

Measurement of Local Air/Fuel Ratio and Evaluation of Accuracy of Engine Simulation Using Micro-Cassegrain Sensor

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ABSTRACT

The fuel consumption rate of gasoline engines can be decreased by reducing cyclic variation and variations in the combustion state between cylinders, but this necessitates high-precision combustion control. Control of the air-fuel ratio (A/F) in the cylinders, in particular the local A/F near the spark plugs, is an important factor in combustion control. A three-dimensional engine simulation model enabling prediction of the local A/F near the spark plugs was therefore constructed. A micro-Cassegrain sensor able to measure the local A/F near the spark plugs in a real engine was used to evaluate the accuracy of the prediction. The results indicated that the local A/F can be predicted within the range of cyclic variation.

1. Introduction

Today's increased focus on environmental issues has generated demands for the achievement of cleaner exhaust emissions and decreased fuel consumption rate in gasoline engines. Conventional gasoline engines precisely control the air-fuel ratio of the exhaust gas in order to maximally exploit the performance of the catalyst. In the future, it will be necessary to increase combustion efficiency and maintain optimal combustion at all times, even in transient states, in order to achieve decreased fuel consumption rate.

Achieving normal combustion in all cylinders during each cycle is desirable from the perspective of increasing combustion efficiency. If it is hypothesized that the in-cylinder pressure in each cycle in which the pressure drops below the average figure could be increased to the average pressure, the engine shown in Fig. 1 would achieve a mean fuel efficiency per cylinder of 3.3%, and a fuel efficiency of 13.3% overall. However, in real engines, variations in the fuel concentration⁽¹⁾ and the distribution of internal EGR gas⁽²⁾ produces cyclic variations⁽³⁾ and variation between cylinders. These are considered to be factors contributing to a decline in the

average performance of the engine.

It has been determined experimentally that the ignition delay period in a spark ignition engine varies depending on whether or not the air-fuel mixture around the spark plugs at ignition is in an ideal state, and this results in fluctuations in main combustion in each cycle. Given this, the research discussed in this paper focused on the air-fuel mixture, in particular the air-fuel mixture around the

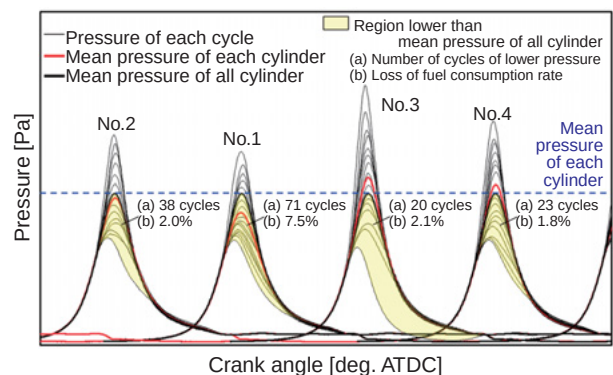


Fig. 1 Pressure history of each cylinder and cycle

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spark plugs which affects ignitability, with the goal of developing a method to enable its control.

In order to study the behavior of the air-fuel mixture, it was decided to apply three-dimensional simulations, which are today extensively employed in automotive applications. However, in the case of research reported by Ishikawa, et al⁽⁴⁾, despite the fact that the results obtained for the distribution of the air-fuel mixture in the combustion chamber in a simulation of the in-cylinder A/F distribution in a port-injected visualized engine corresponded well with actual measurements, the study was not able to quantitatively evaluate the A/F around the spark plugs. In order to enable quantitative evaluation of the accuracy of prediction of the A/F around the spark plugs in the present study, a micro-Cassegrain sensor able to quantitatively measure the A/F around the spark plugs in a vehicle-mounted engine without engine modification was employed in evaluating the accuracy of A/F predictions in a three-dimensional simulation.

2. Principle of Measurement of Local In-cylinder A/F

In-cylinder A/F measurements have normally been conducted using gas sampling or visualization methods such as laser-induced fluorescence (LIF) in a one-cylinder engine. However, these methods involve a number of issues. Numerous engine modifications are necessary; changing the shape of the pistons and changing the in-cylinder flow, for example by reducing the compression ratio, results in changes in charging efficiency and A/F, among other factors. As a result, setting conditions for the simulations represents a challenge. In addition to these issues, given the focus in the present study on variations between cycles and variations between cylinders, it would be desirable to conduct measurements in a multi-cylinder engine fitted in a vehicle rather than in a single cylinder engine. The micro-Cassegrain sensor used in the present study provided the advantage of enabling the analysis to be conducted without modifying the engine.

