficient data reduction techniques for the time-consuming spectral curve-fitting routines. Finally, and most importantly, is the need to develop a physically-based model of the pressure narrowing effect that results from molecular interactions at the high

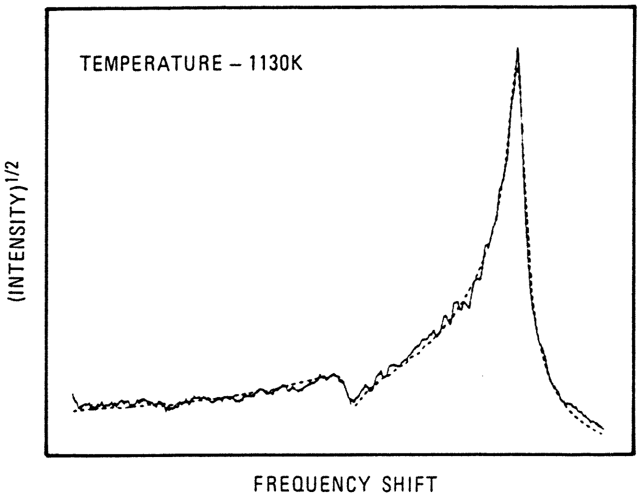

Fig. 9 Broadband CARS measurements of end-gas temperature just prior to autoignition in a knocking engine are key to kinetic model validation. Pressure-narrowing of the spectra must be properly modeled to achieve reliable measurements. (from Ref. 32)

pressures experienced in the engine combustion chamber. Within the last year, significant advances have been made by the physics staff at the CRF (33) that will hopefully lead to even more reliable engine measurements in the near future.

IMAGING TECHNIQUES

Point measurements, by nature, do not provide information on how conditions at the measurement location relate to those in neighboring regions of the chamber. For example, it is difficult to infer the presence of a corner vortex in the chamber from the velocity measurements at a point. Extensive spatial scans can help resolve the problem to some extent, but generally are quite time-consuming to obtain. In this case a simple shadowgraph photo would clarify the flow situation. Because of the far greater power of a quantified picture, it is much more desirable to obtain complete spatial maps rather than either qualitative pictures or single point measurements. Although difficult in practice, it is easy to conceive of velocity, pollutant concentration, and temperature maps over the chamber at various crank-angle positions during the burn.

A significant part of our activity has been devoted to the development and application of several visualization techniques, coupling them with other time- and space-resolved point measurements within the chamber and extending them to more quantitative spatial maps.

Stroboscopic Laser Shadowgraph Techniques

In virtually all our laser diagnostic applications in our optical research engine, we have taken advantage of schlieren or shadowgraph images of the fluid motion and combustion processes to complement our point-resolved data. Witze and Vilchis (34) have applied generalized shadowgraph techniques for real time visualization of engine combustion phenomena. They used a cw laser source and an acousto-optic modulator (shutter) to provide a triggered light pulse of variable duration to isolate a particular crank angle for investigation. The paper included a very complete discussion of several laser visualization systems developed within the group and applied to IC engine combustion, injection, and fluid motion phenomena.

An excellent early example of the strength of these simple visualization methods is the work by Witze (35,36) aimed at understanding the effect of mixture motion and spark plug location on the rate of combustion. One technical issue in dilute homogeneous-charge combustion is the inherently slow flame speeds resulting from large quantities of exhaust gas recirculation or lean fuel-air ratios. To compensate, engine designers have relied on enhanced fluid motion either through swirl, squish or higher velocity intake flows. A question debated within the development community involved the appropriate location of the spark plug to achieve the fastest combustion rate in a swirling charge.

The optical research engine was an ideal place to perform a study addressing this question because of the ability to systematically vary and measure the fluid dynamic state of the precombustion mixture (turbulence and swirl levels), in addition to the ease in altering the spark plug location as an independent parameter. Variation in the swirl and turbulence levels was achieved by rotating the orientation of a shroud on the intake valve. LDV was also used to characterize the precombustion fluid motion. Witze used laser shadowgraph photographs of the flame structure to help interpret observed measurements of combustion duration. As expected, without swirl the burn duration was a direct function of flame travel distance, such that central ignition was optimal. When swirl was introduced, off-axis ignition was aided by flameholder effects that enhanced the flame speed in the circumferential direction.

