Cycle Resolved NO Emissions and Its Relation with Combustion Chamber Pressure in an S.I. Engine with Fast Response NO Analyzer

Jung-Min Sung, Hyun-Woo Kim, Kyung-Hwan Lee*
Division of Mechanical and Automotive Engineering, Sunchon National University, 315 Meagok Dong, Suncheon Jeonnam 540-742, Korea

A fast response NO analyzer was applied to investigate the relation between cycle-by-cycle NO emissions and combustion chamber pressure. NO emissions were sampled at an isolated exhaust manifold of 4-stroke spark ignition engine to avoid the interference of exhaust gas from other cylinders. The linear correlation analysis was performed with collected data of NO emissions and combustion chamber pressure with respect to the various air-fuel mixture ratios and engine loads. The sampled data sets were obtained during 200 cycles at each operating condition. The results showed that there was a typical pattern in NO emissions from an exhaust port through a cycle. It was possible to set a block of crank angle in which the linear correlation coefficient between NO emissions and combustion chamber pressure was high. As the engine load increased, NO emissions were more dependent on combustion chamber pressure after TDC. It was also analyzed that the correlation between two parameters with respect to air-fuel mixture ratio tended to increase as mixture went leaner. Furthermore, this correlation coefficient for the mixture near the lean limit seemed to be kept high even though combustion was unstable.

Key Words: Linear Correlation Coefficient, Fast Response NO Analyzer, NO Emissions, Equivalence Ratio

1. Introduction

As the air pollution has been becoming worse gradually, the automotive emission regulations have been stricter continually to reduce exhaust emissions of pollutants. Various researches on emission reduction are spread in correspondence to the ever more stringent limits. Especially, since NOx is an effective pollutant in ozone formation and, in result, is a major source of photochemical smog, there have been so many researches on the production mechanism and reduction technology of NOx (Turns, 1999; Heywood, 1973; Aoyoma et al, 1990). Therefore, the reduction of NOx emissions is one of the most important issues in development of internal combustion engine. Generally, it is well-known that the NOx emissions are influenced by oxygen concentration and flame temperature (Ball et al, 1999; Takagi et al, 1998). The flame temperature gets into maximum in condition that air-fuel ratio is some richer than the stoichiometry, but the lack of the oxygen makes NOx emissions can not reach maximum value in this region. On the contrary, NOx emissions show maximum value by enough oxygen in some leaner air-fuel mixture ratio than the stoichiometry. If air-fuel mixture ratio is richer or leaner than the mixture ratio of maximum NOx emissions, NOx emissions are decreased. Especially, in case of lean burn engine and G.D.I. (Gasoline Direct Injection) engine, there is a

* Corresponding Author,
E-mail: khlee@sunchon.ac.kr
TEL: +82-61-750-3822; **FAX**: +82-61-750-3820
Division of Mechanical and Automotive Engineering, Sunchon National University, 315 Meagok Dong, Suncheon Jeonnam 540-742, Korea. (Manuscript **Received** January 24, 2003; **Revised** June 26, 2003)

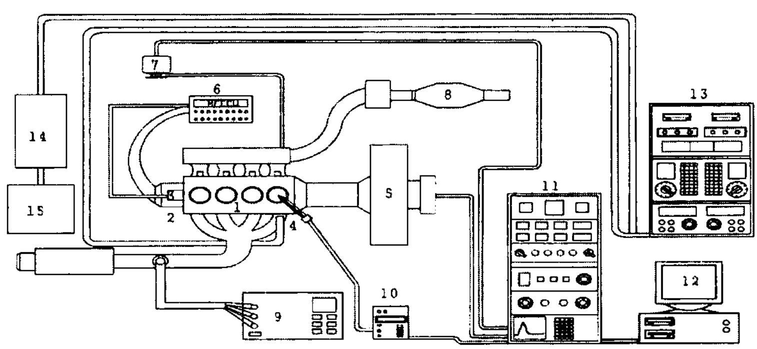
tendency that the stratified and richer air-fuel mixture distribution at the region adjacent to spark plug produces more NOx emissions than lean condition of port-injection type engine which has a relatively more homogeneous air-fuel mixture distribution (Reavel et al., 1997). Therefore, it is necessary to match the NOx reduction technology according to engine type in combustion system in order to obtain a desirable result since the pattern of NOx emissions is dependent on engine characteristics.

