by Daniel C. Haworth and Sherif H. El Tahry

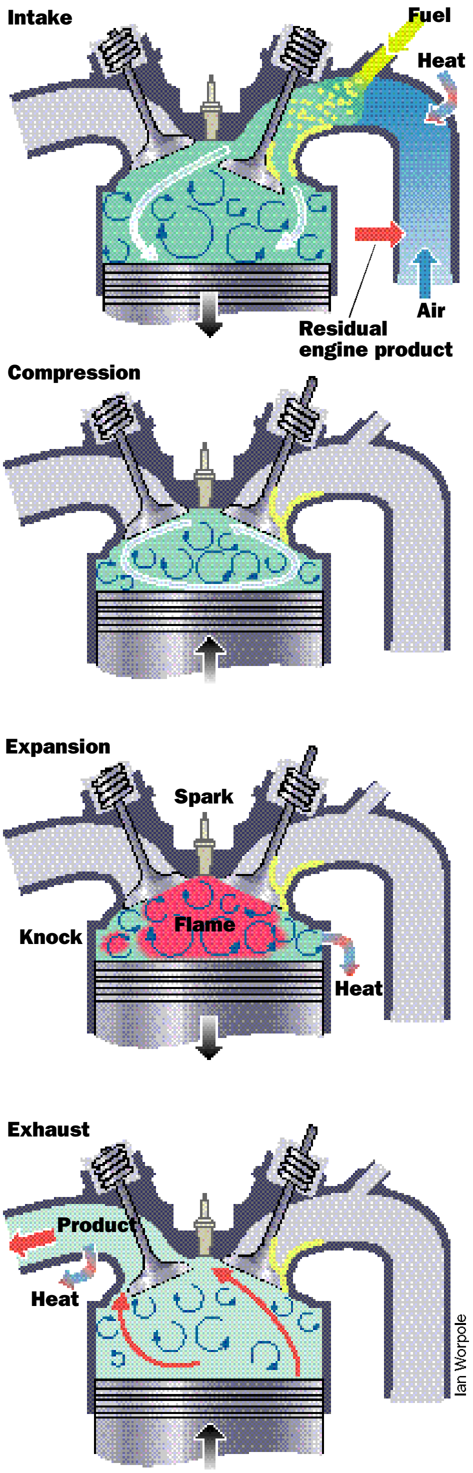
Remodeling the internal combustion engine

Few inventions have had as great an impact on society, the economy, and the environment as the reciprocating internal combustion (IC) engine and the personal transportation culture that it has spawned. Yet for decades, IC-engine design and improvement remained largely a cut-and-try experiential process. Engineers developed new combustion systems by making variations in previously successful configurations. This process proved satisfactory as long as fuel appeared to be plentiful, environmental consequences caused few concerns, and the domestic automotive industry faced little competition; that is, until the early 1970s.

Since then, however, the automotive industry has faced numerous challenges. One of the most compelling has been reducing exhaust emissions. California's Air Resources Board, for example, has proposed light-vehicle emission standards that call for reductions within the next five years of up to an order of magnitude in unburned hydrocarbons and oxides of nitrogen (NO_x), compared with present federal regulations. During this same period, reductions in fuel consumption may be necessary because of concerns about carbon dioxide's potential contribution to global climate change. Vehicle buyers are demanding that the industry achieve these targets without compromising vehicle performance. Simultaneously, global competition is forcing reductions in the time and cost allotted for design, engineering, and manufacturing.

In response to environmental concerns and competitive pressures, the automotive industry has undertaken an R&D effort to rival that of the first half of this century, when the IC engine was still new. One recent manifestation of this effort is the Partnership for a New Generation of Vehicles, initiated in 1993. This cooperative research program between the Big Three automakers and the U.S. government has the objective of developing a midsized "supercar" with fuel economy of up to 80 miles per gallon, low exhaust emissions, and performance and safety that will match those of today's midsized sedans.

Although many varieties of reciprocating IC engines exist, most of the 56 million new personal automobiles and light trucks sold annually worldwide are powered by four-stroke-cycle, port-fuel-injection, spark-ignition (PFI SI) engines and by compression-ignition engines, also known as diesels.



Ian Worpole

Figure 1. Fuel and air mix and burn in the cylinder during the four strokes of the piston in a port-fuel-injection, spark-ignition engine.

During intake in a PFI SI engine, the fuel-air mixture enters the combustion chamber and mixes with residual product gas—the gas remaining from the previous burn cycle (Figure 1). The shapes of the intake ports and chamber establish a specific large-scale flow pattern within the cylinder. Superposed on this large-scale flow are fluctuations (turbulence), which range in size from a large fraction of the bore diameter to submillimeter scale.

