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(1-04) Direct Particulate Sampling Study in a DI Diesel Combustion Chamber

*Satoshi Kato(1), Hideaki Tanabe(2), Junya Yoshizawa(1), G.Takeshi Sato(1)

(1) *Division of Mechanical Engineering, Kanazawa Institute of Technology*

7-1 Ohgigaoka, Nonoichi, Ishikawa 921-8501, Japan

(2) *Gunma University*

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ABSTRACT

Reduction of the Particulate Matter (PM) is very important to achieve the clean diesel engines. Especially, reduction of the Soluble Organic Fractions (SOF) are very important, because the particulate trap can eliminate primarily the Insoluble Fractions (ISF) but does not effectively reduce the SOF, while the latter contains the harmful components for human. A clarification of SOF production in the combustion chamber is required for the SOF reduction. This paper is concerned with the formation of Particulate Matter (PM) in direct injection (DI) diesel engines. A system featuring an electromagnetically actuated sampling valve with internal N_2 dilution was developed for sampling of PM directly from the combustion chamber.

The concentration of Total Particulate Matter (TPM), SOF and ISF, were measured at the twenty different locations in the combustion chamber at different sample timings (different crank angles). The time resolution of the sampling valve is dominated by the opening duration of the valve, which is an order of 1 or 2 milli seconds. In this study, apparent time resolution was improved by the following measure. The sample timing was determined so that the neighboring sample timings were included within the sampling duration. The measured value at each sample timing could be recognized as an averaged value of the instantaneous value at the sample timing and at the neighboring timings. Instantaneous values can be obtained by solving the simultaneous equations between average and instantaneous values. The weight factor were selected to obtain suitable corrected values by trial and error.

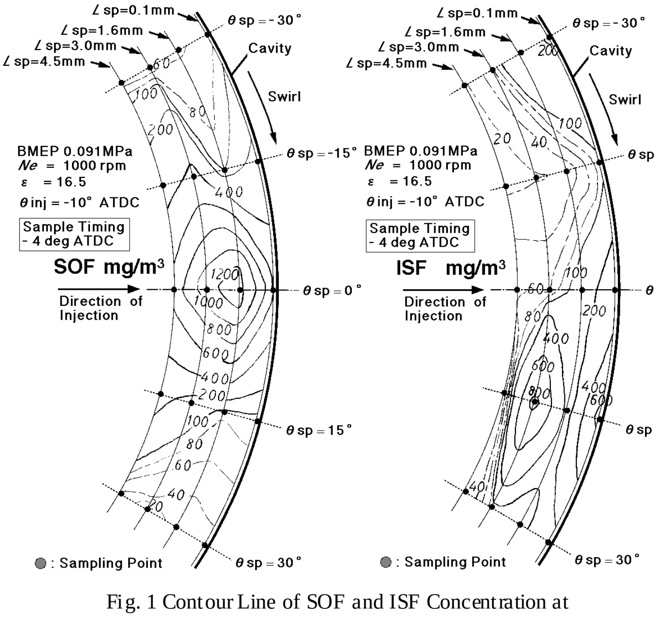

Fig. 1 Contour Line of SOF and ISF Concentration at Sample Timing of - 4 ° ATDC

The combustion gases (CO, CO_2, O_2, THC) were also analyzed by the gas chromatography for the local air fuel ratio calculation. The concentration of SOF was higher at the sampling positions on spray flame axis. The concentration of ISF was higher at the sampling positions on downstream of the spray flame. Both SOF and ISF concentration are higher at near the wall than away from the wall. It is also made clear that the PM formation is strongly affected by the wall quenching at the combustion chamber wall.

INTRODUCTION

Reduction of the Particulate Matter (PM) is very important to achieve the clean diesel engines. Especially, reduction of the Soluble Organic Fractions (SOF) are very important, because the particulate trap can eliminate primarily the Insoluble Fractions (ISF) but does not effectively reduce the SOF [1, 2], while the latter contains the harmful components for human. A clarification of SOF production in the combustion chamber is required for the SOF reduction. Previous studies have indicated that the spray flame quenching the combustion chamber walls played a significant role in the formation of SOF [3,4].

A system featuring an electromagnetically actuated sampling valve with internal air dilution was developed for sampling the PM directly from the combustion chamber [5]. The concentration of SOF, ISF, CO, CO_2, O_2, and THC were measured at the twenty different locations in the combustion chamber at different sample timings (different crank angles).

