特集 Carbon Dioxide Measuring Technology in Engine Combustion Chambers*

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The authors have developed an instrument that measures the CO_2 concentration in engine combustion chambers using the infrared absorption method.

The characteristics of this technology are as follows:

(1) Measuring can be carried out while the engine is running at 600r/min to more than 3000r/min, full load operation. (Applicable to all EGR conditions)

(2) Quick response: 2ms

(3) High linearity: ±1% Full Scale and under (FS: 10%)

(4) No aggravation is caused to the intake/exhaust performance of engines

This technology contributes to the improvement of the in-cylinder EGR system using, for instance, a variable valve-timing mechanism that is now expanding in number of applications, and also the conventional EGR system.

Key words : Carbon dioxide measuring technology, Engine combustion chambers, CO_2 concentration, EGR system

1．INTRODUCTION

Development of engines with lower emission and lower fuel consumption is carried out quite actively today. Main technologies being applied are the DI, VVT, and VVL for gasoline engines, and the common-rail system and extensive EGR for diesel engines. These technologies cause change in the amount of residual gas in combustion chambers, with or without intention. Since such change is related to the engine performance, the compression end temperature, the burning velocity, and etc., engineers are now striving to study and grasp the amount of residual gas. In order to respond to such needs, several reports have been made on the measurement of CO_2 concentration in the intake and exhaust manifolds with quick response. The CO_2 concentration was described as an index for residual gas. In this paper, the authors have developed a tool that can measure the in-cylinder CO_2 concentration directly. This system is useful in the development process of engines.

In this measurement system, the detection method uses the well-known, non-dispersive infrared (NDIR) technique. Its structure has some way to measure the in-cylinder CO_2 with quick response and high accuracy to apply to all engine operations using EGR control. The ways to satisfy both performances are as follows.

(1) Quick response

A gas sampling method that can feed a suitable amount of gas is composed, and such gas can be analyzed in a miniaturized detection zone.

(2) High accuracy

Pressure and temperature in the detection zone, whose fluctuation is a concern, are made controllable.

On this basis, the developed system has high performance; response time is 2ms or less and linearity is within ±1% Full Scale, and the system is applicable to all EGR conditions. Moreover, it is confirmed that measurement can be performed with an amount of sampling that hardly affects the combustion (below 5% of intake air volume).

The authors measured the cyclic behaviors of CO_2 concentration in combustion chambers, for instance, the cycle fluctuations, the in-cylinder distribution and transient characteristics using various engines. These evaluations proved that the developed apparatus is very useful in engine development.

2．NEEDS FOR IN-CYLINDER CO_2 MEASUREMENT

It is possible to evaluate the residual gas by measuring the in-cylinder CO_2 concentration. Residual gas represents the burnt gas that remains in the combustion chamber, and the amount of burnt gas is proportional to the CO_2 concentration.

3. DEVELOPMENT OF MEASURING APPARATUS

3.1 Specifications

A measuring apparatus was developed with the aim to achieve the targets indicated in **Table 1**.

The measuring range was assigned as 0-10%, which can cover all EGR conditions, because CO_2 concentration in the exhaust gas shows a maximum approximate of 16%, and maximum EGR of engine shows 60%. Response time is 2ms or less, which is applicable to 6000r/min engine operation. ±1%FS was assigned to ensure accuracy for both repeatability and linearity, of which performances are enough to compare with the conventional NDIR analyzer. In addition, measurements under all EGR conditions were made possible in the engine.

Table 1　Targets of measurement

<Target performances>

Measuring element		CO_2
Measuring range		0 - 10%
Response time		2ms or less (T10-90)
Accuracy	Repeatability	±1%FS.
	Linearity	±1%FS.
Measurable engine conditions		for All EGR conditions

3.2 Measuring apparatus development

3.2.1 Principle of CO_2 concentration measurement

For the measurement principle of CO_2 concentration, the NDIR technique is adopted. (See **Fig. 1**) This method makes use of the capacity of CO_2 to absorb infrared rays of 4.3μm wavelength, and the IR detector detects the rate of light-absorption according to CO_2 concentration in the sampling gas.