Particulate Emission and Absorption Imaging

In the late 1970's, with the accelerated production of fuel-efficient diesel engines, public concern for the long-term health effects of particulate emissions stimulated increased research and interim control measures. Although the market penetration of automotive diesel engines has not met those early projections, diesel particulate formation and oxidation processes are still identified as important research topics. The reasons for this interest are clear. Regulations to control heavy-duty truck diesel particulate emissions have now been implemented by the EPA to take effect in 1988. Secondly, as we shift more toward utilization of alternative fuels characterized by high aromatic content and high carbon-to-hydrogen ratio, the propensity to form soot will be increased.

To this end, experiments to characterize soot particulate formation processes during the combustion of rich homogeneous mixtures were conducted in our constant volume combustion bomb (37,38). Soot formation was observed to occur very rapidly in the flame front, and the particles were dispersed over the burned gas region as these gases were continually compressed. Particles sampled and analyzed by transmission electron microscopy exhibited three-dimensional chain-like structures.

Since the scattering and absorption of light by particles depend on the size, shape, composition, and quantity of those particles, measurements of scattering and absorption may be used to obtain information about those properties. For example, a technique has been developed to map the instantaneous distribution of soot over the entire combustion chamber (38). An expanded argon-ion laser beam was passed through the chamber, down-collimated, and projected on a mylar screen located in the image plane of the chamber. The 2-D map of light absorption through the bomb was then photographed with an electronically shuttered camera. The photograph shown in Fig. 10 was then analyzed with a microdensitometer to produce the soot loading contours.

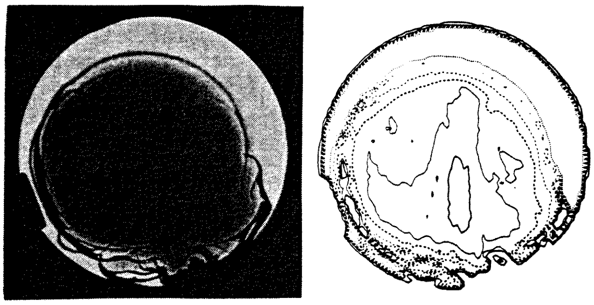

Fig. 10 Attenuation of a collimated laser by soot in the burned gas region during rich premixed combustion in a high pressure bomb is used to quantify the particulate concentrations. Microdensitometer analysis yields soot volume fraction contours ranging from 10^{-5} near the center of the chamber to an order of magnitude lower near the flame front. (from Ref. 38)

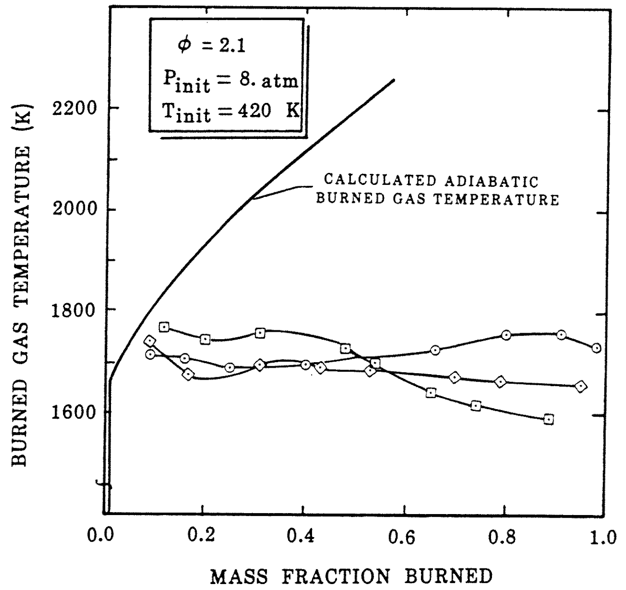

Fig. 11 An optical pyrometer is used to measure the temperature history of the soot particles within the first burned gases of the combustion bomb. Measured temperatures in three separate tests are nearly constant in time and well below calculated values. This suggests that radiation heat transfer is a controlling factor in these tests. (from Ref. 38)

