KSME International Journal, Vol. 16 No. 2, pp. 219~226, 2002

Effects of Gas Composition on the Performance and Emissions of Compressed Natural Gas Engines

Byung Hyouk Min, Jin Taek Chung*, Ho Young Kim and Simsoo Park
Department of Mechanical Engineering, Korea University 5-1, Anam-dong, Sungbuk-gu
Seoul 135-701, Korea

Natural gas is considered to be a promising alternative fuel for passenger cars, truck transportation and stationary engines providing positive effects both on the environment and energy security. However, since the composition of natural gas fuel varies with location, climate and other factors, it is anticipated that such changes in fuel properties will affect emission characteristics and performance of CNG (Compressed Natural Gas) engines. The purpose of the present study is to investigate the effects of the difference in gas composition on the engine performance and emission characteristics. The results show that THC (Total Hydrocarbon) decreases with increasing WI (Wobbe Index) and MCP (Maximum Combustion Potential). On the other hand, it is observed that NOx slightly increases as WI and MCP increase. The TLHV (Total Lower Heating Value of Intake) is proposed in this study as a potential index for compatibility of gas fuels in a CNG engine. There is a variation in power up to 20% depending on the composition of gas when the A/F ratio and spark timing are fixed for a specific gas fuel.

Key Words : CNG (Compressed Natural Gas), Emission, Gas Composition, MCP (Maximum Combustion Potential), Total Lower Heating Value of Intake (TLHV), WI (Wobbe Index).

1. Introduction

Enhanced regulation on the environment and growing concerns about shortage of petroleum resources in recent years have led to active research on alternative automobile fuels. One of the promising alternative fuels which has lower emission levels is CNG (Kim et al., 1997). Since CNG is a gaseous fuel, it is obvious that gas composition, and therefore, gas properties vary significantly according to the location and weather condition. In recent years, Indonesia has been the main source of the imported natural gas used in Korea. For city buses in Korea, diesel engines have been replaced by CNG engines since 2000, the number of which will gradually increase up to 70,000 by 2007. If natural gas vehicles become popular in the near future, the demand for natural gas may increase dramatically, resulting in inevitable diversification of the import countries. Change of the gas composition according to production locations will, then, become a critical issue. A CNG engine, however, has to be developed and tested for a specific gas fuel with fixed composition. It is known that the engine performance and emissions are affected by the natural gas composition from previous studies (Ishii et al., 1995, Sakai and Kuroda, 1996), and therefore, the specific requirements, such as fuel metering and spark timing, imposed by its use in engines as a vehicle fuel are required.

The purpose of this study is to investigate the effects of the gas composition on engine performance and emissions, especially THC and NOx, which are the principal exhaust gas components

---

* Corresponding Author,
E-mail : jchung@korea.ac.kr
TEL : +82-2-3290-3364; **FAX** : +82-2-926-9290
Department of Mechanical Engineering, Korea University 5-1, Anam-dong, Sungbuk-gu Seoul, 135-701, Korea. (Manuscript **Received** February 21, 2001; **Revised** November 22, 2001)

Table 1 Specification of the test natural gas fuels

Composition	Specification of Test Gas							
	Gas A Mix 2	Gas B NG	Gas C Mix 1	Gas D Methane	Gas E Mix 3	Gas F Mix 4	Gas G Mix 9	Gas H Mix 10
CH_4	75.0	90.87	80.0	100.0	90.0	85.0	91.0	83.0
C_2H_6	22.5	5.81	15.5	0	4.0	4.0	0.5	2.3
C_3H_8	2.5	2.38	2.5	0	2.0	2.0	0.4	1.5
$i\text{-}C_4H_{10}$	0	0.45	0	0	0	0	0	0
$n\text{-}C_4H_{10}$	0	0.44	0	0	0	0	0	0
$i\text{-}C_5H_{12}$	0	0.02	0	0	0	0	0	0
$n\text{-}C_5H_{12}$	0	0.01	0	0	0	0	0	0
N_2	0	0.02	2.0	0	4.0	9.0	6.9	3.4
CO_2	0	0	0	0	0	0	0	9.2
H_2	0	0	0	0	0	0	1.2	0.6
Total	100	100	100	100	100	100	100	100
HHV (Kcal/nm^3)	11534.3	10505.3	10833.2	9525.9	9587.0	9254.0	8886.1	8674.8
LHV (Kcal/nm^3)	10447.5	9500	9799.6	8574	8777.1	8348.4	7968.30	7804.14
WI	13769	13233	13189	12711	12362	11569	11606	10484
MCP	45.1	41.5	42.6	40.2	38.9	36.5	37.9	33.6

of natural gas. The result of this study may provide useful data for choosing importing regions and developing new CNG engines. Eight different kinds of test gas fuels were chosen to consider the composition of gases from various regions. The MBT conditions were obtained with changing A/F ratio and spark timing for each test gas. Emission tests were carried out for the MBT condition at 1800rpm, bmep of 2.0 bars and at 2400 rpm, bmep of 2.5 bars.

