20056014

# 12 Total In-Cylinder Gas Sampling Experiment on Emission Formation Processes in a D.I. Diesel Engine

Kazunori HIRABAYASHI, Katsuya MARUSHITA, Keiya NISHIDA
University of Hiroshima

1-4-1 Kagamiyama, Higashi-Hiroshima, 739-8527, Japan

Measurement of in-cylinder gas, such as nitric oxide, total hydrocarbon, and smoke, was made on a converted single-cylinder out of a 4-cylinder, 2 L, direct injection Diesel engine, using a newly developed total in-cylinder gas sampling technique. The sampling method was composed of a fast-acting blowdown valve installed in the cylinder head and a collection system which can transfer and quench the in-cylinder contents rapidly. The sampling experiment gave histories of the spatially averaged emission concentrations in the cylinder. The effect of fuel injection pressure on the emission formation processes was investigated.

**Keywords: Engine Combustion, Performance / Diesel Engine, Emission Formation Process**

## 1. INTRODUCTION

Direct Injection (D.I.) Diesel Engines have been used in a lot of heavy duty vehicles owing to their fuel economy, a factor which has been regarded to be of major importance. Since every internal combustion engine, including the Diesel engine, has been greatly required to consider their environmental effects, fuel economy has not been the most valuable advantage of the D.I. Diesel engine. One of the most important subjects in the current technology of the D.I. Diesel combustion is to reduce such pollutant emissions as nitric oxide (NOx) and particulate matters.

Some efforts by using combustion improvement techniques thanks to practical using of the modern electronic controlled common-rail injection system have recently made remarkable progress in the Diesel emission control. However obtaining a better understanding of combustion and emission formation processes in the cylinder is a significant goal in the present effort to produce a D.I. Diesel engine with low pollutant emissions as well as improved fuel economy.

Rapid sampling experiments of the in-cylinder gas, which gave time- and space-resolved histories of the combustion events, should help in the effort to meet these objectives. Sampling probe studies [(1)] have been limited to sampling from the local small volume in the cylinder, and were not suitable for comprehending the overall combustion processes in the D.I. Diesel engine. Total in-cylinder sampling experiments, using a dumping apparatus installed in the cylinder head or the elongated piston, were made to investigate the spatially-averaged composition in the cylinder. [(2-5)]

The total in-cylinder sampling method employed in this study consists of a fast-acting blowdown valve installed in the cylinder head and a collection system which can transfer and quench the in-cylinder contents rapidly. The spatially-averaged concentrations of NOx, THC and smoke are measured at a given crank angle.

This paper describes the experimental method used for the total in-cylinder sampling, the evaluation of the performance of the blowdown apparatus and the typical histories of the NOx, THC and smoke concentrations in the cylinder. Discussion is also made in terms of the effect of the fuel injection pressure on the combustion and emission formation processes.

## 2. EXPERIMENTAL APPARATUS AND PROCEDURES

### 2.1 ENGINE AND BLOWDOWN APPARATUS

A 4-stroke D.I. Diesel engine was used in this study. The main specifications of the engine are shown in Table 1. The engine was modified for the total in-cylinder sampling experiment as shown in Fig. 1. One of the two exhaust valves was removed, and the sampling unit with the blowdown valve was installed in the cylinder head of the engine. Figure 2 shows the gas sampling mechanism. When the prop of the blowdown valve is pulled by the solenoid actuator at a given crank angle after the start of injection, the cylinder pressure cause the blowdown valve to be pushed upward. Then the blowdown valve rapidly opens, and most of the in-cylinder contents are quickly transferred into a large sampling chamber shown in Fig. 1. This sampling chamber has a volume of ten times of the displacement of the engine and is filled with an argon quench gas. If the blowdown process was rapid and the cooling rate was high enough, the chemical reactions would thus be quenched so that the composition of the gas in the sampling chamber would be representative of the composition in the cylinder at the instant of the blowdown.