As it is well known that NOx emissions are the results of combustion phenomena such as flame temperature or combustion chamber pressure and NOx emissions and combustion chamber pressure are influenced by engine load or air-fuel mixture ratio, it is interesting to catch hold of the relation between NO emissions and combustion chamber pressure as two different results of combustion at each cycle. In this study, combustion chamber pressure at each cycle was measured and the temporal NO emissions trace was collected at different air-fuel ratio and engine load conditions using a fast response NO analyzer installed at an isolated exhaust manifold of 4 stroke S.I. engine to avoid the interference of exhaust gas from other cylinders. Through this measurement, the level and cycle-by-cycle variation in NO emissions for each operating condition were attempted to analyze and the relation between NO emissions and the combustion chamber pressure was investigated.

2. Experiment

2.1 Experimental apparatus

Even under the steady-state operation, a crank angle time scale measurement was required to detect NO emissions to obtain in cycle-by-cycle based NO level. Figure 1 presents a schematic diagram of experimental apparatus. A fuelling & spark timing controller was applied to adjust the spark timing, fuel injection timing, and amount of fuel injected for each operating condition. A piezo-electric type pressure transducer (Kistler 6053C60) was installed at the cylinder head of 4^{th} cylinder to measure the combustion chamber pressure. An optical encoder with 0.1° CA (Crank Angle) resolution was also applied to sample data with an enough resolution. An exhaust emission analyzer (Horiba, MEXA-554JK) was used to measure exhaust emissions and air-fuel mixture ratio, and a fast response NO analyzer (Cambustion, LHC500) was applied to sample the cycle-by-cycle NO emissions in the exhaust manifold. For NO sampling, a sampling probe was installed 15 mm from 4^{th} cylinder exhaust valve to reduce the delay in NO sampling. The pressure data and NO emissions trace were collected by a data acquisition system simultaneously. A schematic diagram of NO emissions measurement system is shown in Fig. 2. The CP (Constant Pressure)



1. Engine 2. ECU 3. Encoder 4. Pressure-Sensor 5. Dynamometer 6. Fuelling & Spark-timing Controller 7. Throttle Actuator 8. Laminar flow meter 9. Exhaust Gas analyzer 10. Charge amplifier 11. Dynamometer controller & Data acquisition system 12. Computer 13. Fast NO analyser 14. Ozone-generator 15. Vacuum pump

Fig. 1 Schematic diagram of experimental apparatus

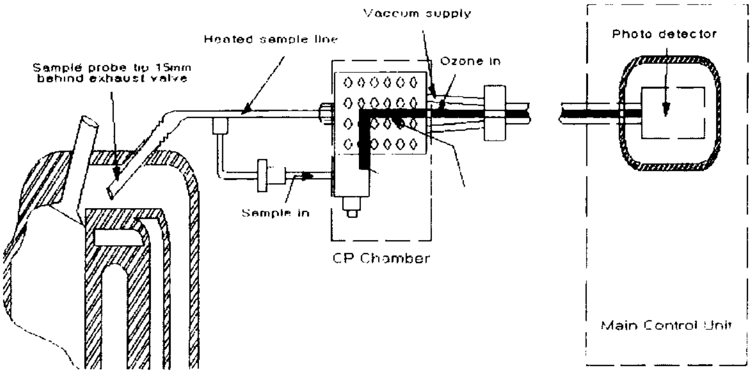


Fig. 2 Measurement system of NO emissions

Table 1 Specification of fast response NO analyzer

Sensitivity	0.1 mV/ppm to 50 mV/ppm in 9 ranges as NO at an step sample flow of 50 cc/min
Linearity	±1% of full scale to 5000 ppm NO ±2% of full scale to 10000 ppm NO
Noise	rms. <1% of mean for 1000 ppm NO, gain 20
Response time	10-90%~4 ms with a standard sampling configuration

