An Engine Simulator for Laser Diagnostic Studies of One-Dimensional Turbulent Flame Propagation

Peter O. Witze
Sandia National Laboratories
Livermore, CA 94550

ABSTRACT

An experimental facility for investigations of turbulent flame propagation velocities in piston engines is described. Two-component laser Doppler velocimetry is used to measure the expansion velocity and turbulence intensities in the preflame gas. A laser-schlieren flame-position detector simultaneously records the flame location on a cycle-resolved basis. Conditional sampling procedures are used to reduce bias errors introduced by cyclic variations in the combustion rate.

At the time of ignition the engine head and piston form an idealized combustion chamber designed to reduce cyclic variations in the fluid motion, while at the same time providing a high turbulence level characteristic of production engines. Combustion rates and velocity measurements are used to compare this chamber with an open disc chamber and with a research configuration having grid-like turbulence. The combustion rate in the idealized configuration is shown to be comparable to the rate in the open disc chamber, but with greatly reduced cyclic variation.

INTRODUCTION

Combustion in a spark-ignited homogeneous charge engine is governed by the mechanisms of turbulent flame propagation. Although many research studies have been reported on this subject, a recent review of theories for turbulent burning velocities by Abraham et al. (1) demonstrated that there is considerable uncertainty and controversy in our current understanding of the relationships between the flame speed, turbulence intensity, and turbulence length scales. The review concludes that while an appreciable number of experimental measurements are available on turbulent burning velocities, the data are insufficient to resolve controversies in the proper formulation of flame speed models, such that further experimental studies are urgently needed. The purpose of the current paper is to describe an experimental apparatus intended to provide data of the type needed. First, however, a brief review of previous work will be presented.

Non-Engine Flame Speed Studies

Williams (2) describes a variety of experimental configurations that have been used to study turbulent premixed flames, including open and confined steady flames, and spherical and plane unsteady flames. The advantage of the steady flame is that the turbulent burning velocity is obtained directly from the velocity of the combustible gas, for which the turbulence can also be accurately known. Disadvantages include variations in scale and intensity of turbulence with position in the flame surface, difficulties in obtaining homogeneous and isotropic regions of high turbulence intensity, and the added complications of divergence and strain along the flame surface. The freely propagating unsteady flame resolves many of these problems, but with the added complexity that the growth of the flame is composed of two effects, the turbulent burning velocity and the expansion of the hot combustion products.

Prior to the advent of the laser Doppler velocimeter, it was not possible to directly measure velocities and turbulence during combustion. This deficiency led to compromises in the experiments that could be performed on freely propagating flames. Andrews and Bradley (3) reviewed a number of experimental techniques, and concluded that the method of double flame kernels in a closed vessel offers a simple yet accurate method for determination of burning velocities. The technique relies on the visualization of combustion created by simultaneous ignition at two widely separated locations. As the two flame surfaces approach each other, the expansion velocity ahead of the flames is cancelled, permitting the direct measurement of the flame velocity from high speed movies.

Subsequent applications of the technique by Andrews and Bradley (4) and Abdel-Gayed et al. (5), however, show an appreciable spread in the measurements of turbulent burning velocity, which appear to be characteristic of the related phenomenon of cyclic variation that is prevalent in spark ignition engines. The turbulence field in the vessel was created by four opposed fans, which resulted in a measured integral length scale on the order of 40 mm. This large length scale suggests a complex three-dimensional flowfield when compared to the characteristic scale of the flame thickness, which Smith (6) has found experimentally to be less than a millimeter. It is also not clear how truly simple the opposed-flame experiment is. By the very nature of a turbulent flow, the approach of the two flame surfaces is very chaotic, such that the measurement of the flame speed is not well defined.

The problem of large and uncontrolled length scales inherent in a fan-stirred vessel is corrected, at least in principle, by the grid-stirred technique of Hamamoto et al. (7), in which a screen or grid is rapidly pulled across the combustion chamber. The length scale of turbulence is controlled by the grid spacing, but it is not evident whether the method can produce the high levels of turbulence characteristic of an engine.

Engine Flame Speed Studies

Since complex fluid motion is an inherent characteristic of reciprocating engines, the question is often raised as to whether an engine is a suitable environment for investigating turbulent flame propagation mechanisms. Admittedly, it is a difficult experimental environment, but an engine does produce conditions that cannot all be simulated by steady flames or constant volume bombs: 1) elevated pre-ignition gas temperatures and pressures; 2) confined volume, such that the preflame gas is further compressed during combustion; 3) high turbulence intensity levels that can be varied by changing the engine speed; and 4) high repetition rates, which are beneficial for statistical measurements.

Whereas many studies have been made on turbulent flame propagation in engines, only a few have included a direct measure of the turbulence. Lancaster (8) used a hot-wire anemometer to measure the turbulence intensity and length scales, and then correlated the results with combustion rate measurements and analysis (9). A similar and more comprehensive study was made by Groff and Matekunas (10), in which the flame frontal area was also determined from high speed movies of the combustion event. Although these two studies have contributed greatly to our understanding of engine combustion, they are limited by the uncertainties associated with the use of a hot wire probe in a flow of varying temperature and direction and high relative turbulence intensity (large fluctuations relative to the mean velocity). In addition, the relationship between motored turbulence measurements and the actual conditions in the preflame gases during combustion has not been established.

In an earlier study (11), we used a laser Doppler velocimeter (LDV) to make motored turbulence measurements that were correlated with combustion results. We have also reported LDV measurements obtained during combustion (12,13) which demonstrate that the expansion velocity ahead of a propagating flame can be accurately measured by the LDV technique. This result is important, because it suggests that if the flame position can be measured with good temporal resolution, then the actual flame propagation speed of a single freely propagating flame can be determined directly from measurements, without relying on thermodynamic analysis.

Simulated Engine Environments

The fluid motion developed during induction plays a major role in generating the turbulence needed for fast combustion. However, it is unlikely that the turbulence produced during intake is of significance, because the turbulence dissipation rates are fast when compared to the cycle time of an engine. What appears to be important are the large scale flow patterns established within the engine cylinder during induction, since these structures store the kinetic energy of intake until it can be transformed to small scale turbulence late in the compression stroke, near TDC. It is by the interactions of such structures with each other and with the walls during compression that high levels of turbulence are found at the time of ignition. The important motions can be in the form of swirl, tumbling (or roll), ring vortices, and other smaller separated-flow regions.

