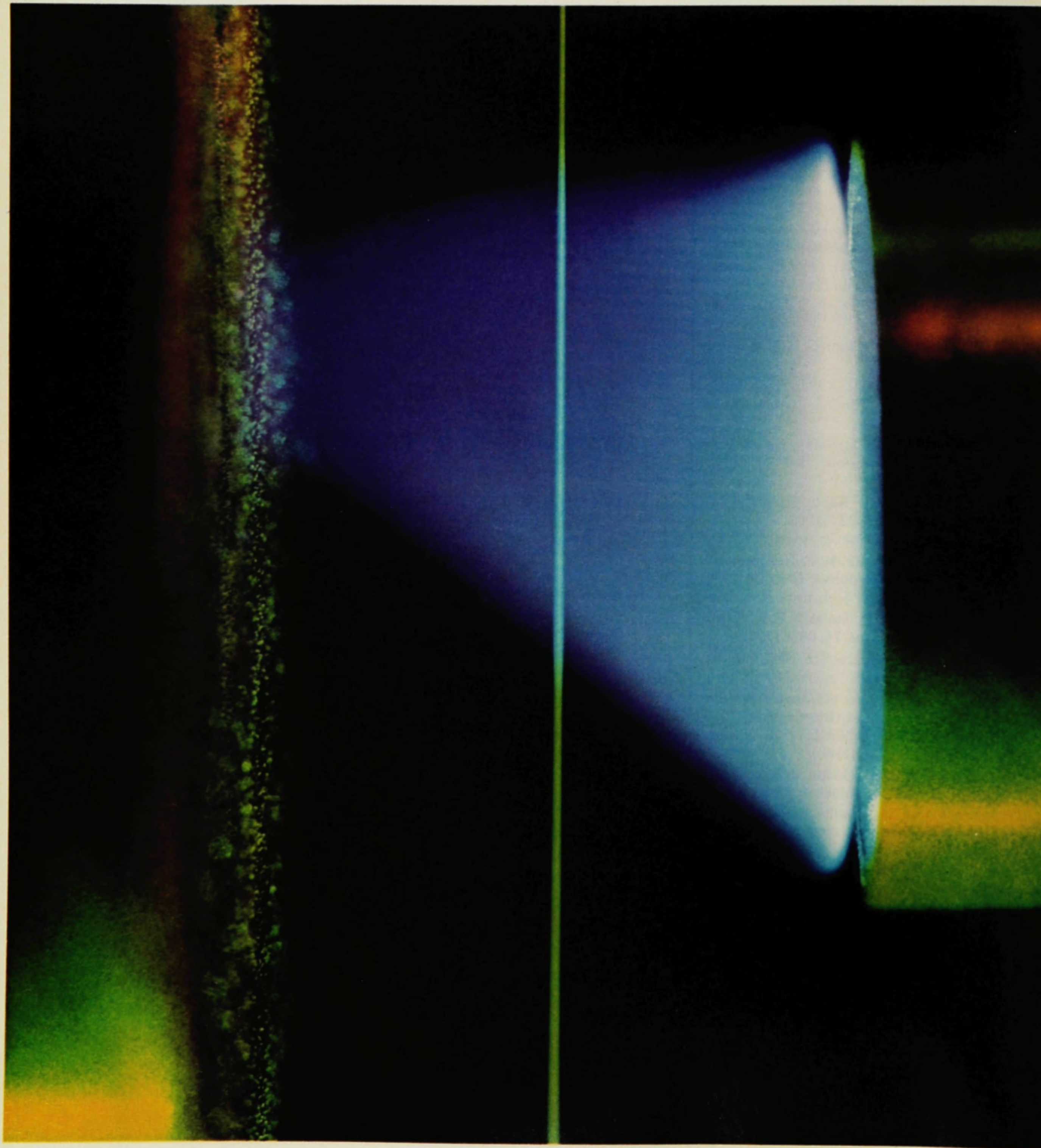
Physics in combustion research



Modelling and diagnostics are two areas in which physics can contribute to reduced pollutant emissions and improved engine efficiency—a 1% increase would save the US 14.5 million barrels of oil a year.

Danny Hartley, Marshall Lapp and Donald Hardesty

Virtually all the energy we derive from fossil fuels is obtained through some form of combustion. Any technical advance that can result in more efficient combustion systems without sacrificing environmental quality would therefore be a major contribution to energy conservation. For example, every one-percent increase in auto engine combustion efficiency saves about 14.5 million barrels of oil per year, gaining the US over 150 million dollars per year in balance of payments. Although research in specific technological areas is usually difficult to justify from economic arguments, this is not the case for combustion research, as these figures show. The return on the investment pays for combustion research many times over. In addition, improved control of combustion processes should result in lower pollutant emissions and thereby reduce such hidden costs of burning fossil fuels as exhaust-gas cleanup and damages to health and environment. However, combustion devices, like most other engineering systems, face performance limitations of an inherently scientific nature.