2.1. Principle of Measurement Using Micro-Cassegrain Sensor

Figure 2 shows the structure of the micro-Cassegrain sensor. A micro-Cassegrain sensor permits the radical chemiluminescence produced by combustion to pass through concave and convex mirrors that face each other. The light passes through an optic fiber and, with the involvement of a dichroic mirror and narrow band pass filter, the emission intensity of the characteristic wavelengths of OH radicals, and the like is detected by a photomultiplier tube.

The core diameter of the fiber is 230 μm , and it can be fitted inside a spark plug. The measurement domain is 0.1 mm and below, and the distance from the sensor tip to the measurement position is 3 mm.

2.2. Method of Measurement of Local A/F

As Fig. 3 shows, the micro-Cassegrain sensor detects the emission intensity of a variety of radicals, including OH*, CH*, and C₂*. A/F can be identified by means of the ratio of the peak values of these emission intensities of these radicals⁽⁵⁾⁻⁽¹⁰⁾, and if the A/F is changed, the ratio also changes linearly. Figure 4 shows a conceptual diagram of the relationship between flame propagation around the spark plug and the measurement position in the cylinder. A flame kernel is formed from the air-fuel mixture ignited by the spark plug; the flame propagates and passes the measurement position, and the luminescence of the radicals is detected. The ignition delay period is calculated from the time of detection of the emission intensity peaks by the sensor and the timing of the ignition signal. Using this data, the flame propagation speed can be calculated from the distance

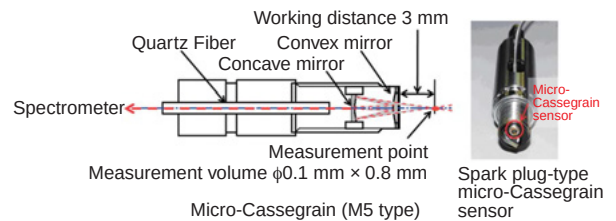


Fig. 2 Schematic of micro-Cassegrain sensor and shape of spark plug-type micro-Cassegrain sensor

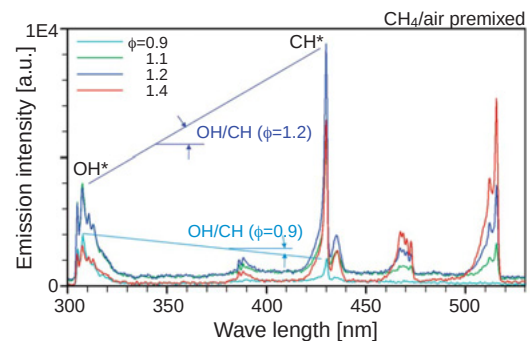


Fig. 3 Emission intensity of fuel wave length

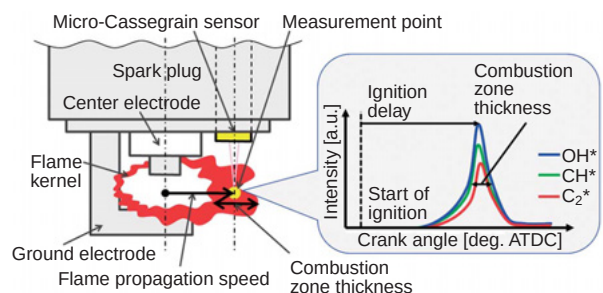


Fig. 4 Schematic of flame propagation and measurement point in cylinder

Table 1 Engine specifications

Engine	2.2L 4-cylinder gasoline engine
Bore × Stroke	87 × 90.7 [mm]
Compression ratio	11.1
Engine speed	1500 [rpm]
Tumble control valve opening	15 [deg.]
Injection	Twin, Primary, Secondary
Injection timing	44.5 [deg. ATDC] (Twin) 25.5 [deg. ATDC] (Primary, Secondary) =>60 [deg. ATDC] (Injection end)
Spark timing	35 [deg. BTDC]

from the plug to the measurement position. In addition, the width of the combustion domain can be determined from the width of the time series data for emission intensity.