Since soot particles suspended in the high-temperature burned gases emit thermal radiation at their instanteous temperature, Planck's Law may be used to obtain the temperature history of the burned gases, as illustrated in Fig. 11. Optical pyrometric techniques that simultaneously yield time-resolved soot quantity and temperature at a given position in the chamber of the combustion bomb were developed (38). Emission and transmission of light by the particles were measured simultaneously to ascertain the spectral emissivity. An informative extension of this technique was implemented to photograph the near-infrared emission from the particles, producing a spatial map of temperature over the burned gas region to complement the soot maps described previously. Temperature contours inferred using this technique are shown in Fig. 12. Using these measurements, temperature was shown to be a key parameter in determining the tendency of these premixed mixtures to soot.

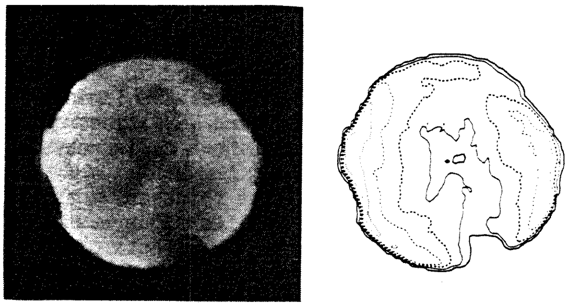

Fig. 12 Infrared particulate emission maps from rich combustion bomb tests (similar to those in Fig. 9) show that temperature is nearly constant over the burned gas region, again suggestive of strong radiation heat transfer. Temperature contours range from 1685K near the center to 1747 near the flame front. (from Ref. 38)

Those combustion bomb studies demonstrated the utility of several laser-based methods for soot research, and identified several key questions concerning fundamental steps in the the formation and oxidation of soot particles under a variety of environments. We have continued those studies at a more fundamental level in a steady high pressure laminar diffusion flame by Bill Flower and visiting scientist, Tom Bowman (39).

Turbulent Flame Structure Imaging

Perhaps one of the most fundamentally important issues in homogeneous-charge engine combustion is the structure of the turbulent flame. The insight gleaned from measurements of this structure is key in how these flames are modeled. Pursuing this goal, Ray Smith developed a unique imaged Rayleigh scattering technique to directly measure turbulent flame thickness in an operating engine (40). Spatial resolution of 0.1 mm and time resolution of 0.01 microsecond were achieved by using a multielement detector and a pulsed laser. The turbulence level in the engine was varied by varying the engine speed and by using shrouded and unshrouded valves. Mean flame thickness indicated in Fig. 13 was found to increase gradually from

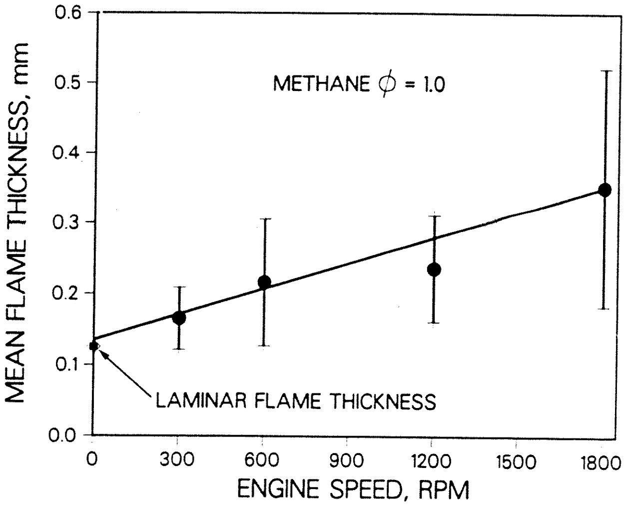

Fig. 13 Rayleigh scattering along a laser beam imaged onto a 1-D multielement detector array provides the first measurements of turbulent flame thickness in an engine. (from Ref. 40)

slightly greater than laminar values at very low engine speed to two to three times the laminar value at 1800 rpm. The standard deviations of the thickness distributions were shown to increase with increasing engine speed.