Fortunately, a great deal of effort has already gone into identifying those areas of technology that would have the greatest impact on energy conservation and into assigning priority for energy-related research and development.[1] One of the aims of an American Physical Society summer study conducted at Princeton University during July 1974 was to define what options to explore next and what areas of physical research can contribute to this exploration. This article is based upon the results and the conclusions of that study.[2]

We choose here to elaborate on two specific areas of combustion research that are fundamental in nature and require direct physics input: combustion diagnostics (particularly laser-oriented schemes, as illustrated in figure 1) and combustion modelling. A third topic, emulsified fuels, was also evaluated in the APS report,[2] having been chosen because of the recent interest in it and because such virgin territory might offer challenge for unconventional and hopefully constructive input from the physics community.

Although the technology that has gone into the development of practical combustion systems has evolved over several decades, it is still in its infancy in scientific detail. The opportunity for technical breakthroughs and innovation still exists—it has been the impetus for this study.

A beam from a krypton-ion laser is scattered by a propane–air flame from a 2.5-cm water-cooled porous-plug burner supported horizontally. The photograph was made by multiple exposures for beam, flame and burner. The scattered light, detected by spectroscopic apparatus, yields highly specific information about the molecular species in the flame. Photo: Russell F. Ley, General Electric Research and Development Center. Figure 1

Combustion technology

With the recognition of the energy crisis, both regulatory and scientific pressure is being brought to bear on a wide range of energy-related studies, with added emphasis on sound technical solutions rather than temporary stop-gap measures. Our engineering capabilities, now perhaps more strained than ever before, require the tools and insight of the broader, more innovative base of fundamental physics.

Figure 2 shows the energy flow pattern for the US and identifies the major utilizing devices and their overall efficiency in converting available fuel to useful energy. In all energy sectors, the efficiency of that energy conversion process can be increased with improved combustion technology. The greatest immediate impact can be realized by the potential for significant increases in fuel economy for the automobile alone. New engine concepts employing complex combustion processes are currently emerging after decades of relative stagnation in engine design. However, our limited understanding of the combustion process involved is, in virtually every case, hindering the development and adaptation of these new engines.

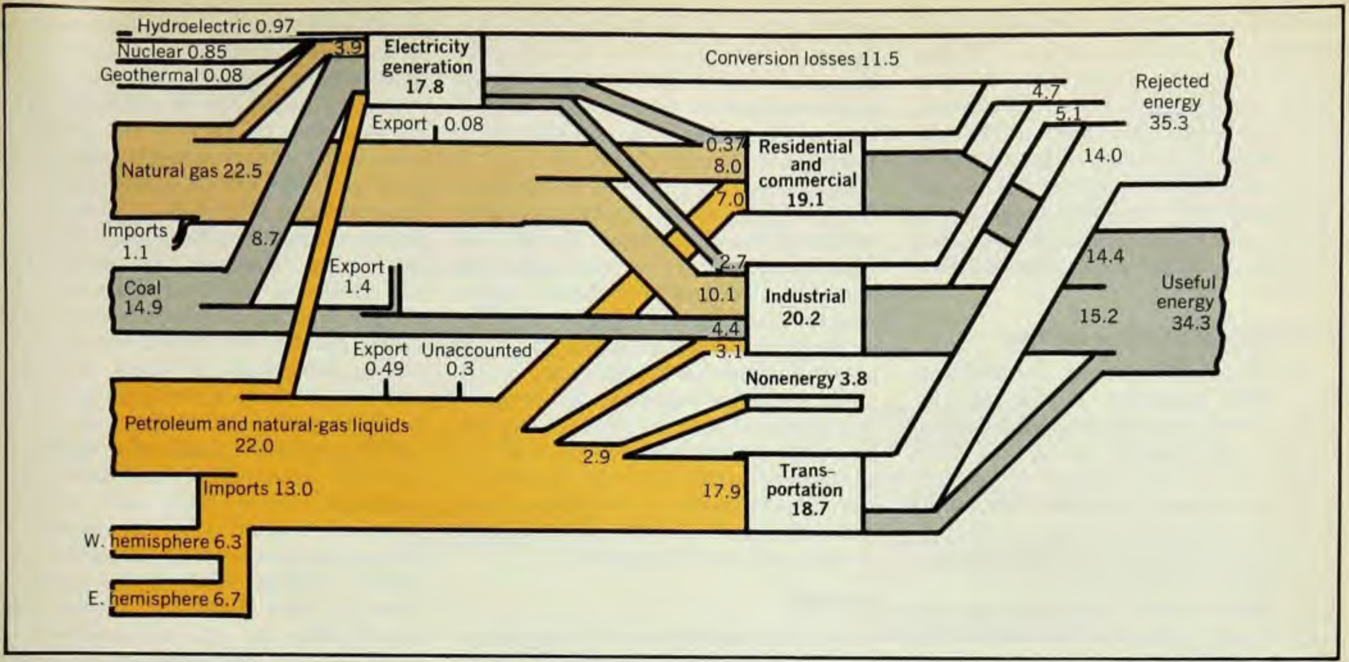
The so-called "stratified-charge engine," for example, has recently been introduced commercially by Honda, and has been on the back burner at Ford and Texaco for a number of years. This engine, in which the fuel charge in the combustion chamber is nonuniformly distributed, shows promise for 25–30% increase in fuel economy with significantly reduced emissions. This concept has not yet proved to be compatible with current engine design, in part because of a lack of understanding of the more complex combustion process. High production costs and unacceptably high levels of hydrocarbon emission are associated with most prototypes of these engines. Diesels offer a potential for 15–20% increase in fuel economy but present such difficulties as combustion-induced noise, smoke, odor and excessive emissions of nitric oxide.