EXPERIMENTAL SETUP

A schematic diagram of the experimental setup is shown in Fig. 2. The intake air temperature and intake air pressure were maintained at 298 ± 0.1 K and 1013.25 ± 0.25 hPa, respectively, by the air temperature and pressure control system, while the cooling water temperature and lubricating oil temperature were maintained at 353±0.5 K and 353±2 K, respectively. The strict control of these operating conditions have assured acceptable repeatability of the test results.

The specifications of the test engine are shown in Table 1. A single cylinder DI diesel engine with a round troidal combustion chamber is employed. The cylinder head was built to suit the sampling valve.

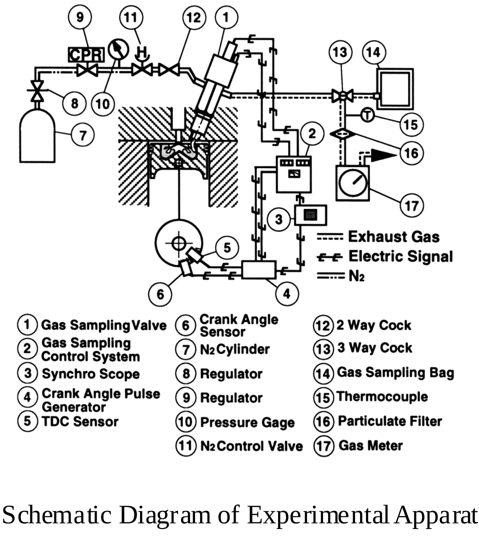

Fig. 2 Schematic Diagram of Experimental Apparatus

SAMPLING VALVE AND SAMPLING PROCEDURE

An electromagnetically actuated sampling valve with dilution system was developed for direct gas sampling from combustion chamber as shown in Fig. 3. The N_2 gas is introduced to the very vicinity of the valve seat, where the dilution occurs to cool particulate sufficient enough for SOF to coagulate and to prevent the PM from adhering onto the surface of the sampling line. The sampling probe is connected to a sampling valve inlet to collect gas–particulate mixture from the selected sampling point in the combustion chamber. The sampling probe is a piece of stainless steel tube with an inner diameter of 1 mm and length of 14 - 17 mm to minimize dead volume.

Table 1 Test Engine Specifications

Engine Type		Water Cooled Vertical 4 Stroke Direct Injection Compression Ignition
Cylinder		1
Bore x Stroke		83 x 85 [mm]
Displacement Volume		460 x 10^{-6}[m^3]
Intake Port		Tangential Port
Injection Timing		Variable
Injection Nozzle		Hole(6 - ϕ0.20mm)
Injection Valve Opening Pressure		24.5[MPa]
Compression Ratio		16.5
Injection Pump		Bosch Type
Maximum Output		5.5[kW]/2200[rpm]
Maximum Torque		25.5[Nm]/1600[rpm]
Number of Valves	Intake	1
	Exhaust	2
Valve Timing	int.Open[deg]	540
	int.Close[deg]	48
	Exh.Open[deg]	309
	Exh.Close[deg]	532

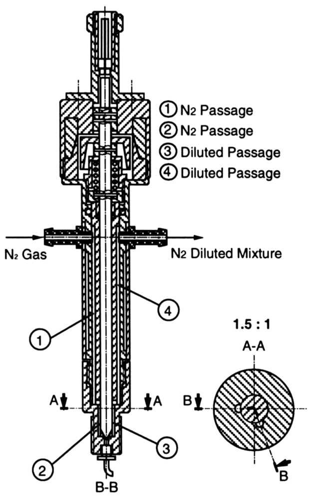

Fig. 3 Electromagnetically Actuated Gas Sampling Valve with Dilution System

The PM concentrations were shown in Fig. 4 sampled with and without dilution. The dilution helps the PM to avoid adhesion onto the surface of the sampling line and SOF to coagulate as mentioned before. The apparent PM concentrations were measured much less than actual PM concentration without. Thus the dilution is necessary for the accurate PM sampling.

The sampled PM was then collected on a PTFE coated glass-fiber filter (Pallflex TX40 HI 20-WW) typically used for PM measurement for exhaust emission. The collected TPM was separated into the ISF and the SOF using the Soxhlet extraction method with dichloromethane for solvent.

