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MEASUREMENT OF CO_2 CONCENTRATION AND A/F RATIO USING FAST NDIR ANALYZER ON TRANSIENT CONDITION OF SI ENGINE

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ABSTRACT–A fast response CO_2 analyzer has been developed to study transient characteristics on an SI engine. The analyzer has the delay time of 4.5 ms and time constant of 2.8 ms, which is fast enough to measure CO_2 concentration on a transient condition. Wide range of A/F (Air/Fuel) ratio can be estimated using the analyzer with an additional switch type oxygen sensor. The results of measurement of CO_2 concentration and A/F ratio on a transient condition including rapid acceleration/deceleration and EGR (Ehxaust Gas Recirculation) on/off are presented and compared with a commercial exhaust gas analyzer and UEGO (Universial Exhaust Gas Oxyzen) sensor.

KEY WORDS : FRNDIR (Fast Response NDIR), NDIR (Non-Dispersive Infrared), CO_2 concentration, A/F ratio, Transient condition

NOMENCLATURE

I : intensity (V)
I_0 : initial intensity (V)
c : concentration of CO_2 (%)
α : absorption efficiency (constant)
L : optical path length (constant)
ϕ : fuel/air equivalence ratio
φ : molar N/O ratio of fuel
K : equilibrium constant
y : molar H/C ratio of the fuel
n_i : moles of species i per mole O_2 reactant

1. INTRODUCTION

As emission regulation has become severe, more and more various researches on the development of a clean engine are being performed. Reducing emission at transient operating condition of an engine is one of the big issues for the engine researches. Fast measurement of CO_2 gas can be a useful tool for investigating transient behavior of the engine. However, a conventional CO_2 analyzer using photo acoustic effect is not fast enough to measure CO_2 concentration in real time due to mechanical limits including rotation speed of mechanical chopper. Since a PbSe type semiconductor and a exhaust gas sampling module have been devolped, fast measurements of CO_2 concentration have been tried by many researchers reducing the response time less than 10 ms (Steula *et al.*, 1999, 2000). It is called NDIR (Non-Dispersive Infrared) method.

On the other hand, A/F ratio measurement using oxygen sensor is also important for stoichoimetric fuel control which is necessary to maximize the efficiency of catalytic converter. UEGO (Universal Exhaust Gas Oxygen) sensor is widely used for researches but it has very long time delay more than 200 ms. A/F ratio is closely related to CO_2 concentration of exhaust gas, so fast measurement of A/F ratio is also possible by using NDIR method only if switching type oxygen sensor is used together. In this study, a NDIR is developed to measure CO_2 concentration and A/F ratio on transient condition and verified by comparing with a conventional analyzer. A sampling module is designed for fast sampling of exhaust gas and applied to the analyzer. Fast responsiveness of FRNDIR analyzer and applicability to engine, especially on transient condition, are confirmed.

2. FRNDIR ANALYZER DESCRIPTION

2.1. Measurement Part

2.1.1. NDIR method

NDIR method has been generally used to analyze CO_2 concentration. The principle is based on the absorption rate of infra-red radiation by CO_2 (Adachi *et al.*, 1992). That is, the system detects the change of transmittance of mixture gas including CO_2 at the strongest C-O vibrational-rotational absorption band, which is centered

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around the wavelength of 4.28 μm. The amount of radiation transmitted at the wavelength is given by Beer-Lambert law.

$$I = I_0 \times e^{-\alpha \times c \times L} \quad (1)$$

From equation (1), the sensitivity of I to concentration changes is given by :

$$\frac{dI/I}{dc/c} = -\alpha \times c \times L \quad (2)$$

As known from equation (2), the intensity change of infra-red is generated by CO_2 concentration change. Therefore, if the voltage due to intensity is measured at the detector, concentration is obtained from the voltage.