Introducing minicomputer engine and transmission control would provide additional fuel economy, but this would require a combustion-process computer model to interrelate engine-control and performance parameters for optimum operation. Such a model currently does not exist.

Other alternative automotive propulsion systems are also possible, based on accelerated development of such concepts as Stirling-cycle engines and on the development of innovative concepts such as the variable-displacement engine and the rotary Ericsson engine. Some of these new concepts show promise for 50–100% increases in fuel economy, but the effects of changes such as the variation of engine geometry on combustion are not predictable.

We believe that a concerted and well organized research effort in combustion would not only help accelerate the introduction of these engine concepts into production, but would be reflected as an increase of several percent in fuel economy. The knowledge gained would also provide a sound technical basis for government regulatory decisions.

Automotive application is not the only area where increased combustion



Flow patterns of energy for the United States in 1973. The numbers shown for the various channels are in units of 10^{15} Btu; the total consumption is 75.6×10^{15} Btu. For greater clarity some paths have been omitted from the diagram. They are: *Natural gas* to *nonenergy* (0.72) and to *transportation* (0.8), and *coal* to *residential and commercial* (0.37) and to *transportation* (0.005). Figure 2

technology can have a significant impact. Projected increased usage of aircraft in the 1980's lends significance to efforts to improve the efficiency and pollutant characteristics of their engines. Utility boilers, although designed to operate at 85–90% efficiency, do not always operate at maximum efficiency and, for large systems, require combustion modification for pollution control. New concepts for coal-fired power-generating systems offer considerable challenge to the combustion scientist and the physicist. Fluidized-bed steam generators, with integrated schemes for the catalytic removal of oxides of sulfur (SO_x) are poorly understood and would benefit greatly from improved combustion technology.

Combustion modelling

In its broadest context, combustion modelling may be defined as the mathematical description of the details of the physicochemical processes that comprise laboratory-scale devices and practical systems. Several factors have recently provided positive reinforcement for the application of more extensive models of combustion processes. For example, design modifications based on predictive models of gas-turbine combustors have successfully reduced pollutant emissions. To a lesser degree, combustion modelling has influenced operational and design changes in internal combustion engines. The details of combustion are important, as emphasized by John Heywood. Small empirical modifications in the combustion process and fuel composition in conventional spark-ignition engines have produced significant changes in emission characteristics.[1] Similarly, emissions and performance of large utility boilers have responded to empirical adjustment and predictions based on new, relatively crude models of combustion.[3]

A second, perhaps equally important contribution to increased interest in combustion modelling is the rapidly growing availability of large computers with a concurrent advancement in efficient numerical techniques.

Another factor in the emergence of detailed combustion modelling is the recent appearance of several new tools, which may be applied by the experimentalist and diagnostician to the study of basic combustion phenomena and systems. Many of these new tools involve the application of laser technology in diagnostic probe techniques; they are discussed below.

The fact must be stressed that combustion science necessitates an integrated effort in experimental diagnostics and analytical modelling. A theoretical model is no more and no less than a mathematical representation of a set of interacting physical processes. It is therefore only as real and meaningful in describing the physical system as our understanding of these processes.

These considerations are illustrated in figure 3, which schematically depicts the constituent elements of the modelling process. The first step is the specification of the physical system to be described, which could range from laboratory-scale experiments to the testing of practical combustion devices. The objectives of the modelling effort for any particular system are:

- the prediction of combustor performance, thermodynamic efficiency and pollutant emissions,
- the determination of scaling laws, and
- the determination of the sensitivity of the predictions of the model to changes in all major variables.

In meeting the above objectives, the output of combustion modelling is expected to be a predictive model (for example, a "user-oriented" computer program) that reflects the modeller's knowledge of the fundamental physics and chemistry involved. Thus, the second major step in the development of a combustion-system model involves the identification and modelling of the *essential* collective or "subscale" processes and the boundary conditions.

The so-called "subscale processes" include classical flame phenomena, droplet and spray combustion and the

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chemical kinetics of combustion and pollutant-formation reactions. Examples of modelling of many of these processes are given[4] by Forman Williams, Robert Fristrom and Arthur Westenberg, Bernard Lewis and Guenther von Elbe, and Brian Spalding. In all circumstances the development of appropriate subscale models relies on a strong interaction with experimental diagnostics.