However, while these large structures are advantageous for storing fluid energy, they are also the source of fluid-mechanic-related cyclic variations in combustion. By their very nature they are not exactly repeatable from cycle to cycle, nor are they totally random, particularly when viewed on the time scales of the combustion process. The situation thus exists where the conditions needed for rapid combustion are also a direct cause of cyclic variations. This obviously creates problems for the engine designer, but the engine researcher may be even more troubled, since the proper treatment of cyclic variations in engine velocity and turbulence measurements remains an unresolved issue.

Unlike the engine designer, the researcher often has the liberty to work around a difficult problem, rather than solve it directly. This has been our approach to experimental studies of engine fluid mechanics, through the use of idealized engine simulators. The simulators are designed to have extensive optical access and simple geometries, permitting easy application of various laser diagnostic techniques.

Our first LDV engine study during combustion (12) was made at a very low engine speed (300 rev/min) in a simple "disc" chamber (right circular cylinder). The low engine speed provided the time needed for the turbulence to relax to a state of near isotropy and homogeneity at the time of combustion. The flow was still influenced by cyclic variations, but was well-enough behaved to allow identification of the sources and effects of the cyclic variations.

In a follow-on study (14) made in the same combustion chamber, the engine speed was increased to 1200 rev/min in an attempt to obtain turbulence and burn rate data at more representative engine conditions. LDV measurements revealed that the precombustion base flow was so strong that it dominated the expansion velocity, resulting in a net gas velocity directed toward the flame. Not only do complex motions of this type make it difficult to isolate the true flame speed, but they also contain low frequency variations that introduce bias errors into turbulence measurements.

The disc-shaped chamber used for these studies permits flow structures as large as the cylinder diameter to exist. In an attempt to limit the scales of turbulence present at the time of combustion, a study (13) was made using a perforated plate grid placed across the entire engine cylinder, one millimeter above the piston surface when at top-dead-center (TDC). The intent was to generate uniform, small-scale turbulence just prior to combustion. The result was that too much energy was removed from the flow, resulting in a very low turbulence level. In retrospect, it is now realized that when the piston surface is close enough to the grid to produce turbulence, it is moving too slowly to have an appreciable affect.

The experiences described have led us to conclude that the production of small-scale high-intensity turbulence cannot be achieved by perturbing the flow during intake, but rather must be done by restricting the length scales that can exist at the time of combustion. Our design for achieving this goal is an engine combustion chamber that is essentially a long channel of square cross section, such that the width of the channel determines the largest length scale that can be accomodated. In essence, the design is similar to the combustion chamber used by Quader (15) to study flame propagation under lean operating conditions.

EXPERIMENTAL APPARATUS AND PROCEDURES

Single-Cylinder Research Engine

The Sandia research engine has a modified air-cooled single-cylinder L-head block. The modifications include a second flywheel for steadier operation, a water jacket around the cylinder for improved temperature control, and grease fittings for the connecting rod bearings, to allow for cleaner oil-less operation. The engine bore diameter is 76 mm, the stroke is 83 mm, and the connecting rod length is 203 mm.

The original L-head design has been replaced with a specially-designed water-cooled head that has the valves located in the side wall of the combustion chamber. The radial motion of the valves is provided through a mechanical linkage driven by the pushrods of the standard valve mechanism. The purpose for placing the valves in the side wall is to create a disc-shaped combustion chamber with total optical access from above the piston.

The engine is driven by an electric motor, which also acts as a brake when the engine is fired. The intake air flows through a copper ball heat exchanger to bring it to the 80°C control temperature used for all tests. Gaseous propane fuel is injected into the intake manifold by a solenoid valve. The fuel and air are then mixed by a series of reverse direction swirl vanes and baffles located in the intake line, which is heated with electrical heat tape. To ensure a well-mixed mixture free of unscavenged combustion products, the engine is fired only every fifth cycle.

Combustion chamber design. The goal of our chamber design is to reduce the length scales of motion without significantly reducing the turbulent kinetic energy. The design modifies the induction/compression flow only during the late part of the cycle, near TDC. Interlaced flanges located on the piston and head partition the flow into three distinct zones, as illustrated in Fig. 1. The volume between the inner flanges is square in cross-section with 19.6 mm sides. For the bore diameter of 76 mm, the aspect ratio (length/width) of the channel is 3.9. The volumetric compression ratio of the combustion chamber is 7.6:1.

During intake and much of the compression stroke, the flow created by the side-wall located valve is largely uninhibited by the flanges. However, as the flanges begin to interlace the length scales of fluid motion become limited to the clearance height in the channel, since the maximum size of a vortex structure is controlled by the smallest dimension in the plane normal to the vortex axis. The configuration does produce a squish motion just prior to TDC. This design decision was based on a desire for maximum turbulence intensity during combustion, but admittedly at the risk of a potentially more complex flowfield. If the squish motion is ultimately found to be a problem, it can be greatly reduced by reducing the thickness of the inner pair of flanges.

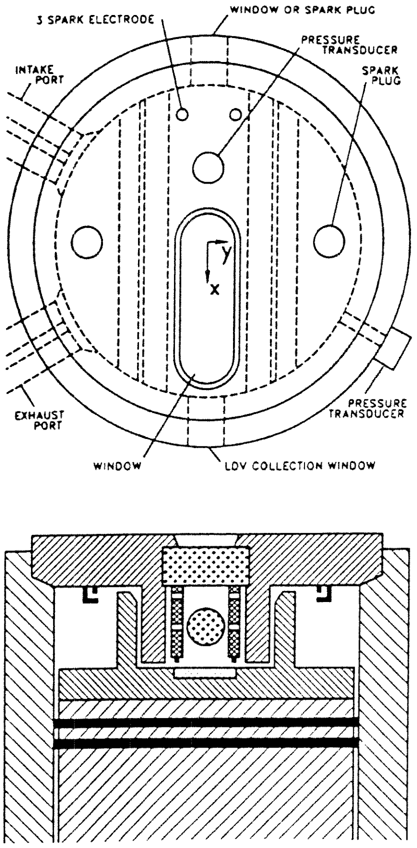


Fig. 1 Diagram of the one-dimensional combustion chamber formed when the piston is near TDC

An initial goal of the design was to contain the gases in the channel during combustion; that is, minimize the flow of gases from the channel into the two segments of the clearance volume outside the channel itself. This was done by specifying a close fit between the cylinder wall and the ends of the flanges in the head, and a very close tolerance (0.5 mm) between the pairs of interlaced flanges. The planned approach was to independently measure the pressure in the channel and one of the segments, and use delayed ignition in the segments to obtain the simultaneous occurrence of maximum pressure in all three chambers. However, we have never detected a pressure differential between the chambers, leading us to suspect that gases are escaping from the channel through the piston-cylinder clearance gap above the top piston ring. In retrospect, this appears to be a favorable condition, since the simultaneous ignition of the gases in the channel and segments at one side of the combustion chamber should lead to similar burn durations for all chambers.