3.2.2 System structure and characteristics

In-cylinder CO_2 measurement system is shown in **Fig. 2**. A sample tube is connected to the cylinder, through which sample gas flows into the Detection Area. Then, CO_2 in

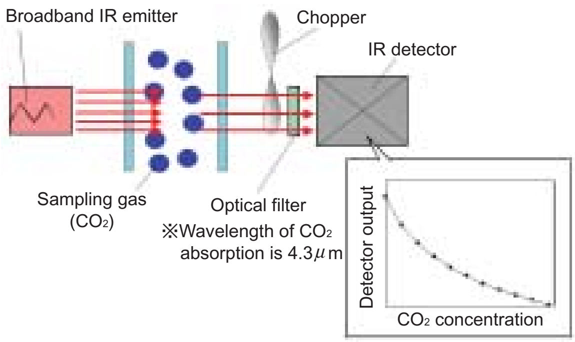


Fig. 1　Principle of CO_2 concentration measurement (NDIR technique)

such gas is measured in the Detection Area, where the afore-mentioned NDIR technique is incorporated. Measured gas is exhausted through the surge tank and the vacuum pump.

This system proves to have the following characteristics to realize quick response and high accuracy performances.

(1) Quick Response

Suitable amount of sampling gas can be obtained through feed by compression pressure and suction by the vacuum pump. Gas volume needed for measurement can be reduced owing to the small capacity of analyzing cell.

(2) High accuracy

Pressure inside the analyzing cell, whose fluctuation determines an error level, is controllable at constant pressure of 50kPa abs. Analyzing cell temperature, which is another influence factor, is controlled at 80 degrees Centigrade.

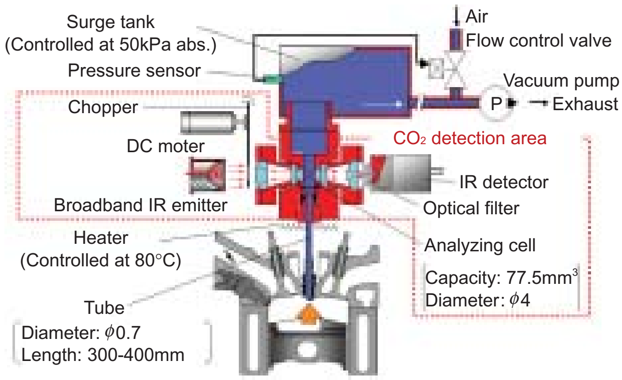


Fig. 2　System structure of the in-cylinder CO_2 measurement

3.3　The appearance of the apparatus

Figure 3 shows the outer appearance of the apparatus that was developed. It is composed of the analyzing unit, the pressure control unit, and the operation control unit.

Figure 4 shows the installation to the engine. In the proximity of the engine is installed the Analyzing Unit, which is connected from the combustion chamber via the spark plug and with a tube of 0.7 inside diameter.

Fig. 3　Appearance of the appaeatus

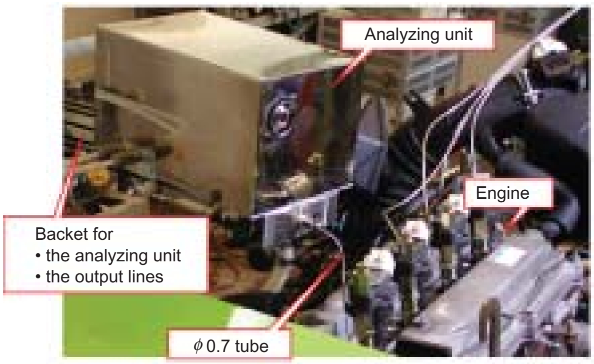


Fig. 4　Installation to the engine

3.4　Performance of the apparatus

The following are the results of performance verification, described in order.

3.4.1　Component performances

Figure 5 shows the response time result. In the state of 0.3MPa, when CO_2 concentration was switched from 0% to 9.9%, the response time between 10% and 90% was 1.7ms, which satisfied the target of 2ms and under. In this measurement existed a delay of 4ms, which was the time spent to exchange gas in the sampling tube. (The tube had a length of 400mm.) However, we judged that such delay had no influence on the measurement because accurate concentration could still be obtained despite the delay using the tube length of 400mm and under.