3. Test Method and Measurement System

3.1. Characteristics of Test Engine

Figure 5 shows the layout of the test engine intake manifold. To enable the tumble ratio to be varied, the engine was fitted with a tumble control valve and a tumble plate which enables adjustment of the gas flow in the intake port. In addition, an inlet for external EGR gas was positioned below the tumble plate to enable the EGR flow to be controlled, and one injector was positioned in each port, facing the respective intake valves, to enable control of air-fuel mixture formation, even during fuel supply.

3.2. Operating Conditions and Measurement Position

Table 1 shows the measurement conditions employed in this study of A/F prediction accuracy. The tests were conducted using the same fuel injection amount and injection end timing under different injection conditions: with both of the injectors discussed above in operation, only the primary-side injector in operation, and only the secondary-side injector in operation.

Figure 6 shows the positioning of the micro-Cassegrain sensor and pressure sensors employed to

enable evaluation of calculation accuracy. Pressure was measured at seven points from upstream to downstream to enable evaluation of the gas flow and charging efficiency, parameters which are important in evaluating A/F. A sensor manufactured by Kistler (type 6052B) was employed inside the cylinder, for a total of eight pressure sensors recording simultaneous measurements. The pressure sensor in the cylinder was replaced by the micro-Cassegrain sensor when it was used to measure A/F.

3.3. Measurement System

Figure 7 shows the measurement system employing a micro-Cassegrain sensor used in this study to measure local in-cylinder A/F in a vehicle-mounted engine. The measurement system, which enables bench-top measurement, is made up of a sensor that is integrated with the spark plug which detects in-cylinder emissions, a light divider unit that detects the emissions from the sensor, and analytic software. The sensor was created to match the specifications of the test engine. The system synchronizes the angle signal output by an engine crank angle detector and the fuel injection signals used to discriminate cylinders with the detected emission signal, and determines the flame propagation speed, and the like, based on emission intensity, detection timing, and the like.

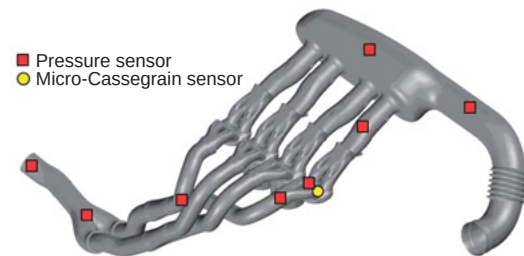


Fig. 6 Measurement point

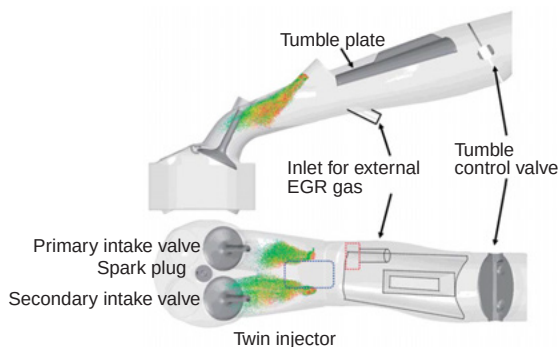


Fig. 5 Test engine intake manifold layout

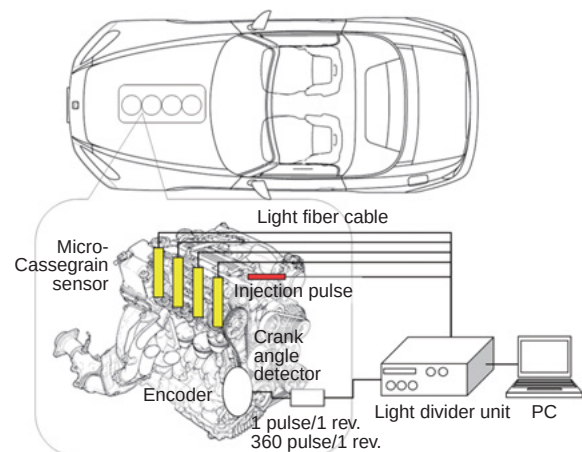


Fig. 7 Micro-Cassegrain measurement system

4. Measurement Results

4.1. Results of Measurement of Local A/F Using Micro-Cassegrain Sensor

Figure 8 shows the results of measurement of local A/F in each cycle when the pre-set engine A/F was varied. When the pre-set A/F was varied from 12 to 20, the average value of the local A/F also increased, with 3.5% or less deviation between pre-set A/F and average local A/F.