There are two ignition options for the channel. In the first option, a spark plug can be positioned at the end of the channel, at its center. This results in an initially spherical burn that is analogous to the side-wall ignition of the disc chamber studied previously. The other option is the six-point ignition system illustrated in Fig. 1. The two spark plugs shown in the channel each produce three ignition sites, in the manner described by Dyer (16). The purpose of this design is two-fold: first, the flame development time is greatly reduced, and a nearly one-dimensional flame surface is quickly established; second, the two

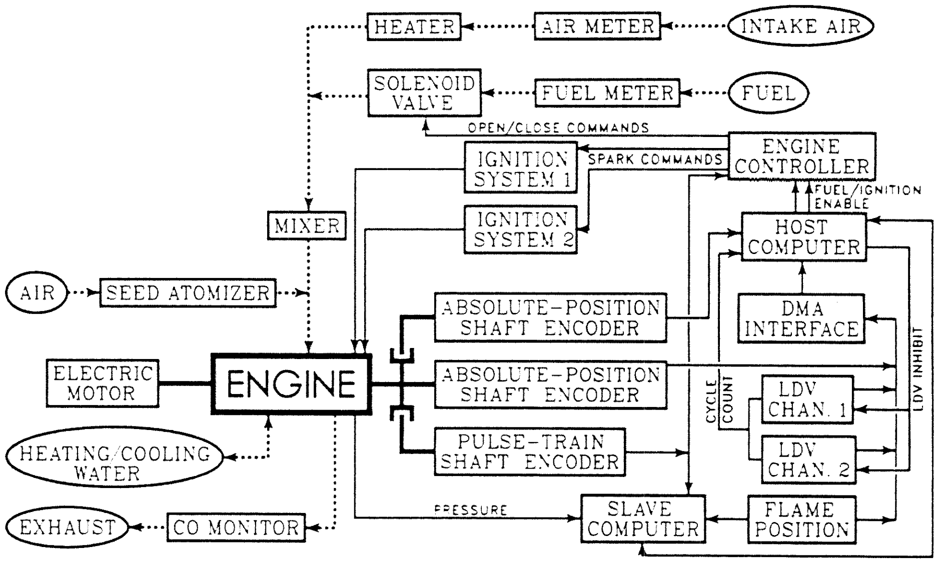


Fig. 2 Schematic diagram of the engine control and instrumentation system

electrodes used to generate the six sparks have been positioned to allow access to 9 mm diameter windows located at each end of the channel, permitting study of the turbulent flame structure by the microschlieren technique developed by Smith (17).

Figure 1 also shows the position of the fused silica window in the head, which gives optical access to the fully developed portion of the burn. There is a mirror in the bottom on the channel, on the piston, for flame visualization using a double-passed laser schlieren system.

Engine control and instrumentation. Figure 2 presents a schematic diagram of the entire engine control, instrumentation, and data acquisition system. A PDP-11/34 computer serves as the heart of the laboratory, having ultimate control of all aspects of the experiment.

The heating/cooling water, intake fuel-air mixture, and the engine head and cylinder walls are all instrumented with thermocouples to monitor the temperature. Water-cooled piezoelectric pressure transducers are located in both the channel and one of the segments to measure the chamber pressures. The CO content of the exhaust gases is measured to determine the stoichiometric operating conditions. Electronic flow meters are located in the fuel and air lines prior to the heating and mixing sections to monitor the repeatability of the experiment from day to day. They are not used to measure the fuel/air mixture because of the skip-firing mode of operation used.

A custom-built engine controller is used to regulate ignition timing and fueling of the engine. Switches select the following timing functions:
1) crank-angle position to begin fuel injection;
2) crank-angle duration of fuel injection; 3) crank-angle positions to fire the two independent ignition systems; 4) crank-angle position of synchronous strobing of the laser beam for schlieren flow visualization. Timing information for the controller is provided by a pulse-train type shaft encoder geared down 2:1 to give a resolution of one crank-angle-degree (CAD) for the full four-stroke cycle, defined to consist of 720 CAD, with TDC of the compression-expansion stroke at 360 CAD.

Both the ignition and fueling functions are activated by the laboratory computer through enable commands, giving the computer priority control of engine operation on an individual-cycle basis. In the standard mode of operation, the engine is first brought up to the desired speed by motoring with the electric motor. The engine speed is determined by the computer by timing a number of rotations of the shaft encoder. A test is begun with the computer enabling the engine controller for a number of warm-up cycles, during which the engine is fueled every cycle, but fired only on the fifth cycle. Following the warm-up period, data acquisition commences for a specified number of either engine cycles or LDV measurements. Upon completion of the test, the computer disables ignition and fueling.

Data Acquisition System

Two computers are used to acquire the data. The host computer stores the LDV measurements in a direct-memory-access (DMA) mode, while the slave computer records the cylinder pressure and flame position at one CAD intervals. This procedure is used because the pressure and flame position are smoothly varying quantities that need not be measured at the high data rates and random intervals of the LDV signals.

The host computer is synchronized with the engine by an absolute-position digital shaft encoder geared down 2:1, with 0.2 CAD resolution. This encoder is interfaced to the computer through a specialized input board that issues an interrupt command whenever a prespecified crank angle is encountered. Used in conjunction with a digital output board, the encoder interface is programmed to issue discrete commands that serve the following functions: 1) grounding of the pressure transducer charge amplifier prior to each cycle of pressure recording, to ensure a constant baseline condition; 2) ignition and fuel enable signals to the engine controller; 3) definition of the window in the engine cycle for which LDV measurements are to be taken; the signal inhibits the LDV signal processor when the window is not open; 4) actuation of the camera shutter for still schlieren photography. Each command issued by the encoder interface is also used to illuminate a diode in an event display, for visual monitoring of the control system sequencing.