To complement these flame thickness measurements, a novel microschlieren technique was developed by Ray Smith to observe the effects of turbulence on flame structure (41). The unique aspect of this experiment was the interpretation that the flame acted as a marker of the turbulence field, allowing the turbulent scale features to be observed through shadowgraph or schlieren techniques. The photographs shown in Fig. 14 illustrate the variation in turbulent length scales as the engine speed was varied. This study demonstrated that the turbulent Reynolds number based on the Taylor microscale correlated both the observed scale of flame structure and the total burn duration in the engine. The early time evolution of the flame kernel was also observed to develop a wrinkled structure very shortly after ignition.

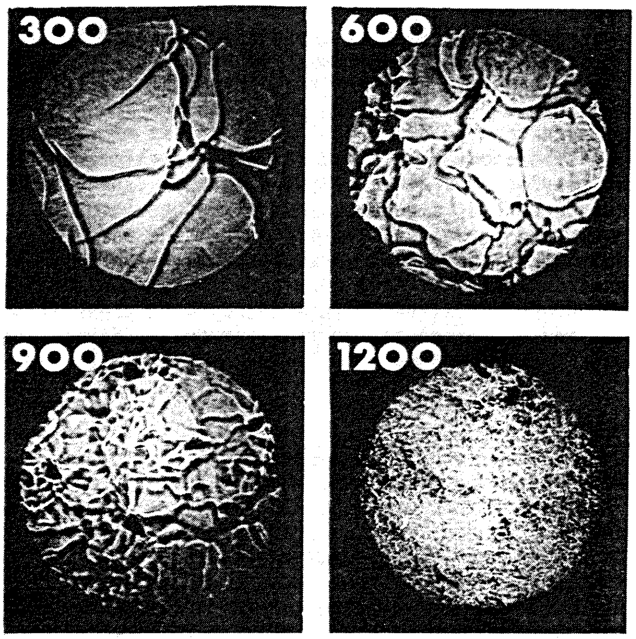

Fig. 14 High resolution schlieren photographs of flames propagating toward the viewer show increased wrinkling as the the engine speed increases. Scale of the pictures is determined by the 9 mm clear aperture of the windows. (from Ref. 41)

The thickness measurements, combined with the microschlieren measurements, generated great interest within the community because they provided the first direct evidence that the flames in an engine were highly wrinkled as a result of the larger scale turbulent motion in the chamber. He was also able to observe the disrupted nature of the turbulent flame by the presence of small pockets of unburned mixture being found immediately behind the flame front as engine speed increased.

In a recent complementary study Pete Witze has developed a technique for measuring the one-dimensional time-resolved location of a propagating flame (42). The technique uses a linear photodiode array to identify the flame surface in a schlieren image of the combustion event. By processing the signal with a standard LDV burst counter, data rates as high as 30 kHz were achieved. The method is broadly applicable in combustion studies in that it is capable of measuring any motion that can be imaged as a sharp spatial gradient in the intensity of a light field.

These one-dimensional flame structure measurements have stimulated the extension of the technique to two dimensions both by zur Loye and Bracco at Princeton and by Thierry Baritaud, a CRF visiting researcher from the Institut Francais du Petrole. The objective of both experiments is to develop insight into the physical processes controlling turbulent flame propagation in engines, thus guiding the development of more realistic submodels for incorporation into the multidimensional computer simulations. As an initial stage in these studies, the interface between burned and unburned gas is identified using Mie scattering from particles seeded into the intake mixture. Our future work will expand upon the existing CRF applications of two-dimensional laser-induced fluorescence (43), Rayleigh scattering (44), and Raman scattering to identify directly the presence of radical and intermediate species formed in the flame front or in the postflame gases.