Figure 9 shows the results of A/F measurements using a UEGO sensor manufactured by NTK and local A/F measurements using the micro-Cassegrain sensor when the intake pressure was varied. The results for the UEGO

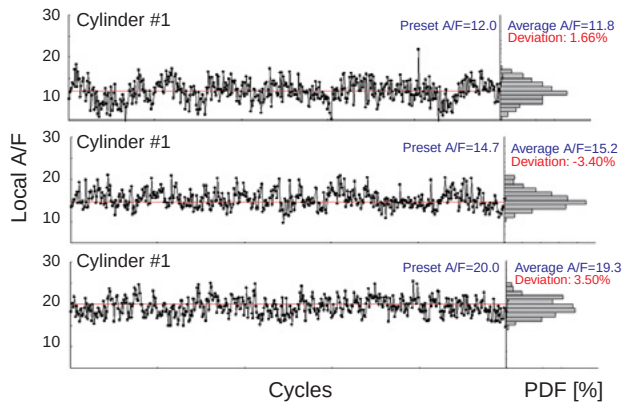


Fig. 8 Results for local A/F using micro-Cassegrain sensor

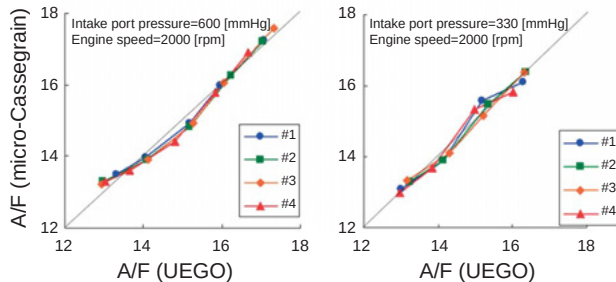


Fig. 9 Comparison of micro-Cassegrain and UEGO sensors

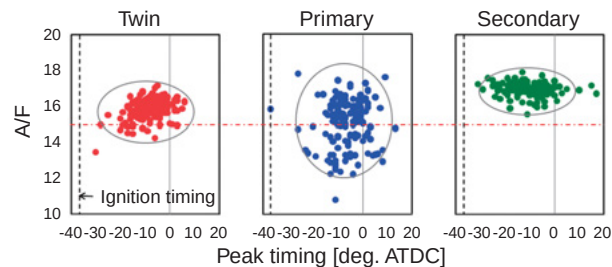


Fig. 10 Results for peak timing and A/F for different injection conditions

sensor and the micro-Cassegrain sensor are virtually identical for both intake port pressures, indicating that the output of the micro-Cassegrain sensor demonstrates sufficient accuracy.

4.2. Results of Local A/F Measurements when Fuel Injection Conditions Were Varied

The differences in A/F for each cycle under different injection conditions [injection using both injectors (“Twin”), injection only in the port fitted with an inlet for external EGR (“Primary”), and injection only in the opposite port (“Secondary”)] were measured and compared. The results are shown in Fig. 10. The areas bounded by circles in the graphs show the operating conditions produced by each form of injection. An ideal combustion state would be shown by a circle with a low radius, centered on a stoichiometric A/F. Compared to Twin injection, injection on the Primary side only produced greater variation in A/F. Variation was lower in the case of injection only in the Secondary side, but while the chain of points in the graph indicates a gasoline stoichiometric A/F, overall there is a shift to the lean side. These results show that when injection conditions are varied, there is a considerable variation in the local air-fuel mixture concentration around the spark plugs in each cycle.

The horizontal axes of the graphs show the timing of the radical emission intensity peaks, more specifically, the ignition delay period. Variations in the ignition delay period are displayed for all the forms of injection, but there is no significant difference in the radii of the circles or the position of their centers in the direction of the time axis, indicating that there is little correlation between A/F fluctuations and the ignition delay period. It was therefore considered that some factor other than A/F fluctuations, such as EGR gas concentration, is involved in the phenomenon of ignition delay.

