

Combustion Diagnosis of Formula One Engine Using Micro-Cassegrain Sensor

Naoki HANADA*
Yuji IKEDA**

Atsushi HIRAIDE*
Atsushi NISHIYAMA**

Kohei YAMADA*

ABSTRACT

Combustion diagnosis of a Formula One engine during wide open throttle (WOT) acceleration and deceleration operations was performed using a micro-Cassegrain system.

The air/fuel mixture (A/F) in each cylinder was measured, which helped in the development of controls to minimize the torque loss due to unstable combustion.

In transient conditions where acceleration and deceleration are performed repeatedly, the air/fuel mixture around the spark plugs becomes too rich or too lean, and results in unstable combustion. In addition, the air/fuel mixture formation is different inside each cylinder.

The fuel distribution to each cylinder needed to be controlled to a high degree of accuracy, and to do this, a highly responsive air/fuel ratio sensor (LAF sensor) is required.

1. Introduction

To increase the engine output, it is important to find a way to efficiently combust the air/fuel mixture. Combustion involves a series of processes, including forming the air/fuel mixture inside the cylinder, performing an effective ignition, promoting combustion with turbulence, and scavenging. Making the initial flame more stable by performing an effective ignition can minimize unstable combustion and lead to increased thermal efficiency.

Although analysis of the air/fuel mixture formation and flame propagation inside all the cylinders was also required, priority was given to analyzing the engine issue as described by the driver. The A/F around the spark plugs, which directly affects the ignition performance, was measured using a micro-Cassegrain sensor.

In Formula One engines, nearly all throttle operations are WOT or in fully closed positions. For this reason, fuel control is required that matches sudden changes in the amount of induction air, and if the fuel correction is inappropriate, unstable combustion will occur and the drivability will be reduced.

The flame will not be able to propagate quickly if the air/fuel mixture is too lean or too rich.

To enhance the drivability, fuel need be supplied to

the cylinder so that the appropriate A/F is provided to each cycle.

As shown in Fig. 1, as the indicated mean effective pressure (IMEP) rises, the misfiring occurs in some cycles. This is because the appropriate A/F is not formed around the spark plugs, resulting in unstable combustion. It is important to analyze why the misfiring occurs and to take preventive measures.

Existing combustion diagnosis methods include measuring the induction pressure, in-cylinder pressure, exhaust pressure, and exhaust gas characteristics; and

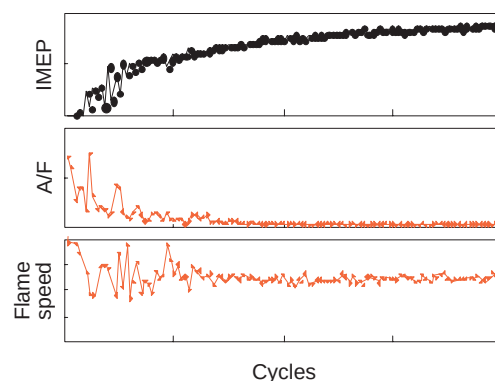


Fig. 1 Combustion characteristics under acceleration

* Automobile R&D Center

** Imagineering, Inc.

measuring the A/F ratio between the cylinders with the LAF sensor. Regarding the measurement of the combustion variation between cylinders, published reports include those that describe pressure^{(1), (2)}, ion probes⁽³⁾, the IR absorption method^{(4), (5)}, and the chemiluminescence measurement method^{(6), (7)}.

As a new combustion diagnosis method, a micro-Cassegrain sensor was used to directly measure the A/F around the spark plugs, and measurement was performed of the corresponding time series variations and combustion variations between cylinders. In this method, time series analysis can be performed up to 20000 rpm.

This document is a report about the results of the unstable combustion analysis performed under the transient operation of a Formula One engine.

2. Measurement Device

A V8 race engine in 2008 that had a displacement of 2400 cm³ was used. Figure 2 shows the exterior of the engine.

A micro-Cassegrain system (made by Imagineering, Inc.) was used to measure the A/F around the spark plugs.