2.1.2. Emitter and detector

The detector and the emitter are installed at both sides of optical path. The concentration analysis using NDIR method depends on small voltage of detector changed by CO_2 concentration. Therefore, the signal distortion caused by noise and drift must be considered. In order to increase S/N ratio, the infrared source is normally modulated by optical chopper. In this study, the light source of emitter is modulated electrically at a frequency of 1 kH by chopping emitter power (on/off). The detecting part includes a PbSe type photoconductor with response time below 30 ms at infra-red absorption wavelength. In order to keep the sensitivity and to minimize drift due to the temperature change, a thermoelectric cooler with a thermistor is installed at the detector and the emitter. Using these devices, temperature is controlled under 20°C.

2.2. Sampling Module

The development of a fast sampling module is essential for the fast analyzer. The sampling module adopted for this system has been designed with response time below 10 ms using previous researches (Kim *et al.*, 2003; Kim, 2004). The schematic of the fast response CO_2 sensor is shown in Figure 1. The sampling module is composed of the capillary part (sampling tube, NDIR tube) and the expansion part (expansion tube, optical cell), and CP chamber to control the pressure of expansion tube constant. The capillary part includes the sampling tube that picks up exhaust gas from the engine and the NDIR tube that is maintaining the pressure drop between the expansion tube and the optical cell constant in order for constant mass flow rate to the optical cell.

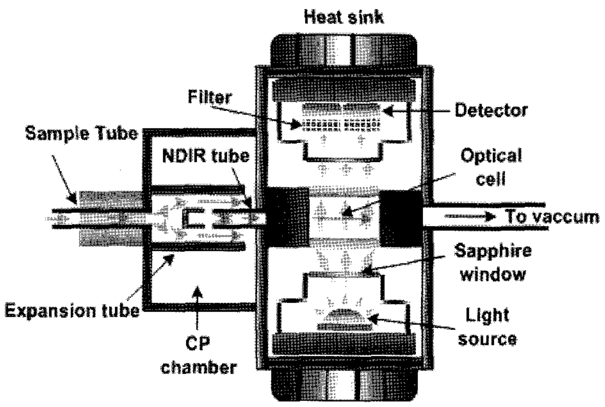

Figure 1. Schematic of a FRNDIR.

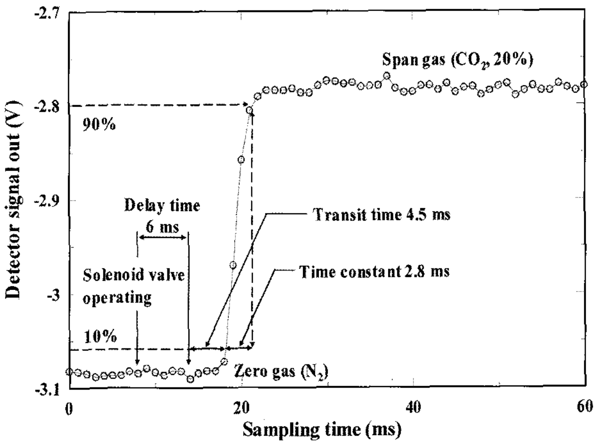

Figure 2. Response of the sensor with sudden change of CO_2 concentration.

The expansion part includes the expansion tube which is inducing constant pressure at the inlet of the NDIR tube and reducing the speed of flow developed at the sampling tube rapidly. The optical cell is for measuring the CO_2 concentration. The CP chamber controls the pressure of expansion tube to keep the pressure at inlet of the NDIR tube constant.

2.3. Response Time

Response time includes transit time and time constant. Response characteristics acquired from the experiment are shown in Figure 2. When the solenoid opens the valve, the CO_2 concentration changes from the zero gas (N_2, 99.999%) to the span gas (CO_2, 20%). The solenoid valve has the delay time of about 6ms and the transit time of the sensor means the time elapsed from valve opening point to 10% changing point of the detector output. The time constant is defined as the time elapsed when the output of the sensor changes from 10% to 90%.