5. Results of Verification of A/F Prediction Accuracy Using Three-dimensional Simulation

Calculations were conducted following the flow shown in Fig. 11 in order to evaluate the accuracy of predicting local A/F using a three-dimensional simulation. Using measured intake and exhaust pressure and temperature as a reference, a one-dimensional gas exchange simulation was conducted to determine boundary and initial conditions for the three-dimensional simulation. Fuel spray parameters were created for the three-dimensional simulation based on the fuel spray conditions used in unit tests and the results obtained in the tests. An air-fuel mixture distribution was calculated taking into consideration the mixture of the intake air and fuel, and the dispersion and wall-adhesion of the fuel as the input data for the three-dimensional gas flow simulation. To

evaluate the accuracy of the simulation results, A/F values were determined at the same position as the measurement position used for the micro-Cassegrain sensor, and compared with measurement results for the three injection conditions.

5.1. Three-dimensional Engine Simulation

VECTIS, manufactured by Ricardo, was employed for the three-dimensional engine simulation. Figure 12 shows the simulation model. The boundary and initial conditions formulated using the one-dimensional simulation and the fuel spray parameters were input into this model and calculations were conducted. The mesh used for the calculations is shown in Fig. 13. A mesh size of 1 mm was used for the combustion chamber and the areas around the intake and exhaust valves, 0.1 mm for the tumble control valve flow channel, and 2 mm for all other areas.

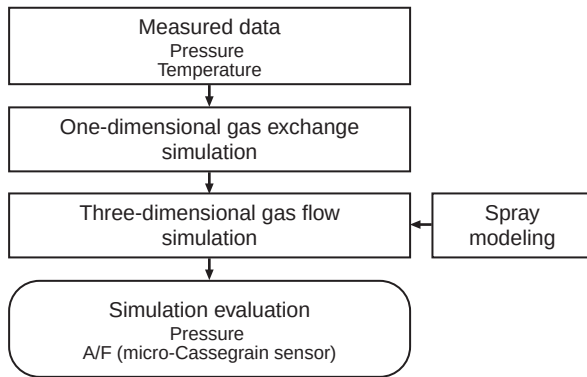


Fig. 11 Engine simulation flow

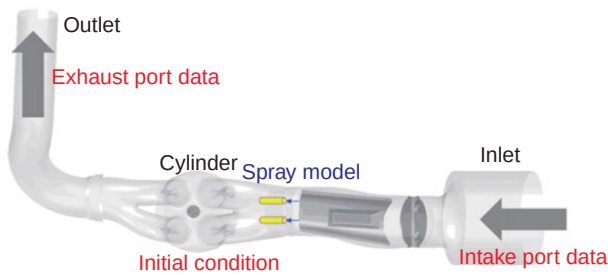


Fig. 12 Three-dimensional simulation model

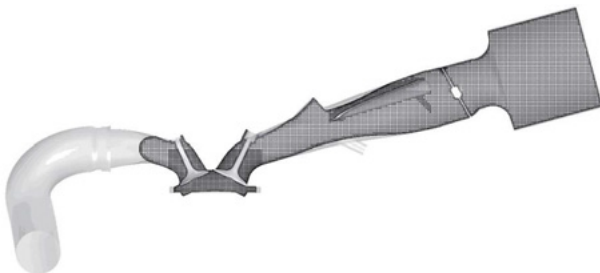


Fig. 13 Mesh used for calculation

5.2. One-dimensional Gas Exchange Simulation

WAVE, again manufactured by Ricardo, was employed for the one-dimensional gas exchange simulation. The simulation model is shown in Fig. 14. The tumble control valve and external EGR pipe used in the test engine were modeled. Figures 15(a) and (b) show measurement and simulation results for in-cylinder pressure and intake port pressure. The measurement results for in-cylinder pressure in Fig. 15(a) are an average for 100 cycles, but the simulation reproduces them well. The measured intake port pressure in Fig. 15(b) is always 60 kPa or below as a result of restriction due to the tumble control valve fitted in the test engine, but optimal setting of the restriction parameters has enabled good reproduction of the pressure history in the simulation.

5.3. Determination of Fuel Spray Calculation Parameters

A fuel spray injected into a constant volume chamber was visualized in order to determine the fuel spray calculation parameters. Scattered light was employed to