When the flame passed a certain point (about 0.1 x 0.1 mm), the chemiluminescence intensities of four radicals (OH, CH, CN, C₂) from the flame chemiluminescence was measured using a band-pass filter and a photomultiplier.

The intensity ratios of these radicals have an unambiguous correlation with the equivalence ratio in the flame⁽⁸⁾⁻⁽¹⁶⁾. This means that an approximate measurement can be made of the flame propagation speed and the A/F in the flame.

The measurement system was comprised of an optical fiber sensor that measures the local chemiluminescence, hardware that processes the chemiluminescence intensity ratio in high-time resolution, control software, and a monitor.

The sensor type used was an M10 spark plug with a built-in Cassegrain optical element. The distance of the focal point from the ignition position was 3 mm.

The effect on combustion by inserting the sensor into the spark plug was checked. Figure 3 shows the results of the evaluation of the combustion variation using the pressure sensor. Normal spark plugs were installed for cylinders 1 to 4, and spark plugs with the built-in micro-Cassegrain sensors were installed for cylinders 5 to 8.



Fig. 2 Honda Formula one engine

The combustion pressure for 500 cycles was measured with an engine speed of 16500 rpm and WOT.

The air excess ratio (set Lambda) was set at 0.95.

The deviation of combustion pressure between cylinders was 16.7%, and so it was shown that the built-in micro-Cassegrain sensors did not greatly affect the combustion variation.

It was also confirmed that negative effects from the rpm, loads and Lambda value and the plasma from early discharge were not detected by the micro-Cassegrain sensors.

Sapphire glass was installed on the end of the micro-Cassegrain sensors as a countermeasure for heat and pressure resistance.

Figure 4 shows an overall view of cylinders 5 to 8 to which the micro-Cassegrain sensors were attached. Figure 5 shows a view of the optical fiber attached to a spark plug in a plug hole.

Figure 6 shows the device configuration. The Cassegrain sensor output value, in-cylinder pressure, induction pipe pressure, exhaust pipe pressure, LAF sensor output value, and crank angle signal were synchronized and imported.

SPB2000 (made by Imagineering, Inc.) and DS2000 (made by Ono Sokki Co., Ltd.) were used as the data processing devices. SPB2000 is equipped with a band-pass filter and interference filter for each radical, and the light signal from each cylinder is converted into an electrical signal by the photomultiplier.

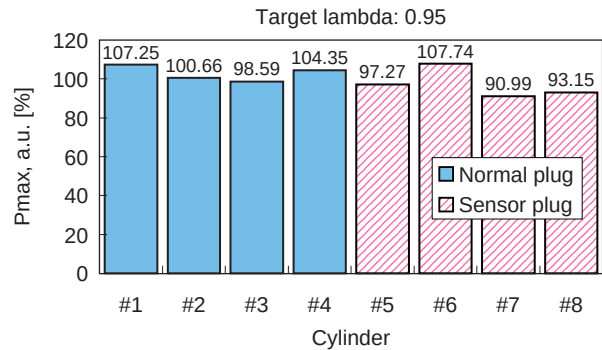


Fig. 3 Comparison of maximum cylinder pressure (Pmax) using normal plug and sensor plug

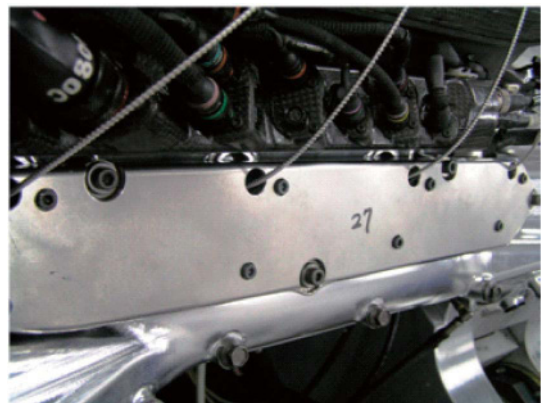


Fig. 4 Photograph of overview of cylinders to which micro-Cassegrain sensors were attached