Table 2 Engine specification

Bore (mm)	75.5
Stroke (mm)	83.5
Connecting rod length (mm)	131.0
Engine displacement (cc)	1495
Compression ratio	9.5 : 1
Valve timing (°CA)	5/35 43/5

chamber has a function that it reduces the influence of pressure variation due to cycle-by-cycle variation of combustion. NO emissions are measured by the photo detector that detects the light from the reaction between NO and ozone produced in the ozone generator. Through optical fiber band the NO in the sampled exhaust gas flow and ozone join at the reaction chamber in CP chamber, then the chemilumine-scent reaction mechanism takes place. Table 1 shows the specification of fast response NO analyzer which has 4 ms response time enough to measure the cycle-by-cycle NO emissions. The engine used in this study was a 4-stroke DOHC (Double Over Head Camshaft) spark ignition engine which had a semi-wedge type combustion chamber with 4 valves. More detailed specification is presented in Table 2.

2.2 Experiment and data analysis

The engine was operated under the condition that the coolant and oil temperature were approximately 85℃ and 90℃, respectively, after engine warmed-up fully. The MBT (Minimum spark timing advance for best torque) was applied to all test conditions. The traces of combustion chamber pressure and NO emissions were collected for continuous 200 cycles with 1°CA interval considering cycle-by-cycle variation.

The measurements were performed with the change of two variables ; engine load and air-fuel ratio. The engine load was changed from 2 to 5 bar in BMEP (Brake Mean Effective Pressure) at 1800 rpm with stoichiometric condition. The air-fuel mixture ratio was also varied from stoichiometry to 18.5 : 1 at 1800 rpm and 2bar BMEP condition. With those data the correlation between NO emissions and combustion pressure was analyzed.

The investigation of the relation between NO emissions and combustion chamber pressure was performed using the regressive analysis. When two variables have been measured on the same set of individuals, a simple and effective way of describing them is the scatter diagram. From the scatter diagram it can be seen how these two variables are related. Linear correlation coefficient explains how 2 variables, X and Y, are related. If X and Y were defined as

X_i : X on the i-th individual for i=1, 2, ⋯, n.
Y_i : Y on the i-th individual for i=1, 2, ⋯, n.

The covariance of X and Y for this set of data could be calculated as following.

$$Covar(X, Y)=\frac{\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})}{n-1} \quad (1)$$

Where $\bar{X}$: mean value of X, $\bar{Y}$: mean value of Y
The standard deviation for X, V(X) is given as follows :

$$V(X)=\left[\frac{\sum(X_i-\bar{X})^2}{n-1}\right]^{\frac{1}{2}} \quad (2)$$

Therefore, the correlation coefficient between X and Y usually denoted by R, where

$$R=\frac{Covar(X, Y)}{V(X)V(Y)}=\frac{\sum(Xi-\bar{X})(Yi-\bar{Y})}{[\sum(Xi-\bar{X})^2\sum(Yi-\bar{Y})^2]^{\frac{1}{2}}} \quad (3)$$

For more information on linear correlation coefficient, reference will be helpful (Dunn et al, 1997).

3. Results and Discussion

With a fast response NO analyzer and a combustion analyzer in the experimental set-up as shown in Fig. 2, the cycle-by-cycle NO emissions and combustion pressure were measured simultaneously for 200 cycles at each operating condition. Figure 3 presents an example of temporal NO emissions traces measured at 1800 rpm and 2.0 bar BMEP condition with fast response NO analyzer during 200 cycles, which shows serious cycle-by-cycle variation in NO emission level. The crank angle count is started from bottom dead center of compression stroke of 4^{th} cylinder. The profile of NO emissions traces with respect to crank angle shows a certain tendency in this figure even though there are some scattered ranges. To find out the representative temporal trace of NO emissions with the fluctuation through a 4-stroke cycle, all NO traces during 200 cycles were averaged. The traces of averaged NO emissions and combustion chamber pressures are shown in Fig. 4. In this figure, it shows that there is a timing difference between EVO(Exhaust Valve Opening) timing and abrupt rising point of NO emissions. This difference can be considered as a delay time including the passing time of exhaust gas to reaction chamber through sampling probe and the response delay of fast response NO analyzer. In this experiment, this delay