During compression, the fuel, air, and residual gases continue to mix. By the time of ignition, the composition is approximately uniform; hence, the terms "homogeneous-charge" and "premixed" are used interchangeably to describe this type of combustion. A flame, initiated by a spark discharge, propagates into the fuel/air/residual mixture, converting unburned reactants into combustion products. Most of the combustion occurs during the expansion stroke.

Fuel consumption in PFI SI engines is reduced by high compression ratios, but compression ratio is limited by "knock." Knock is a phenomenon that occurs when the unburned reactants spontaneously ignite ahead of the flame. To help reduce fuel consumption in today's PFI SI engines, some exhaust may be recycled back into the intake manifold for the next burn cycle. This exhaust-gas recirculation also has the benefit of lowering NO_x emissions.

In a diesel engine, liquid fuel is injected directly into the combustion chamber rather than into the intake ports, but injection is delayed until the piston nears top dead center (the highest position in the stroke). This delay in injection results in a highly nonhomogeneous fuel/air/residual mixture. Combustion is initiated by autoignition, in which compression of the air increases combustion-chamber temperature enough that burning begins as soon as fuel vaporizes and mixes with air. Diesel combustion occurs

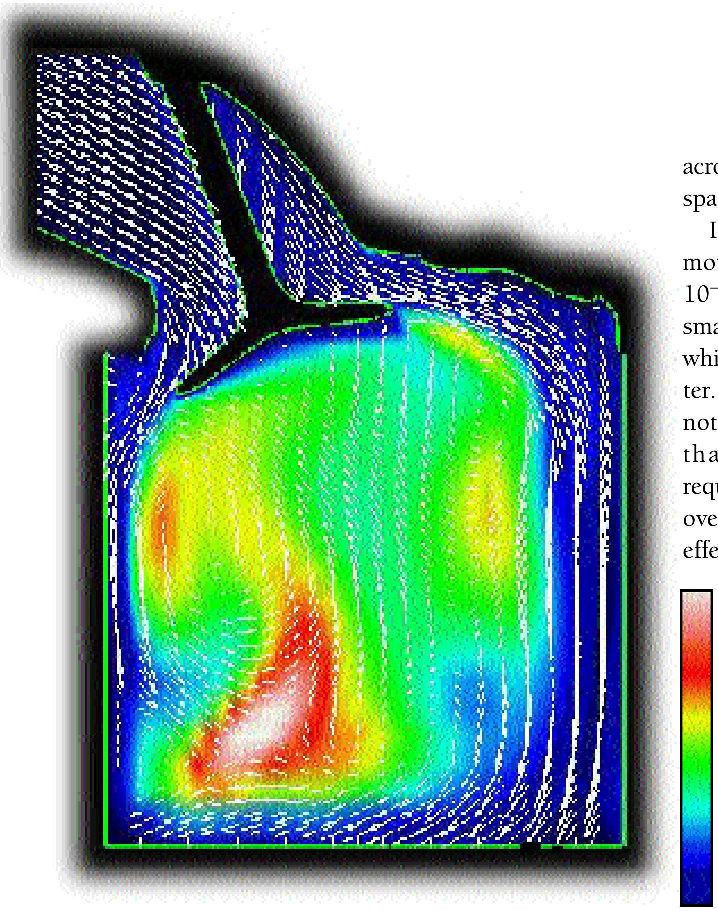


Figure 2. Computer simulation of the turbulent flow inside an engine cylinder when the piston is 70° before bottom dead center.

mostly in a "diffusion mode," in which fuel and air are still mixing during burning. In diesel engines, the combination of a high compression ratio (which is not limited by knock) and a high overall ratio of air to fuel results in low fuel consumption. However, diesel engines pose several problems, including particulate matter emission, limited power density (power generated per unit of displacement volume), and noise.

The complete combustion of a hydrocarbon fuel/air mixture yields carbon dioxide and water. At high temperatures, NO_x is formed by oxidation of nitrogen in the air. Strategies for reducing NO_x typically involve lowering the combustion temperature in various ways, such as by using exhaust-gas recirculation. Other unwanted products of combustion are carbon monoxide, unburned hydrocarbons, and particulate matter. These three products generally result from poor preparation of the fuel/air/residual mixture before burning or from incomplete combustion. Incomplete combustion also adversely affects fuel consumption.

The ideal IC engine would operate smoothly and produce high power with no emissions and with low fuel consumption. Modeling provides a way of examining the various tradeoffs that must be made to move current designs toward the optimum.

Innovative response

Given the IC engine's high state of refinement and the physical complexity of in-cylinder processes, experience alone is not sufficient to create the significant improvements now sought. Although cut-and-try is still used, we need newer approaches to achieve today's performance targets in a timely and cost-effective manner. One powerful tool for meeting these demands is called multidimensional modeling. In this type of modeling, three-dimensional, time-dependent numerical simulations elucidate how flow, fuel sprays, mixing, and combustion vary in space and time in the engine cylinder.