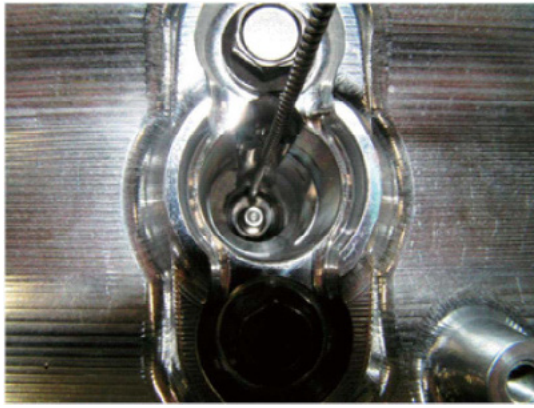


Fig. 5 Photograph of plug hole in which plug with sensor was attached

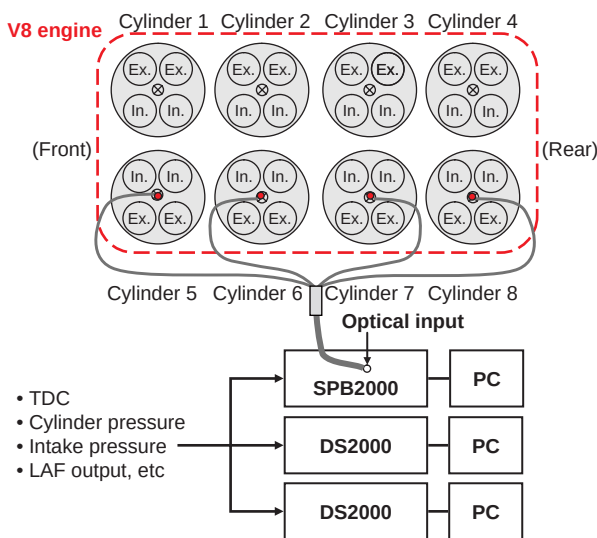


Fig. 6 Schematic diagram of measurement system

The hardware is comprised of an amp, filter, and A/D converter (14-bit). It can import data simultaneously and perform measurement with a resolution of a crank angle of 1° at an engine speed of 18000 rpm. The light emission data and pressure data for each cylinder can be checked on the monitor.

3. Results and Discussion

The ram pressure changes in accordance with the vehicle velocity, then the air flow pattern inside the air box changes. Therefore, the air inflow amount of each cylinder also changes. The air inflow amount also changes in accordance with the shape of the air box. In particular, unstable combustion may be triggered under transient conditions. The combustion analysis of the V8 Formula One engine was performed under such conditions. In the analysis, the Lambda around the spark plug, the flame propagation speed (FPS), reaction zone thickness, IMEP, P max, induction pressure and exhaust pressure were calculated, and the combustion difference and time series combustion variation were compared.

3.1. Combustion Characteristics at 18000 RPM Engine Speed, WOT Load, and Steady Condition

Figure 7 shows a comparison of the results with different vehicle velocities and air box specifications. The horizontal axis is Lambda, and the vertical axis is the average values and the variation range. The combustion difference and the time series combustion variation were compared between cylinders 5 and 6.

The faster the vehicle velocity, the higher the IMEP becomes because of the lam pressure. The highest pressure was reached when the set Lambda was around 0.9.

However, P max and IMEP values varied between cylinders. The combustion pressure variation range also varied according to the Lambda value.

At 120 km/h and 300 km/h in the standard air box, the average A/F and the A/F around the spark plugs were approximately the same, which is a desirable result.

The air box inlet shape was changed and measurement was performed at a vehicle velocity of 300 km/h. The A/F around the spark plug in cylinder 5 became richer by about 0.5 from the set value. The inlet shape affects the air flow pattern, and so it also likely affects the A/F distribution inside the combustion chamber.

No significant change was seen in the FPS within a Lambda range of 0.8 to 0.95. The same trend has been reported in another combustion analysis for Formula One engines⁽⁷⁾.

