Technical notes

An optical imaging technique for measuring time-resolved flame position

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1 Introduction

An experimental diagnostic for measuring the one-dimensional time-resolved location of a propagating flame has been developed. The technique uses a linear photodiode array to identify the flame surface in a schlieren image of the combustion event. Data rates as high as 30 kHz can be achieved by processing the signal with a standard laser Doppler velocimeter (LDV) burst counter. The method is generally applicable to the measurement of any motion that can be imaged as a sharp spatial gradient in the intensity of a light field, although it was developed specifically for the purpose of making simultaneous measurements of velocity and flame position in a reciprocating engine.

An inherent problem in the study of engine fluid mechanics is a lack of repeatability in the combustion rate from cycle to cycle. Because the volume expansion of the reacting gas mixture creates a strong velocity gradient at the flame surface, cyclic variations in flame position will bias cycle-averaged velocity measurements. The ultimate effect is a smearing in the amplitude of mean velocity gradients and, more importantly, a false contribution to the turbulence intensity that causes erroneously high results. In a recent study, Witze et al. (1984) demonstrated that conditional sampling procedures that use the location of the flame surface on an individual cycle basis can significantly reduce these bias errors. Those measurements were obtained using an ionization probe to detect the moment of flame arrival at the LDV probe volume. In a later study by Martin et al. (1984), a multibeam laser refraction technique was used to obtain additional information about the individual-cycle flame speed and the early flame-development period. However, this technique is still not sufficient to completely remove bias errors, since the necessary condition is to consider the complete history of the flame location throughout the burn period.

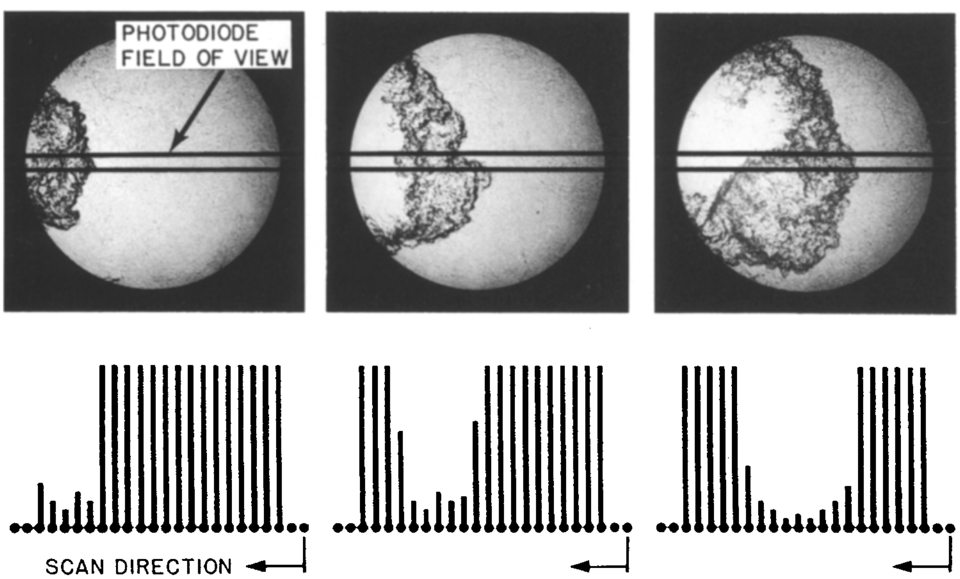

Fig. 1. Laser schlieren images and simulated photodiode array response signals

2 Concept

The multibeam refraction experiment of Dyer (1979) used four equally spaced laser beams along the path of flame propagation to measure both flame position and local flame speed. A logical extension of this approach is to dramatically increase the number of beams used until a nearly continuous measurement is obtained. This is the essence of the technique developed for this paper. The concept of the method is simple, as illustrated in Fig. 1: a) the schlieren image of the flame propagation path along the line of symmetry is focused onto a linear photodiode array; b) prior to combustion, all of the photodiodes aligned with the engine cylinder will be uniformly illuminated; c) as combustion takes place, the photodiodes corresponding to the flame surface will detect reduced illumination because of refraction; d) the location of the flame surface is simply proportional to the number of fully-illuminated photodiodes before the flame.