Table 1 Engine Specifications

| | |
|---|---|
| Engine Type | Converted single-cylinder out of 4-cylinder D.I. Diesel engine |
| Diaplacement | 0.4995 L |
| Bore × Stroke | 86mm × 86mm |
| Compression Ratio | 15 |
| Valve System | SOHC 2 Intake Valves 2 Exhaust Valves |
| Injection System | Common Rail |

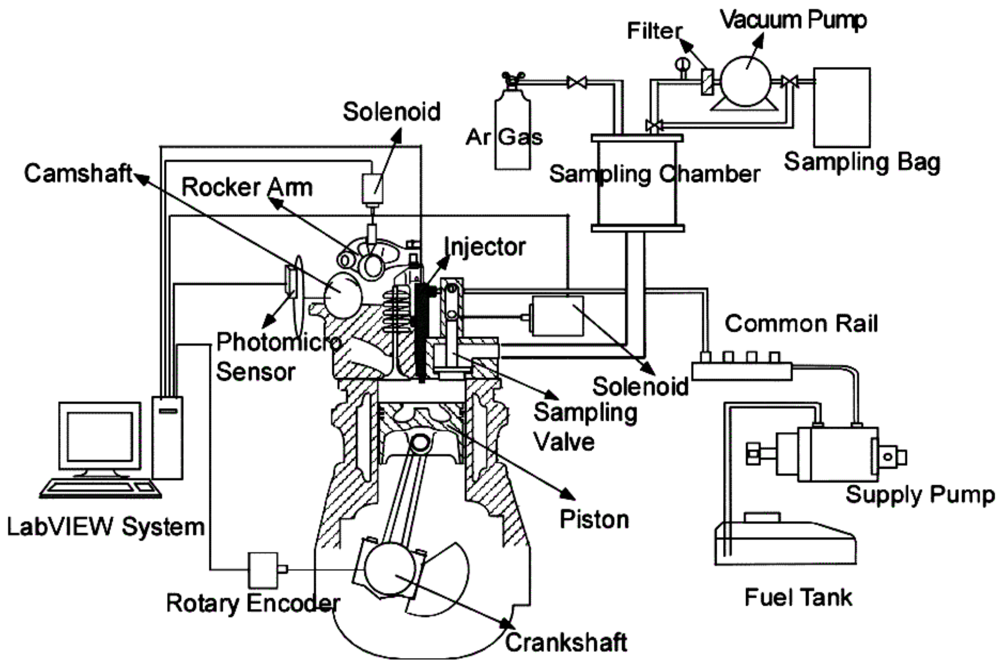


Fig. 1 Experimental Apparatus

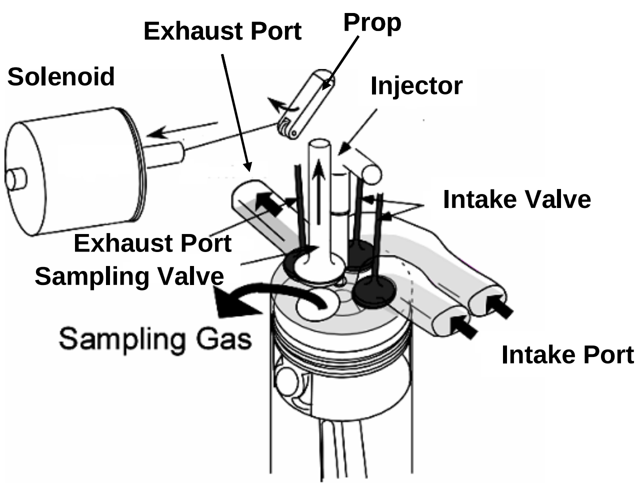


Fig. 2 Gas Sampling Mechanism

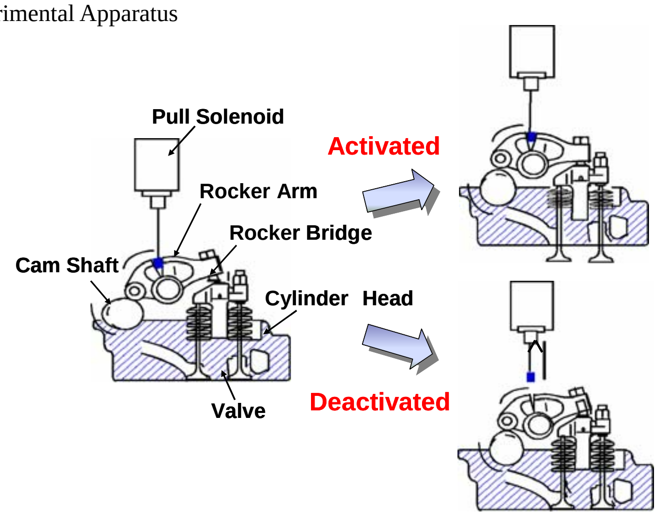


Fig. 3 Deactivation Mechanism of Intake and Exhaust Valves

## 2.2 SAMPLING PROCEDURE

The engine was driven by an electric motor at a constant speed, and the sampling was made in the second combustion cycle. As shown in Fig. 3, at the beginning of the compression stroke in the blowdown cycle, the intake and exhaust valves were deactivated by pulling the spacers inserted between the rocker arm, so that the combustion chamber and the sampling chamber were isolated from the intake and exhaust ports.

All of the blowdown system, consisting of the blowdown valve actuation, the valve train isolation and the fuel injection, was controlled by a computer. The software which used to control the blowdown system was the LabVIEW. Figure 4 shows the timing chart of blowdown experiment. The computer was also used for the acquisition of the cylinder pressure, the needle lift signal and the crank angle signal, and for the calculation of the rate of heat release in the normal combustion cycle without the blowdown. The beginning of the blowdown was determined by a comparison between the pressure traces in the blowdown cycle and in the normal combustion cycle.

After the blowdown, the gas in the sampling chamber was sucked out by a vacuum pump through a glass fiber filter, as shown in Fig. 3. The smoke density on the filter sample was measured by a Bosch-type smoke meter. The NOx and the THC in the gas passing through the filter were collected in the sampling bag. Then they were measured by a chemical luminescence type NOx analyzer and a FID type THC analyzer, respectively. The NOx and THC concentrations were corrected for any argon dilution in the sampling chamber.

The inlet air and the cooling water in the cylinder head were heated up to 60 ℃ and 73 ℃ respectively to get the same ignition delay and combustion pressure as those of the running engine.