Figure 6 shows the results of repeatability and linearity, which are evaluation items for accuracy. As to repeatability, ±0.39% FS at ±3σ was shown after 100 measurements. As to linearity, ±0.74% FS was shown upon comparing the standard gas ranging from -10%. Both performances proved to satisfy the target figures.

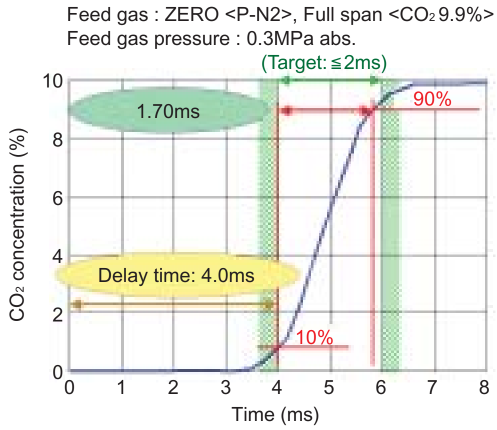


Fig. 5　Response time

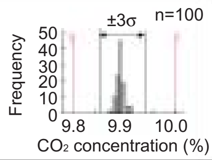
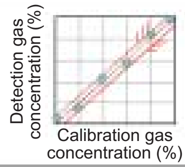
Items	Result	Performance/Target
Repeatability		±0.39%FS ±1%FS.
Linearity		±0.74%FS ±1%FS.

Fig. 6　Repeatability and linearity

3.4.2　Operating performances

The results shown below were obtained in the engine test. The specifications of the engine for evaluations are described in **Table 2**.

Table 2　Engine specifications

Configuration	V6
Total displacement	3 liter
Cylinder head	4 valves with VVT-i
Fuel injection	Electronic fuel injection

• **Output validity:**

Waveforms measured on the engine are indicated in **Fig. 7**. This is the result shown under the 3200r/min 25kPa abs., which is the most critical condition within the targeted engine operation. By the rise of in-cylinder pressure in the compression and combustion processes, the amount of sample gas increased and gas was introduced to the cell. The measured CO_2 behavior was as follows:

(1) –30 °CA - +15 °CA

CO_2 remaining in the tube sections (dead volume) was detected; the concentration behaved inconsistently.

(2) +15 °CA - +45 °CA

Residual CO_2 in the combustion chamber was detected; concentration was consistent at each cycle.

(3) +45 °CA - +180 °CA

Burnt CO_2 was detected; the concentration had risen. In addition, the timing of rise came at a delay of about 2.5ms from spark plug ignition.

On these grounds, it was confirmed that in-cylinder CO_2 concentration in residual gas detection is consistent, as measurement can still be performed even under the most critical conditions.

Validity of measurement upon engine application is confirmed by investigations on change of intake CO_2 concentration. **Figure 8** indicates the comparison between intake and in-cylinder CO_2 concentration when intake concentration increased by 1%, using external EGR. The in-cylinder concentration was at a higher level than the intake concentration because this apparatus can measure the CO_2 included in residual gas. On comparing the difference of with and without EGR, it was confirmed that the difference between intake and in-cylinder were at the same level, below ±1%FS.

• **Applicability to all EGR conditions:**

Results of application to all EGR conditions are described in **Fig. 9**. Measurement was taken on the white dots (marked with a circle), which were points measurable to determine the in-cylinder CO_2 concentration (to get constant concentrations in residual gas detection period). In addition, using another gasoline engine (2L, In-line 4), this apparatus was measurable at 4800r/min.

• **Influence of gas sampling on engine performance:**

This evaluation was carried out to see whether gas sampling has any negative impact on the engine performance.