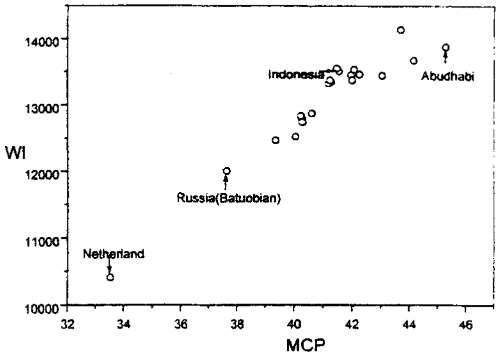


Fig. 1 Property variation of natural gases

2. Experimental Apparatus and Procedure

2.1 Selection of test gas fuels

Over 30 types of natural gases around the world are listed with respect to Wobbe Index (WI) and Maximum combustion potential (MCP) in Fig. 1. The WI, which is related with the heating value of gas fuels, is defined as the caloric value divided by a square root of the specific gravity. The MCP, which is known to be an indicator of the combustion characteristics in engines, is an index for combustion speed and defined as Eq. (1).

$$MCP = \frac{1.0H_2 + 0.6(CO + C_mH_n) + 0.3CH_4}{\sqrt{d}} \qquad (1)$$

H_2, CO, C_mH_n and CH_4 are volumetric fractions of H_2, CO, C_mH_n and CH_4 in gas fuels, respectively and d represents specific gravity of the fuel.

Properties show a wide variation from one location to another. In the present study, eight test gases with different compositions representing the worldwide gas productions were chosen and fabricated considering WI and MCP. The specifications and compositions of the CNG used in this study are given in Table 1. Gas B is the gas from Indonesia, which is supplied for general household use in Korea. Gas D is 100% methane that is the main species of natural gas. Gas A represents the largest value of WI and MCP while Gas H has the lowest value of MCP. Properties of Gas E are located between Gas D and F. Gas C has WI and MCP values similar to those of Gas B, but have a different gas composition. Note that nitrogen, carbon dioxide and hydrogen are used as inert gases for Gas C, E, F, G and H.

2.2 Experimental apparatus

Engine Cell-The test engine was based on a 1.5-liter gasoline engine. The piston crown geometry was modified to raise the compression ratio over 12:1. The CNG that is stored under a maximum pressure of 20 MPa flows to the engine cell through the first pressure regulator that reduces the pressure to 2 MPa. The gas is again decompressed in the second pressure regulator to 0.7 MPa before it is injected into the cylinder through the fuel injector. The gaseous fuel injector is a peak-and-hold type, which has a large injection rate. Figure 2 shows a layout of the engine cell. In order to change and control the amount of gas fuel (A/F ratio) and spark timing, an Engine Control System was fabricated and used. The A/F ratio is monitored from the output signal of a wide range O_2 sensor.

Emission Test Facility- A gas chromatograph (M600D GC) with a FID (flame ionization detector) was used to measure and analyze low -range HC species (C1-C4) of raw emission. Carbosieve B column and Chromosorb W AW column were used to detect C1-C3 species and C4 species, respectively. Figure 3 shows the gas chromatography and direct sampling system for HC of exhaust gases. NOx and CO were measured using the Horiba Gas Analyzer. The exhaust gas was directly sampled between the exhaust manifold and the catalyst.