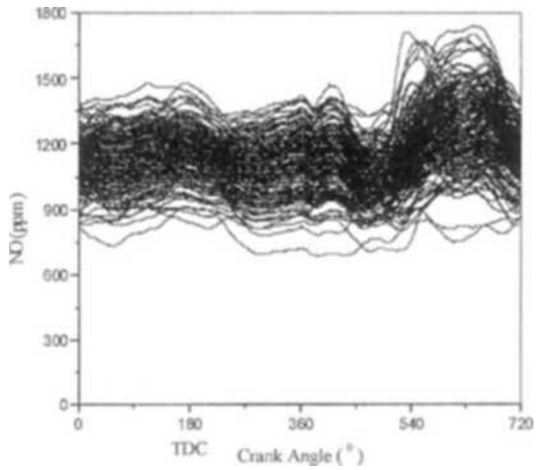


Fig. 3 NO traces with respect to crank angle at 1800 rpm and 2.0 bar BMEP

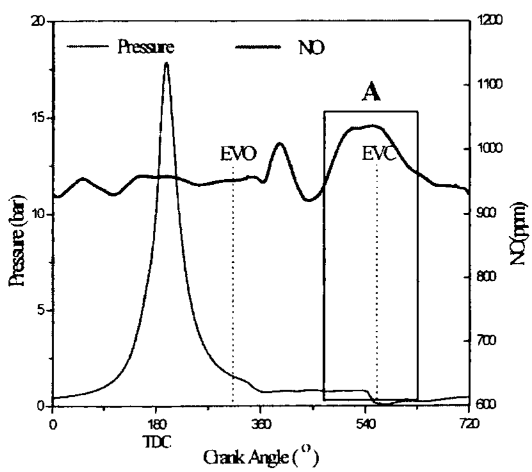


Fig. 4 Averaged NO and pressure trace at 1800 rpm and 2.0 bar BMEP

time seemed to be about 48°CA (4 ms) after the exhaust valve is opened. It is considered that the first peak of NO emissions is affected by a strong exhaust gas flow with relatively high pressure at the start point of blow down process, which flows out through the exhaust valves and exhaust port when the exhaust valve is opened. After this peak, however, NO emissions were decreased in the range that piston was moving downward to BDC (Bottom Dead Center). This is thought to be that even though the combustion was almost completed near TDC (Top Dead Center) region and the burned gas also stayed there, the rapid combustion chamber volume change by downward movement of piston could make the kinetic energy of burned gas larger. As a result, the burned gas seemed to be distributed much dense near the piston as the piston goes close to BDC. Therefore, in contrary to that the exhaust gas is emitted very fast and has a high concentration level during blow-down, the exhaust gas with a relatively low concentration is emitted in the range that piston was moving around BDC (Heywood, 1999). The typical NO emission trace through whole stroke processes is also shown in Fig. 4.

Meanwhile, Fig. 5 presents two different averaged NO emissions traces at 1800 rpm and 2.0 bar BMEP with stoichiometric mixture ratio. One trace is obtained with an isolated exhaust manifold from other branches and the other with normal exhaust manifold. They were normalized by dividing averaged NO emissions at each crank angle by averaged NO emissions at the response starting point after the exhaust valve opens in the isolated sampling port. The difference in the trace profile of thicker line with normal exhaust manifold was considered as an interference of adjacent ports in sampling. To avoid the effect of interference, the exhaust port of 4th cylinder should be isolated from other exhaust ports. The typical profile of NO emissions trace could be obtained with the isolated sampling port.

In Fig. 6, the linear correlation coefficients between NO emissions during specified crank angle, sections which have 30°CA duration, respectively after expansion BDC, and combustion chamber pressures at specific crank angles was shown. Even though the linear correlation coefficient was scattered below 0.8, there seemed to be some regions in which linear correlation coefficient was relatively high. The relatively higher correlation between NO emissions and combustion chamber pressures was found mostly between 480°CA and 630°CA, which are indicated as 'A' in Fig. 4. The combustion chamber