The mass of TPM was obtained as a mass difference between pre-sampling filter and post-sampling filter. The concentration of TPM was determined by dividing the mass of TPM collected on the filter by the volume of the sampled gas at the room temperature and pressure. The sampled gas volume was obtained by dividing the volume of the diluted gas by the dilution ratio. The volume of diluted gas was measured using a volumetric flow meter located downstream of the PM sampling filter. The dilution ratio was determined from the concentration of carbon dioxide (CO_2) in the diluted sampled gas and undiluted sampled gas.

The concentration of O_2, CO, and CO_2 were measured by the gas chromatography with Thermal Conductivity Detector (TCD). Hydrocarbon concentration was measured as a total hydrocarbon (THC) by gas chromatography with Flame Ionization Detector (FID). For THC measurement, no separation of hydrocarbon components is required. The short column length of 0.5 m with non-coated column packing was, therefore, used. The column temperature was set at 200 °C.

The local air fuel ratio $(A/F)_L$ was calculated from the local concentration of CO, CO_2, O_2, and THC with the equation presented by Spindt [6]. Then the local air excess ratio λ_L was calculated from local $(A/F)_L$.

The local O_2 excess ratio ΛO_2 was obtained the ratio of measured local O_2 concentration to required O_2 concentration for oxidation of local unburnt fraction of CO, THC, SOF, and ISF. The local O_2 excess ratio ΛO_2 indicates available O_2 that is needed to oxidize the unburnt fraction.

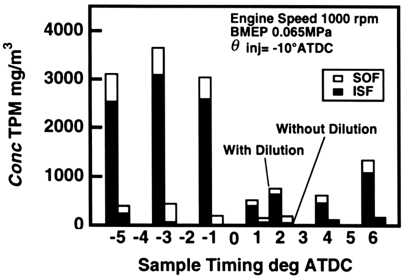

Fig. 4 Particulate Matter Concentration Obtained by Sampling Valve with and without Dilution Was

Table 2 Engine Operating Conditions and Gas Sampling Conditions

Engine Operating Conditions	Speed	1000 [rpm]
	BMEP	0.091 [MPa]
	Injection Timing	-10 [° ATDC]
	Swirl Ratio	0.4
	Cooling Water Temperature	80±[0.5 ℃]
	Lubricating Oil Temperature	80±[2.0 ℃]
	Suction Air Temperature	25±[0.1 ℃]
	Suction Air Pressure	1013.25±0.25 [hPa]
Sampling Conditions	Sampling Number	200 [cycles]
	Interval	10 [cycles]
	Duration	12 [° CA]

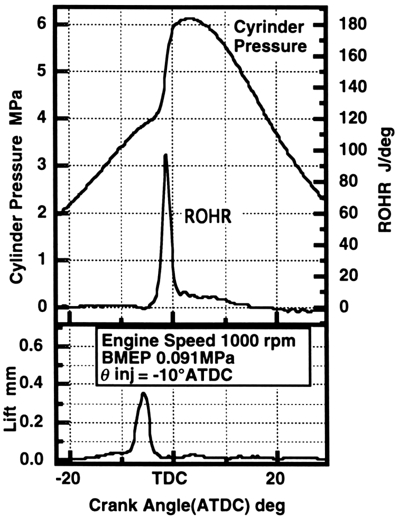

Fig. 5 The Cylinder Pressure, Rate of Heat Release, and Nozzle Lift Traces

The engine operating conditions were fixed throughout the test to simulate service under low load, idling conditions shown in Table 2. Under these operating conditions, the piston wall temperature is expected to remain moderately low, therefore promoting wall quenching effects. The fuel injection timing and the fuel injection duration were set at 10 °BTDC and 5 °CA, respectively. The nozzle lift, rate of heat release (ROHR), and cylinder pressure traces were shown in Fig. 5.

The exhaust emissions were listed in Table 3. The air excess ratio λ_{in} was the ratio calculated from inlet air mass flow rate and fuel mass flow rate. The exhaust emissions were the base line data to consider the emission level in the combustion chamber.

The sampling was operated every 11cycles so as to minimize the affects of the sampling procedure on the engine operation. The PM samples from 200 intermittent engine cycles were collected on the filter.