3 Instrumentation

It is not necessary to construct special electronics to process the photodiode array signal, since commercially available LDV counters operated in the total burst mode are directly suitable. The use of a burst counter also makes it a simple task to make simultaneous measurements of velocity and flame position, since multiplex electronics for several channels of LDV are commercially available. Scanned at a fixed clock rate, the analog output signal from the photodiode array electronics is analogous to the Doppler signal produced by a photomultiplier tube. Band-pass filtering of the signal at the scanning-frequency produces an ac signal of constant amplitude when the illuminating light field is uniform, such as found in the unburned gases ahead of the flame. If the array is scanned in the direction corresponding to the path from the end wall toward the spark plug, the number of cycles in the first "Doppler burst" of each scan is a measure of the distance of the flame surface from the wall. Calibration of the system is simple: by adjusting the magnification of the schlieren image to be slightly smaller than the physical length of the photodiode array, the number of cycles in the Doppler burst obtained without combustion corresponds to the total path length under investigation, which in this case is the diameter of the engine cylinder.

The linear photodiode array selected was an EG & G Reticon C Series Model RL-256C/17, which consists of 256 photodiodes on 25.4 micron centers. This particular configuration was chosen as a compromise between spatial resolution and the total time required to complete a scan. The electronic circuitry available for this array can scan at rates from 500 Hz to 10 MHz, such that the total time required for a single scan can be as low as 26.4 microseconds.

4 Results

To demonstrate the use of a burst counter to process the photodiode array output signal, previously developed computer software intended for LDV engine measurements was used. The flame position signal was simply connected as if it were the LDV photomultiplier output. The scanning clock of the array electronics was operated at a 500 kHz rate, and the photodiode array output signal was processed by a TSI Model 1990 counter. With the array clock free-running, the procedure used was to read and store the crank-angle of occurrence of each validated output from the counter for many successive engine cycles; data acquisition was gated with the engine cycle to store only measurements made during the combustion period.

Results for the average transient flame position computed for twelve successive engine cycles are shown in Fig. 2. The measurements were made along a diameter of a disc-shaped combustion chamber, as previously illustrated in Fig. 1. The data processing procedure involved averaging the measurements over one crank-angle-degree intervals. The average cylinder pressure measurements taken with this flame data are also shown. One important feature of this curve is the lack in sensitivity of pressure measurements early in the burn period, illustrating the importance of flame position measurements to the understanding of the early flame development period.

The principle advantages of the technique described are the speed at which the flame position can be recorded, and the ready availability of the instrumentation needed to process the signal produced by the photodiode array. A

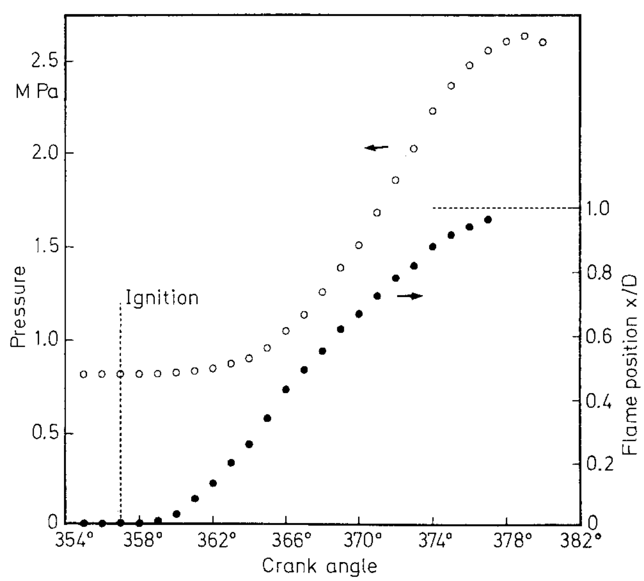

Fig. 2. Cycle-averaged flame position and pressure measurements for stoichiometric propane combustion at 300 rev/min

particularly important application of the method would be the measurement of the tip penetration rate of fuel sprays, since to date this is typically determined by the analysis of high speed movie films, which is exceedingly laborious and cannot be done in real-time.

Acknowledgements

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