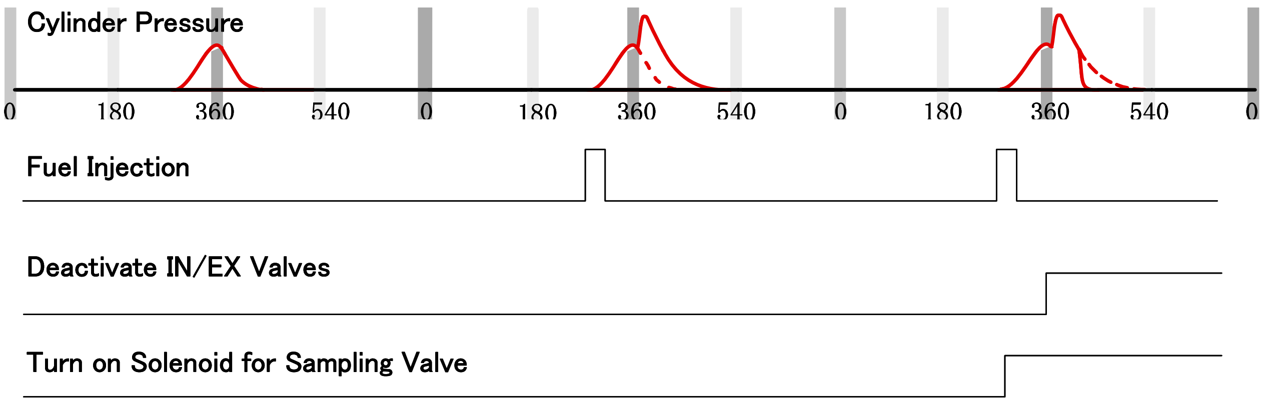


Fig. 4 Timing Chart of Blowdown Experiment

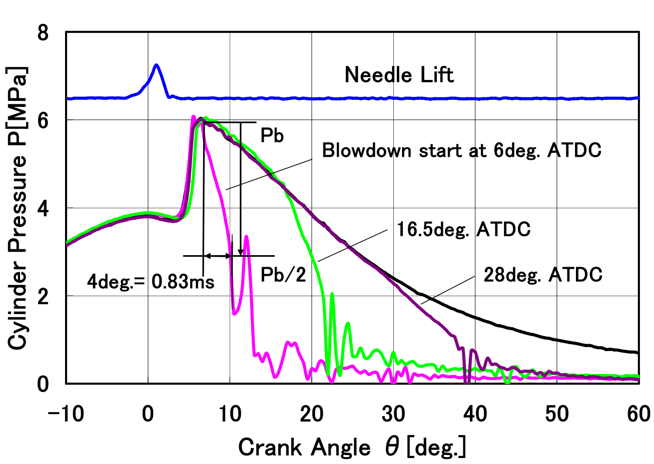


Fig. 5 Cylinder Pressure Diagrams for Various Blowdown Timings

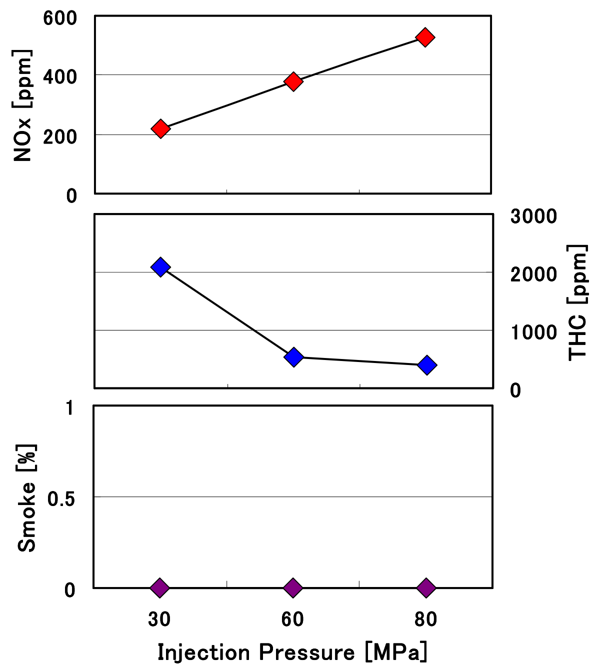


Fig. 6 Effect of Injection Pressure on Exhaust Emission Characteristics

Table 2 Experimental Conditions

| | | | |
|---|---|---|---|
| Engine Speed [rpm] | 800 | | |
| Hole Diameter [mm] | 0.135 | | |
| Number of Holes | 6 | | |
| Injection Pressure [MPa] | 30 | 60 | 80 |
| Mass of Fuel Injected [mg] | 8.1 | 9.3 | 9.9 |
| Injection Timing [deg. ATDC] | - 2.0 | | |
| Intake air and cooling water temperature [℃] | 60 and 73 | | |

### 2.3 EVALUATION OF BLOWDOWN

Figure 5 shows the typical pressure traces in the blowdown and normal combustion cycles at engine speed 800 rpm, mass of fuel injected 9.3 mg, injection timing –2 deg. ATDC and injection pressure 60 MPa. In the case of the blowdown start at 6 deg. ATDC, the cylinder pressure decreased rapidly after the beginning of the blowdown. And then, it took only 4 degree crank angle to reduce the pressure by half. In the previous studies[4, 5], the pressure half-decay period was 6 degree, and the in-cylinder flame radiation signal got zero after 8 degree. Compared with the previous sampling experiment, it takes less time to reduce the pressure by half. Such a rapid decrease of the cylinder pressure and the dilution with the argon gas seemed to result in enough quenching immediately after the blowdown valve was opened. Therefore in this study, the concentrations of the contents in the gas quenched in the sampling chamber were assumed to be the concentrations of the in-cylinder contents at the beginning of the blowdown.

### 2.4 EXPERIMENTAL CONDITIONS

Table 2 shows experimental conditions. The nozzle used had 6 holes whose diameter was 0.135 mm. The fuel injection pressure was set at 30, 60 and 80 MPa and the mass of fuel injected were 8.1, 9.3 and 9.9 mg/stroke, respectively.