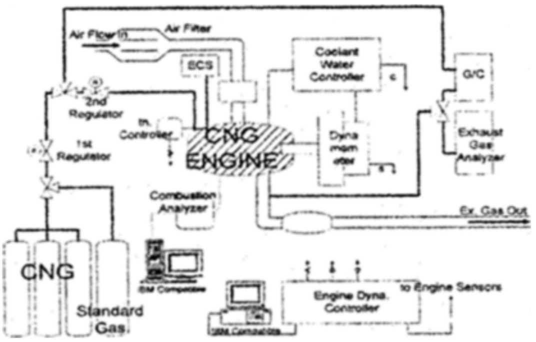


Fig. 2 Schematic of the engine cell

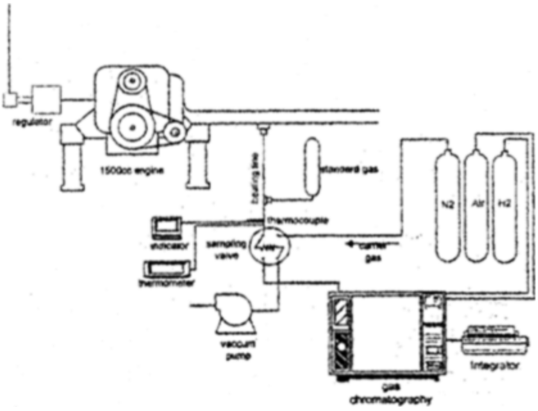


Fig. 3 Schematic of the exhaust gas sampling line

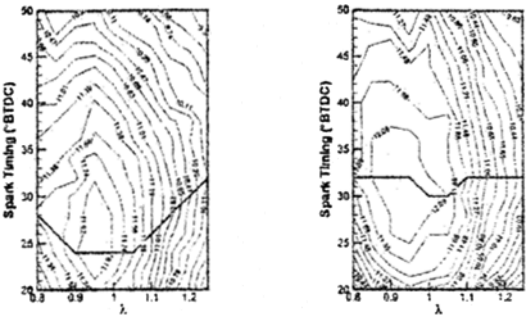
2.3 Test conditions

The performance tests were conducted at the WOT condition with the engine speeds of 2000 rpm and 3500 rpm. The A/F ratio and spark timing were controlled to obtain the MBT (maximum advance for best torque) condition for each gas fuel. In order to check compatibility of natural gas fuels in a pre-developed engine, the power output for eight test gases at the fixed conditions for Gas B, such as the A/F ratio or the spark timing, were compared (swing test). Part load tests were conducted at 1800 rpm, bmep 2.0 bars and 2400 rpm, bmep 2.5 bars, which are also the conditions for the emission tests.

3. Results and Discussions

3.1 General engine performance test

Swing Test - Figure 4 shows engine perform-



(a) 2000rpm (h) 3500rpm

Fig. 4 Contours of the engine torque (WOT, Gas B)

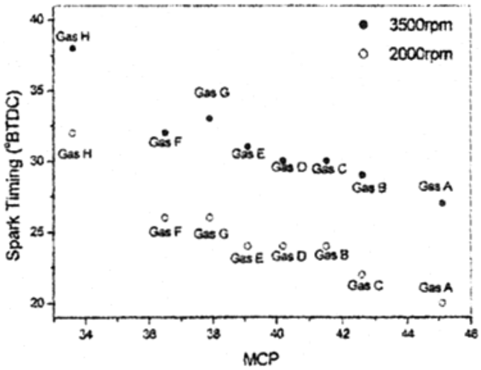


Fig. 5 Variation of MBT with respect to MCP

ance contours with a variation of the A/F ratio and the spark timing for 2000 rpm and 3500 rpm when Gas B is used. The values in the figure indicate the torque (Kg-m) at each operating point and the solid line represents MBT points at each λ(relative A/F ratio) value. At 2000 rpm unstable combustion phenomena such as knocking do not occur up to 50° BTDC of spark timing for all cases. In general, power shows the maximum value near $\lambda=0.95$, then reduces gradually towards both lean and rich regions. The engine shows stable operation even in the fuel condition as lean as $\lambda=1.25$, as observed in previous studies (Ishii et al., 1994, Turns, 1996). It is also observed that power decreases gradually as the spark timing advances after the MBT condition. This trend is similar at a higher engine speed of 3500 rpm, while power is more sensitive to change of λ than to change of the spark timing.

Effects of MCP on Spark Timing - The MBT condition varies with composition of gas since each gas has a different MCP value. Figure 5 shows variation of the MBT with respect to the MCP. The MBT is inversely proportional to the combustion potential, indicating that the gas with a smaller MCP should be ignited earlier since it requires more time for an initial flame to develop sufficiently. The spark timing for Gases E, F and G needs to be advanced because nitrogen retards development of the flame. It is also observed that the amount of methane in fuels plays an important role to determine the spark timing for fuels without inert gases. It is because methane, which has the smallest MCP among HC species, is the main species in natural gas.