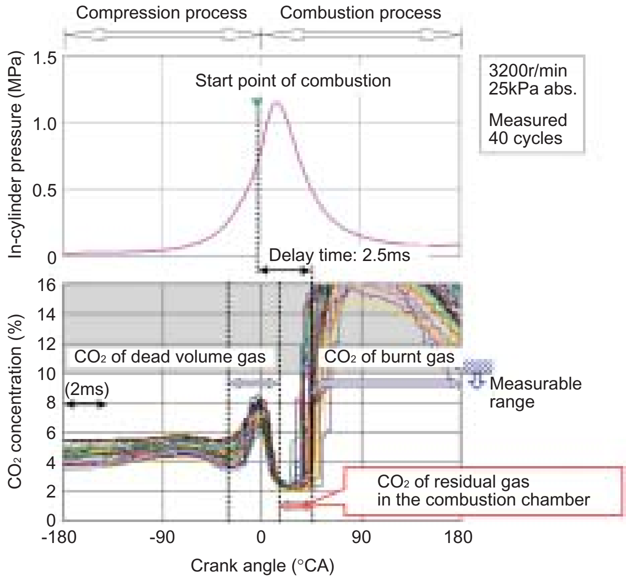


Fig. 7　Waveform of CO_2 concentration at engine operation

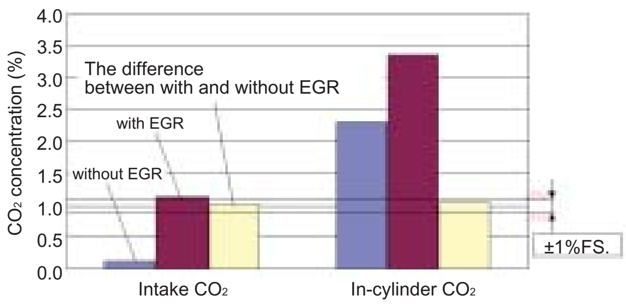


Fig. 8　Comparison with intake CO_2 concentration

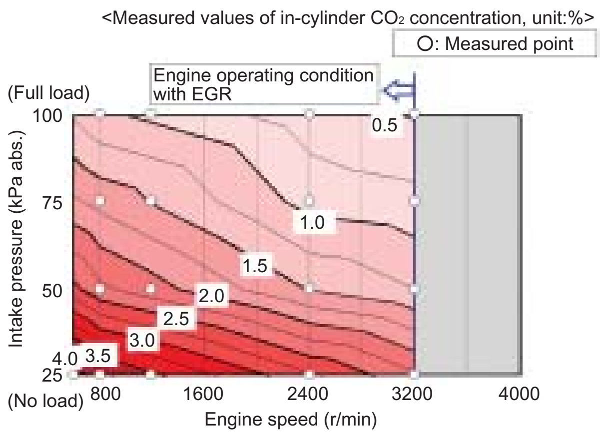


Fig. 9　Applicability to all EGR conditions

Figure 10 indicates the sampling volume, and the ratio between the sample volume and the intake air volume. Such volume ratio was almost constant, regardless of the intake pressure, and proved to be below 5% at Max.

Also, IMEP of the engine was examined comparatively, both with and without the sample. IMEP when sampling, was almost the same as when the sampling was not performed, and was included in the fluctuation (±3σ) of IMEP when there was no sampling.

Based on these results, it can be judged that gas sampling by this apparatus exerts hardly any influence on the engine performance.

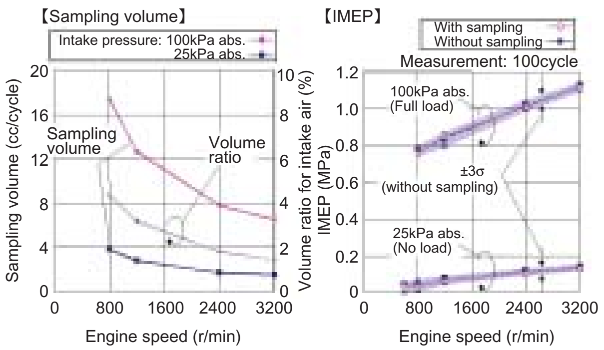


Fig. 10　Influence of gas sampling on the engine performance

4. IN-CYLINDER CO_2 MEASUREMENTS USING VARIOUS ENGINES

4.1 Characteristics under different EGR systems

The merit and demerit on engine control of two EGR systems, internal EGR and external EGR, were clarified by cyclic measurements of the in-cylinder CO_2 concentration.