## 3. RESULTS AND DISCUSSION

### 3.1 EXHAUST EMISSION CHARACTERISTICS

Emission concentrations in the exhaust gas from the running engine were estimated by taking the sampling results which hardly showed any crank angle variation after 60 deg. ATDC. Figure 6 shows the effects of fuel injection pressure on the exhaust emissions. With increasing the injection pressure, the NOx concentration increases, the THC concentration decreases, and there is no obvious variation for the smoke. It supposed that the fuel evaporation was promoted by increasing the injection pressure, the premixed burning was enhanced, and the exhaust emission characteristics in the above appeared.

### 3.2 EMISSION FORMATION PROCESS

Figure 7 shows the spatially-averaged concentrations of the NOx, THC and smoke obtained from the sampling date. The upper figure shows the cylinder pressure, needle lift, the temperature and the rate of heat release in the normal combustion cycle. The histories of the in-cylinder content concentrations could be described as follows: Both NOx and smoke form rapidly, reaching maximum values in a stage of the premixed burning period. The NOx concentration shows a slight decrease after its maximum, a large increase from 10 to 20 deg. ATDC, and then shows a constant value until the end of the combustion cycle. The smoke shows a great decrease after taking the maximum due to oxidation. The THC concentration shows a sudden decrease during the premixed burning period, and then showed a few increase. After reaching the maximum, the THC concentration shows a large decrease again until the end of the combustion.

### 3.3 EFFECT OF FUEL INJECTION PRESSURE

The fuel injection pressure influences the histories of the in-cylinder content concentration. Figure 8 shows the comparisons of the histories of the in-cylinder content concentration between the fuel injection pressure 30 MPa and 60 MPa. The ignition delay was 0.8 ms and 0.5 ms, respectively. The results of the low injection pressure experiments are described as follows. The NOx concentration decreases as a whole. The maximum of the THC concentration increases and the final exhaust concentration also increases. The maximum of the smoke increases and the final exhaust concentration remains as high as that of 60 MPa. It is supposed that the droplets diameter of the fuel spray becomes larger by reducing the fuel injection pressure, it takes more time to evaporate, premixed burning is suppressed and thus the change of the history of the in-cylinder content concentration described in the above occurs.