Effects of TLHV on Engine Power - The WI is a standard to determine gas compatibility for general gas appliances regarding the amount of heat. It is not applicable for gas compatibility in engines since WI is defined based on the HHV (higher heating value) for the same volume flow rate of gases. In internal combustion engines, the volume of the gas fuel entering a cylinder is different for each gas since the theoretical A/F ratio is different for each gas even though the size of the cylinder is the same. Moreover, the LHV (lower heating value) is appropriate for calculating the amount of heat generated in engines. Figure 6 indicates the variation of engine power with respect to the WI. The power is generally proportional to the WI, but Gas D, which is 100% methane, has quite a low value. This is probably because Gas D has a relatively large difference between HHV and LHV, and its smaller A/F ratio indicates a smaller volume of gas burning in the engine. In order to confirm this, the TLHV (total lower heating value of intake) is proposed for the standard index to determine gas compatibility for natural gas engines. This value is defined as an actual amount of the gas entering an engine multiplied by the LHV of the gas. Figure 7 shows the relationship between the engine power and the value normalized by that of Gas B. Gases D and G move far to the left so that power appears to be proportional to the TLHV of intake. Therefore, the

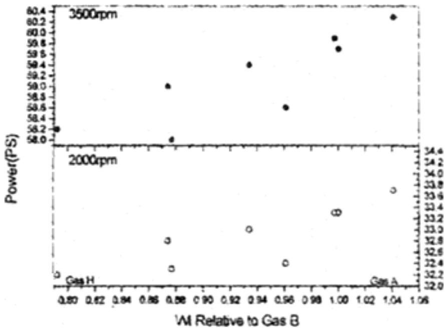


Fig. 6 Variation of the power with respect to WI

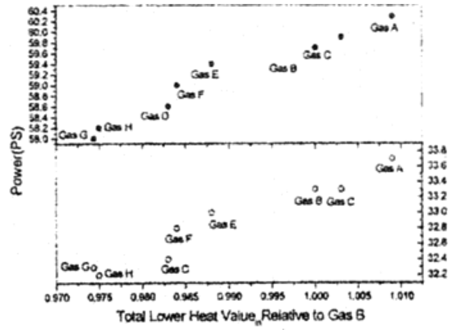


Fig. 7 Variation of the power with respect to the Total Lower Heating Value of Intake

TLHV can be considered as a potential index for compatibility of gas fuels in engines. It is, however, also obvious that the engine power depends not only on the heating value but also on the combustion characteristics in the cylinder. Detailed study on the combustion characteristics of each gas in the cylinder is required in the future.

Effects of the Engine Operation condition on Power - Figures 8 and 9 show a comparison of power for the following three cases: (1) while the spark timing is fixed at the MBT of Gas B (2000 rpm: BTDC 24CA, 3500 rpm: BTDC 32 CA), the A/F ratio is controlled to obtain the maximum power for each gas, (2) while the volume of the supplied gas is fixed at the value for Gas B obtaining the maximum power ($\lambda=0.95$ for Gas B), the spark timing is controlled to be MBT for each gas fuel, (3) both the volume of supplied gas and the spark timing are fixed at values for maximum power of Gas B. When the spark timing was fixed at MBT for Gas B, there was a power variation up to 5-6 % for eight kinds of gas fuels at both engine speeds. This result is similar to what Sakai and Kurada (1996) observed in their study. When the volume of the supplied gas is fixed, on the other hand, the change of the power is even bigger than previous case, as much as 9 % with the change of gas. It is because the power of the natural gas engine is more sensitive to the change of A/F ratio than that of the spark timing as shown in Fig. 4. Finally, when both conditions are fixed at values for Gas B, the variation of the power with respect to the gas fuel is dramatic. Since the condition of engine was adjusted to Gas B, the power for Gas B provides the maximum value in this case. The reduction of the power is as large as 20% for Gas F at the engine speed of 3500 rpm.