However, it should be noted that the FPS varies greatly regardless of the Lambda.

3.2. Combustion Characteristics at 14000 RPM Engine Speed, Partial Load, and Steady Condition

Figure 8 shows the combustion characteristics of cylinders 5 and 6 with a throttle position of 30%, an

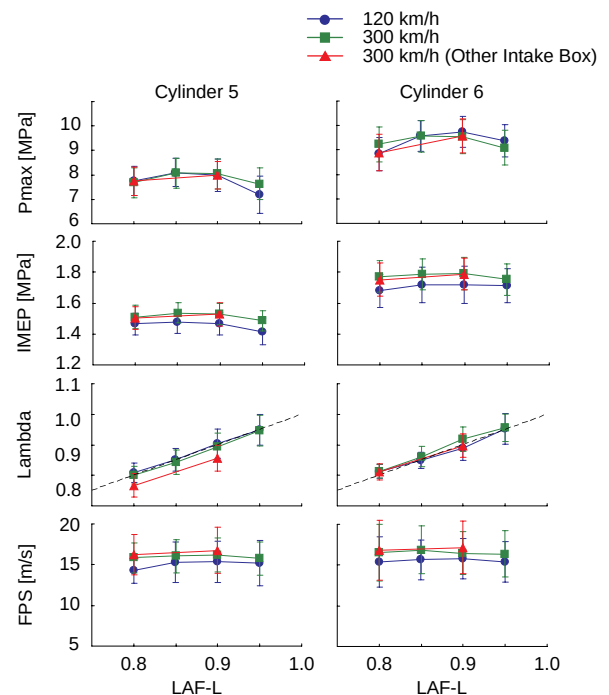


Fig. 7 Combustion characteristics at 18500 rpm and WOT

engine speed of 14000 rpm, and steady condition. It shows that the Lambda value shifts from the set value, and that the flame propagation value and the value of its variation changes significantly.

For cylinder 5, it is shown that the Lambda around the spark plug is lean under all conditions, and that a bias occurs in the A/F distribution around the spark plug under a partial load. For cylinder 6, the Lambda value is closer to the set value than it is for cylinder 5.

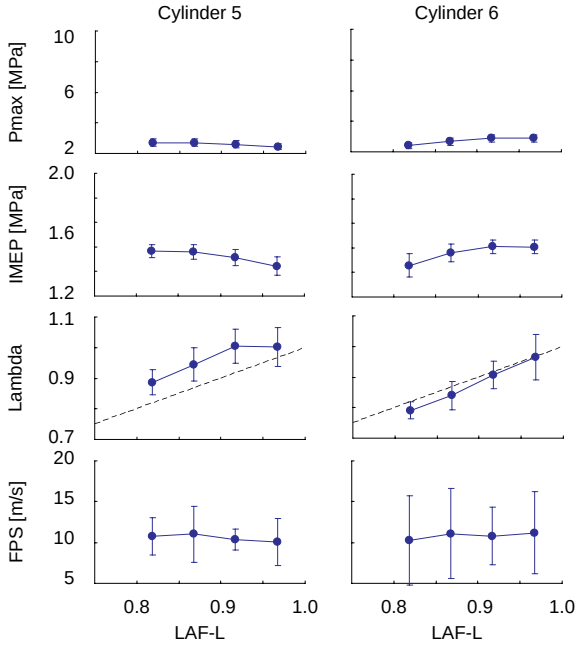


Fig. 8 Combustion characteristics at 14000 rpm and 30 % throttle opening

However, its FPS variation is larger than for cylinder 5, and it can be found that significant combustion instability occurs even though the formation of the air/fuel mixture is even.

In this way, the relationship between the set Lambda and the Lambda around the spark plug is greatly different even in cylinders that adjoin each other, and the corresponding time variation may also vary greatly. This is proof that although the macro-level state of all the cylinders can be ascertained from the pressure and LAF sensors, the detailed state around the spark plugs cannot be ascertained, and so there is a limit to the optimization that can be performed based on these measured values.