The sampling valve opening duration was set at 12 °CA, resulting in a sampled gas volume of ca. 6 ml at ambient conditions. The sampling valve, cylinder head, and piston were cleaned prior to each testing to keep reproducibility.

Twenty sampling positions were selected to investigate the effect of location around the fuel spray on the PM formation as shown in Fig. 6. The sampling probe was positioned with an accuracy of +0.1 to +0.2 mm for distance and ± 0.3 degree for angular location.

The measured concentration at each sample timing could be recognized as an averaged value of the instantaneous value at the sample timing and at the neighboring timings. Instantaneous values can be obtained by solving the simultaneous equations between average and instantaneous values with suitable weight factors, which considers the sampling gas velocity profiles.

Sampling duration is split into three sections, as shown in Fig. 7. The instantaneous concentration, Ci, of each ith section can be formularized as follows:

$$A_1C_0+A_2C_1+A_3C_2=B_1 \qquad \text{----} \; (1)$$

$$A_1C_{i-1}+A_2C_i+A_3C_{I-1}=B_i \qquad \text{----} \; (i)$$

$$A_1C_{n-1}+A_2C_n+A_3C_{n+1}=B_n \qquad \text{----} \; (n)$$

$$A_1+A_2+A_3=1$$

Where, A_1, A_2, A_3 are the weight factors considering the sampling velocity profile during each sections, and B_1, ---B_n were the measured concentration of sample timing at t_1, ---t_n.

Too large A_1 and A_3 brought trivial value as shown in Fig. 8. The weight factors, A_1, A_2, and A_3 were then selected to obtain suitable corrected value by trial and error, as they are not so much sensitive as far as they obtain non negative concentration.

The representative time of sample timing (crank angle) corresponds to the middle point of a 12 °CA sampling duration.

EXPERIMENTAL RESULTS AND DISCUSSION

PM FORMATION ON THE SPRAY FLAME AXIS

The concentrations of gaseous components (CO, CO_2, and THC) and local excess air ratio, λL, and particulate matters (ISF and SOF) concentration are shown in Fig. 9 and 10, respectively, as a function of sampling timing in a crank angle basis. The sample timing of -16 °ATDC corresponds to the residual gas

Table 3 Gaseous Exhaust Emission and PM Emission

λin	-	4.39
CO	%	0.031
CO_2	%	3.55
O_2	%	16.08
THC	ppmC	102.6
PM	mg/m³	17.9
SOF	mg/m³	14.8
ISF	mg/m³	3.06

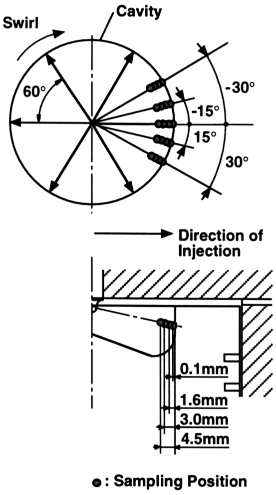

Fig. 6 Illustration of Sampling Positions around the Fuel Spray Axis

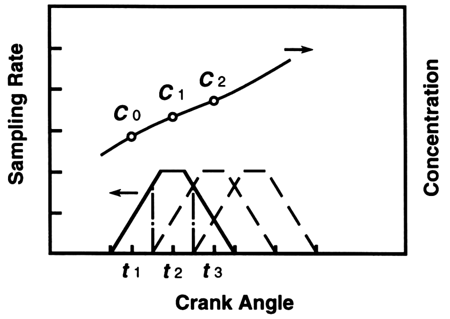

Fig. 7 Actual Sampling Duration Split into Three Sections

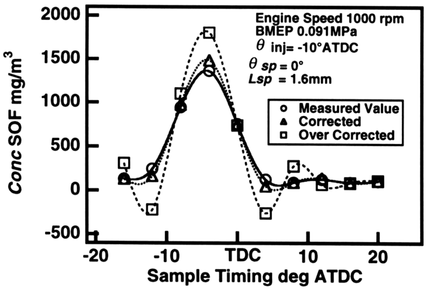

Fig. 8 Measured Value and Corrected Value of SOF Concentrations

component just before the fuel injection. The fuel injection starts at -10 °ATDC and as soon as the fuel is injected the THC and SOF concentrations steeply increase and reach to highest value at -4 °ATDC. After that, the concentration of these components steeply decreases and approach to constant value at 4 °ATDC. These concentration changes correspond to the fuel injection duration and combustion period of -5 to 15 °ATDC. The concentrations of SOF and THC are higher at near the wall.