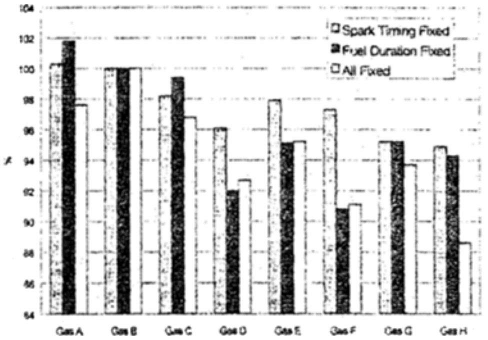


Fig. 8 Comparison of powers for various operating condition (2000 rpm)

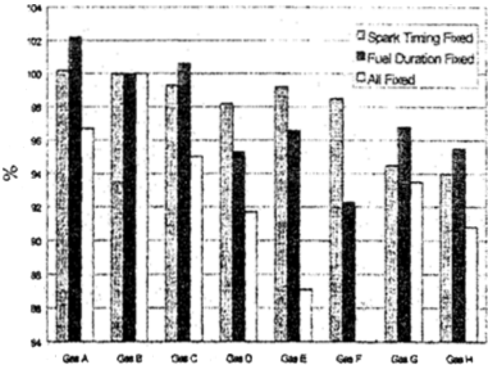


Fig. 9 Comparison of powers for various operating condition (3500 rpm)

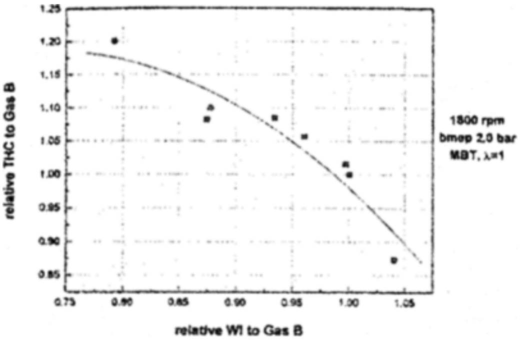


Fig. 10 Variation of the relative amount of THC with relative WI to Gas B (1800 rpm)

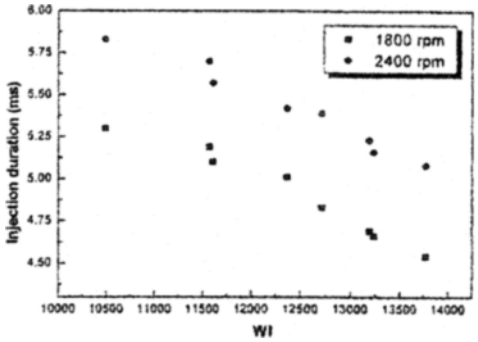


Fig. 11 Variation of the injection duration with respect to WI

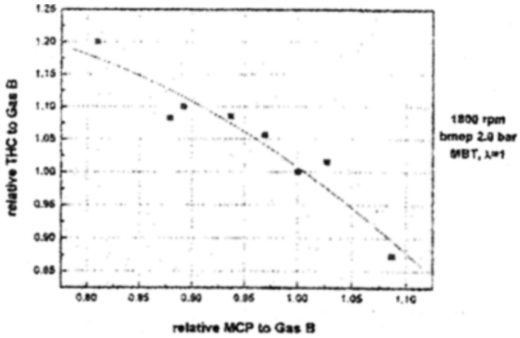


Fig. 12 Variation of the relative amount of THC with relative MCP to Gas B (1800 rpm)

3.2 Variation of THC with the gas composition

Variation with respect to WI - Figure 10 shows variation of THC with the change of relative WI to Gas B at the engine speed of 1800 rpm. As WI increases, the amount of THC in the exhaust gas decreases. Since WI indicates the heating value for unit volume, the gas with lower WI value has to be supplied to the cylinder in a larger amount than that with higher WI in order to obtain the same bmep of the test condition. This point is confirmed in Fig. 11, which shows that the amount of supplied gas fuel is inversely proportional to WI. If the amount of supplied gas increases, the unburned hydrocarbon captured in the crevice increases so that the THC in the exhaust gas increases (Matthews, et al., 1996). In the cases of Gas F and G which have lower WI values, the amount of THC does not increase even though the amount of fuel increases. The reason is that the HC in the gases does not increase proportionally to the amount of fuel compared with Gas E since these two gases contain large amount of nitrogen. A similar trend was shown in the result for 2400 rpm.

Variation with respect to MCP - The effect of the MCP of natural gas fuels on THC of the raw emission is shown in Fig. 12. The THC, which is normalized by that of Gas B, decreases as the combustion potential of natural gas increases. As MCP increases, the combustion pressure in the cylinder increases resulting in a higher combustion gas temperature. Therefore, the amount of THC for the gas with larger MCP decreases in the emission of natural gases.