Elemental processes in devices

Let us discuss some of the problems for which improved models are required; *both* experimental and analytical work are needed on each of these problems. They include:

- better characterization of turbulence;
- better characterization of liquid-droplet and solid-particle vaporization, pyrolysis and combustion;
- models of *in situ* nucleation, condensation and agglomeration of particles such as soot (where the role of electrically charged species remains controversial), and of the influence of quenching environments on hydrocarbon formation in well mixed combustion;
- chemical kinetics of combustion and pollutant-formation reactions (including elementary reaction processes), as well as engineering-oriented global kinetics, which permit us to estimate overall heat-release rates;
- the influence of gas turbulence on the motion, combustion and agglomeration of droplets and particles in sprays and dusts;
- the influence of nonsteady phenomena on all finite rate processes and their interaction with turbulent time scales, and
- the partitioning of the heat transfer among radiative, convective and conductive modes.

Turbulence—one of the most important unsolved problems in physics—is common (in fact, essential) to most practical combustion devices. The hope is that, through diagnostic experimentation coupled with modelling, fundamental laws will emerge to allow the description of whole groups of turbulent flows, including various compressible flows with chemical reaction and heat release.

A difficult problem in the treatment of turbulent flows is the development, from the Navier–Stokes equations, of a complete set of equations governing the properties of the mean flow. This so-called "closure problem" is inherent in both the phenomenological and the new statistical theories of turbulence. The correlation terms due to turbulence that appear in the time-averaged form of the equations should be evaluated to determine which are the important ones. The Reynolds stresses and equivalent scalar-transport terms in the species and energy conservation equations will be important, as will the impact of turbulent fluctuations on mean volumetric chemical-reaction rates. New turbulence-production terms may appear, due to the presence of combustion- or flame-generated turbulence.

An alternative approach to the problem involves solving for the necessary temperature–composition distribution function required by the statistical methods. The payoff from such an approach would be considerable, but the applicability of the statistical approach to complicated flows is not clear.

An extensive experimental program in support of these modelling efforts is essential. A significant amount of empiricism will most likely be involved in any closure model of turbulence, and thus experimental data are needed to develop and test the models.

Priorities

Accurate prediction of the details of practical combustion flow fields will require the direct numerical solution of the governing equations. Controversy exists over what can or should be done *now* toward meeting this goal. With large and growing computer capabilities, numerical capabilities have advanced to the stage where it is indeed possible to "turn on" coupled arrays of nonlinear, elliptic, partial differential equations and see what happens. The question of course remains as to what is to be gained by turning on equations that may be incomplete or even incorrect.

The answer to this question depends upon one's viewpoint. Perhaps it is easiest to argue that efficient and convergent numerical schemes will be required to treat combustion flows when the subscale processes are understood. It is also reasonable to assume that our ability to develop suitable schemes will improve as more people spend more time experimenting with them.

Problems in numerical analysis arise due to specific features of chemically reacting flows. Some of these problems are most likely yet to be discovered, and they may well depend upon the schemes used to handle particular flow situations. In addition to the uncertainties of turbulent closure, the appearance of major new difficulties will be associated with the use of chemical-species equations and strongly temperature-sensitive reaction rates. The inclusion of detailed chemical kinetics involving numerous chemical species demands a systematic validation of the overall model. High priority is accordingly attached to deducing compact kinetic mechanisms that reliably simulate the extensive kinetics obtained physically.

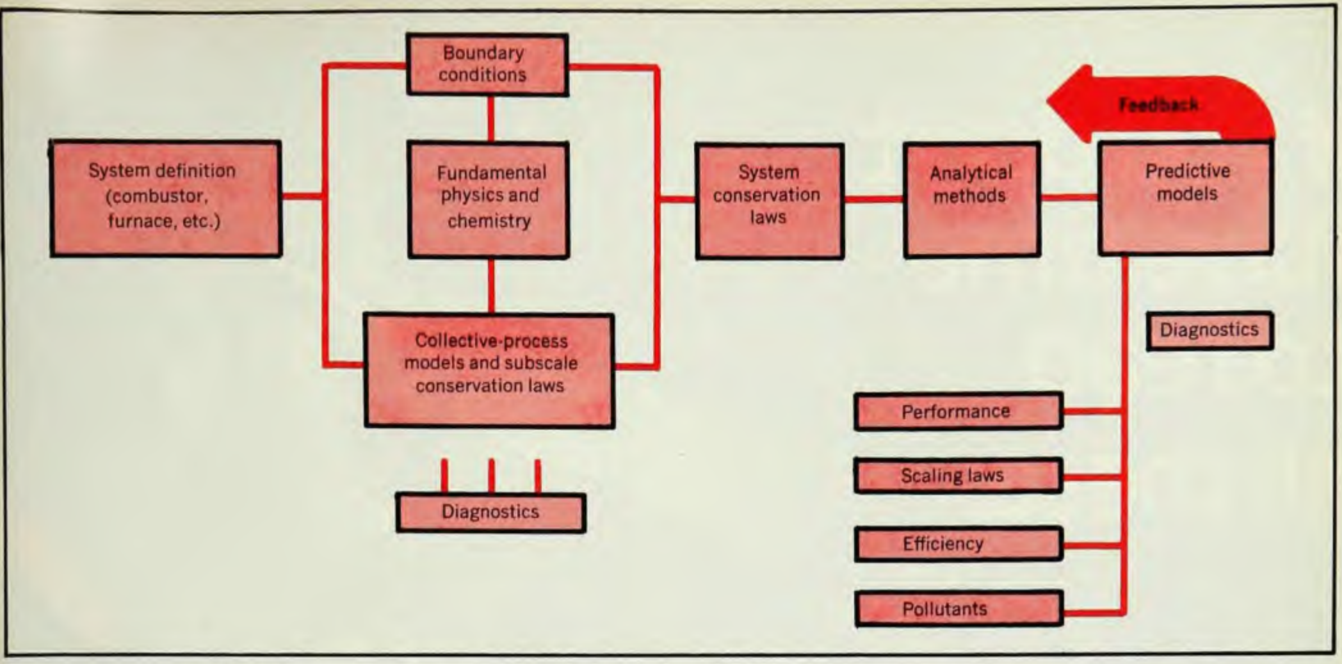
The most difficult practical problem is that of the time-dependent flow and flame spread in internal combustion engines. Given our present level of understanding of combustion in these systems it is questionable whether even qualitatively accurate information on realistic systems can be obtained. The requirement to unravel the multiple time scales of piston motion, turbulent flow and the reactant and pollutant chemistries is formidable. The numerics are difficult but probably not insurmountable. However, the treatment of the details of the fluid dynamics, the physics and the chemistry now requires a large number of *ad hoc* assumptions.