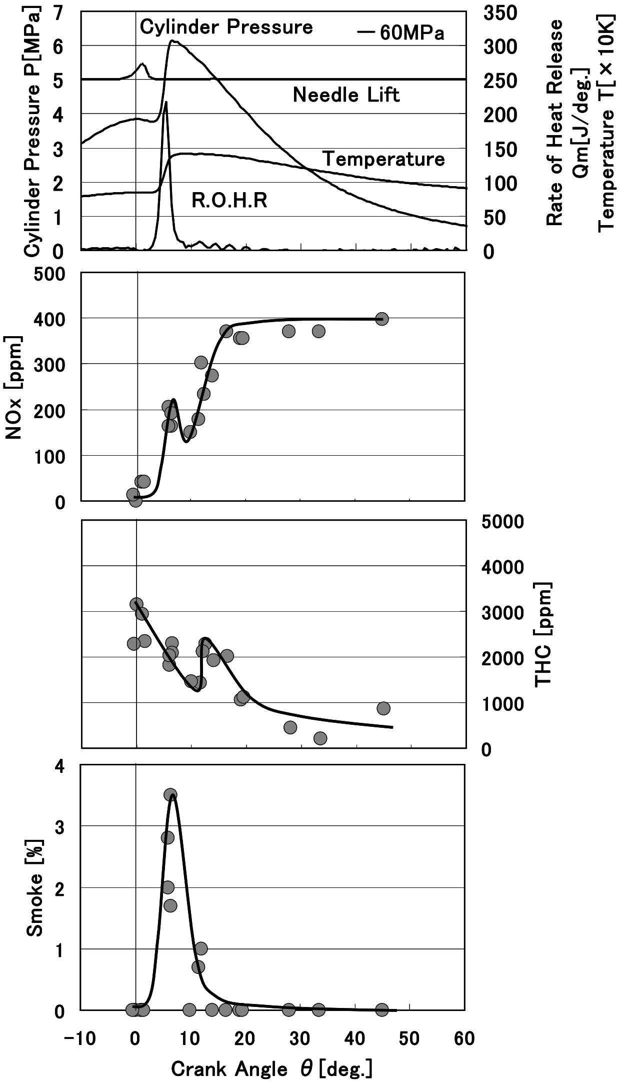


Fig. 7 Emission Formation Process for Injection Pressure of 60 MPa

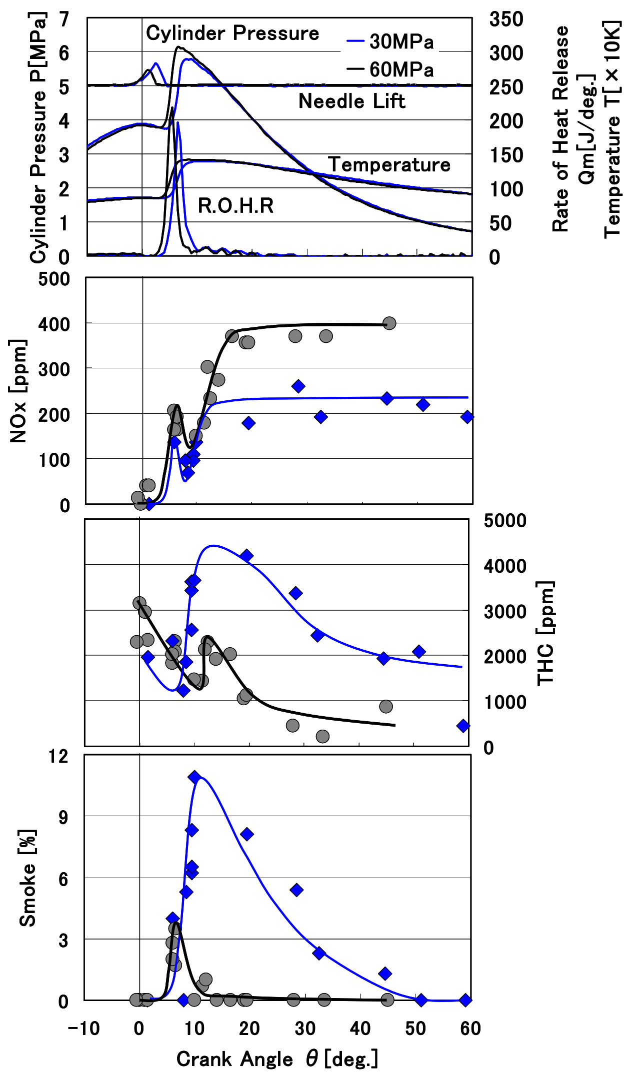


Fig. 8 Comparison of Emission Formation Process between Injection Pressure 30 MPa and 60 MPa

Figure 9 shows the comparisons of the histories of the in-cylinder content concentration between the fuel injection pressure of 60 MPa and 80 MPa. Both of the ignition delay was 0.5 ms. The results of the high injection pressure experiments are described as follows. The NOx concentration increases as a whole. The THC concentration decreases. The smoke is produced few. It is supposed that with increasing the fuel injection pressure, the evaporation is promoted premixed burning is enhanced, and thus the change of the history of the in-cylinder content concentration described in the above occurs.