Variation of NMHC - For eight kinds of test gases, it was observed that the main species in NMHC (non-methane hydrocarbon) is C2 species, especially ethane. Figure 13 shows the variation of the volume fraction of NMHC with the fraction of CH_4 in HC of gas fuel. Gas A and Gas C show relatively larger value since the emission for two gases has relatively large portion of C2 species. Gas B shows the next large value because it contains larger portions of C3 and C4 species in the emission than any other gases. Gas D gives the smallest amount of NMHC since the main fraction in THC for this gas is methane.

Relative Ozone Reactivity - Table 2 shows the ozone forming potential for each HC species. In this study, the hydrocarbon emissions are report-

Table 2 Ozone reactivity of hydrocarbons

	Molecular weight	gO_3/ g HC	gO_3/ mole HC	Molar rel. Reactivity
Methane	16.04	0.0148	0.237	1.00
Acetylene	26.04	0.50	13.0	54.8
Ethylene	28.05	7.29	205	861
Ethane	30.07	0.25	7.52	31.7
Propyne	40.07	4.10	164	692
Propylene	42.08	9.40	396	1670
Propane	44.10	0.48	21.2	89.2
Iso-butane	58.12	1.21	70.3	296
n-butane	58.12	1.02	59.3	250
Iso-butene	56.11	5.31	298	1250
1, 3-butadiene	54.09	10.9	589	2480

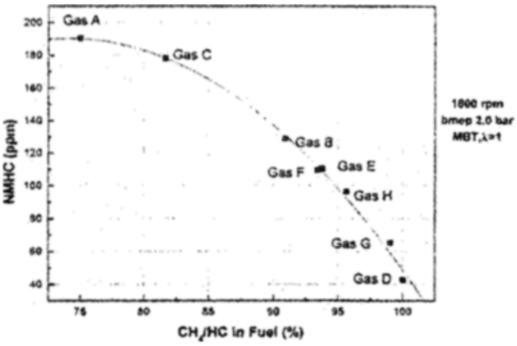


Fig. 13 Variation of NMHC with CH_4/HC in gas fuels (1800 rpm)

ed on a volume fraction basis. Therefore, the last column represents the relative ozone reactivities of the hydrocarbons on a molar basis, which are normalized by the value of methane. It is noted that the ethylene, which was observed to be the third major species after methane and ethane in the emission for natural gases, has the value as large as 861 (Paulsen and Wallace, 1994). The equivalent CH_4 reactivity of the THC for ozone formation can be calculated by Eq. (2) using values in Table 2.

$$\textit{Equivalent } CH_4 \textit{ reactivity} = \Sigma(\textit{volume fraction})_{HC} \times (\textit{molar rel. reactivity})_{HC} + \textit{volume fraction of } CH_4 \times 1 \qquad (2)$$

Figure 14 represents variations of the equivalent CH_4 reactivities for ozone of THC, NMHC and ethylene with the methane fraction in HC of gas fuels. Since ethylene has a large reactivity value, the gases with a large ethylene fraction in the emission such as Gas A appear to form a large amount of ozone. Since the relative reactivity of methane is 1, there is no difference between the values for THC and NMHC even though the amount of methane is dominant in the emission. Furthermore, it is observed that the formation of ozone of natural gas emission is inversely proportional to the amount of methane in gas fuels.

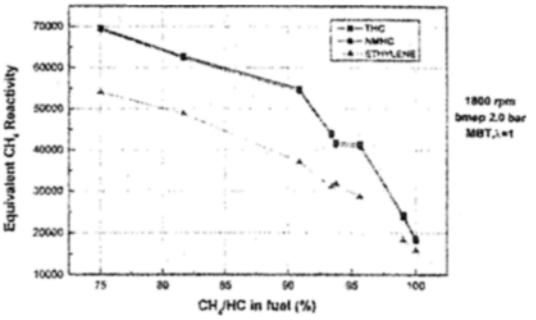


Fig. 14 Variation of the equivalent CH_4 reactivity for the ozone formation with the fraction of methane in fuel (1800 rpm)

3.3 Variation of NOx with the gas composition

Variation with respect to WI - Figure 15 shows variation of NOx with a change of the relative WI to Gas B at 1800 rpm. As the WI increases, the amount of NOx in the exhaust gas increases. The higher the burned gas temperature is, the higher the rate of formation of NOx is. Since WI indicates the heating value for unit volume, the higher WI gives the higher temperature of gas in cylinder. But, the curve has a gentle slope. It is also possible that the inert gas contained in gas fuels of lower WI reduces the combustion gas temperature.