The complexity of these considerations leads us to accord highest priority to the application of direct numerical techniques to the study of a variety of carefully constructed laboratory-scale turbulent flows, with and without chemical reaction. This recommendation carries special weight in light of the recent advances made in the development of laser diagnostic probes that should allow *in situ* measurement of many of the properties of turbulent flows required by various closure schemes.

Diagnostics in combustion research

Modelling would be an empty art without significant effort spent in diagnostics, because the basic aim of modelling is the prediction of new phenomena from a simplified view of a physicochemical combustion system. The validity of such simplifications can only be judged from experimental data. Conversely, diagnostics would be greatly diminished in importance without conceptual models, since *practically every* set of potentially useful experimental conditions would then have to be subjected to measurement. The development of modelling and diagnostics therefore must go hand in hand, and the theoreticians who perform combustion modelling must enter into a close dialogue with the experimentalists who perform combustion diagnostics to determine what can and should be measured, how the measurements are to be performed and how the resultant data are to be interpreted and fed into the theoretical framework.

Useful data for combustion science and engineering have been supplied by solid perturbing probes such as thermocouples, hot wires and sampling devices, and undoubtedly the use of these probes will continue. However, combustion systems present hostile environments, which severely limit the lifetime and accuracy of solid probes. Thus attention has been directed to non-immersed optical probes. We will here emphasize techniques based upon light scattering, which include: laser Doppler measurements of velocity; Raman scattering, Rayleigh scattering and fluorescence measurements of temperature, density and composition; particle-scattering measurements of pa-



The major elements involved in combustion modelling are here represented in schematic form. Such models—mathematical descriptions of the physicochemical processes occurring in laboratory devices—have suggested effective design modifications. Figure 3

rameters relating to particle and droplet densities and size distributions.

The advantages and disadvantages of using these diagnostic schemes will be discussed below, but here we point out that, in addition to the usual advantages of optical diagnostics (such as their nonperturbing quality and capability of remote operation), light-scattering methods offer the additional advantage of three-dimensional resolution. This characteristic is very useful for research in combustion systems, which often have geometrical properties such that good spatial resolution is required. Previously most applications of nonperturbing optical diagnostics to combustion have been restricted to emission or absorption studies. While these techniques are limited to line-of-sight resolution, they are relatively well developed compared to the scattering techniques, and thoroughly discussed in the literature.[5]

The various scattering techniques, once developed and employed, together with other diagnostic methods utilized in an integrated fashion, should lead to significant advances in our knowledge of practical combustion processes. Data obtained from these techniques should help provide the necessary basis for model development, which in turn should provide a rationale in combustion processes for balancing fuel utilization between maximum energy extraction and minimum pollutant formation.

Laser Doppler velocimetry

The technique of velocity measurement currently most discussed is laser Doppler velocimetry. The most common scheme used is the differential or dual-scatter-fringe method diagrammed in figure 4, in which two laser beams of equal intensity are made to intersect at a common focus. Light scattered from this control volume is then collected at some angle by a photodetector. A fringe system is formed at the intersection of these two beams so that a particle passing through the fringes scatters a light signal the intensity of which varies with a frequency proportional to the component of the particle velocity normal to the plane of the fringes.