3.3. Combustion Characteristics in Transient Conditions

Combustion analysis in transient conditions was performed to confirm for misfiring and torque loss in transient conditions and identify why they occur. Measurement was performed at the set Lambda of 0.8 while accelerating at a ratio of 3000 rpm/sec from the engine speed of 9000 rpm. Figure 9 shows the P max, IMEP, Lambda and FPS for cylinders 5 and 8. The Lambda graph shows three types of data. (a) is the Lambda around the spark plug derived from the Cassegrain sensor, (b) is the value from the LAF sensors installed on the exhaust pipes of each cylinder, and (c) is the set Lambda. The horizontal axis is the number of cycles, and the 4500th cycle is the start of acceleration. Combustion variations that involve misfiring were observed from cycles 4530 to 4540. The IMEP also dropped dramatically.

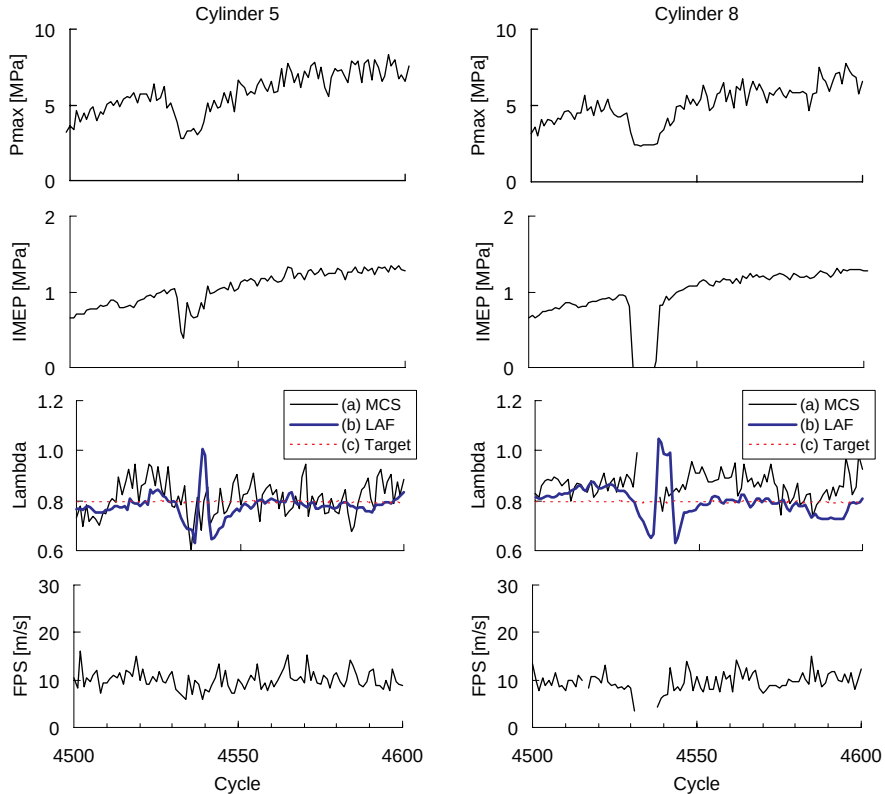


Fig. 9 Cyclic variations of combustion characteristics under transient condition

In cylinder 5, the Lambda value dropped but did not reach misfiring. However, the A/F around the spark plug was too rich, leading to a drop in output.

On the other hand, the misfiring phenomenon can be clearly seen in cylinder 8. In contrast to cylinder 5, it misfires because the A/F is too lean. After the misfiring, combustion does not start again immediately. It starts after four cycles.

This is likely the effect of the rigid vortex that occurs in the air box. A recirculating vortex is formed in the air box by the inertia force of the induction air. This is likely to result in different air fuel ratios between cylinders. This fuel bias state occurs even in steady conditions. A corresponding amount of fuel injection is set. However, it was found that a setting based on a steady condition is insufficient under a transient condition.

Because the vehicle is always driven under transient conditions during a race, engine calibration is required for these conditions.