Variation with respect to MCP - The effect of the MCP of natural gas fuels on NOx of emission is shown in Fig. 16. NOx, which is normalized by that of Gas B, increases as the MCP of natural gas increases. As MCP increases, the combustion gas temperature increases. Therefore, the amount of NOx for fuel with larger MCP increases in the emission even though the change is not dramatic.

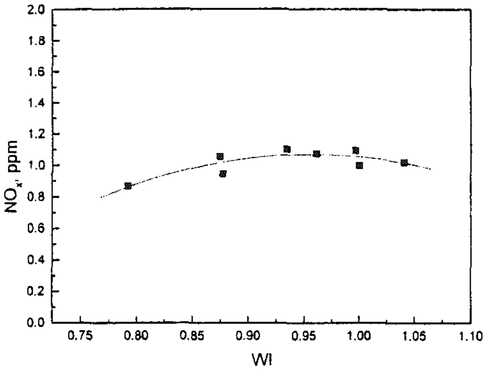


Fig. 15 Variation of NOx with respect to WI (1800 rpm)

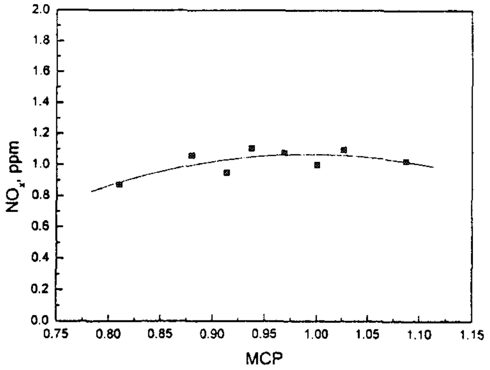


Fig. 16 Variation of NOx with respect to MCP (1800 rpm)

4. Conclusion

(1) The natural gas engine shows different power outputs depending on the gas fuel. The discrepancy may be up to 20 % when the operation conditions such as spark timing and the amount of supplied gas are fixed for a specific gas. Therefore, if various gases are to be used in a CNG engine, the spark timing and the A/F ratio should be controlled for each gas.

(2) In case that only one operating condition is free to be controlled and the composition of gas fuel is subjected to change, it is better to control the amount of supplied gas at a fixed spark timing rather than controlling the spark timing at a fixed amount of gas.

(3) The MBT for natural gas is inversely proportional to the combustion potential (MCP) of the fuel.

(4) Engine power is shown to be proportional to the total heating value of the actual amount of gas entering a cylinder. The value of TLHV is proposed as a potential index for compatibility of gas fuels for natural gas engines.

(5) The THC in the emission of natural gas fuels increases as WI and MCP decrease.

(6) The equivalent methane reactivity for ozone decreases as the fraction of methane in gas fuel increases.

(7) The amount of NOx of CNG engines increases slightly as the WI and MCP increase.

References

Ishii, M., Ishizawa, S. and Inada, E., 1994, "Experimental Studies on a Natural Gas Vehicle," *SAE paper* No. 942005.

Ishii, M., Ishizawa, S., Nakagawa, T., Idoguchi, R., Inada, E. and Tanaka, T., 1995, "164 Effects of Natural Gas Fuel Composition on Exhaust Emission Characteristics," *IPC8*, Paper No. 9530625, pp. 363~368.

Kim, B., Lee, Y. and Ryu J., 1997, "A Fundamental Study of Hydrogen Supplemented Natural Gas Vehicle to Meet ULEV," *Transactions of KSME*, Vol. 21, No. 3, pp. 358~370.

Matthews, R., Chiu, J. and Hilden, D., 1996, "CNG Composition in Texas and the Effects of Composition on Emissions, Fuel Economy and Derivability of NGVs," *SAE Paper* No. 962097.

Poulsen, J. H. and Wallace, J. S., 1994, "Operating Parameter Effects on the Speciated Hydrocarbon Emissions from a Natural Gas Fueled Engine," *SAE Paper* No. 942007.

Sakai, T. and Kurada, E., 1996, "Effect of Fuel Composition on Engine Performance and Exhaust Emission," *Jidosya Kennkyu*, Vol. 18, No. 1, pp. 23~26.

Turns, S. R., 1996, *An Introduction to Combustion*, McGraw-Hill, pp. 232~240.