Several hundred papers have been written on this method since its inception, approximately ten years ago. Much of this work has been reviewed recently by James Trolinger.[6] Technological development is still being carried out, but more slowly, and instrument design has now largely stabilized on a single basic type of instrument with variations. Laser Doppler velocimetry apparatus is now being used to make measurements with quite impressive accuracy and spatial resolution. Among the flows studied are laminar and turbulent jets and channel flows in liquids and gases, gas-turbine compressor flows, free-air turbulence, aircraft wake studies, gas-turbine exhausts, premixed-gas combustion flows, magnetohydrodynamic channel flows and solid-fuel rocket flows.

Laser velocimetry is the most developed diagnostic technique discussed in this article. Nevertheless, a number of significant improvements can be made to overcome some of the current limitations that exist in applications to combustion problems. Some of these limitations are:

- refractive-index fluctuations,
- short survival times of the particles,
- background interference,
- sampling bias,
- droplet and solid-particle combustion and
- window fouling.

Laser Raman and Rayleigh scattering

A general schematic for Raman, Rayleigh and fluorescent light scattering is shown in figure 5. Here, an incident laser beam causes the scattering, which is inelastic (and relatively weak) in the Raman case and essentially elastic (and a bit stronger) in the Rayleigh case. In the case of fluorescence the scattering consists of optical absorption and emission (and is considerably stronger).

During the past few years, Raman scattering has been evaluated in laboratory experiments and by theoretical analyses for its applicability to spatially resolved combustion and fluid-mechanics measurements. It was the subject of a highly focussed workshop held in 1973 and reported in a series of 39 papers published in the workshop *Proceedings.*[7] In compensation for the weakness of Raman scattering, its virtues include:

- specificity;
- well determined, independent response;
- accessibility of temperature information;
- capability for probing systems not in chemical or thermal equilibrium, and
- relative lack of interferences.

The motivations for studying laser Raman scattering for combustion is principally the high specificity of the temperature, density and composition information that is gained. In view of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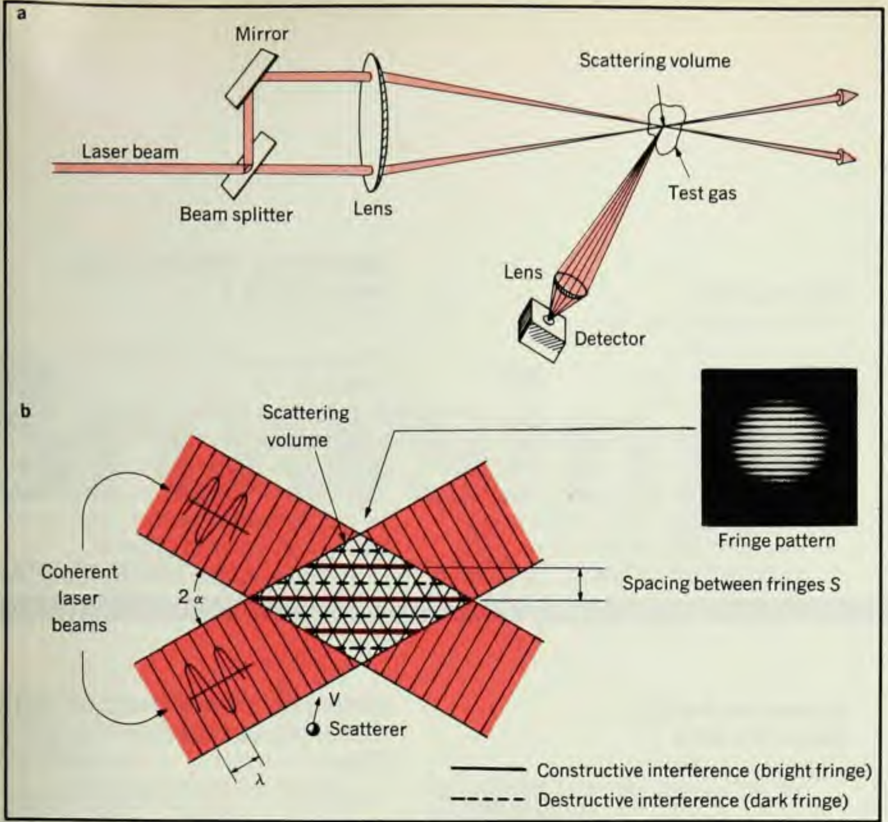

The velocity of the particles in a combustion chamber can be measured from the frequency of the light pulses that they scatter in their passage through an interference-fringe pattern. Diagram **a** is a schematic of the method, known as the laser Doppler velocimetry differential (or dual-scatter) measurement scheme. The geometry of the pattern formed by the two parts of the split laser beam, and a photo of it in the normal plane, is shown in **b**. Figure 4

the small scattering cross sections for this process, the technique can, however, be difficult in many instances.

The application of Raman scattering to the study of nonreacting turbulent flows has already generated new insights. Single-pulse Raman-scattering experiments have been performed in a turbulent isothermal jet and in experiments designed to determine pressure effects on global turbulent mixing in multispecies mixtures. The temperature and density behind a shock wave have also been investigated with Raman scattering.