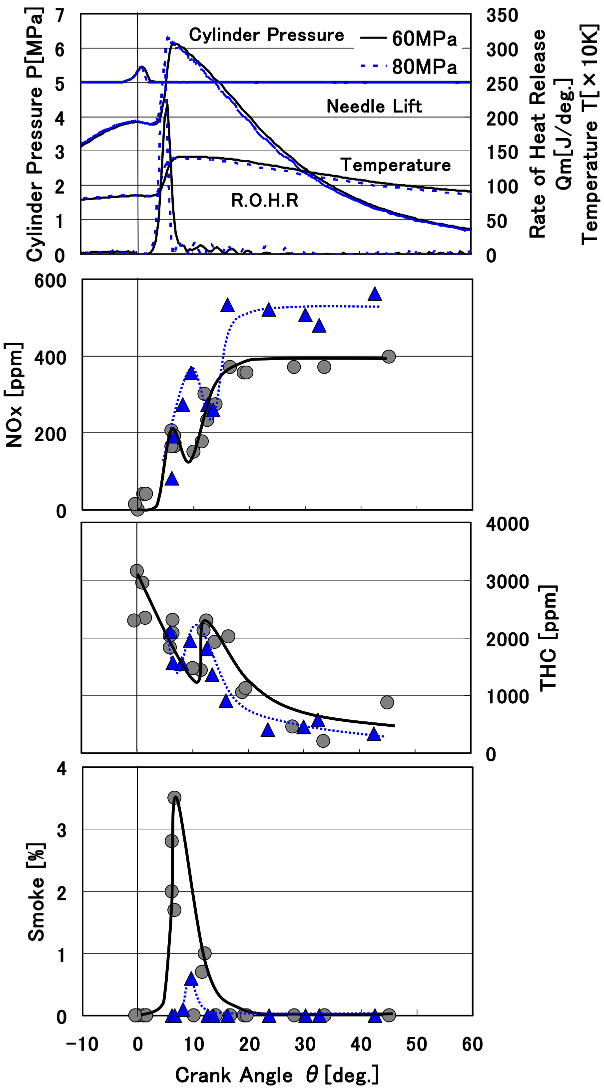


Fig. 9 Comparison of Emission Formation Process between Injection Pressure 60 MPa and 80 MPa

## 4. CONCLUSIONS

An experimental study on emission formation processes of NOx, THC and smoke in the D.I. Diesel engine was carried out by using a total in-cylinder gas sampling technique. The main results obtained are summarized as follows:

1. The total in-cylinder gas sampling technique and the device was developed. The pressure half-decay period for this experiment is 4 degree (0.83 ms) under the engine speed of 800 rpm. Such a rapid decrease of the in-cylinder pressure seems to enough quenching.
2. After the ignition, the NOx concentration forms rapidly in the beginning of the premixed burning period and then slightly decreases. After reaching the minimum in the end of the premixed burning period, the NOx concentration increases again and shows a constant value after the end of the combustion. The THC concentration suddenly decreases in the premixed burning period and then slightly increases in the diffusion burning period. After reaching the maximum, the THC concentration decreases again until the end of the combustion. The smoke concentration increases in the premixed burning period. Then it suddenly decreases and reaches the final exhaust concentration. Even if the injection pressure is changed, the tending of the crank angle variation of NOx, THC and smoke concentrations does not change.
3. By decreasing the fuel injection pressure from 60 MPa to 30 MPa, the minimum of the NOx concentration became smaller and the final concentration becomes lower. The maximum of the THC concentration becomes larger and the final concentration becomes higher. The maximum of the smoke concentration becomes larger and the final concentration is the same level as that of 60 MPa.
4. By increasing the fuel injection pressure from 60 MPa to 80 MPa, the maximum and the minimum of the NOx concentration became larger and the final concentration becomes higher. The maximum of the THC concentration becomes a little lower and the final concentration becomes lower. The maximum of the smoke concentration becomes lower and the final concentration is the same level as that of 60 MPa.

## ANKNOWLEDMENTS

The authors gratefully acknowledge the technical support of Mazda Motor Corporation. We would also thank Mr. Zhang Wu, doctor course student of University of Hiroshima, for his assistance in the preparation of this paper.

## REFERENCES

1. Aoyagi Y. et al., A gas sampling study on the formation processes of soot and NO in a DI Diesel engine, SAE Paper No. 800254 (1981).
2. Voiculescu I. A. et al., An experimental study of Diesel engine cylinder – Averaged NOx histories, SAE Paper No.78228 (1978).
3. Liu X. et al., Total cylinder sampling from a Diesel engine (Part Ⅱ), SAE Paper No.820360 (1982).
4. Hiroyasu, H. et al., Total in-cylinder sampling experiment on emission formation processes in a D.I. Diesel engine, SAE Paper No.902062 (1990).
5. Hiroyasu H. et al., Analysis of emission formation processes in a D.I. Diesel engine by total in-cylinder sampling (1st Report, effects of L/D of nozzle hole and piston cavity diameter), Trans. Japan Soc. Mech. Eng. Vol. 63, No. 606, pp. 730-735 (1997)( in Japanese with English summary).