The LDV data obtained by the two signal processors are transferred to the computer in DMA mode by a multichannel interface. The interface has the capability to transfer the time duration of the Doppler measurement, the number of cycles used in the measurement, and the time between consecutive bursts (for time-correlation measurements), together with the crank-angle position of the measurements. A second absolute position digital encoder is used for the latter. This encoder is coupled directly to the engine crank shaft, giving a resolution of 0.1 CAD.

Because the LDV data are normally obtained in the fixed-cycle mode, where a prespecified fixed number of cycles are timed for each LDV measurement, it is not efficient to record this quantity with each measurement. The interface can be set to ignore the cycle count (as well as the time between bursts) during the DMA transfer, but because this selection must be made with the hardware, rather than in software, the cycle count is completely lost. To recover this information, we have chosen to use the digital output buffer register of the timer module of the counters. Since the cycle count is only the lower byte of the output word, the cycle count for each channel of LDV can be combined to form one word of digital input to the computer. When the DMA transfer of a test is completed, the computer stores this one word to obtain the cycle count settings of each counter.

A fourth, optional channel is available in the DMA interface, if it is desired to record the instantaneous flame position at the moment of each LDV measurement. This would be desirable, for example, if high resolution conditional sampling on flame position is to be performed. Because the flame position technique uses a conventional LDV burst processor to process the signal, the measurement is readily compatible with the multichannel interface. More will be said about this later.

As previously mentioned, the slave computer is used to make pressure and flame position measurements at a uniform data rate, in parallel with the LDV measurements. At the beginning of each data cycle the host computer enables the slave to accept data in an external interrupt command mode. The one CAD interval pulses from the pulse-train encoder are used as the interrupt signal. At each interrupt, an analog-to-digital (A/D) conversion is made of the pressure signal, and a digital transfer is made from the output buffer of the flame-position-measurement timer module.

Optical Diagnostics

The optical arrangement diagrammed in Fig. 3 permits the simultaneous use of LDV and schlieren techniques, where the latter is used to provide the measurement of flame position. A single, 15 watt argon-ion laser is used to obtain the three optical measurements. The two components of velocity are measured using the 488 and 514.5 nm lines of the laser, and the flame position is obtained with the 476.5 nm line.

Flame position measurement. The position of the flame is measured using a high speed schlieren imaging technique (18). A mirror on the piston surface reflects the incident schlieren light field back from the engine and onto a linear photodiode array, which is aligned to image the diameter of flame propagation in the line of sight of the photodetectors. Prior to combustion, all of the photodiodes aligned with the engine cylinder will be uniformly illuminated. As combustion takes place, the photodiodes corresponding to the flame surface will detect reduced illumination because of refraction, such that the location of the flame surface is simply proportional to the number of fully-illuminated photodiodes before the flame.

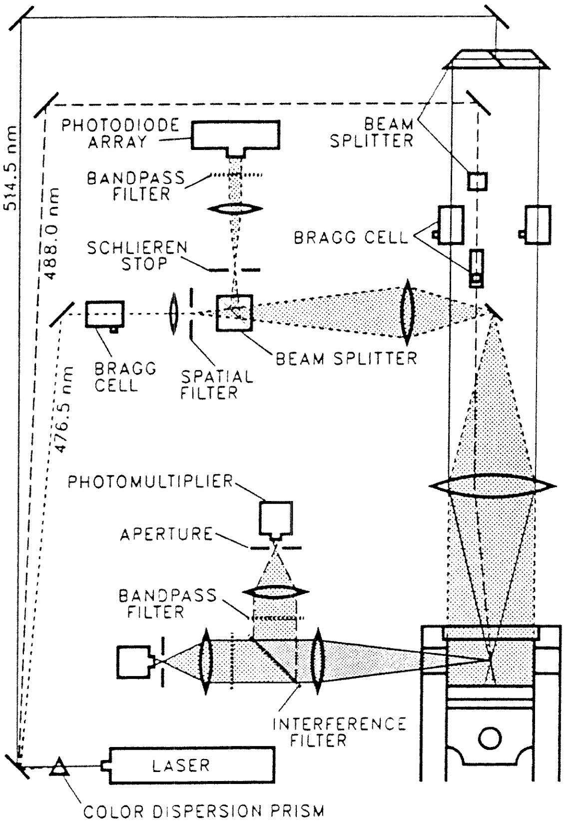


Fig. 3 Optical arrangement for the simultaneous application of LDV and laser schlieren visualization

The source laser beam for the schlieren image is passed through a Bragg cell used to solve a problem introduced by using a mirror on the piston to return the schlieren light to the photodiode array. During each engine cycle the piston is subject to a rocking motion about the wrist pin. The effect of this motion is a nonstationary image at the schlieren aperture location. Fortunately, the rocking motion is reasonably in-phase with the engine cycle, such that synchronous strobing of the laser beam freezes the focal point well enough for the schlieren stop to be positioned. The Bragg cell is aligned such that one of the first-order refracted beams creates the schlieren light field. A command from either the host computer or the engine controller is then used to energize the Bragg cell for a short period, synchronously with the engine cycle. This procedure can also be used to take fast still photographs of the combustion event using a conventional camera (19), whereby exposure times as short as one microsecond can be achieved.

The electronic circuitry for the photodiode array reads the charge on each element continuously at a fixed clock rate, such that the analog output signal is analogous to a Doppler signal of known and constant frequency. If the signal is processed by a standard LDV burst counter operating in the total burst mode, the number of cycles measured in the first "burst" encountered in each scan of the array is a direct measure of the flame position. For the uniform-data-rate record of flame position made by the slave computer, this signal can be obtained directly from the output buffer of the timer module. If the measurement is to be made simultaneously with each LDV measurement, then it is necessary to record the time duration of the "burst", since the multichannel interface has been set for this quantity for the two channels of LDV. However, because the frequency of the photodiode array signal is known, the time duration measurement is proportional to the number of illuminated photodiodes ahead of the flame.

Velocity and turbulence measurements. The LDV optical arrangement shown in Fig. 3 is nearly conventional. Dual Bragg cells are used to resolve directional ambiguity. We have found the dual cell arrangement to be far superior to using a single cell with electronic down-mixing. The Bragg cells require greater driving power than those commonly used, which allows the transmission of a larger diameter beam with less loss and distortion than is typically encountered.