3.4. Combustion Characteristics in Fuel Cut and Recovery Cycles

In order to perform torque control, the fuel injection control was performed in which the fuel was cut during deceleration and the fuel injection was recovered during acceleration. At this time, sometimes unstable combustion occurred during fuel recovery. In response, the fuel recovery state was simulated on a test bed, and the combustion state was measured. Figure 10 shows the results. It shows the P max, IMEP, MFB 0 to 10%, Lambda and FPS cycle data from the fuel cut to recovery for cylinder 6. The same as in Fig. 9, the Lambda graph

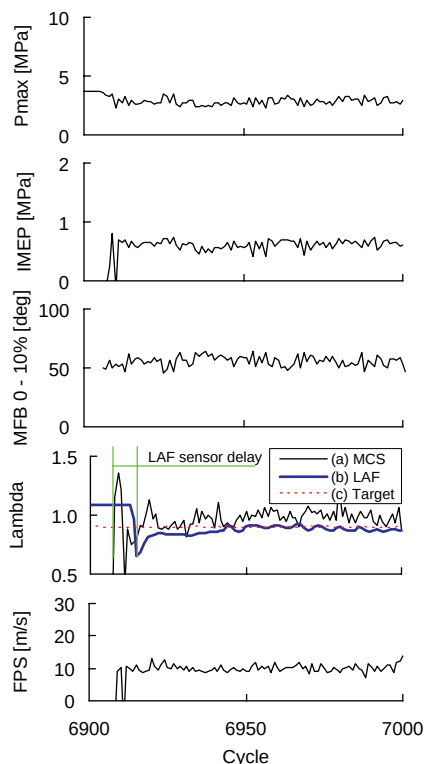


Fig. 10 Cyclic variations of combustion characteristics in fuel cut recovery test

includes the value around the spark plug, the LAF measurement value, and the set value.

Looking at the FPS, IMEP, and Lambda around the spark plug, it can be seen that there is no ignition in the first cycle after the fuel recovery. However, in the next cycle the mixture is rich and there is an ignition, and in the following cycle, the mixture changes to a lean one. It can be clearly observed that the Lambda around the spark plug changes alternately between rich and lean, and there is significant variation between cycles.

It was demonstrated that the micro-Casagrain sensor can measure the Lambda for each cycle and has a high responsiveness.

On the other hand, because the responsiveness of the LAF sensor is low, it cannot measure the behavior of each cycle. It detects the Lambda value after fuel cut recovery with a delay of eight cycles.

4. Conclusion

The results obtained when combustion diagnosis of a Formula One engine has been performed using a micro-Casagrain sensor are described below.

- (1) Except under certain conditions, in WOT operations with an engine speed of 18500 rpm, average cylinder Lambda and Lambda around the spark plugs are approximately equal and so are in a desirable state.
- (2) Under the operating conditions described above, the FPS is not influenced by the Lambda.
- (3) The tendencies of the A/F distributions between cylinders differ under WOT and partial throttle conditions. Even if the average A/F in the cylinder is set to an appropriate value using the LAF sensor, the A/F around the spark plug may not be appropriate.
- (4) The A/F behavior during transient operation was shown to be different from that during steady operation. When torque loss or unstable combustion occurred during transient operation, the A/F around the spark plug was too rich or too lean. Further, it was shown that the A/F behaviors were different between cylinders even during the same cycle.
- (5) In the future, highly accurate fuel control will be required under transient conditions, and to achieve this, highly responsive measurement instruments will be required. The micro-Casagrain sensor provides this function, and by using this instrument, it may be possible to accelerate future engine development.

References

- (1) Neo, G. H., Collings, N.: Pressure Data Analysis of Formula One Racing Engines, SAE Paper, 970061 (1997)
- (2) Alten, H., Illien, M.: Demands on Formula One Engines and Subsequent Development Strategies, SAE Paper, 2002-01-3359 (2002)
- (3) Shimasaki, Y., Sakaguchi, J., Maki, H., Suzuki, H., Kondo, N., Yamada, T.: Study on Combustion Monitoring System for Formula One Engines Using Ionic Current Measurement, JSAE Technical Paper, No.