The THC concentration was a range of measured concentration with Rapid Compression Machine for the diesel combustion which was reported by others[7].

The CO$_2$ concentration is highest at near the wall. The local air excess ratio is lowest near the wall. The SOF concentration is higher than the ISF concentration during combustion period and decrease to constant value after 4 °ATDC.

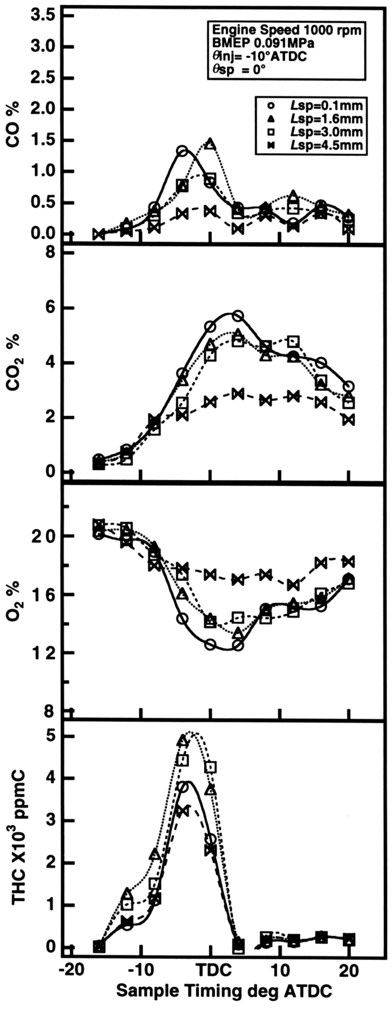

Fig. 9 CO, CO$_2$, O$_2$, and THC Concentrations at 4 Different Sampling Positions on Spay Flame Axis (θsp = 0°, *L*sp = 0.1, 1.6, 3.0, 4.5 mm)

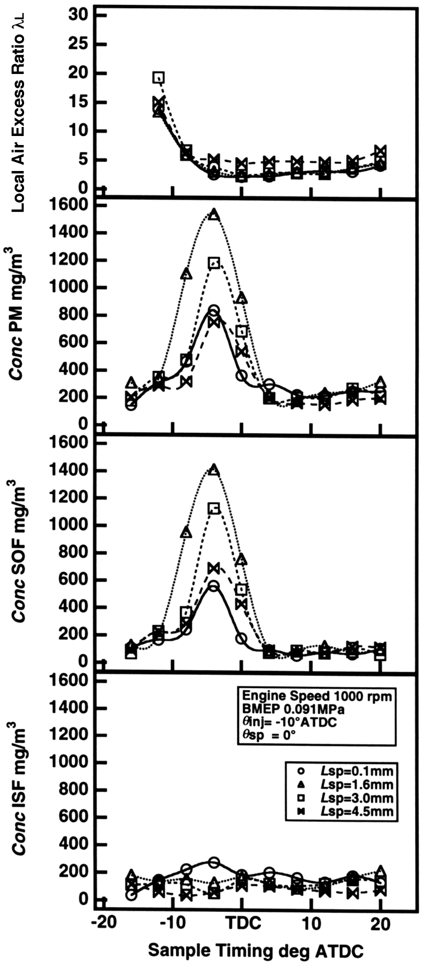

Fig.10 Local Air Excess Ratio and PM, SOF, and ISF Concentration at 4 Different Sampling Positions on Spay Flame Axis (θsp = 0°, *L*sp = 0.1, 1.6, 3.0, 4.5 mm)

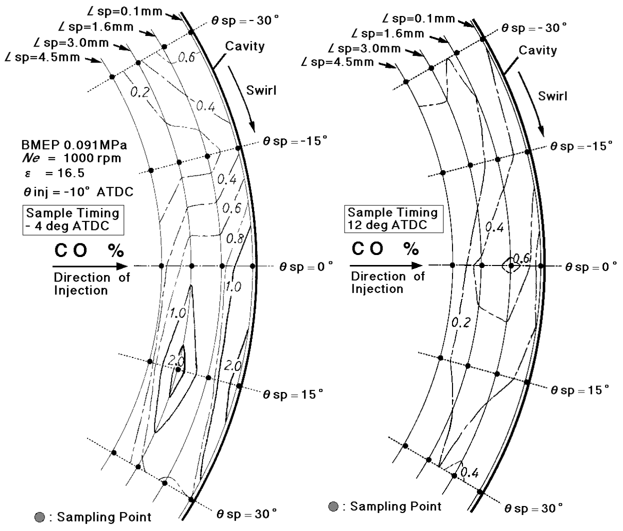

Fig. 11 Contour Line of CO Concentration at the Sample Timing of –4° and 12 °ATDC