The LDV signal is collected at right angles to the incident beam axis, to alleviate the problems of background flare of the laser beams from the window and piston surfaces. The signal-to-noise ratio with this configuration is far superior to direct backscatter. Because of the mirror on the piston, there is a problem with the velocity component in the viewing direction, since the incident beams reflect off the mirror and pass through the line of sight of the photodetectors, creating a noise problem. This is alleviated by tilting the incident optical axis for this component relative to the cylinder axis, so that the reflected incident beams pass to the side of the probe volume.

The LDV signal is created by scattering from a powder introduced continuously into the intake manifold. To obtain a steady flux of particles of constant size, the powder is suspended in water continuously agitated by a magnetic stirrer. A blast atomizer creates a fog of water droplets containing the powder, which is dried by a dessicant prior to being introduced to the engine.

Two different powder materials are used, depending on whether the engine is being motored or fired. For motoring tests, we have found titanium dioxide (TiO_2) to be very satisfactory. The fundamental size of these particles is 0.2 microns, and we estimate that we are detecting either individual particles or agglomerates that are less than 0.5 microns in effective size. With combustion, however, we have found that at engine temperatures the Doppler signal from titanium dioxide is greatly reduced, often to an undetectable level. Measurements appear to be possible for lean operating conditions, but with a stoichiometric mixture there is no detectable scattered light. We do not know the cause of the signal loss, but because we are convinced that it is not related to deagglomeration of particles, we suspect that the particles are melting, and that inherent with the phase change is a sizeable reduction in the scattering cross section.

For LDV with combustion, in the past we have had some success using aluminum oxide (Al_2O_3), but have found it to be far too abrasive for regular use. Recently, we have begun using zirconium fluoride (ZrF_4) with good success. We do not know the size or hardness of this powder, but find that it yields high data rates from the postflame gases, and does not appear to be detrimental to the engine bore. We also do not know why this material scatters light so efficiently with combustion, since it is supposed to sublime at $600^{\circ}C$. Zirconium fluoride is slightly soluble in water, but we are using a suspension that we estimate produces particles between 0.1 and 0.5 microns. The suspension has a tendency to form agglomerates as large as a millimeter, so it is necessary to remove large particles from the aerosol. When compared to titanium dioxide, the signal intensity and data rates obtained with zirconium fluoride are not as good, but it tends to foul surfaces far less than titanium dioxide.

Data Reduction Procedures

The existence of cyclic variations in the fluid motion in engines raises a fundamental question about how to properly describe the velocity field. Are these variations compatible with a statistical definition of turbulence, for which the mean velocity and turbulence intensity are calculated from the phase average (or ensemble average) of many engine cycles? Or, if such averages are made, will the results be biased because the average is being made from an ensemble of different events, and not from a flow having a repeatable mean velocity for each cycle, with superposed random fluctuations occurring within each cycle?

One proposed solution to this uncertaintly is to filter the LDV signal on an individual cycle (real-time) basis. This has been done by Rask (20) using curve-fitting techniques, and by Liou and Santavicca (21) using Fourier analysis. In essence, both techniques remove the low frequency fluctuations attributed to cyclic variations in the mean flow, such that only the high frequency fluctuations are included in the calculation of the turbulence. A major shortcoming of these procedures is the arbitrariness of the selection of the cutoff frequency, since it has yet to be shown that a definitive characteristic frequency exists. A second problem that arises is the question of the relation of such measurements to analytical models, since it is not obvious that the low frequency fluid motion can be neglected in the analysis. For these reasons, we have chosen a different approach in which all frequencies of fluid motion are retained, but with the individual engine cycles subdivided into subsets of similar events that are averaged as discrete groups. We refer to this procedure as conditional sampling.

Conditional sampling. In its application, conditional sampling involves the selection of one or more combustion parameters to identify individual engine cycles that are similar in nature, thereby permitting statistical averages to be computed for a group of physical processes that are described as possessing only stochastic differences. When used to resolve cyclic variations from turbulence, the method inherently assumes that there is a direct cause-and-effect relationship between the fluid motion and the combustion process. The effectiveness of the procedure is therefore dependent on the selection of the correct deterministic condition parameters, which often involves some degree of subjectiveness.

A conditional sampling study by Cole and Swords (22) successfully demonstrated a correlation between fluid motion in the spark gap at the time of ignition with the overall combustion duration, and the existence of cyclic variations in the bulk turbulence intensity has been shown to correlate with cyclic variations in the burn rate (12). A somewhat less successful study made using three simultaneous but independent conditions for selective sampling found that the combustion process can be too complex for analysis by conditional sampling even when multiple parameters are considered (14).

The experimental setup described in this paper has been designed to provide the information needed to allow single point velocity and turbulence measurements to be processed and analyzed. The key to the experiment is the achievement of a nearly planar flame surface, since the linear photodiode array detects the flame location based on a line-of-sight measurement along a single diameter of the combustion chamber. If the flame surface is significantly distorted on a scale large compared to the flame thickness, then the flame location measurement will not have a unique relation to the volume fraction burned.

Two levels of conditional sampling on flame location have been incorporated in the experiment. The lower-order procedure is to use the uniformly-spaced flame position obtained by the slave computer to identify similar combustion cycles by matching the flame position history for the complete combustion period, in the manner demonstrated previously using the pressure history (14). Differentiation of the flame position curve gives the local flame propagation speed, which together with the expansion velocity and turbulence intensity ahead of the flame yields the necessary information to correlate the turbulent flame speed with the turbulence intensity. Although a direct measurement of the turbulent length scales is not currently planned, it has been shown (11) that the measured decay rate of turbulence prior to combustion can give a consistent indication of the dissipation length scale.

The second, higher-resolution level of conditional sampling designed in the experiment uses the instantaneous flame position relative to each individual velocity measurement. Because the flame surface is characterized by a nearly discontinuous velocity jump associated with the expansion of the gases, velocity measurements made near the flame are heavily influenced by both the position and orientation of the flame surface relative to the probe volume. In particular, flame speed variations and wrinkles in the flame surface increase the measured turbulence intensities and bias the Reynolds stress. Thus, as the flame surface approaches the LDV probe volume there is a transition from a conventional freefield turbulent flow to one dominated by the large velocity gradient normal to the highly wrinkled and possibly multiply connected flame surface. Very near the front of the flame surface it will not be possible to accurately measure the position of the flame relative to the probe volume, because of the line-of-sight nature of the schlieren measurement, but it is expected that some insight into the flame structure will be obtained from conditioned turbulence intensity and Reynolds stress measurements made within the transition region.