- 20055017 (2005)
- (4) Ikeda, Y., Nishiyama, A., Kawahara, N., Tomita, E., Baritaud, T.: Application of IR Absorption Method to a Racing Engine, 2007 JSAE Annual Congress proceedings, No.13-07 (2007)
 - (5) Ikeda, Y., Nishiyama, A., Baritaud, T.: Flame Speed Measurement of a Racing Engine by IR Method and Chemiluminescence Method, 14th Lisbon International Symposium on Applications of Laser Techniques to Fluid Mechanics (2008)
 - (6) Ikeda, Y., Nishiyama, A., Kim, S. M., Takeuchi, A., Winklhofer, E., Baritaud, T.: Cyclic Variation of Local A/F and Mixture Quality in SI Engine Using Local Chemiluminescence, Proc. of 7th international symposium on internal combustion diagnostics, p. 277-284 (2006)
 - (7) Ikeda, Y., Jeong, H., Nishiyama, A., Baritaud, T.: Cylinder to Cylinder A/F Fluctuations Measurement in a Racing Engine by Chemiluminescence, Proc. of 7th International Conference on Modeling and Diagnostics for Advanced Engine System, p. 535-540 (2008)
 - (8) Lee, J. G., Kim, K., Santavicca, D. A.: Measurement of Equivalence Ratio Fluctuation and Its Effect in Heat Release During Unstable Combustion, Proc. of the Combustion Institute, 28, p. 415-421 (2000)
 - (9) Ohya, Y., Ohsuga, M., Kuroiwa, H.: Study on Mixture Formation and Ignition Process in Spark Ignition Engine Using Optical Combustion Sensor, SAE Paper, 901712 (1990)
 - (10) Ikeda, Y., Kaneko, M., Nakajima, T.: Local A/F Measurement by Chemiluminescence OH*, CH* and C2* in SI Engine, SAE 2001 Transactions, Journal of Engines, Section 3, 110 (2001-01-0919) (2001)
 - (11) Ikeda, Y., Nishihara, H., Nakajima, T.: Measurement of Flame Front Structure and Its Thickness by Planar and Local Chemiluminescence of OH*, CH* and C2*, SAE 2001 Transactions, Journal of Engines, Section 3, 110 (2001-01-0920) (2001)
 - (12) Ikeda, Y., Kojima, J., Hashimoto, H.: Local Chemiluminescence Spectra Measurements in a High-Pressure Laminar Methane/Air Premixed Flame, Proc. of the Combustion Institute, 29, p. 1495-1501 (2002)
 - (13) Kojima, J., Ikeda, Y., Nakajima, T.: Multi-point time-series observation of optical emissions for flame-front motion analysis, measurement Science and Technology, Vol. 14, P. 1714-1724 (2003)
 - (14) Ikeda, Y., Kawahara, N., Tomita, E.: Time-series A/F Analysis in a SI Engine by Micro-Local Chemiluminescence Technique, Proc. of 6th COMODIA 2004, Paper No.C3-3 (2004)
 - (15) Kawahara, N., Tomita, E., Takeuchi, A., Arimoto, S., Ikeda, Y., Nishiyama, A.: Measurement of flame propagation characteristics in an SI engine using micro-local chemiluminescence technique, SAE Paper, 2005-01-0645 (2005)
 - (16) Ikeda, Y., Nishiyama, A., Kawahara, N., Tomita, E., Arimoto, S., Takeuchi, A.: Spark-plug-in sensor for initial flame analysis and its flame structure in an SI engine, SAE Paper, 2005-01-0644 (2005)

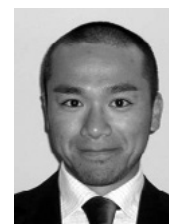
■ Author ■



Naoki HANADA



Atsushi HIRAIDE



Kohei YAMADA



Yuji IKEDA



Atsushi NISHIYAMA