SUMMARY

This paper has reported on the evolution of the engine combustion research program at the CRF over the last ten years. The goals have changed during those years, largely as a result of open dialogue with industry through technical working groups. Yet the original problems remain evasive. We cannot yet measure to the sensitivity and accuracy we would like in order to stay abreast of the advances in computer modeling. Nevertheless we have made important progress and have achieved things we only dreamed of ten years ago--and real payoff is measurable in industry. The improved understanding has had its impact. Is it the end of the line? Was the means to an end only the end itself? Hardly! We are on the brink of some of the most critical combustion-related issues ever to face us. As we press the knock barriers for more efficiency we have to understand detailed kinetics on scales we have yet to measure. As we introduce new fuels, however modestly different from today's, we will have to understand the roles played by small quantities of undesirable components; as we continue refining novel engine designs we will rely more and more on our detailed understanding of all aspects of the combustion process; as we use computer models increasingly to assist our designers, we will need better physical insight from experiments and more carefully selected validation experiments. This will certainly rely on multidimensional and multiparameter measurements. We've only begun.

ACKNOWLEDGEMENTS

We are pleased to acknowledge the continuous support of this work from the U.S. Department of Energy, Division of Energy Conversion and Utilization Technologies under the direction of M. E. Gunn, Jr. and from the Motor Vehicle Manufacturers Association of the United States. The strong technical contributions of Peter Witze, Sheridan Johnston, Bob Green, and Ray Smith have been essential to the continued vitality of this program. A close working relationship with several automotive industry partners has been essential in helping to guide this work toward the needs of the industrial community.