Editing and averaging. Due to memory limitations in the computer, it is necessary to execute each test case in stages, periodically halting data acquisition to transfer data to a storage device. We typically record five blocks of data, where each block contains 1500 sets of velocities, crank angle, and flame position. Because a test is interrupted to store each block, we occasionally use this opportunity to readjust signal levels.

Upon the completion of a test, the first step in data processing is to display each block of velocity data as a scatter-plot; that is, the measurements for each component are displayed in the order of acquisition. The purpose for this is to look for patterns in the data that correlate with the period of the test, such as a drift or broadening of the velocity range. If a pattern is observed, the test is discarded. Typically, a drift in velocity corresponds to changes in the engine operating conditions, and broadening occurs as the windows become fouled.

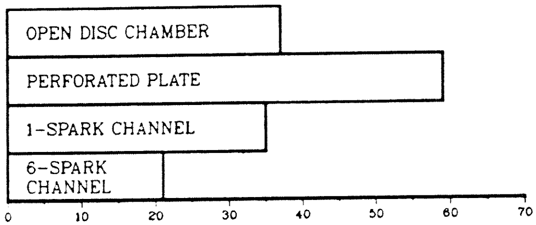
Because the conditional sampling is applied on an individual cycle basis, it is necessary to keep all the raw data in this form. When the condition parameters have been selected, the corresponding cycles of data are then retrieved and phase averaged. Because of the random arrival time of LDV measurements it is necessary to perform the phase average over a finite crank-angle window. Selection of the window size depends on the crank-angle transients in the velocity. Typically, for motored measurements 5-10 CAD resolution is sufficient, whereas with combustion 1-2 CAD windows are required.

An inherent characteristic of the LDV technique is the unavoidable occurrence of occasional "bad" data points. Under conditions of good signal-to-noise ratio, bad measurements can usually be avoided. However, with less favorable conditions, such as encountered in a combusting environment accessed through windows, bad measurements have to be expected, and therefore procedures have to be developed to discriminate and remove them. This is particularly important when calculating the standard deviation and other higher moments, since even one statistical outlyer among thousands of measurements used in the average can result in an appreciable computed error.

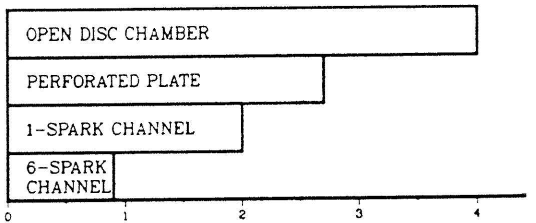
The easiest editing procedure to implement is to simply discard all data that lie outside a range specified as a multiple of the standard deviation (i.e., discard all data outside four standard deviations). However, such a procedure can be very risky, particularly for data obtained during combustion, since both skewed and broadened distributions can occur locally in both space and time. For this reason we have found it to be necessary to edit LDV data in an interactive mode. The procedure is to simultaneously display the data for each crank-angle window in two forms. One display is a histogram of the data, while the other is a scatter-plot displayed in the order of acquisition. The purpose is to again look for patterns in the scatter-plot, particularly with regard to correlations with outlyers displayed in the histogram. If editing is required, after removal of the bad data these two displays are again generated. Occasionally, several iterations are required. As a general rule, unless there is an obvious block or region of bad data, we reject the entire test if as much as one percent of the data is bad. For example, the highest rejection rate for the data presented in this paper was 0.3 percent.

RESULTS

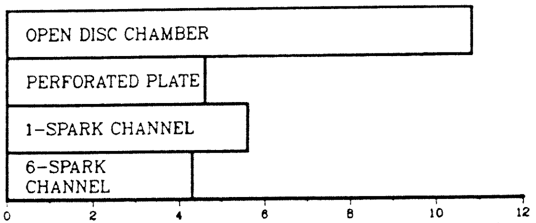
Preliminary evaluation of the channel design was performed with focus on the burning rate and



a. BURN DURATION (CAD)



b. STANDARD DEVIATION IN BURN DURATION (CAD)



c. RELATIVE STANDARD DEVIATION IN BURN DURATION (%)

Fig. 4 Combustion performance, where the burn duration has been defined as the crank-angle interval between ignition and maximum pressure

cyclic variation. Of primary interest was whether the channel would achieve a combustion rate comparable to an disc chamber, while reducing cyclic variations to the same order as was achieved with the perforated plate. Results will be presented comparing these three configurations, along with a comparison between one point and six point ignition in the channel. Initial LDV results will then be presented to illustrate the general nature of the channel flowfield, again as compared to an open disc chamber and the perforated plate configuration. The results presented will emphasize the 1200 rev/min test condition, since it was at this speed that the disc and perforated plate configurations were previously found to be unsuitable for research purposes.

All tests were run on a stoichiometric mixture of propane and air, with the engine fired every fifth cycle. Ignition timing was set to give maximum pressure at 17 CAD after TDC, except for the case of the channel with six ignition points. In this instance the burn rate was extremely fast, such that the ignition time was selected so that ignition and maximum pressure occurred the same number of CAD before and after TDC.

The pressure results were obtained from an ensemble of 50 engine cycles, using a resolution of one CAD. The mean velocity and turbulence calculations were made using a minimum of 300 measurements in each averaging window. Ten CAD windows were used to process the motored velocity results.

Pressure Measurements

The combustion performance results are summarized in Fig. 4. The burn duration has been defined simply at the time between ignition and maximum pressure, and the variation in burn duration is used as a measure of cyclic variation.

The burn duration results show that the channel with one spark burns slightly faster than the open disc chamber, indicating that the flanges did not have the detrimental effect observed for the perforated plate. It should be noted that the compression ratio for the open disc and perforated plate configurations was 4.5:1, as compared to 7.6:1 for the channel chamber, so that the laminar flame speed is higher for the channel. At TDC, we estimate the laminar flame speed for the higher compression ratio to be 1.2 times that of the lower compression cases. Figure 4a also shows that the effect of using six ignition sites is to reduce the burn duration by more than forty percent.

The standard deviations in burn duration given in Fig. 4b indicate the absolute degree of cyclic variation in combustion. However, because the level of cyclic variation does in general decrease with faster combustion, it is also necessary to look at the relative cyclic variation, which is shown in Fig. 4c. This figure shows that it is the very long combustion duration with the perforated plate that led to the large cyclic variation indicated in Fig. 4b.