3. THEORETICAL CONSIDERATION

A/F Estimation using CO_2 Concentration

The composition of the burned gas fraction can be calculated from the unburned mixture as follows

Table 1. CO_2 mole normalized by mole of O_2 reactant.

	n_{CO_2}, moles/mole O_2 reactant	
	$\phi \le 1$	$\phi \ge 1$
CO_2	$\varepsilon\phi$	$\varepsilon\phi - C$
SUM	$(1-\varepsilon)\phi+1+\varphi$	$(2-\varepsilon)\phi+\varphi$

$$CH_y + \frac{\left(1+\frac{y}{4}\right)}{\phi} \cdot (O_2 + \varphi N_2) \rightarrow n_{CO_2}CO_2 + \quad (4)$$

$$n_{H_2O}H_2O + n_{CO}CO + n_{H_2}H_2 + n_{O_2}O_2 + n_{N_2}N_2$$

where, $\varphi = 3.772$ for air, $y = 1.87$ for gasoline.
This combustion equation can be rearranged per mole of O_2 reactant as Table 1.
C is acquired by using equation (5)

$$(K-1)C^2 - C\{K[2(\phi-1)+\varepsilon\phi]+2(1-\varepsilon\phi)\}+2K\varepsilon\phi(\phi-1)=0 \quad (5)$$

Where, K=3.5, $\varepsilon = 4/(4+y)$

From Table 1, if the condition of mixture is lean, the mole fraction of CO_2 among exhaust gases can be arranged as equation (6)

$$[CO_2]_{Lean} = \frac{2(1-\varepsilon\phi)+C}{(2-\varepsilon)\phi+\varphi} \times 100[\%] \quad (6)$$

Also, if the condition of mixture is rich, mole fraction of CO_2 is acquired from equation (7)

$$[CO_2]_{Rich} = \frac{2(1-\varepsilon)\phi}{(1-\varepsilon)\phi+1+\varphi} \times 100[\%] \quad (7)$$

As shown in Figure 3, A/F ratio can be estimated using

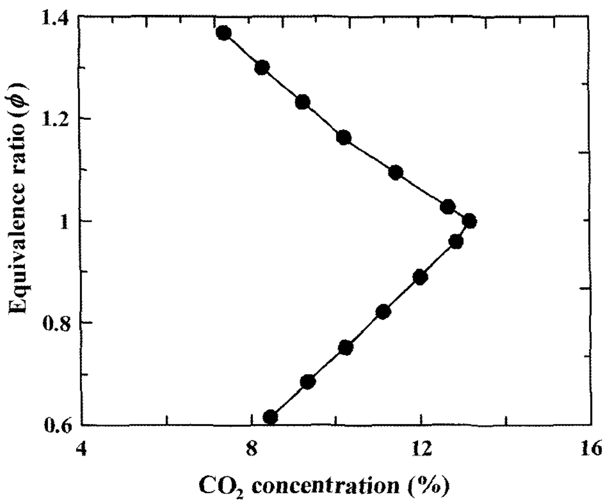

Figure 3. Equivalence ratio corresponding to CO_2 concentration.

the measured CO_2 concentration and Lean/Rich determination at that point.

4. EXPERIMENT EQIUPMENT AND METHOD

4.1. Experimental Equipment

Equipment for the experiment is shown in Figure 4 and specifications of the engine are shown in Table 2. FRNDIR analyzer is installed at the exhaust manifold to measure the CO_2 concentration in real time, and HORIBA MEXA- 110λ and UEGO sensor are used to measure λ. Also, HORIBA MEXA–8120 (Exhaust gas analyzer) is used to verify CO_2 concentration measured by the developed analyzer. In order to measure A/F ratio using CO_2 concentration, additional lean/rich information is necessary which is acquired using a switch type O_2 sensor. EC type dynamometer is used to control the engine speed and load during rapid acceleration and rapid deceleration.