REFERENCES

1. Dyer, T. M., Witze, P. O., Johnston, S. C., and Smith, J R., "Application of New Diagnostic Techniques to Combustion Studies in Engines," AIAA 20th Aerospace Sciences Meeting, Paper No. AIAA-82-0235, Orlando, FL, January 1982. (also Sandia National Laboratories Report SAND81-8831.)
2. Witze, P. O. and Dyer, T. M., "Laser Measurement Techniques Applied to Turbulent Combustion in Piston Engines," ASME 105th Winter Annual Meeting, New Orleans, LA, December 1984. (accepted for Experiments in Fluids)
3. Dyer, T. M., "New Experimental Techniques for In-Cylinder Engine Studies," SAE International Congress and Exposition, Paper No. 850396, Detroit, MI, February 1985.
4. Witze, P. O., "Hot-Wire Measurements of the Turbulence Structure in a Motored Spark-Ignition Engine," AIAA 14th Aerospace Sciences Meeting, Paper No. 76-37, Washington D.C., January 1976. (also Sandia Laboratories Reports SAND75-8697 and SAND77-8233.)
5. Witze, P. O., "Measurements of the Spatial Distribution and Engine Speed Dependence of Turbulent Air Motion in an I.C. Engine," SAE Trans., Vol. 86, Paper No. 770220, pp. 1012-23, 1977.
6. Witze, P. O., "Application of Laser Velocimetry to a Motored Internal Combustion Engine," Laser Velocimetry and Particle Sizing, (H. D. Thompson and W. H. Stevenson, ed.) Hemisphere Press, Washington, pp. 239-250, 1979.
7. Witze, P. O., "A Critical Comparison of Hot-Wire Anemometry and Laser Doppler Velocimetry for I.C. Engine Applications," SAE Trans., Vol. 89, Paper No. 800132, pp. 711-39, 1980.
8. Dyer, T. M. and Witze, P. O., "Laser Velocimeter Measurements in a Constant Volume Internal Combustion Engine Simulator," Laser Velocimetry and Particle Sizing, (H. D. Thompson and W. H. Stevenson, ed.) Hemisphere Press, Washington, pp. 267-270, 1979.
9. Witze, P. O., (ed.), "Comparisons between Measurement and Analysis of Fluid Motion in Internal Combustion Engines," Sandia National Laboratories Report SAND81-8242, 1981.
10. Witze, P. O., Martin, J. K., and Borgnakke, C., "Measurements and Predictions of the Precombustion Fluid Motion and Combustion Rates in a Spark Ignition Engine," SAE Trans., Vol. 92, Paper No. 831697, pp.786-96, 1983.
11. Witze, P. O. and Martin, J. K., "Cyclic-Variation Bias in Spark Ignition Engine Turbulence Measurements," 2nd International Symposium on Applications of Laser Anemometry to Fluid Mechanics, Lisbon, Portugal, July 1984.
12. Witze, P. O., Martin, J. K., and Borgnakke, C., "Conditionally-Sampled Velocity and Turbulence Measurements in a Spark Ignition Engine," Comb. Sci. Tech., Vol. 36, pp. 301-17, 1984.
13. Witze, P. O., Martin, J. K, and Borgnakke, C., "Fluid Motion during Flame Propagation in a Spark Ignition Engine," SAE Paper No. 840377, 1984. (accepted for SAE Trans.)
14. Martin, J. K., Witze, P. O., and Borgnakke, C., "Multiparameter Conditionally Sampled Laser Velocimetry Measurements During Flame Propagation in a Spark Ignition Engine," Twentieth Symposium (International) on Combustion, Ann Arbor, MI, August 1984.
15. Martin, J. K., Witze, P. O., and Borgnakke, C., "Combustion Effects on the Preflame Flow Field in a Research Engine," SAE International Congress and Exposition, Paper No. 850122, Detroit, MI, February 1985.
16. Setchell, R. E., "Initial Measurements Within an Internal Combustion Engine Using Raman Spectroscopy," Sandia Laboratories Report SAND78-1220, 1978.
17. Johnston, S. C., "Precombustion Fuel/Air Distribution in a Stratified Charge Engine using Laser Raman Spectroscopy," SAE Trans., Vol. 88, Paper No. 790433, pp. 1608-36, 1979.
18. Smith, J. R., "Pulsed Raman Measurements in a Stratified Charge Engine," AIAA Journal, Vol. 18, No. 1, pp. 118-20, 1980.
19. Smith, J. R., "Time-Resolved Raman Spectroscopy in a Stratified-Charge Engine," in Laser Probes for Combustion Chemistry, (D. R. Crosley ed.) ACS Symposium Series No. 134, pp. 261-68, 1980.
20. Smith, J. R., "Temperature and Density Measurements in an Engine by Pulsed Raman Spectroscopy," SAE Trans., Vol. 89, Paper No. 800137, pp. 808-16, 1980.
21. Smith, J. R., "Instantaneous Temperature and Density by Spontaneous Raman Scattering in a Piston Engine," AIAA 13th Fluid and Plasma Dynamics Conf., Paper No. AIAA-80-1359, July 1980.
22. Johnston, S. C., Robinson, C. W., Rorke, W. S., Smith, J. R. and Witze, P. O., "Application of Laser Diagnostics to an Injected Engine," SAE Trans., Vol. 88, Paper No. 790092, pp. 353-370, 1979.
23. Dyer, T. M., "Characterization of One- and Two-Dimensional Homogeneous Combustion Phenomena in a Constant Volume Bomb," SAE Trans., Vol. 88, Paper No. 790353, pp. 1196-1216, 1979.
24. Johnston, S. C., "Raman Spectroscopy and Flow Visualization Study of Stratified Charge Engine Combustion," SAE Trans., Vol. 89, Paper No. 800136, pp. 786-807, 1980.
25. Johnston, S. C., "An Experimental Investigation into the Application of Spontaneous Raman Scattering to Spray Measurements in an Engine," in Fluid Mechanics of Combustion Systems, (T. Morel, R. P. Lohmann, and J. M. Rackley ed.) ASME, New York, pp. 107-18, 1981.
26. Johnston, S. C. and Green, R. M., "Engine Hydrocarbon Concentration Measurements: A Comparison between a Sampling Probe and Raman

Spectroscopy," SAE Trans., Vol. 91, Paper No. 820499, pp. 2077-90, 1982.