The conclusion to be drawn from Fig. 4 is that the combustion rate in the channel with one ignition site is comparable to that of the open disc chamber, but with a fifty percent improvement in the cyclic variation. If six ignition sites are used, a very fast and repeatable burn is achieved.

In Fig. 5 the burn duration results are displayed as a function of the piston motion that takes place during combustion. The convention used is that TDC is at 360 CAD. The purpose of this figure is to illustrate that the combustion process for the channel with six ignition sites can be approximated as a constant volume burn. This is a useful feature, since it broadens greatly the scope of analytical models that can be used to evaluate data obtained for the channel configuration.

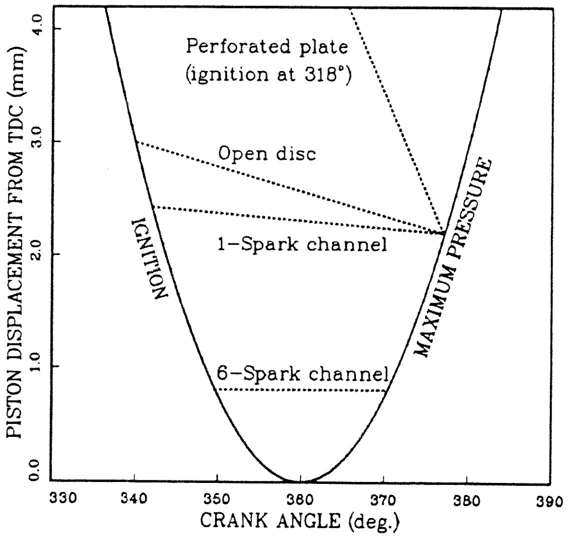


Fig. 5 The times of ignition and maximum pressure are plotted on the curve of piston displacement versus crank-angle, showing that the piston motion is negligible for the combustion duration of the 6-spark channel

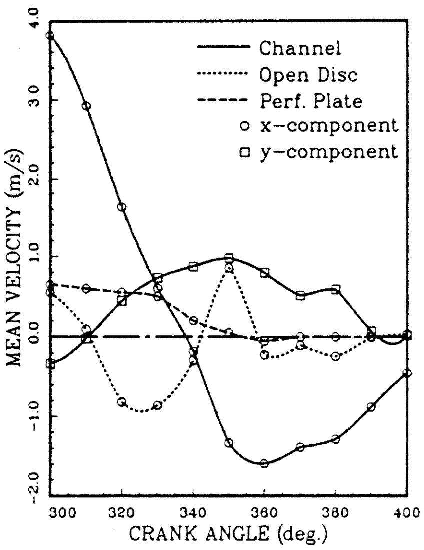


Fig. 6 Comparison of LDV mean velocity measurements made at x/R=0.66 at 1200 rev/min for the coordinate system shown in Fig. 1

LDV Measurements

Mean velocity measurements taken at x/R=0.66 (R is the cylinder radius) are compared in Fig. 6. A very surprising result is the large velocity along the centerline of the channel. Because LDV measurements have been made at only a few locations in the channel, the nature of the base flow in the channel is not known. We speculate that one effect of the channels on the piston and head is to stabilize the orientation of the roll vortex created by the side-wall location of the intake valve. For the open disc chamber, the orientation of this motion can vary considerably, such that on the average the mean velocity is significantly lower.

The mean velocity measured cross-wise to the channel axis is also not negligible, as seen in Fig. 6. However, the question raised earlier regarding possible undesirable complexities in the flow resulting from squish areas would appear to be unimportant, considering the large and seemingly complex flow patterns in the direction of the channel axis. The critical feature to be determined about the flow is whether the flame surface is reasonably one-dimensional with respect to the channel, or whether the mean motions indicated in the figure result in a highly distorted flame characterized by large cyclic variations in shape and orientation. This question is expected to be resolved from flow visualization and conditionally sampled velocity measurements.

The turbulence intensity, normalized by the mean piston speed, is shown in Fig. 7 for the three combustion chamber configurations. These results indicate how poorly the open disc chamber turbulence intensity scales with engine speed, and how much larger the measured turbulence is for the open disc as compared to the channel chamber. We believe these two observations are related, and are the result of the open disc chamber flowfield being dominated by large-scale, low frequency structures.

The channel data shown in Fig. 7 scale only reasonably well with engine speed. The trends of the three curves indicate less production of turbulence during compression for the highest speed, followed by a slower rate of dissipation. The rate of decay from the 340 CAD point is quite uniform for all speeds, indicating a degree of relaxation. The turbulence levels for the channel are approximately fifty percent higher than for the perforated plate case, which explains at least a part of the slow burning rate characteristics of the latter.

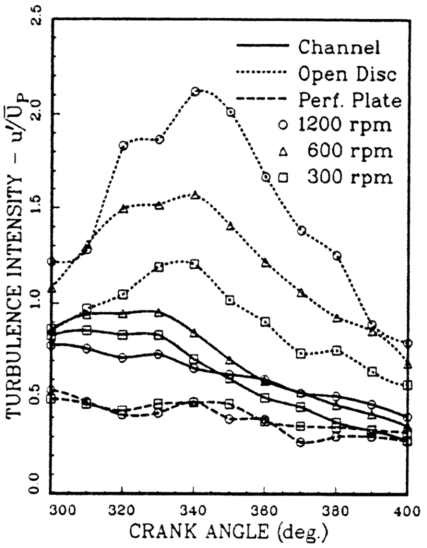


Fig. 7 Comparison of the x-component of turbulence intensity, normalized by the mean piston speed, for x/R=0.66

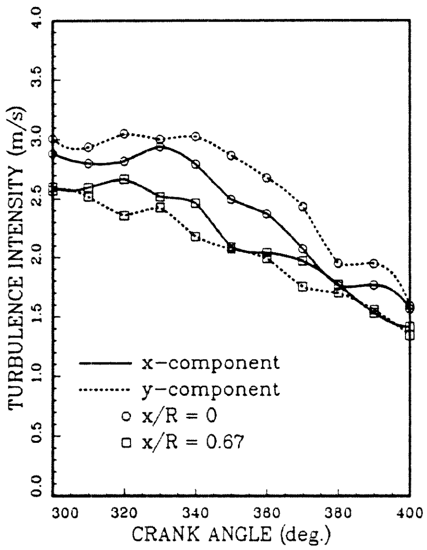


Fig. 8 Turbulence intensity results at 1200 rev/min for the channel chamber, showing the degree of isotropy and homogeneity present

Figure 8 summarizes initial measurements concerning the homogeneity and isotropy of the turbulence field in the channel. The flow appears to be more nonhomogeneous than it is anisotropic, which is consistent with the earlier observations of a complex mean flow and a uniform decay rate of turbulence. The relative variation in turbulence shown is approximately thirty percent. This is higher than desired for our research needs, but hopefully conditional sampling procedures will help to reduce the variation.