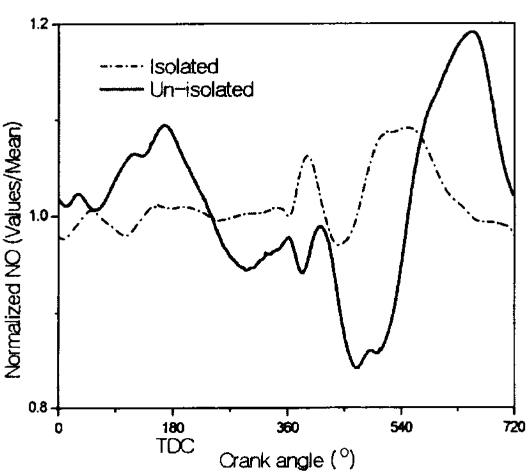


Fig. 5 Normalized NO trace with isolated and un-isolated sampling port

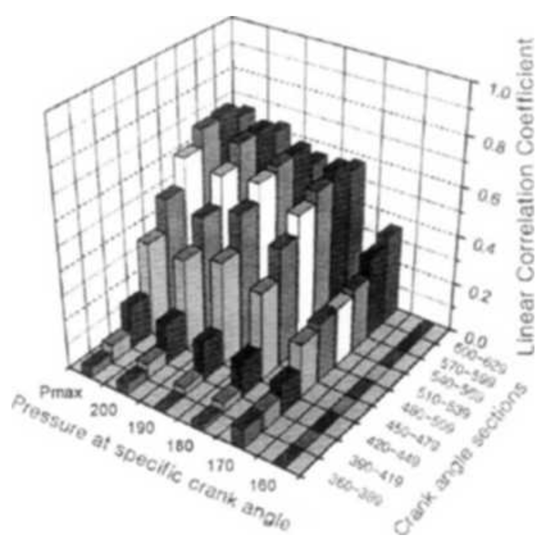


Fig. 6 Linear correlation coefficient between NO and pressures with respect to sampling crank angle sections

pressures after compression TDC had also higher correlation coefficient with NO emissions than the pressures before compression TDC. Furthermore, it is observed that the relation between NO emissions and maximum combustion chamber pressure shows the highest correlation (Ball et al, 1999). On the contrary, the correlation between NO emissions and initial combustion chamber pressure is relatively low, which means that the initial combustion occurred before TDC is thought to be insufficient to affect the whole combustion process and consequently NO production. However, it can not be explained clearly because NO sampling was not done in the combustion chamber but at exhaust manifold.

3.1 Engine load variation

The effect of combustion chamber pressure on NO emissions at 1800 rpm for different engine loads can be found in Fig. 7. NO_{avg} and NO_{peak} are mean and maximum of averaged NO emissions on the block A shown in Fig. 4 respectively. Since the block A has a constant crank angle duration, NO_{avg} indicates the level of total NO emissions in block A. The NO emissions and maximum pressure were increased as the engine load was increased. The increase of engine load at constant air-fuel mixture ratio makes combustion temperature increase, as a result, it is expected that NO emissions will be increased. Additionally, NO_{peak} indicates 1.1~1.2 times higher level than NO_{avg} at these engine load conditions. This means that temporal traces of NO emissions in block A are similar to each other, and NO_{peak} can be considered as a representative quantity to indicate the level of NO emissions.

The effect of engine operating load conditions on the correlation between NO emissions on block A and combustion chamber pressures at specific crank angles is shown in Fig. 8. The linear correlation coefficient between NO emissions and combustion chamber pressures after compression TDC shows higher value at all tested engine load conditions. The correlation coefficient between NO emissions and maximum pressures is the highest at each engine load condition. This means combustion after compression TDC has a closer relation with NO emissions than initial combustion. In addition, higher correlation coefficient was found at the higher engine load. This is thought to be that the temperature of burned gas in combustion chamber is increased at higher engine load, and higher burned gas temperature makes much NO emissions.

The linear correlation coefficients between NO emissions at each crank angle section that has 30°CA duration after expansion BDC and