The system structures of internal EGR and external EGR are shown in **Fig. 11**. The internal EGR is the method of changing valve overlap by VVT system and introducing EGR gas through the combustion chamber. The external EGR is the method of introducing burnt gas from an exhaust manifold to the intake. The features on the engine performance in two systems, which were one of the investigations, are shown in **Fig. 12**. Since the internal EGR can introduce the gas immediately after combustion, the gas temperature in the compression process can be higher than the external EGR, and THC emission can be reduced. However, as for torque fluctuations, the internal EGR is larger than the external EGR.

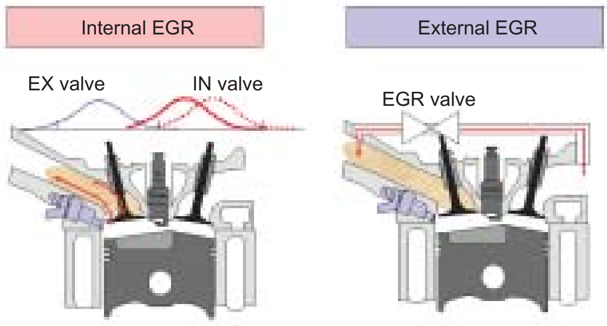


Fig. 11　The system structures of internal EGR and external EGR

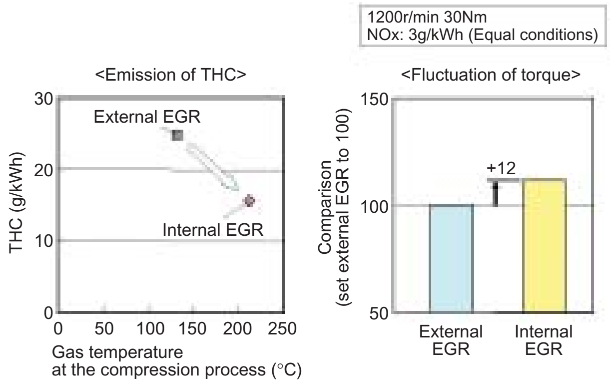


Fig. 12　Features on the engine performance

4.1.1　Cycle fluctuations at steady operation

The cycle fluctuations of the EGR rate in steady operation are shown in **Fig. 13**. The EGR rate was calculated from the lower formula, using measured CO_2 concentration in the exhaust manifold and in the combustion chamber.

$$\text{EGR rate (\%)} = \frac{\text{In-cylinder } CO_2 \text{ (\%)}}{\text{Exhaust } CO_2 \text{ (\%)}} \times 100$$

EGR rate in Internal EGR showed greater fluctuation than in External EGR. This result is in agreement with the result of torque fluctuations.

In order to clarify the factor of fluctuations, the EGR gas distribution in the combustion chamber, at the spark plug point, on intake valve side, and exhaust valve side, was investigated. (See **Fig. 14**)

With internal EGR, gas distribution was mostly seen on the intake valve side, and it was not uniform. With external EGR, it was distributed almost uniformly in the cylinder. This difference of EGR mixture in the combustion chamber is one of the factors in the EGR cycle fluctuation.

