Local Chemiluminescence Measurement for Flame Propagation Analysis

Yuji Ikeda, Satoaki Ichi, Hiroshi Nakai and Tsuyoshi Nakajima
Department of Mechanical Engineering, Kobe University, Rokkodai, Nada, Kobe 657-8501, Japan

ABSTRACT

Local chemiluminescence intensities of OH, CH and C2 were measured at several locations in an engine cylinder. Cassegrain optics were designed to increase spatial resolution of the same order as conventional LDV techniques. Three chemiluminescence intensities were measured using an optical filter and PM tube.

Measurements were carried out on a small 125 cc two-stroke motorcycle engine. Optical access was provided through the use of an optical cylinder head and modified spark plug. Radial intensity profiles can be used to indicate combustion status and flame propagation speed and its thickness in the cylinder, this approach has not been mentioned in the literature. The relationships between radical intensity, heat release ratio, and IMEP were examined and their typical cyclic variations were explained. The speed of a flame propagation was calculated from its arrival time at the measurement point and its flame thickness from its duration. The flame propagation speed was calculated from the cyclic variation in OH radical measurements. The strong relationship between flame speed and RHR was also clearly illustrated and explained.

1. Introduction

In SI engines, a flame kernel is produced at ignition and this flame then propagates through the fuel-air mixture. The turbulent structure near the spark plug influences the development of the flame kernel, and local turbulence near the flame front is the dominant factor in the propagation of the flame. In order to understand the structure of a propagating flame, it is necessary to examine its time series reaction data.

Examining the details of a flame front structure and its relationship to the heat release rate has been an important research topic in engine development. Many contributions have been made to our knowledge of flame front structure, the effect of turbulence on the flame propagation rate and misfiring resources, and to our understanding of ignition delay and factors affecting heat release using techniques such as LIF\(^{[1, 2]}\), LDV\(^{[3, 4]}\), PDA\(^{[5]}\), PIV\(^{[6, 7]}\), Schlieren photography\(^{[8, 9]}\), ion probe\(^{[10]}\), and others. LIF is a very powerful tool in the visualization of a flame surface and its spatial structure, but the details of the flame structure, front thickness and propagation speed require measurement at a higher temporal and spatial resolution. Local chemiluminescence measurements can be used to provide the high spatial and temporal resolutions needed.

In fundamental combustion research, a continuous combustion chamber was used\(^{[11]}\) to obtain measurements of flame speed and turbulent scale. Ion probe techniques have also been employed to measure flame speed with a high degree of accuracy. Unfortunately, neither of these tools is able to distinguish which reaction is dominant. Chemiluminescence measurement can be used as an alternative to the aforementioned techniques. Chemiluminescence techniques have been used extensively in investigations of knock\(^{[12, 13]}\) and combustion characteristics. OMA has been used to record the flame spectroscopy\(^{[14]}\) but it is difficult to identify the local measurement point with high spatial and temporal resolution.

Cassegrain optics\(^{[15, 16, 17, 18]}\) have been modified to detect local chemiluminescences and the capabilities of this technique have been demonstrated in simple burner flame experiments\(^{[19, 20]}\). These Cassegrain optics offer several advantages over other techniques: there is no wavelength abbreviation, they can collect light from a very small volume (of same order as LDV techniques), and their measurement volumes are small enough to analyze the turbulent scale and structure of the flame front. In a previous study\(^{[19]}\), it was demonstrated that these optics are capable of measuring the chemiluminescences of OH, CH and C2 radicals with a spatial resolution of 0.1 mm – 1 mm and that there is sufficient light to observe the structure of the flame front.

The purpose of this study is to utilize chemiluminescence and Cassegrain optic techniques to measure flame propagation speed and further understanding of flame front structures in combustion engines. To do this, time-series measurements of the spectral bands of three local radicals (C2, CH and OH), were carried out in the combustion chamber of a small two-stroke motorcycle engine.

2. Measurement System

2-1 Test Engine

The test engine used for this research was a 125 cc two-stroke motorcycle engine\(^{[20, 21, 22, 23]}\). Optical access to the cylinder was achieved by using an optical cylinder head and modi-
fied ignitor as shown in Fig. 1. A fuel mixture of gasoline and oil (50:1) was used. For these experiments, the engine was operated at a constant 3000 rpm and 7.5% throttle opening ratio, in order to demonstrate cyclic variations.

Pictures of the flame were modified with their Sobel-filtered equivalents to illustrate the flame characteristics.