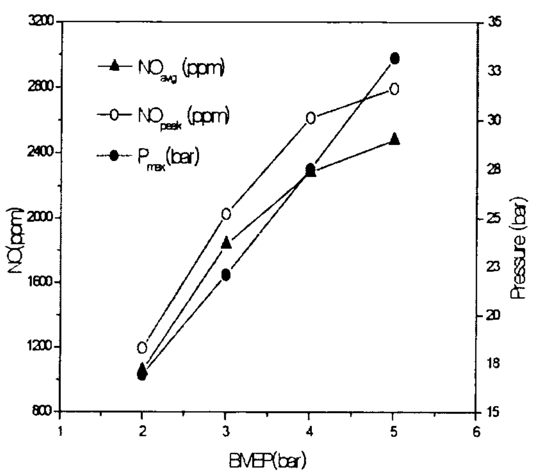


Fig. 7 NO emission and maximum combustion chamber pressure

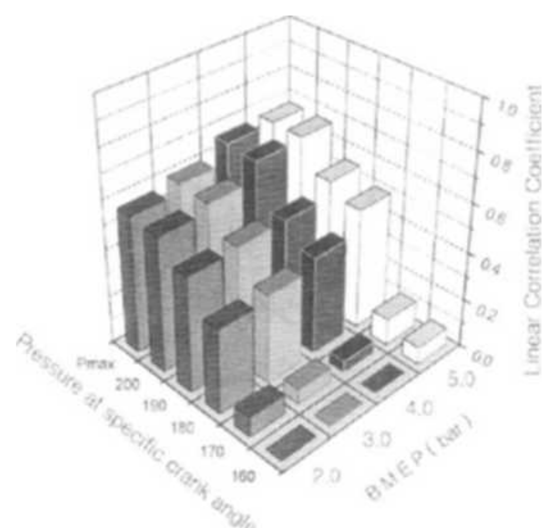


Fig. 8 Linear correlation coefficient between NO emission and pressure with respect to BMEP

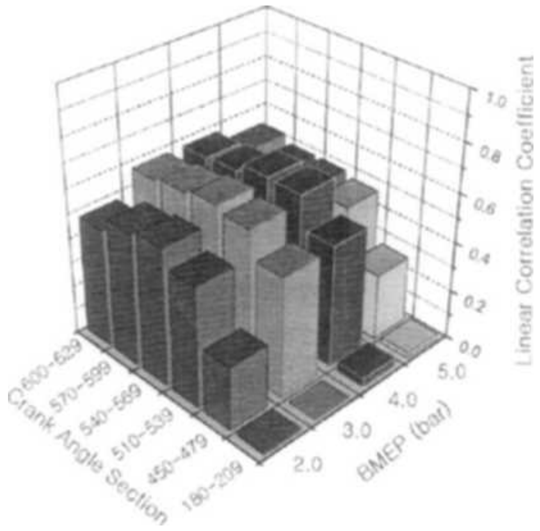


Fig. 9 Linear correlation coefficient between NO emission and maximum pressure at separated CA section

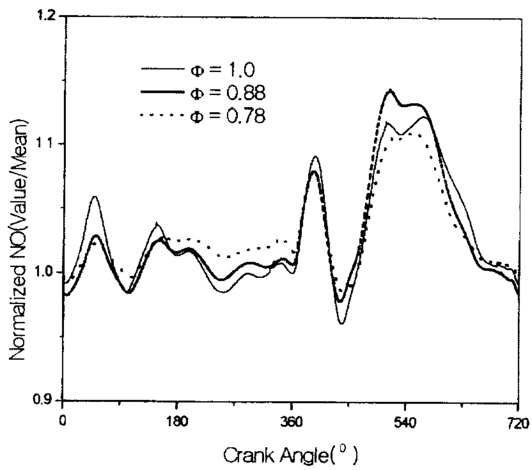


Fig. 10 Normalized of NO at 1800 rpm and 2.0 bar BMEP with respect to equivalence ratios

maximum pressure present in Fig. 9. It is shown that the correlation coefficient of high NO emissions section has a higher correlation value as expected, which means that the higher NO emissions section can represent the NO level in that cycle.

3.2 Air-fuel mixture ratio variation

The effect of air-fuel mixture ratio on normalized NO emissions traces and cycle-to-cycle peak level of NO were shown in Fig. 10 and Fig. 11. In this case, normalization of NO emissions was performed with the NO level of $\Phi=1.0$ at the start point of block A as a base. NO emissions showed its peak at $\Phi=0.88$ and decreased as the air-fuel mixture ratio is increased or decreased away from $\Phi=0.88$. However, the reduction in NO emissions level was larger at $\Phi=0.78$ than at $\Phi=1.0$, which means that NO emissions are reduced with a steeper rate in the leaner side. It was also shown that temporal NO emissions traces in block A were similar to each other even though mixture conditions were different, but they had different NO_{peak}. In Fig. 11, it is observed that the distribution of pressure and NO is quite concentrated at $\Phi=1.0$, but the distribution at $\Phi=0.78$ is scattered, which implies that combustion processes are more unstable at $\Phi=0.78$.