CONTOUR LINES OF THE GASEOUS EMISSION AND PM CONCENTRATION

The contour lines are obtained by interpolating the concentrations of all sampling positions. As typical contour lines, the sample timing of –4 °ATDC and 12 °ATDC are selected. The sample timing of –4 °ATDC represent the rapid combustion period and the sample timing of 12°ATDC represent the end of combustion period.

The contour line of the CO concentration at –4 °ATDC and 12 °ATDC are shown in Fig. 11. The highest value of CO concentration is observed on the downstream of the spray flame axis (θsp = 15°) at –4 °ATDC.

The contour line of the CO_2 concentration at –4 °ATDC and 12 °ATDC are shown in Fig. 12. The CO_2 concentration is higher at near the wall. The CO_2 concentration increases as crank angle advance, as the oxidation progresses.

The ISF concentration is unsymmetrical and is higher in downstream of the spray flame axis than the upstream as shown in Fig. 13. Significantly high concentration of ISF can be seen in the head vortex region of the spray [8] as well as in the vicinity of the cavity wall, both in the downstream side.

The highest concentration point of the CO, CO_2, and ISF agreed precisely.

The contour lines of the O_2 concentration, local excess air ratio, λL, and excess O_2 ratio, ΛO_2, are shown in Fig. 14, 15, and 16, respectively. The region of the high CO_2 concentration and lower λL suggest the high temperature region. And in this region, sufficient O_2 concentration and high excess O_2 ratio were observed.

The contour line of the O_2 excess ratio, ΛO_2, at –4 °ATDC and 12 °ATDC are shown in Fig. 16. During the combustion period, at –4 °ATDC as an example, lowest O_2 excess ratio, ΛO_2, of 2.0 or less can be seen on the spray flame axis. The highest ISF concentration is observed at 15° downstream of spray flame axis, where the sufficient O_2 remains though.

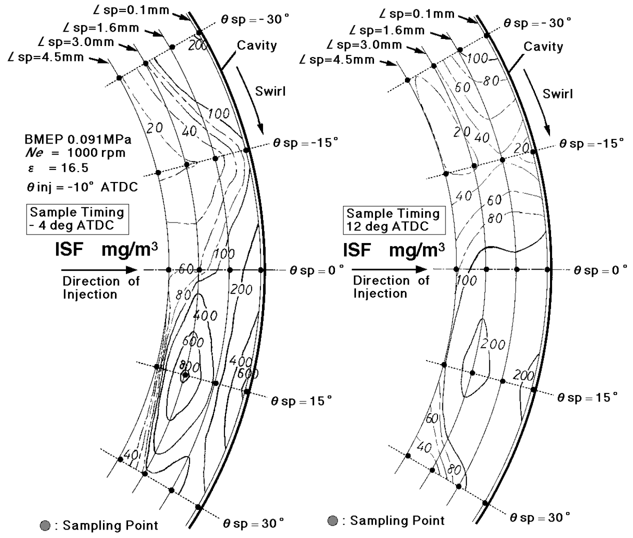

Fig. 13 Contour Line of ISF Concentration at the Sample Timing of -4 °and 12 °ATDC