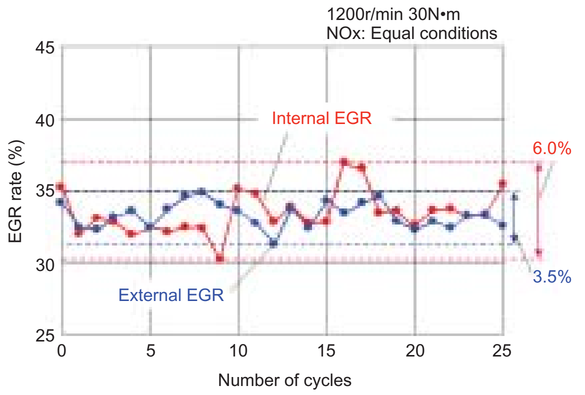


Fig. 13　Cyclic fluctuations under different EGR systems

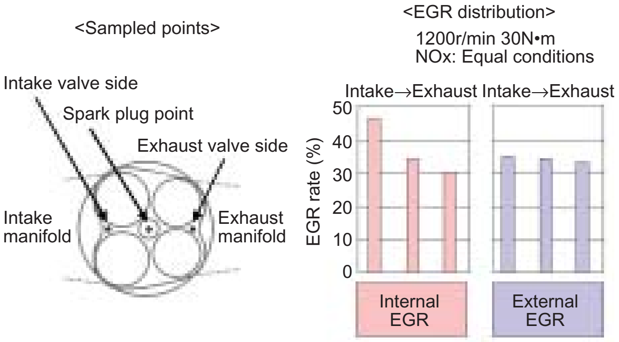


Fig. 14　EGR distribution in the combustion chamber

4.1.2　Transient characteristics

The transient characteristic of such systems is shown in **Fig. 15**. In external EGR, although the operation of EGR valve finished in 2 cycles from start, CO_2 in the combustion chamber had the delay of 3 cycles (5 cycles from start) until it reached a target condition. In internal EGR, CO_2 concentration changed as almost synchronizing with the change in valve timing, and there was no response delay. As a result, it can be said that internal EGR is more controllable than external EGR in the transient engine operation.

From the above results, the authors pinpointed subjects and achieved methods for both systems as follows:

With internal EGR, fluctuation reduction at steady operation is the subject under consideration, and a new valve timing control method or variable valve timing system, which can improve the mixing of in-cylinder EGR, needs to be devised. Moreover, with External EGR, the EGR control at transient state is the subject, and models of the delay time in EGR system need to be built including all delay factors.

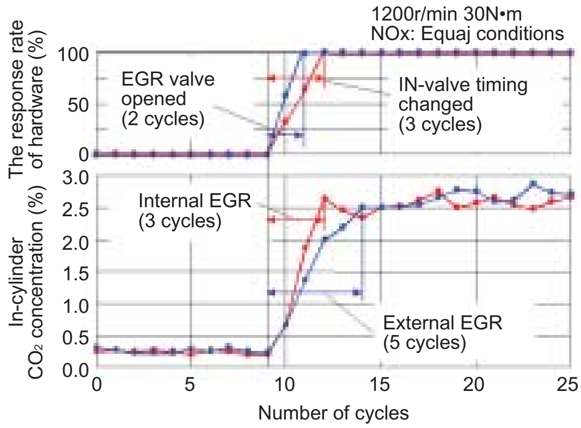


Fig. 15　Transient characteristics under different EGR systems

4.2　Future expansion of measuring capability

Measurement in the diesel engine is also possible with this apparatus, by making small adjustments. For the measurement of diesel engines, where there is much generation of particulate matters (PM), such problems can be solved by installing a filter in a part of an engine before the cell. The filter is of quartz with suitable pore size enough to trap the PM. Its construction, which is aimed only at PM removal, is simple, compact (effective-diameter, f10) and yet able to suppress the increase of dead volume as much as possible.

Result from the measurement of EGR rate at transient operation using the diesel engine (of 3L, 4-cylinder with common-rail system and turbo-charger) is described. This measurement on the CO_2 concentration made use of two apparatuses that were developed, of which one was used for in-cylinder measurement and the other for measurement in the exhaust manifold.　(See **Fig. 16**)

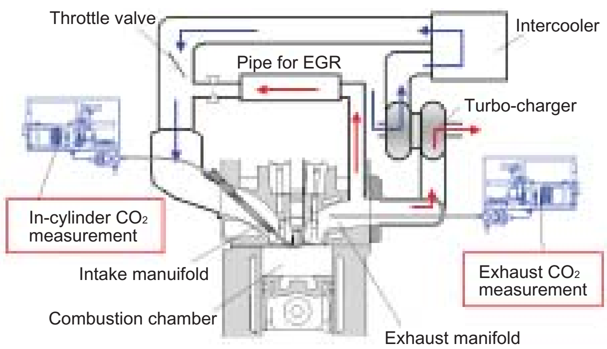


Fig. 16　The system structures of cyclic EGR measurement

Figure 17 shows the cyclic behaviors of the EGR rate and other elements in connection with the engine condition that are observed along with the gradual change in the amount of injection over 10 cycles. Likewise, those measurement results from constant operation at each cycle condition, which was usually used for engine matching, are represented by the dotted line.