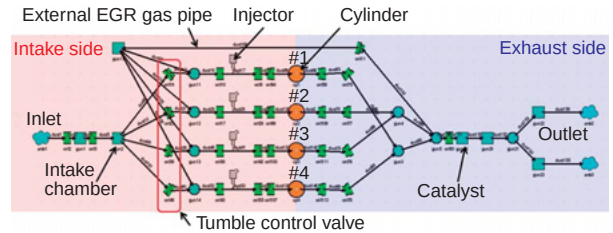
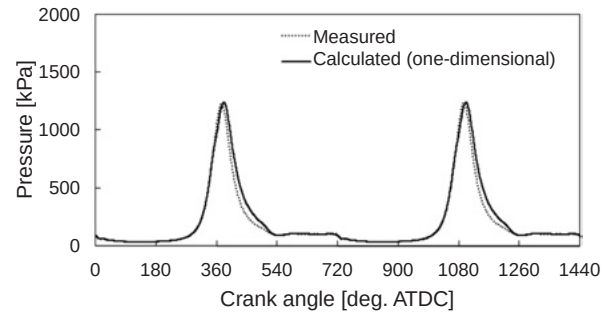
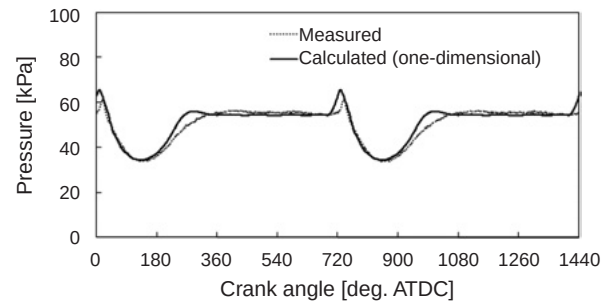


Fig. 14 One-dimensional simulation model



(a) In-cylinder pressure



(b) Intake port pressure

Fig. 15 Comparison between measured pressure and one-dimensional gas exchange simulation

enable imaging of the fuel injected into the bottom of the chamber. The atmospheric conditions for the measurements were atmospheric pressure and ambient temperature.

A discrete droplet model (DDM) was used in the fuel spray calculations. The measured droplet size distribution was employed as the boundary condition, and a Reitz-Diwakar model⁽¹¹⁾ was used for droplet break-up (“secondary break-up”). The atmospheric conditions at the time of the measurements were used as the initial conditions for the simulation. The mesh size was set at 2 mm, and the time step at 1.0×10^{-5} s. Figure 16 shows the visualized spray and the calculated spray. The time is 0.4 ms following injection. The spray angle for the measurements was set at 18°; while the angle is slightly wider in the calculation results, they show an oval-shaped spray overall, and can thus be judged as having reproduced the measurement results well. Figure 17 shows a comparison of measured spray tip penetration and calculation results. There is good correlation between the results for all points in time, indicating that the simulation demonstrates sufficient accuracy.

5.4. Evaluation of Accuracy

Figure 18 shows measurement results and three-dimensional simulation results for in-cylinder pressure, and the level of deviation between the results. The

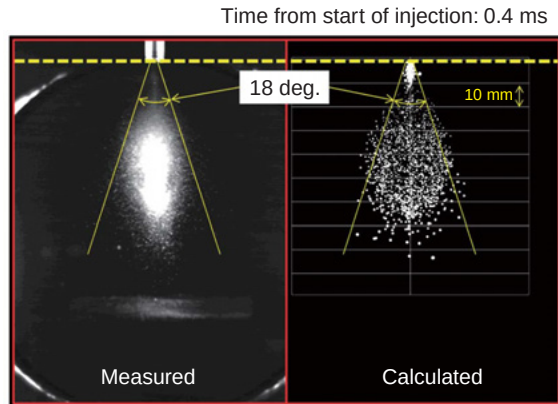


Fig. 16 Comparison of form of fuel spray

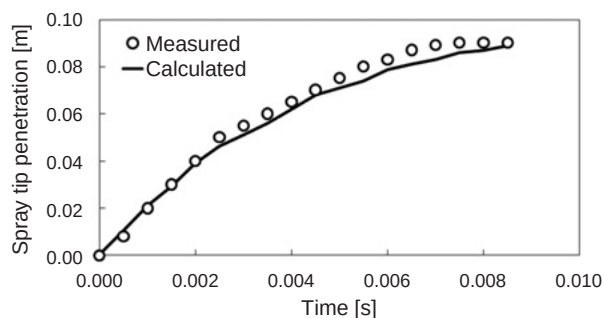


Fig. 17 Comparison between measured spray tip penetration and calculation result

calculations were conducted up to the point of gas flow and mixing of the fuel and air, and are therefore complete at the ignition timing of 35 deg. BTDC. The deviation between the results is high at 4.8% at the ignition timing, but the pressure history in both sets of results corresponds well, indicating that the simulation reproduces the in-cylinder pressure field with good accuracy. Given this, the simulation can be considered to accurately reproduce the flow rate and behavior per unit time of the air and fuel flowing into the cylinder through the intake port and the valve. The 4.8% deviation in results for pressure increases by 0.8% if expressed as charging efficiency and decreases by 0.66% if converted to A/F. This is quite low when compared to the amplitude of cyclic variation in measured local A/F, and sufficient accuracy to enable evaluation can therefore be considered to have been achieved.