27. Dyer, T. M. (ed.), "Sources of Unburned Hydrocarbon Emissions from Homogeneous-Charge Automotive Engines," Sandia National Laboratories Rept. SAND83-8241, 1983.
28. Green, R. M., Smith, J. R., and Medina, S. C., "Optical Measurements of Hydrocarbons Emitted from a Simulated Crevice Volume in an Engine," SAE International Congress and Exposition, Paper No. 840378, Detroit, MI, February 1984.
29. Smith, J. R., Green, R. M., Westbrook,, C. K., and Pitz, W. J., "An Experimental and Modeling Study of Engine Knock," Twentieth Symposium (International) on Combustion, Ann Arbor, MI, August 1984.
30. Cernansky, N. P., Green, R. M., Pitz, W. J., and Westbrook, C. K., "On the Low Temperature Chemistry Preceding End Gas Autoignition," Joint Western/Central States Combustion Institute meeting, San Antonio, TX, April 1985.
31. Rahn, L. A., Johnston, S. C., Farrow, R. L., and Mattern, P. L., "CARS Thermometry in an Internal Combustion Engine," in Temperature: Its Measurement and Control in Science and Industry, Vol. 5, American Inst. of Phys., New York, 1982.
32. Green, R. M. and Lucht, R. P., "An Application of Laser Diagnostics to the Study of End-Gas Autoignition and Engine Knock," presented at the International Symposium on Diagnostics and Modeling of Combustion in Reciprocating Engines, Tokyo, Japan, September 1985.
33. Koszykowski, M. L., Farrow, R. L., and Palmer, R. E., "On the Calculation of Collisionally Narrowed CARS Spectra," accepted for publication Optics Letters, 1985.
34. Witze, P. O. and Vilchis, F. R., "Stroboscopic Laser Shadowgraph Study of the Effect of Swirl on Homogeneous Combustion in a Spark-Ignition Engine," SAE Trans., Vol. 90, Paper No. 810226, pp. 979-91, 1981.
35. Witze, P. O., "Influence of Air Motion Variation on the Performance of a Direct-Injection Stratified-Charge Engine," Paper No. C394/80, Proc. of the I. Mech. E. Conf. on Stratified Charge Automotive Engines, London, November 1980.
36. Witze, P. O., "The Effect of Spark Location on Combustion in a Variable-Swirl Engine," SAE Trans., Vol. 91, Paper 820044, pp. 165-75, 1982.
37. Flower, W. L. and Dyer, T. M., "Time- and Space-Resolved Measurements of Particulate Formation during Premixed Constant Volume Combustion," Sandia Laboratories Report SAND79-8798, 1980.
38. Dyer, T. M. and Flower, W. L., "A Phenomenological Description of Particulate Formation during Constant Volume Combustion," in Particulate Carbon: Formation during Combustion, (D. C. Siegla and G. W. Smith ed.) Plenum Press, New York, pp. 363-89, 1981.
39. Flower, W. L. and Bowman, C. T., "Measurements of the Structure of Sooting Laminar Diffusion Flames at Elevated Pressures," Twentieth Symposium (International) on Combustion, Ann Arbor, MI, August 1984.
40. Smith, J. R., "Turbulent Flame Structure in a Homogeneous-Charge Engine," SAE Trans., Vol. 91, Paper No. 820043, pp. 150-64, 1982.
41. Smith, J. R., "The Influence of Turbulence on Flame Structure of an Engine," in Flows in Internal Combustion Engines, (T. Uzkan ed.) ASME, New York, pp. 67-72, 1983.
42. Witze, P. O., "An Optical Imaging Technique for Measuring Time-Resolved Flame Position," Sandia National Laboratories Report SAND84-8820, 1984. (accepted for Experiments in Fluids)
43. Cattolica, R. J. and Vosen, S. R., "Two-Dimensional Measurements of the OH in a Constant Volume Combustion Chamber," Twentieth Symposium (International) on Combustion, Ann Arbor, MI, August 1984.
44. Dibble, R. W., Long, M. B., and Masri, A. "Two-Dimensional Imaging of C_2 in Turbulent Nonpremixed Jet Flames," Sandia National Laboratories Report SAND85-8709, July 1985.