2.2 Measurement System

The local chemiluminescence intensities of three radicals were measured by specially designed Cassegrain optics. The measurement volume of this equipment was a cylinder 1.6 mm long and 0.2 mm in diameter as illustrated in Fig. 2. The light from the flame was passed through optical filters to separate it into the colours corresponding to the three radicals of interest. The optical filter used for the OH, CH, and C₂ radicals were as follows:

- OH: center wavelength 306 nm, half value width 14 nm, efficiency 61%
- C₂: center wavelength 431.4 nm, half value width 1.5 nm, efficiency 40%
- CH: center wavelength 516.5 nm, half value width 2 nm, efficiency 58%

The optical filters and PM tube were mounted as shown in Fig. 2. A sampling rate of 100 kHz was used for each signal.

Measurements were taken at several locations, as shown in Fig. 3, in order to detect the flame front and accurately determine each chemiluminescence.

3. Measurement Results

3.1 Time series measurement of chemiluminescences and heat release ratios

Three chemiluminescence intensities were measured at 10 and 20 mm from the spark gap (as shown in Fig. 3) with RHR and IMEP. Five consecutive cycles at 10 mm are shown in

![Fig. 1 Test engine](image1)

![Direct pictures of flame (sobel filtered)](image2)

![Fig. 2 Cassegrain optics and measurement system](image3)

![Fig. 3 Sampling point](image4)
As shown in the figure, the OH-radical intensity has a bi-modal peak. The first peak is caused by the chemical reaction and the second may be caused by heating in the high temperature region\textsuperscript{35, 36}. It is well known that the OH radical exists in the reaction zone and high temperature region\textsuperscript{35, 36}.

There are spike peaks in the OH, CH and C\textsubscript{2} radical intensities just before TDC during the first cycle. Peaks were also observed in the second cycle, but not in the third. The third cycle shows lower IMEP than the first, but no significant differences can be seen in IMEP and RHR. The durations of the three radicals differ in cycles subsequent to the first. The peak height, half value width of the peak, and intensity profile can provide more detailed flame front structure and combustion characteristic data. Since the three radical intensities were measured at particular locations in the cylinder, their relationship to RHR cannot be understood by this local information alone. However, this local radical information can be used to show the local flame front thickness, how the flame front propagates, and the strength of the radicals.

The fourth cycle was misfiring by IMEP but showed the same RHR production. The three radicals showed peaks after TDC with lower heights than those of earlier cycles. The radical intensities begin to rise when the flame front reaches the measurement point and this delay can then be used to determine how long it has taken the flame to reach this point. The duration of the peaks is a measure of the structure of the flame front. This will be further discussed in the next section. The relationships between radical intensity profiles and RHR will be examined in order to understand the effect on engine performance of the flame front and its propagation speed.

Measurements were taken 20 mm from the spark gap and the results are shown in Fig. 5. To demonstrate cycle variation, the same misfiring pattern was chosen in this figure. The third cycle had the maximum IMEP and the OH, CH and C\textsubscript{2} radical intensities had longer durations than in other cycles. This is the opposite of the results from measurements taken near the spark gap. This data can show how the flame propagates, the structure of the flame front, and which is the dominant radical reaction.

The second and fourth are misfiring cycles. The RHR can have the same value in both cycles, but the radicals at 20 mm change only in the fourth. This means that RHR is not directly related to the flame front structure and that the cause of misfiring can be evaluated by the radical information. Some flames extinguished themselves, while others propagated at very low intensities.

3.2 Correlation of OH- C\textsubscript{2} and OH-CH

It is well known that OH radicals are produced in the reaction zone and high temperature regions\textsuperscript{35}, and it is common to use C\textsubscript{2} and OH information to define the details of the flame front structure. But the local chemiluminescences are not directly related to heat release. Correlations of OH-C\textsubscript{2} and OH-CH were used to demonstrate their relationship to IMEP, as shown in Fig. 6. The delay between ignition and the arrival of each peak was used to calculate flame propagation speed.

It is clear that both OH-C\textsubscript{2} and OH-CH can be correlated to IMEP, but OH-C\textsubscript{2} is the strongest. Three IMEP levels were defined: IMEP < 0, 0 < IMEP < 0.2, and 0.2 < IMEP. These regions are denoted by white circles, solid circles and solid squares, respectively. When IMEP < 0, the cycle was misfiring and all radical peaks occurred simultaneously. This strong relationship can be clearly seen in the diagrams.
The correlation of IMEP to OH-C2 is much stronger than to OH-CH. At high IMEP values the OH-C2 delay times were shorter than those at lower IMEPs, but this behaviour cannot be seen in the OH-CH diagram.