Figure 19 shows simulation results for the A/F around the spark plug and a cyclic average of measurement results. The error bars in the figure show the cyclic variation in local A/F shown in Fig. 10. The calculated local A/F is within the range of cyclic variation, and the trend for mixture concentration also corresponds well, indicating that the A/F around the spark plug has been calculated with good accuracy.

Figure 20 shows the calculated in-cylinder A/F distribution. There is considerable spatial variation in A/F in the case of injection on the Primary side only. The

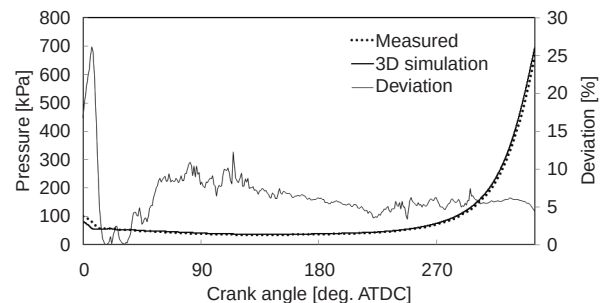


Fig. 18 Comparison between measured in-cylinder pressure and in-cylinder pressure calculation result

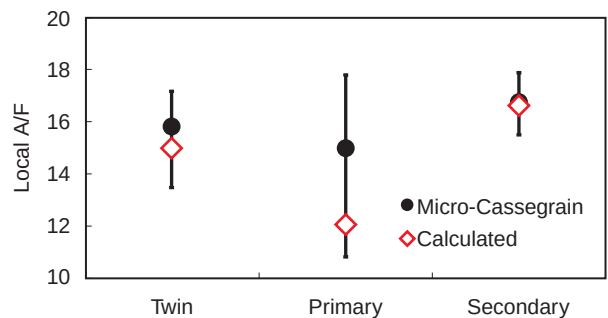


Fig. 19 Comparison between local A/F using micro-Casagrain sensor and calculation result

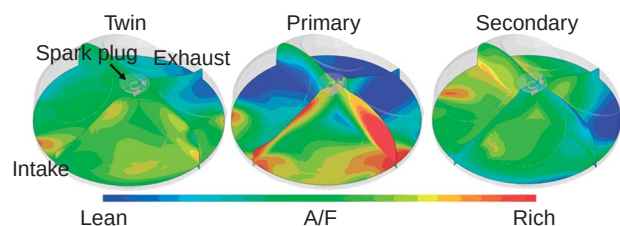


Fig. 20 Three-dimensional A/F distribution

reason that the error bar - the variation in each cycle - is larger for injection on the Primary side only than for the other injection conditions in Fig. 19 can be conjectured to be the fact that the spatial distribution of the air-fuel mixture concentration is greater than it is for the other injection conditions, and there is a minute change in the flow pattern in each cycle, resulting in a greater amplitude of variation in local A/F. Because of this, it is considered that the range and distribution of the air-fuel mixture flow around the spark plugs at the ignition timing would be effective as control parameters in reducing cyclic variation.

6. Conclusion

The A/F around the spark plugs was focused on as a factor in cyclic variation in gasoline engines, and the accuracy of a three-dimensional simulation was evaluated, with the following results:

- (1) A micro-Cassegrain sensor was used to measure the A/F around the spark plugs in a vehicle-mounted engine, previously regarded as a challenge, and the results were virtually identical to results obtained using conventional measurement methods such as UEGO sensors.
- (2) A comparison of the results for the A/F around the spark plug obtained from the micro-Cassegrain sensor and the three-dimensional simulation showed that the calculation results were within the range of cyclic variation, and there was a good correlation between the results for different injection conditions.
- (3) The three-dimensional simulation is judged to be an effective tool for the analysis of the behavior of the air-fuel mixture around the spark plugs and in the surrounding area based on cyclic variation.

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