EGR gas line for connecting the intake and exhaust manifolds is installed to control EGR rate intentionally, and the quantity of exhaust gas flowing into the intake

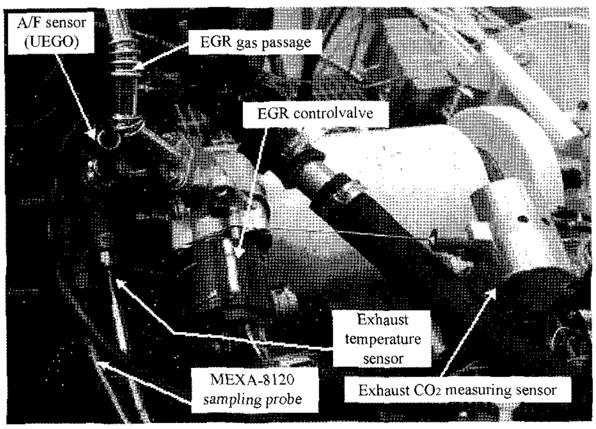

Figure 4. Installation of fast response NDIR analyzer for measuring CO_2 concentration at exhaust manifold.

Table 2. Specification of test engine.

Engine			SOHC, 1495cc
Number of cylinder			4
Bore (mm) × Stroke (mm)			75.5 × 83.5
Compression ratio			10.0
Valve timing	Intake	Open	12° (BTDC)
		Close	52° (ATDC)
	Exhaust	Open	52° (BBDC)
		Close	12° (ATDC)

manifold is controlled by EGR valve.

LabView instrument of NI Co. is used for data acquisition and the signal of MEXA-8120 is acquired with PUMA instrument of AVL Co.

4.2. Experimental Method

The experiment is performed on transient condition including rapid acceleration, rapid deceleration, and EGR on/off. Tests for rapid acceleration and deceleration are performed on the following conditions using dynamometer. Engine operates at 1500 and 2000 rpm, and load is changed from 10 Nm to 60 Nm and 70 Nm for each condition. For above condition, the change of A/F ratio and CO_2 concentration are measured simultaneously. Performance of the new analyzer is verified through the comparison with a commercial device, Horiba MEXA-8120, and the A/F ratio estimated from CO_2 concentration and Lean/Rich signal of O_2 sensor is also compared with UEGO sensor.

EGR valve is installed to control EGR rate of the engine. The valve is controlled by PWM (Pulse Width Modulation) method. Opening range of the valve is calibrated according to the duty, and the test is performed when the duty is 92%. Data analysis is conducted by using the same method which is used for rapid acceleration and deceleration.

5. RESULTS AND DISCUSSION

In the case of load change at constant speed, CO_2 concentrations measured by FRNDIR analyzer and MEXA-8120 are plotted in Figure 5. The engine speed is 1500 rpm and bmep change is from 0.84 bar to 5.0 bar. The measurement of MEXA-8120 shows time delay about 4s while FRNDIR response very quickly to the load change. For the sensitivity, FRNDIR can detect the subtle change

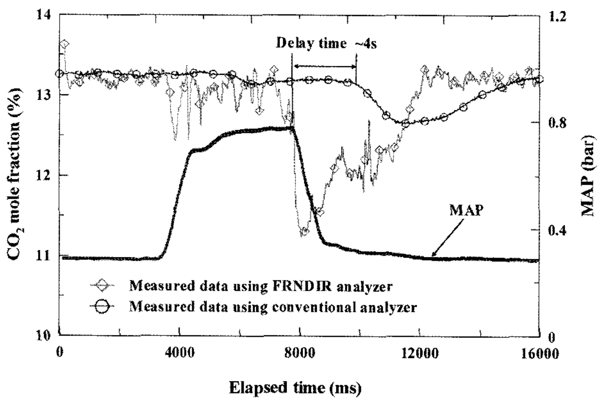

Figure 5. Comparison of CO_2 concentration measured with FRNDIR and MEXA-8120 in case of rapid throttling at 1500 rpm and bmep = 0.84 bar → 5.0 bar.