Several experimental studies of Raman scattering from flames have been reported. These have included use of a pulsed nitrogen laser to record Raman vibrational bands of N_2 and CO_2 at about 1000 K in the post-flame region of a propane–air burner; use of a pulsed ruby laser to record N_2 vibrational bands to determine temperatures from 400 K to 2000 K across a methane–air flame; use of an argon-ion laser to record vibrational bands of N_2, O_2, H_2, CO_2 and H_2O from H_2–O_2 and H_2–air flames, with the temperature determined from the N_2 signature; and use of an argon-ion laser and light-trapping techniques to measure CO profiles in a rich methane–air flame. The detection sensitivity depends on the specific experiment and has been explored for several configurations. Lapp and Hartley have recently prepared a review of the application of Raman-scattering techniques to combustion.[8]

Very accurate data from flames are possible with curve-fitting routines for the Q-branch spectral shape. The sensitivity for this type of probe has been illustrated by computer simulation and demonstrated in laboratory experiments with preliminary success.

Application of Raman scattering to more complex combustion problems is just beginning. It can provide access to needed new combustion data; it is being used in global turbulence problems and in simple flames, and it has the sensitivity to measure specific quantities of interest to the theorist.

Laser fluorescence spectroscopy

Fluorescence, like Raman scattering, can be used as an optical probe to achieve both spatial and temporal resolution. Unlike Raman scattering, however, fluorescence is an absorption and re-emission process, and it requires that the incident laser wavelength correspond to specific energy shifts for the molecule. The process of absorption and re-emission also requires a finite residence time which, except for very low density gases (less than, say, one torr pressure), results in pressure-broadening and collisional-quenching effects that can be extremely difficult to take into account quantitatively. Furthermore, quenching can lead to significant reductions in fluorescence output. However, because of the high laser intensities and relatively high fluorescence-excitation cross sections associated with many small molecules, it is still a potentially useful technique for combustion studies, even at elevated pressures. Results reported for the radicals C_2 and CH from atmospheric flame studies support this premise.[9]

To interpret fluorescence measurements quantitatively at pressures where quenching effects are significant it is necessary to know the appropriate quenching cross sections. Very little data on quenching effects are available and more attention needs to be directed towards the study of these processes for combustion species. Virtually no information is available on the quenching of radicals. Data for the deactivation of radicals and stable flame constituents through collision with CO_2, CO, H_2O, N_2, O_2, H_2 and other species are important and should receive attention. Quenching cross sections for excited atomic states in complex flames have been measured by solving sets of simultaneous algebraic equations for different flame–gas compositions. This same approach should also prove useful for studying the quenching of molecular states in flames.

Although very little work on fluorescence diagnostics has been done in combustion applications, the recent studies on C_2 and CH in atmospheric flames indicate the utility of this technique for the study of small radicals in combustion processes. Fluorescence techniques can be adapted to other molecular species such as OH, NH, NH_2, C_3, CN and NO_2, on the basis of currently available tunable lasers and spectroscopic data.

Basic spectroscopic studies involving combustion species such as CH_2, CH_3, HCO, C_2N and HO_2 are an area where physicists can make important contributions to combustion science. Theoretical predictions of spectral characteristics for small radicals would also be useful as a guide for locating spectral features experimentally.

Developments in tunable lasers will strongly influence the range of molecules that can be monitored with laser fluorescence techniques. Of particular interest is the short-wavelength spectral region down to 2000 Å, which would include the NO signature as well as those for several radicals of current interest.

Particle scattering and other probes

The observation of scattered light often provides the means for measuring

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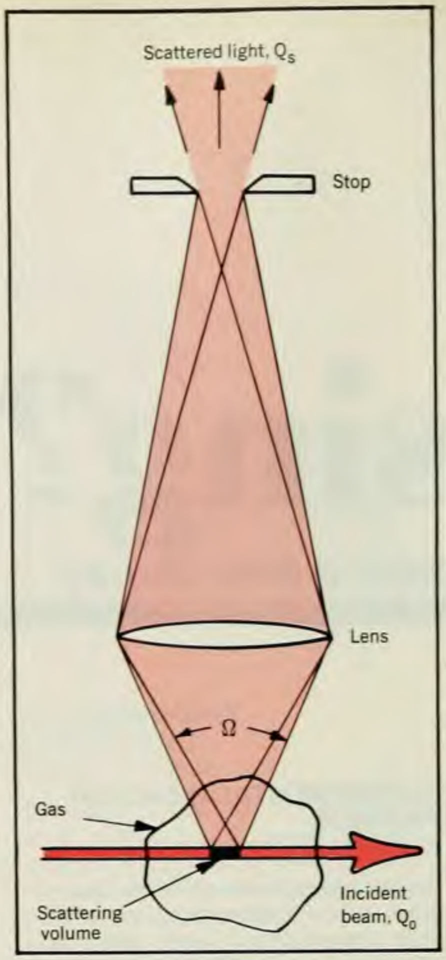
certain properties of assemblages of liquid or solid particles in a flow. Particularly in reacting flows, droplets and particles may be present, the size distribution and concentration of which are not known. In these cases, it is often desirable to use the theory of light scattering by particles to deduce size distribution. The subject of small-particle scattering has been of interest since the Mie theory of scattering by a sphere became available. The power of the Mie theory is, unfortunately, severely limited by two problems that are normally encountered in practical experiments: the lack of homogeneity in particle size and the possible presence of multiply scattered light.