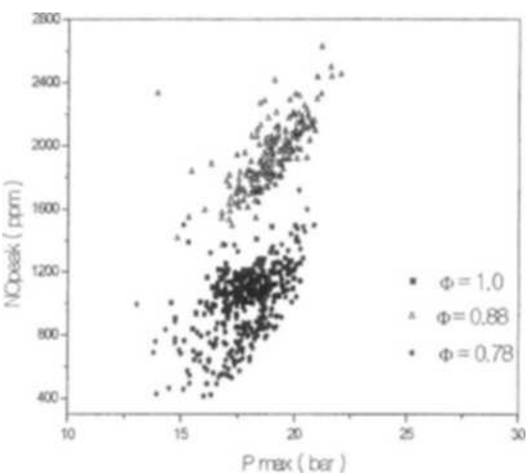


Fig. 11 Relation between NO_{peak} and maximum pressure with respect to equivalence ratios

Figure 12 presents the trend of peak NO emission represented as the block A in Fig. 4 and maximum combustion chamber pressure for different equivalence ratios. NO_{peak} shows its maximum value at near $\Phi=0.9$, which is expected from the former result that NO_{peak} can be handled as a representative of NO emission in block A. The C.O.V (Coefficient of Variation) of NO_{peak} and C.O.V of pressure is presented in the Fig. 13 altogether. The variation of NO_{peak} from $\Phi=0.9$

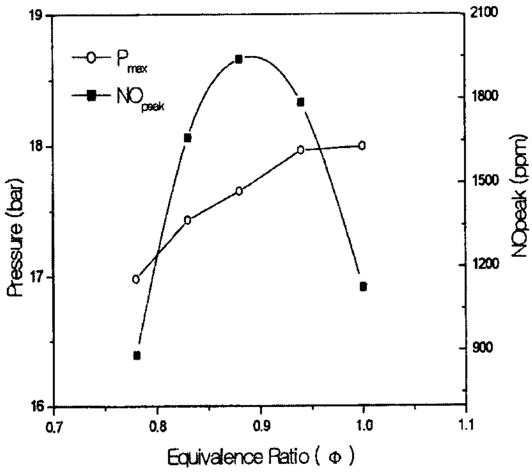


Fig. 12 NO_{peak} and maximum pressure with respect to equivalence ratios

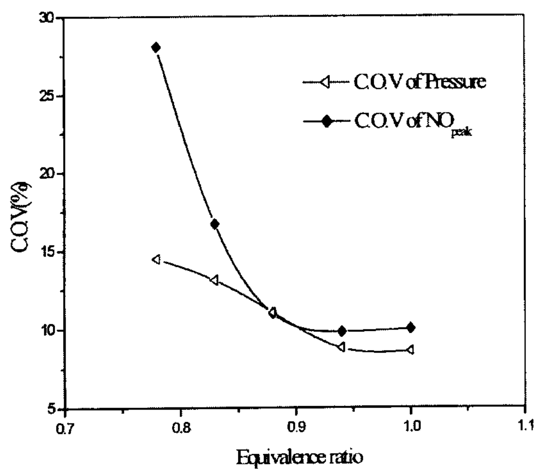


Fig. 13 Coefficient of variation on NO_{peak} and pressure with respect to equivalence ratios