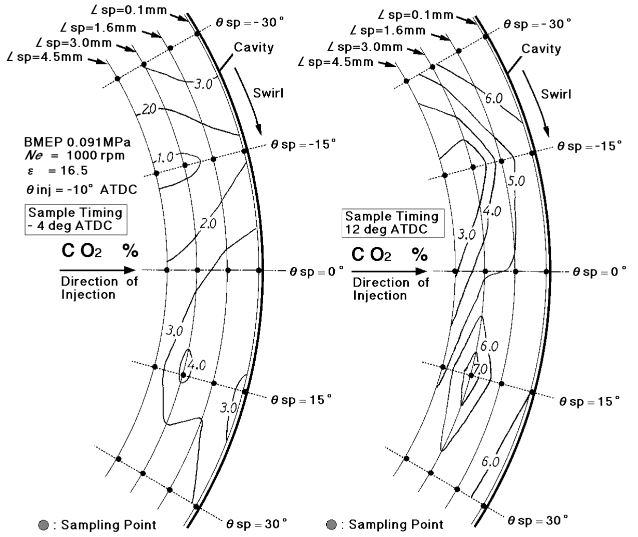

Fig. 12 Contour Line of CO_2 Concentration at the Sample Timing of -4 °and 12 °ATDC

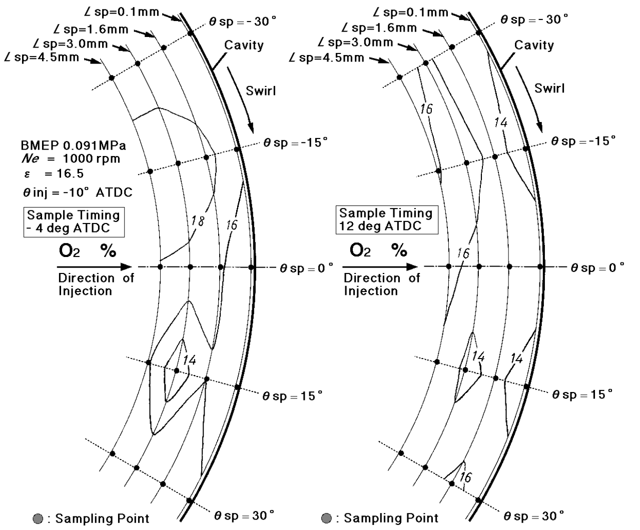

Fig. 14 Contour Line of O_2 Concentration at the Sample Timing of -4 °and 12 °ATDC

From these results, the thermal decomposition should be considered as the reason of high ISF concentration. At 12 °ATDC, almost the end of combustion period, the sufficient O_2 exists. So, there is a possibility of re-oxidation of the unburnt fraction in the continued crank angle.

The contour line of the THC concentration at –4 °ATDC and 12 °ATDC are shown in Fig. 17. The highest THC concentration is observed on the axis of spray flame. And the THC concentration is almost symmetry with respect to the spray flame axis. These tendencies are very similar to that of the SOF concentration described below.

The contour line of the SOF concentration at –4 °ATDC and 12 °ATDC are shown in Fig. 18. The highest SOF concentrations are observed on the spray flame axis. The SOF concentration is almost symmetry with respect to the spray flame axis. The SOF concentration is higher at near the wall. At 12 °ATDC, almost the end of combustion period, the SOF remains still high on the spray flame axis.

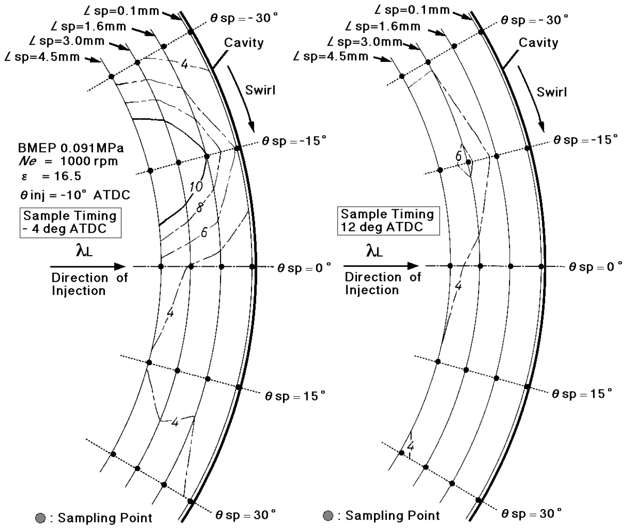

Fig. 15 Contour Line of Local Excess Ratio, λL, at the Sample timing of -4 °and 12 °ATDC