SUMMARY

An experiment has been designed to obtain measurements pertaining to turbulent flame propagation velocities. The simultaneous and direct measurement of flame speed, expansion velocity and turbulence intensity provides the needed information, without relying on thermodynamic analysis or experimental compromises such as flame holders or opposing flames. Because cyclic variations must be considered to be an inherent difficulty in such an experiment, special efforts have been taken to minimize their impact. Simultaneous cycle-resolved measurements of pressure and flame position allow conditional sampling techniques to be applied at their fullest, and a idealized combustion chamber has been designed to achieve the high turbulence intensities found in engines, but with a constraint on the length scales of turbulence to limit the cyclic variation.

The combustion performance of the channel configuation has been shown to be very good, yielding a fast burn rate with greatly reduced cyclic variation in the burn duration. However, LDV measurements of the mean velocities in the channel show the flowfield to be surprisingly complex, particularly with regard to a large mean flow in the direction of the axis of the channel. The turbulence is isotropic and homogeneous to within thirty percent, but it is apparent that the complex mean flowfield has compromised the idealized turbulence field sought. However, the fact that the cyclic variation in the combustion rate has been reduced so significantly provides encouragement for further investigations with this engine configuration.

ACKNOWLEDGMENTS

The author would like to thank James Boehmke, Leo Mara and Eldon Porter for their assistance with the design and construction of the experiment; Dr. Thierry Baritaud of the Institut Francais du Petrole for suggesting the use of zirconium fluoride; and Dr. David Gosman of Imperial College for our discussions on the need for new experimental data on turbulent flame speeds. This work was funded by the U.S. Department of Energy, Division of Energy Conversion and Utilization Technologies, and the Motor Vehicle Manufacturers Association.

REFERENCES

1. Abraham, J., Williams, F. A., and Bracco, F. V., "A Discussion of Turbulent Flame Structure in Premixed Charges," SAE Paper No. 850345, 1985.
2. Williams, F. A., Combustion Theory, Addison Wesley, Reading, pp. 166-170, 1965.
3. Andrews, G. E., and Bradley, D., "Determination of Burning Velocities: A Critical Review," Comb. and Flame, Vol. 18, pp. 133-153, 1972.
4. Andrews, G. E., and Bradley, D., "Determination of Burning Velocity by Double Ignition in a Closed Vessel," Comb. and Flame, Vol. 20, pp. 77-89, 1973.
5. Abdel-Gayed, R. G., Al-Khishali, K. J., and Bradley, D., "Turbulent Burning Velocities and Flame Straining in Explosions," Proc. R. Soc. Lond. A, Vol. 391, pp. 393-414, 1984.
6. Smith, J. R., "Turbulent Flame Structure in a Homogeneous-Charge Engine," SAE Trans., Vol. 91, Paper No. 820043, pp. 150-164, 1982.
7. Homamoto, Y., Ohkawa, H., Yamamoto, H., and Sugahara, R., "Effects of Turbulence on Combustion of Homogeneous Mixture of Fuel and Air in Closed Vessel," Bull. JSME, Vol. 27, pp. 756-762, 1984.
8. Lancaster, D. R., "Effects of Engine Variables on Turbulence in a Spark-Ignition Engine," SAE Trans., Vol. 85, Paper No. 760159, pp. 671-688, 1976.
9. Lancaster, D. R., Krieger, R. B., Sorenson, S. C., and Hull, W. L., "Effects of Turbulence on Spark-Ignition Engine Combustion," SAE Trans., Vol. 85, Paper No. 760160, pp. 689-710, 1976.
10. Groff, E. G., and Matekunas, F. A., "The Nature of Turbulent Flame Propagation in a Homogeneous Spark-Ignited Engine," SAE Trans., Vol. 89, Paper No. 800133, pp. 740-764, 1980.
11. 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. 786-796, 1983.
12. Witze, P. O., Martin, J. K., and Borgnakke, C., "Conditionally-Sampled Velocity and Turbulence Measurements in a Spark Ignition Engine," Comb. Sci. and Tech., Vol. 36, pp. 301-317, 1984.
13. Martin, J. K., Witze, P. O., and Borgnakke, C., "Combustion Effects on the Preflame Flow Field in a Research Engine," SAE Paper No. 850122, 1985.
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, Combustion Institute, Pittsburgh, PA, 1984 (to appear).
15. Quader, A. A., "What Limits Lean Operation in Spark Ignition Engines - Flame Initiation or Propagation?," SAE Trans., Vol. 85, Paper No. 760760, pp. 2374-2387, 1976.
16. 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.
17. Smith, J. R., "The Influence of Turbulence on Flame Structure in an Engine," Flows in Internal Combustion Engines, (Ukzan, T. ed.) ASME, New York, pp. 67-72, 1982.
18. Witze, P. O., "An Optical Imaging Technique for Measuring Time-Resolved Flame Position," Experiments in Fluids (to appear), 1985.
19. 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. 979-992, 1981.
20. Rask, R. B., "Comparison of Window, Smoothed-Ensemble, and Cycle-by-Cycle Data Reduction Techniques for Laser Doppler Anemometer Measurements of In-Cylinder Velocity," Fluid Mechanics of Combustion Systems, (Morel, T., Lohmann, R. P., and Rackley, J. M. ed.) ASME, New York, pp. 11-20, 1981.
21. Liou, T.-M., and Santavicca, D. A., "Cycle Resolved LDV Measurements in a Motored IC Engine," Engineering Applications of Laser Velocimetry, (Coleman, H. W., and Pfund, P. A. ed.) ASME, New York, pp. 33-37, 1982.
22. Cole, J. B., and Swords, M. D., "An Investigation of the Ignition Process in a Lean-Burning Engine using Conditionally Sampled Laser-Doppler Anemometry," Trans. SAE, Vol. 89, Paper No. 800043, pp. 260-275, 1980.