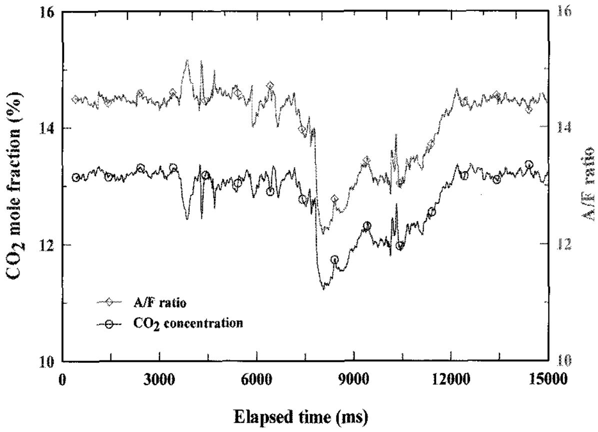

Figure 6. A/F ratio estimated from CO_2 concentration.

of concentration, but MEXA-8120 shows small amount of change due to the time delay. The A/F estimation using CO_2 concentraion is shown in Figure 6. Lean/rich information is needed for the complete A/F estimation which is given by the switch type oxygen sensor as mentioned above.

A/F ratio measured using CO_2 concentration is compared with commercial UEGO sensor in transient conditions. Figure 7 and Figure 8 show the change of A/F ratio at rapid throttling where the engine speed is kept constant, 1500 rpm and 2000 rpm but bmep is changing from 0.84 bar to 5.0 bar and from 0.84 bar to 5.88 bar respectively. The A/F ratio becomes lean in very short

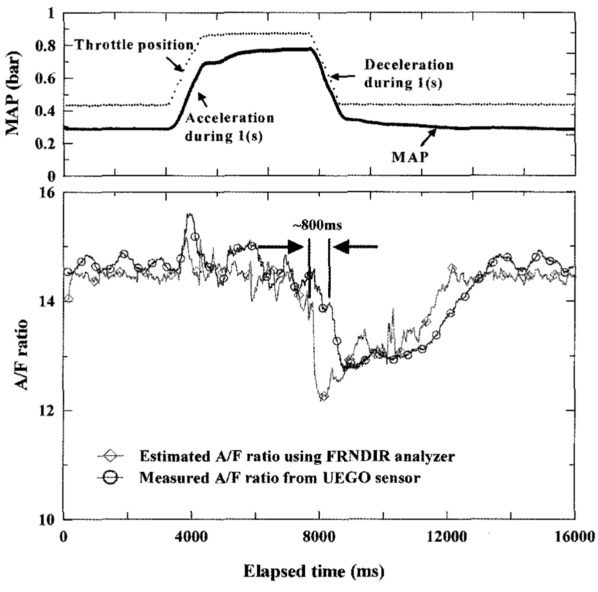

Figure 7. Comparison of A/F ratio measured with FRNDIR and UEGO sensor in case of rapid throttling at 1500 rpm and bmep = 0.84 bar → 5.0 bar.

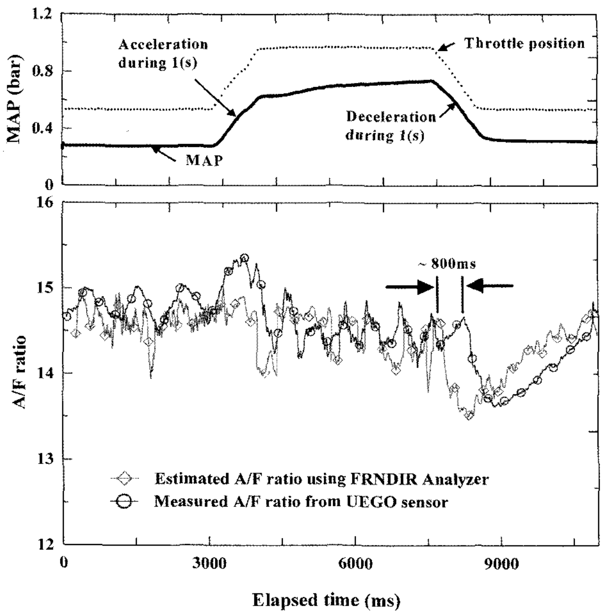

Figure 8. Comparison of A/F ratio measured with FRNDIR and UEGO sensor in case of rapid throttling at 2000 rpm and bmep = 0.84 bar → 5.88 bar.