Although the fundamental thermodynamics of energy conversion in engines have been understood for more than 100 years, the search for deeper physical insight and reliable models leads quickly to the limits of physical understanding and computability. Engine designers are turning increasingly to experimental diagnostics and to modeling to understand the processes occurring inside ports and cylinders.

The basic equations governing the in-cylinder processes, such as those depicted in Figure 1, are known. These nonlinear partial differential equations describe flow-field variations in space and time. A consequence of the nonlinear processes described by the equations is turbulence—the chaotic, three-dimensional velocity fluctuations that occur across a broad range of temporal and spatial scales.

In-cylinder turbulence includes motion at length scales as small as 10^{-5} m. This is a factor of 10,000 smaller than the largest flow scales, which are the size of the bore diameter. Computers do not exist, and will not exist in the foreseeable future, that can store all the numbers required to fully resolve phenomena over such a wide range. Thus, the effects of small-scale, unresolvable features on the large-scale average flow are modeled through modifications to the governing equations. The models used to study combustion in this manner include turbulence models, fuel-spray models, and combustion models.

Turbulence modeling is of particular importance to improving the efficiency of IC engines. Turbulence promotes the mixing of fuel, air, and residual gases, and enhances heat transfer, fuel-spray processes (including droplet breakup), and flame-propagation rates. In the absence of turbulence, for example, a flame could not propagate from the ignition site to the combustion chamber walls at high engine speeds in less than one crank revolution, which would make the engine inoperable. Because of turbulence, however, the combustion duration in a PFI SI engine corresponds to about one-sixth of a crank rotation and is largely independent of engine speed.

Fuel-spray models account for phenomena that include liquid-droplet breakup and coalescence; vaporization; and spray–wall interaction. Gas-phase and liquid-phase flows are tightly coupled. In these models, it is important to include accurate accounting of the exchange of mass, momentum, and energy between the two phases.

Combustion models must accommodate a range of burning regimes, from the propagating premixed flame of homogeneous-charge engines to the diffusion-limited burning of diesel engines. The earliest (ignition) and latest (flame–wall interaction) stages of burning require special consideration.

Model applications

Multidimensional modeling has contributed extensively in recent years to a greater understanding of these complex phenomena and to integrating this knowledge into advanced designs to increase efficiency and reduce exhaust emissions.

In diesel engines, for example, there is strong coupling between gas motion, fuel sprays, fuel/air/residual mixing, chamber geometry, and engine operating conditions. The accurate computation of gas motion, including turbulence, is a prerequisite to predicting fuel-spray behavior, mixing, and combustion. Today, computed large-scale flow patterns generally show good agreement with experimental measurements.

The duration and phasing of combustion affect fuel consumption and NO_x emissions. And the degree of fuel mixing during burning is important to particulate-matter formation and hydrocarbon emissions. Burning "undermixed" fuel—that is, a mixture that is too high in fuel and too low in air in certain areas—produces excessive particulate matter. Allowing "overmixing"—a mixture that locally has too much air relative to fuel—can result in incomplete burning and excessive hydrocarbon emissions.

The burn rate in an engine varies from one engine cycle to another. This variation creates torque fluctuations that are perceived as engine roughness. Thus, in addition to the ensemble mean (the average burn rate over many engine cycles), the magnitude of deviations about the mean is of interest. At present, it is impossible to extract quantitative fuel consumption, emissions (with the exception of NO_x), and cycle-to-cycle variation numbers directly from time- and space-dependent models. Instead, the analyst must look at established "figures of merit," such as burn-rate curves, and draw inferences regarding engine performance from them.

Although modeling can generate a large amount of detailed information that is useful for improving engine design and is not available elsewhere, physical and numerical uncertainties preclude relying on it exclusively. A judicious blend of modeling and experimental measurement remains the most prudent and effective approach to engine design.

Three-dimensional, time-dependent modeling of the kind described here has become feasible for realistic engine configurations only within the past 5 to 10 years. Today, it represents a branch of computer-aided engineering that is changing from a research technology to a practical design tool. Modeling is used both to analyze existing engines and to guide the design of new engines before prototypes are built.

One tangible accomplishment of modeling to date has been to increase the exhaust-gas recirculation tolerance of PFI SI engines without sacrificing peak power. This achievement has reduced fuel consumption and emissions while satisfying performance targets. Besides its role in improving conventional petroleum-fueled engines, modeling has been a key tool in the search for practicable alternative propulsion systems. These new technologies—fuel cells represent a related example—are characterized by turbulent transport processes akin to those within the IC engine.

In developing engine modeling, industry researchers have advanced our understanding of some key scientific and technological topics, such as turbulence, combustion, and computational fluid dynamics. Similar models will likely play a key role in developing the technologies that will ultimately supersede the reciprocating IC engine.

As a result of its successes, three-dimensional transient modeling of in-cylinder flow and combustion has gained acceptance in the automotive community and is becoming an integral part of engine design.

BIOGRAPHY

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