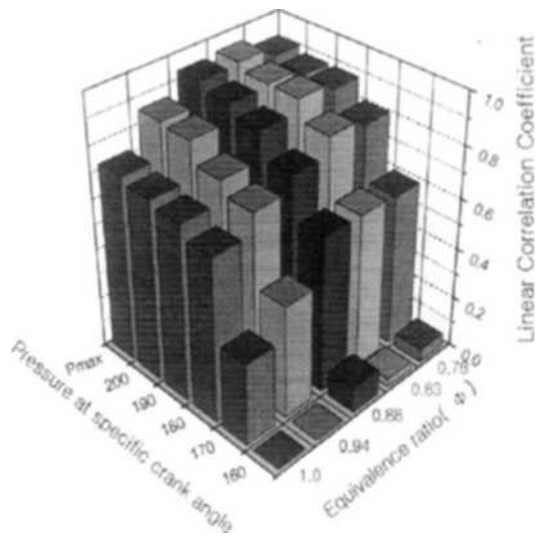


Fig. 14 Linear correlation coefficient between NO and pressures with respect to equivalence ratios

is larger in the leaner region. In Fig. 13, it is shown that C.O.V of pressure and C.O.V of NO_{peak} are increasing when equivalence ratio changes to leaner side away from $\Phi=0.9$, and C.O.V of NO_{peak} is changed rapidly from 10% to 28%, which indicates the unstable combustion at near $\Phi=0.78$ as mentioned above.

Figure 14 presents linear correlation coefficients between NO emission in block A and combustion chamber pressure at each specific crank angle for different equivalence ratios. It is observed that correlation coefficients after compression TDC show higher correlation for all tested conditions of equivalence ratios. As the equivalence ratio decreases to $\Phi=0.8$, the correlation coefficient shows higher value. Meanwhile, even though NO emissions decreases at $\Phi=0.78$, the correlation coefficient is still remained high because combustion chamber pressure also decreases. At leaner air-fuel mixture than $\Phi=0.8$ the correlation coefficients between NO emission and combustion chamber pressure before compression TDC is also relatively high compared to Fig. 8. It can be considered that the spark timing result in this kind of tendency. The spark timing at leaner conditions is more advanced than stoichiometric, so that combustion can be started earlier. As a result, the correlation coefficients between NO emissions and combustion chamber pressure before compression TDC is higher at leaner mixture.

4. Conclusions

The linear correlation coefficients between NO emissions and the combustion chamber pressure for different engine loads and equivalence ratio conditions were obtained with fast response NO analyzer. The conclusions are as followings ;

(1) By averaging NO emissions traces during 200 cycles, a typical pattern under the crank-angle time scale was obtained. It is also possible to set a block of crank angle in which the correlation coefficient between NO emissions and combustion chamber pressures was the highest.

(2) NO emissions were highly correlated with combustion chamber pressure after compression TDC, especially with maximum combustion chamber pressure.

(3) As the engine load increases, the correlation coefficient between NO emissions and combustion chamber pressure also increases.

(4) For the equivalence ratio, NO emissions show the highest concentration at $\Phi=0.9$. As the equivalence ratio decreases to $\Phi=0.8$ approximately, the correlation coefficient between NO emissions and combustion chamber pressure shows higher value.

(5) The correlation between NO emissions and pressures at before compression TDC with leaner mixture is high by dint of earlier spark timing.

Acknowledgment

This study has been performed under the support of Brain Korea 21 Project (2002).

References

Aoyoma, T., et al., 1990, "NOx Reduction by Injection Control," *SAE Paper* 900637.

Ball, J. K., Stone, C. R. and Collings, N., 1999, "Cycle-by-Cycle Modelling of NO Formation and Comparison with Experimental Data," Proc. Instn. Mech. Engrs. Part D, *Journal of Automobile Engineering*, Vol. 213, pp. 175~189.

Dunn, O. J. and Clark, V. A, 1997, "Applied Statistics: Analysis of Variance and Regression," *John Wiley & Sons*.

Heywood John B., 1999, "Internal Combustion Engine Fundamentals," *McGRAW-HILL*, pp. 231~232.

Heywood, J. B., 1973, "Predicting NOx Emissions and Effects of Exhaust Gas Recirculation in Spark Ignition Engines," *SAE Paper 730475*.

Reavel, K. St. J., Collings, N., Peckham, M. and Hands, T., 1997, "Simultaneous Fast Response NO and HC Measurements from a Spark Ignition Engine," *SAE 971610*.

Takagi, Y., Teruyuki, T., 1998, "Simultaneous Attainment of Low Fuel Consumption, High Output Power and Low Exhaust Emissions in Direct Injection SI Engine," *SAE 980149*.

Turns Stephen R., 1999, "An Introduction to Combustion," *McGRAW-HILL*, pp. 172~175.