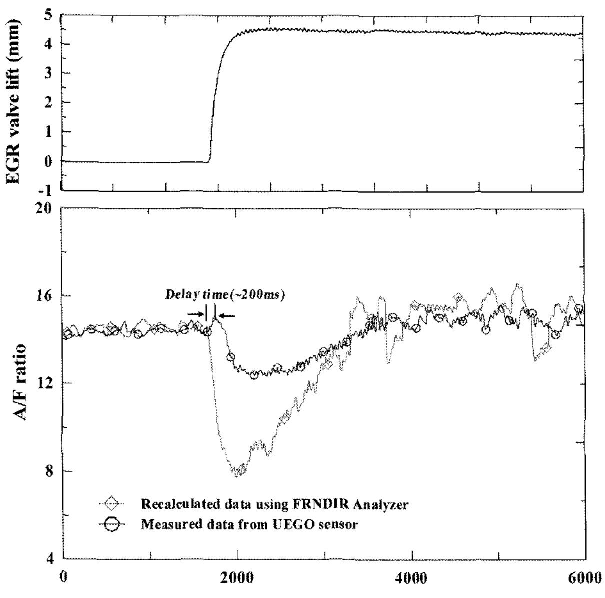

Figure 9. Comparison of A/F ratio measured with FRNDIR and UEGO sensor when EGR valve opening at 2500 rpm, bmep = 0.84 bar → 5.0 bar.

duration at the early stage of throttle opening and is getting rich as throttle is closing again. This is typical phenomenon found with sudden change of throttle position (Heywood, 1986; Kwark *et al.*, 2003).

A/F ratio measured using FRNDIR is changing faster than UEGO which is known to have time delay about 200 ms in steady state. The result shows about 800 ms time defference between the output signals of FRNDIR and UEGO. In addition, the amount of A/F change is larger for FRNDIR than UEGO due to this time delay.

A/F ratio converges to the stoichiometric value immediately after rapid acceleration. But after rapid deceleration, there is time delay of about 4s until A/F ratio converges to the stoichiometric value. This is due to the inflow of fuel wetting on intake port, judgment delay of A/F ratio measured by O_2 sensor, and time delay during determining rapid deceleration. FRNDIR analyzer can be used in order to improve unstable engine control on transient condition, since A/F ratio can be measured at least 200 ms faster than that obtained from UEGO sensor. Figure 8 shows the result of 2000 rpm, which has the same characteristic as the case of 1500 rpm.

Figure 9 shows measured A/F ratio on sudden opening of the EGR valve with the engine operated on steady state. If EGR gas flows into the intake manifold, the engine operates in rich condition due to the decrease of charging efficiency (Green, 2000; Hall and Zuzek, 2000). A/F ratio acquired from NDIR analyzer has changed 1–2 cycles after the EGR valve is opened, but A/F ratio measured by UEGO sensor has changed after delay time of about 200ms like rapid acceleration and deceleration.

The study on the engine transient control is one of the big issues for enhancement of engine performance and emission reduction. The FRNDIR analyzer proposed in this study has fast dynamic response enough to be applied for real time measurement of exhause gas and A/F ratio and is expected to improve the engine characteristics in transient condition.

6. CONCLUSIONS

In this study, a FRNDIR analyzer is developed to understand the characteristic of the engine on transient condition, and CO_2 concentration measured by the developed analyzer on transient condition is compared with the result of the commercial exhaust gas analyzer. Also, real time A/F ratio on transient condition is estimated by using CO_2 concentration and on/off signal of switch type O_2 sensor, and the result is compared with the value measured by UEGO sensor. Conclusions acquired through these processes are as follow.

(1) The FRNDIR analyzer developed in this study has the transit time of 4.5 ms which is needed for the exhaust gas to get into the optical cell, and the time constant of 2.8 ms which comes from the response time of the IR sensor.

(2) A/F ratio can be estimated by the CO_2 concentration and lean/rich distinction. In that case, the measurement of A/F ratio has 200 ms–800 ms faster

response time than that measured by a typical UEGO sensor.

(3) The FRNDIR is successfully applied to the operating engine detecting CO_2 concentration and A/F ratio in transient condition including sudden acceleration and deceleration, and EGR on/off.

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