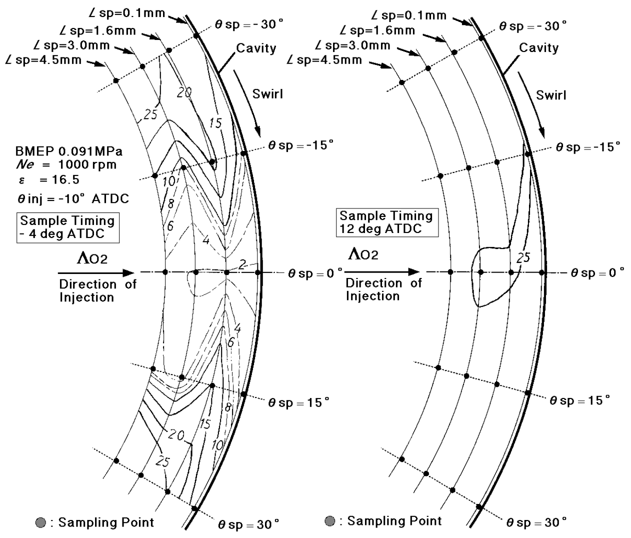

Fig. 16 Contour Line of O_2 Excess Ratio, ΛO_2, at the Sample Timing of -4 °and 12 °ATDC

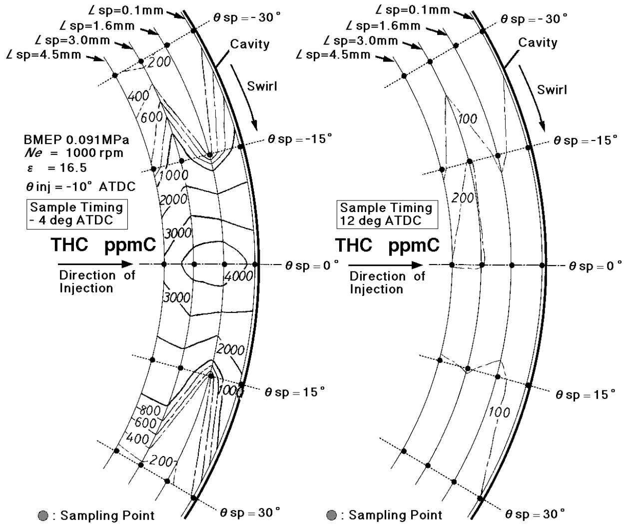

Fig. 17 Contour Line of THC Concentration at the Sample Timing of -4 °and 12 °ATDC

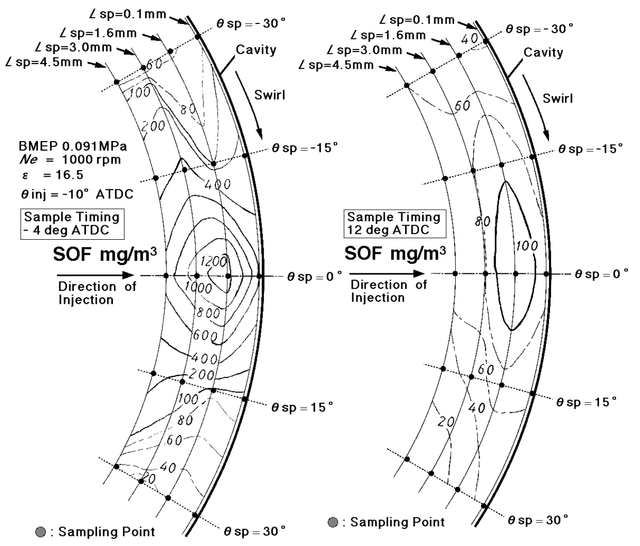

Fig. 18 Contour Line of SOF Concentration at the Sample Timing of -4 °and 12 °ATDC

From these contour lines of the SOF and ISF concentration, both SOF and ISF concentration are higher at near the wall. These results strongly suggest that the wall quenching effects significantly affect to the formation of the SOF and ISF.

CONCLUSION

In order to investigate the PM formation, the concentration of SOF, ISF, and gaseous components were measured at the twenty different locations in the combustion chamber. Following conclusions are obtained.

(1) The SOF and THC concentration are high on the axis of the spray flame during fuel injection period and after injection end.

(2) The maximum ISF concentration is observed at the position near the wall apart from the spray flame axis because of the spray impinge to the wall and form the head vortex. While the maximum SOF concentration is on the spray flame axis near the wall.

(3) Both SOF and ISF concentration are higher at near the wall. These results strongly suggest that the wall quenching effects significantly affect to the formation of the SOF and ISF.

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