The formation of particulate phases in combustion processes and the generation of very fine fuel sprays provide numerous situations in which light scattering is useful for size-distribution measurements. One example is the measurement of carbon-particle temperatures in a methane–air flame, based on observations of particle size and optical extinction. In other experiments, the growth of soot in flames has been estimated by measurements of the angular distribution of scattered light.

In particle-scattering diagnostics, an obvious problem immediately presents itself: the alteration of the test material by the laser beam. The problem here is the interaction of the high-intensity laser light with solid or liquid particles; this problem can be of critical importance and clearly deserves attention. Furthermore, analogous problems exist with each of the other "non-perturbing" laser techniques. For example, the electrical breakdown of gases limits the useful intensities of the laser pulses and consequently those of the scattered signals in the Raman and Rayleigh processes. In addition, the atomic and molecular internal-mode absorption of significant amounts of incident laser radiation can perturb the state of the test gas in these processes as well as in fluorescence.

Other techniques discussed in the APS summer study report[2] include holography, radiography, Ramanography, coherent anti-Stokes Raman scattering, resonant Raman scattering, acoustic excitation and isotopic tracers. All of these techniques are in more primitive states of development than the laser scattering methods described above, and require both basic and applied physics input. The potential for successful application to complex combustion processes clearly exists and should justify their further development. Particular emphasis is currently being placed on coherent anti-Stokes Raman scattering because of the high scattered-signal intensity of the process. The instrumentation is, however, somewhat more complex than for ordinary scattering processes, and the effect of turbulence on the detected signals is not yet well known.



Sensitive scattering methods represented by this diagram include Raman (inelastic), Rayleigh (elastic) and fluorescence scattering. These methods yield temperature, density and composition information as functions of space and time. Figure 5

Further work needed

The major new diagnostic capabilities we have discussed relate to ways of obtaining the major gas-phase state properties—temperature, density, concentration and velocity—of the combustion species, as well as the characteristics of solid or liquid particles. The effective coupling of these capabilities to important combustion modelling questions requires careful study in itself, since the initial experiments are usually neither simple nor conclusive.

In the section of this article dealing with modelling, we recommended the study of hot, turbulent, chemically-reacting flows, and so here again our first priority in diagnostics is the application of optical methods—particularly those of light scattering—to the study of these flows. A major impact on combustion theory can be made with new and better forms of data relating to turbulent combustion and especially to the elucidation of turbulence model closure schemes. We particularly recommend experimental investigations that combine the various techniques. For example, the combination of laser Doppler measurements of velocity with any of the laser schemes (such as Raman scattering or laser absorption studies) that measure thermodynamic properties would be particularly useful. The total information package in such cases should be worth more than the sum of the individual measurements.

As suggestions of specific experimental programs taken from our overall conclusions,[2] we offer the following:

- Raman scattering from flame gases, including theoretical treatment of temperature effects, experimental studies of flame constituents, improved sensitivity and direct application to practical systems.
- Combined Raman–laser Doppler velocimetry measurements, including momentum-transport measurements in nonreacting isothermal turbulent flows, energy-transport measurements in nonreacting nonisothermal turbulent flows, and momentum and energy transport in combustion environments, particularly to investigate possible flame-generated turbulence.
- Fluorescence measurements from flame gases with improved sensitivity or broader application, and the solution of quenching effects, with possible applications to measurements of local pressure fluctuations.
- Flow visualization of turbulent environments.

What is the potential impact by the physics community on combustion research? How can we improve energy utilization with innovative combustion modelling, together with the creative use of new diagnostic techniques?

In the *traditional areas* of combustion research, which include the theoretical and experimental study of the subscale processes, numerous talented workers already populate the field. Perhaps the key inputs by physicists in these traditional areas would be the development of advanced diagnostic and monitoring tools to be applied to laboratory-scale studies and practical system evaluation.

The *developing areas* of combustion research include such efforts as turbulent-flow modelling and the development and extension of numerical techniques to reacting compressible flows. Physicists can make substantial contributions to these fields. We encourage physicists to take a fresh unconventional look at the problems in chemically reacting turbulent flows. A powerful contribution to modelling can also be made in the pursuit of the development of new diagnostic techniques to make the local measurements required by the new phenomenological and statistical theories and to verify the assumptions and predictions of detailed numerical models.

Finally, we consider *advanced or novel areas* of combustion science, which lack unified theories and well understood sets of governing equations. These include lean and catalytic combustion, fluidized-bed and reactive-porous-bed combustion, and electrically or electromagnetically augmented combustion. We find the greatest probability for significant impact by the physicist in these areas, because in such endeavors he may exercise what is perhaps his greatest asset—innovative thinking based on a firm foundation in basic physical and chemical principles. New data obtained by such advanced methods, furthermore, may suggest entirely new directions for research.

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