Different EGR behaviors were observed under transient and constant operations, caused by varying behaviors of the in-cylinder CO_2 concentration. This phenomenon can be explained by changes in boost pressure and the exhaust pressure. Boost pressure and exhaust pressure under transient operation show different behaviors from when constant operation takes place. For this reason, the amount of EGR gas flow increased due to larger pressure difference between intake and exhaust, which determines the amount of EGR.

Based on the above result, in order to control EGR with accuracy by constant operations, conformity cannot be adequately gained, and thus a control method that includes the transient state would be necessary for diesel engines as well as for gasoline engines.

In this way, developed apparatus can be applied to almost all engines, to gasoline and diesel, and can make the studies of parameter and matching of engine easy because it can evaluate the in-cylinder EGR rate directly.

5. CONCLUSION

The authors have developed an instrument that measures the CO_2 concentration in engine combustion chambers using the infrared absorption method.

The developed apparatus, which was composed of two essential elements as to sample suitable amount of gas and to control pressure and temperature in the detection zone, realized high performances as the following.

(1) Quick response is 2ms or less

(2) High linearity is ±1% Full Scale or less (FS: 10%)

This apparatus proved that it could be applied in all EGR conditions. Furthermore, it was verified that gas sampling has any negative impact on the engine performance.

Using this developed system, the authors measured the cyclic behaviors of CO_2 concentration in combustion chambers, cycle fluctuations, the in-cylinder distribution and the transient characteristics, and also in gasoline and diesel engines. These evaluations proved that the developed apparatus is very useful in the engine development process.

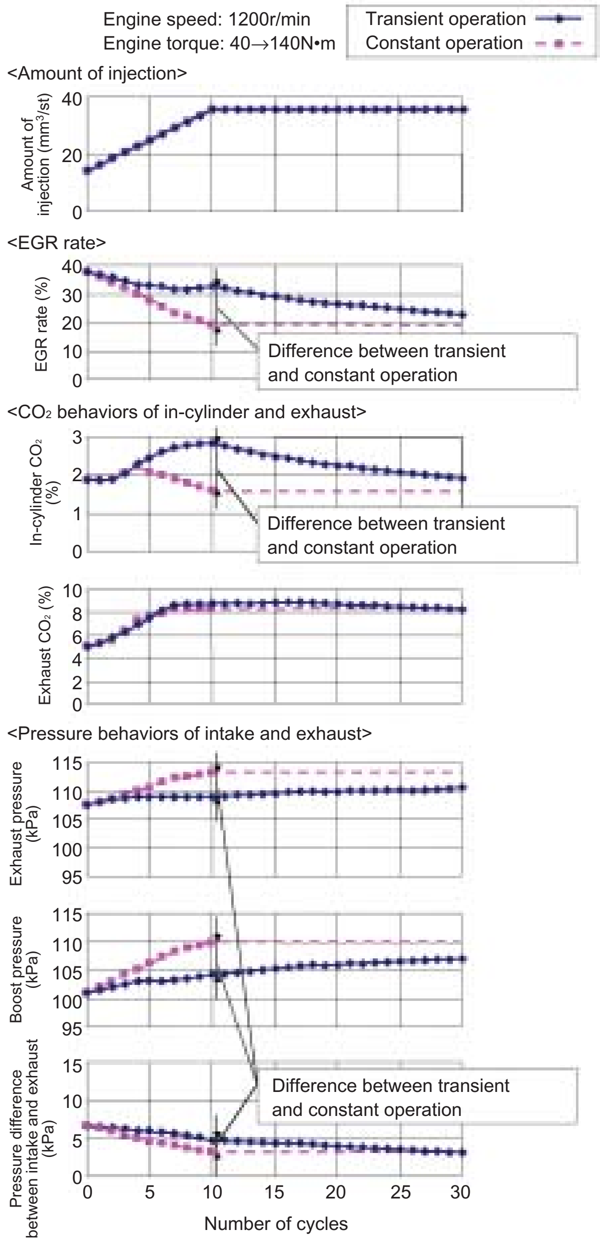


Fig. 17　Transient characterstics under the diesel engine

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