It is obvious that local radical information is insufficient to determine total combustion status in the engine cylinder due to local point measurement but it is very valuable parameter to distinguish the flame structure and its propagation speed. More information can be extracted using the radical intensity profiles. Fig. 7 shows high IMEP cycles with different radical profiles. It was explained above that spikes in the radical intensities were produced in high IMEP cycles. Let's examine this in more detail. These two cycles show almost same RHR values but very different radical profiles. The delay times prior to increased radical intensities were the same, which implies that the flame propagation speeds were nearly identical. Flame propagation speed is the key factor in understanding the relationships between local flame front structure, local chemiluminescence intensity profiles, and RHR. This speed was measured from the starting time of each radical profile.

Simultaneous multi-point measurement is required to show the time-varying three-dimensional flame front structure and flame propagation speed in each cycle. It is obvious that even single point measurements should yield useful information such as flame propagation speed, flame thickness, and ignition delay time estimation.

3.3 Flame propagation speed

As shown in Fig. 7, the radical intensity spiked. From this, the flame propagation speed and flame thickness are defined as

\[ \text{Propagation Speed} = \frac{d}{t_1} \]

\[ \text{Flame Thickness} = \text{Propagation Speed} \times t_2 \]

Fig. 8 Calculation method of the flame propagation speed and flame thickness

![Fig. 8 Calculation method of the flame propagation speed and flame thickness](image)

3000r/min Throttle 7.5%

![Fig. 9 Difference of flame propagation speed due to combustion status](image)

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The distance from the spark gap (d), the half value width of the radial peak from ignition (t_r), and its total duration time (t_c) were used to calculate flame propagation speed and flame thickness. Unfortunately, ignition delay time was included in t_c. Fig. 9 shows the different flame propagation speeds and ignition delays at different IMEP values. The x-axis represents delay time (t_i) (as shown in Fig. 8) and the y-axis is the distance from the spark gap (d). Many cycles were measured at 5 different measurement locations, and PDFs of t_i were plotted for three different IMEP values. The maximum peak of each PDF was also linearized as shown in this figure. These maximum PDF locations gave the gradient for each IMEP, which represents the flame propagation speed. The extrapolated x-intercept of this line represents the ignition delay time for each IMEP. The resulting ignition delay times were 0.15, 0.21 and 0.31 ms for 0.2 < IMEP < 0.5 IMEP < 0.2 and IMEP < 0, respectively.

For the present study, only the OH radical data was examined. CH and C2 intensity data and the corresponding correlations will be discussed in a future paper.

4 Flame thickness and its variation in consecutive cycles

Fig. 10 shows flame thickness, flame propagation speed, RHR and IMEP for 10 consecutive cycles. The flame thicknesses calculated from OH chemiluminescence profiles were much larger than those reported in fundamental studies. This is because the OH radical is produced in the chemical reaction and high temperature regions so that there are some uncertainties to identify that the OH and show the flame region only. However, the relationship between flame thickness, flame propagation speed and RHR are very useful information in cyclic variation analysis. This study has been investigated flame propagation speed analysis in a real engine for the first time.

The flame propagation speed was faster in the firing cycles than in misfiring cycles. The flame speed varied from 5-8 m/s and the flame thickness was 2-4 mm for firing cycles. The flame thickness for misfiring cycles was 8-12 mm. This is probably the result of the high temperature region information contained in the OH data and the fact that combustion may take place much more gradually in misfiring cycles.

The misfiring cycles in the 10 cycle pattern produced different conditions. For example, when misfiring occurred in the 8th cycle the flame self-extinguished and did not reach the measurement point 6 mm away from the spark gap.

Conclusion

The local chemiluminescences of OH, CH and C2 radicals were measured using Cassegrain optics. The measured intensity profiles provide high temporal resolution data that define a flame propagation speed and its thickness. The relationship between the chemiluminescence intensity profiles and RHR was discussed and it was found that the flame propagation speed was fast in flames with high IMEP values and that some radicals exist even when IMEP < 0, as a result of flame extinction or insufficient flame propagation. Flame propagation speed and flame thickness were calculated from OH intensity data. The resultant flame thicknesses were larger than those reported in the literature because the OH radical data contained both the chemical reaction and high temperature regions. Flame extinction can be indicated by these chemiluminescence measurements with RHR and IMEP. The flames showed higher propagation speeds and were thinner in firing cycles than in misfiring cycles.

References


