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EFFECTS OF METHANOL-REFORMULATED FUELS ON TRANSIENT CHARACTERISTICS FOR AN SI ENGINE

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ABSTRACT–There are many methods to test engine emissions depending on the regulations used such as FTP-75(CVS-75) mode, 10-15 mode and ECE-15 mode. Most of these modes consist of transient conditions such as cranking, rapid acceleration or deceleration modes. In this experimental research, the transient characteristics including cranking and accelerating mode in SI engines were studied to compare pure gasoline with methanol-reformulated fuels for performance and exhaust emissions. The results show that methanol-reformulated fuels have a better emissions reduction rate than that of pure gasoline especially for HC, CO and NOx emissions during cranking mode. The acceleration performances conform to the results of the distillation curve and the CO concentration for RM50 varies slightly in acceleration mode.

KEY WORDS : Methanol-reformulated fuel, Cranking characteristics, Acceleration characteristics, Exhaust emissions

1. INTRODUCTION

As environmental and energy concerns are forcing emission standards to tighten, it is necessary to develop low-emission vehicles, for example by modifying combustion processes, adding exhaust after-treatments and changing fuel compositions (Min *et al.*, 2002).

Recently, the regulation of fuel itself has also been becoming stricter. According to the World-Wide Fuel Charter, unleaded gasoline fuel has been classified into four different categories for fuel quality relating to emission regulations (ACEA, 2000). They consist of Categories 1-4 and detailed explanations are given in Appendix.

SI engines mainly use gasoline as fuel, which is a mixture of over 200 different hydrocarbons consisting of C_4–C_{12} with low boiling points relative to the refining processes. These are separated by 4 different components such as paraffin (C_nH_{2n+2}), olefin (C_nH_{2n}), naphthene (C_nH_{2n}) and aromatic series (C_nH_{2n-6}).

Olefins are unsaturated hydrocarbons and, in many cases, are also good octane components of gasoline. However, olefins are thermally unstable and may lead to gummy formations and deposits in an engine's intake system

Furthermore, their evaporation into the atmosphere as a chemically reactive species contributes to ozone formation and their combustion products form toxins. Currently, they are restricted to less than 20% of gasoline by volume and will be required to be less than 10% by volume in the future.

Aromatic components have a high hydrocarbon density with an unsaturated ring structure as in double carbon-carbon bonds giving them a high energy content per unit volume, and have a high octane number. They are used for important anti-knock fomulations against knock, but cause problems like excess smoke and dissolving gasket materials because of their high solvency characteristics. They can increase engine deposits and tailpipe emissions, including CO_2. The fuel quality recommendations restricts them to be less than 35% by volume. Benzene is well known for improving octane number, but is held below 2.5% by volume by regulations to avoid toxicity and will be reduced to below 1% by volume (Kwon *et al.*, 1999).

Much research was conducted to find the effects of fuel components, such as olefins, aromatics, and volatility on the characteristics of engine emissions. The US Auto/Oil program shows that the reduction rate of total olefins from 20% to 5% would significantly decrease ozone formation in three critical cities: Los Angeles, Dallas-Fort Worth, and New York. The European EPEFE program demonstrated a relationship between CO_2 emissions and aromatic content. Mayotte *et al.* (1994) and Korotney *et al.* (1995) conducted research on the effects of olefin levels, aromatic levels and volatility on exhaust emissions. Bennett *et al.* (1995) observed that a reduction of RVP gave benefits in CO and NOx, but had

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*Corresponding author. e-mail: chjeon@pusan.ac.kr no effect on exhaust THC emissions. Reducing aromatic content from 50 to 20% was found to decrease CO_2 emissions by 5%. Further aromatics and olefins were found to have the greatest influence on determining THC emissions and volatility to have the greatest influence on NOx emissions.

As mentioned above, changes in fuel composition are known as an important control option. Many technologically advanced countries and automobile manufacturers have been researching changes in fuel compositions and alternative-fuel vehicles such as those using methanol, ethanol, natural gas, hydrogen and others (Yoon *et al.*, 2001; Han *et al.*, 2000; Min *et al.*, 1999; Kim *et al.*, 1999). Currently it remains difficult to replace vehicles using gasoline by those using electricity or hydrogen. Although viable vehicles using these energy sources can be produced, it is still better that, for the near future gasoline substitutes be developed that do not require modifications of engine components. Methanol is a promising and alternative fuel because it has properties similar to gasoline, such as a high octane rating, an excellent lean limit ignition, and the potential for direct utilization.

The emissions rate and performance of methanol in constant speed and load conditions has been studied experimentally by a number of researchers. Alasfour (1997) studied the performance, brake specific fuel consumption (bsfc) and thermal efficiency under a wide-range fuel/air equivalence ratios (Φ=0.8–1.3) for a fuel blending 30% methanol and butanol and gasoline as well as pure gasoline in a single cylinder engine. Also Abdel-Rahman *et al.* (1997) studied the effects of the compression ratio and blending volumes (ranging up to 40%) on SI engine performance. Moses *et al.* (1995) studied the effects of methanol admixtures on gasoline knocking in SI engines. Li *et al.* (1995) investigated the effects of blended methanol on hydrocarbon oxidation and auto-ignition in a single cylinder SI engine.

Sato *et al.* (1995) observed combustion and NOx emission characteristics of a direct-injection methanol engine under light load conditions varied heating the charge air and EGR. Bowman *et al.* (1995) investigated reductions to both ozone-forming volatile organic compound (VOC) emissions and toxic air emissions of vehicles using reformulated gasoline and alternate fuels. Huai *et al.* (2003) studied the exhaust emissions for a fleet of 10 alternative fuel vehicles including LPG, CNG and methanol. Fieweger *et al.* (1997) studied the self-ignition of diverse SI engine fuels such as methanol, iso-octane, methyl tert-butyl ether and three different mixtures of iso-octane and n-heptane. As the volume percentage of methanol fuel is increased, the exhaust emissions are reduced considerably except for CO_2 emissions. As inlet temperature increases, CO and HC emissions are reduced at the same percentage by volume.

As mentioned above, the bulk of the research has studied not reformulated alcohol fuels but mostly blending fuels under constant speed and load conditions (Cho *et al.*, 2003; Yoon *et al.*, 2001). Practical regulation test modes, such as CVS-75, consist of many transient operating conditions including cranking, acceleration and deceleration. Though the transient driving conditions involving accelating and decelating is increasing due to severe traffic density in urban areas, there is little research of alternatives fuels in such conditions.

The objective of this work is to investigate the effects of methanol reformulated fuel, not blended fuel, on transient characteristics without modifying engine components. In the cranking phase of the transient modes, engine revolution, fuel injection duration, oxygen sensor signals and exhaust emissions are investigated. For two linear accelerating modes, engine revolution, excess air ratio and exhaust emissions are examined.

2. EXPERIMENTAL SETUP

2.1. Fuel

Generally methanol has a content similar to aromatics in terms of octane rating high, and also has oxygenated functions (OH hydroxyl) that reduce exhaust emissions such as smoke. Most experiments using gasoline blended with methanol, but this experiment uses a reformulated methanol that uses gasoline aromatic and non-aromatic additives. Table 1 gives the properties and characteristics of gasoline and the reformulated fuel. We call these fuels gasoline, RM30 and RM50 respectively. The low heating value (LHV) of RM 50 is lower due to the lower LHV of methanol, but it also has some advantages including a higher octane number and oxygen fration due to methanol.

It is important to compare fuel properties between reformulated fuels and gasoline as a reference fuel. Table 2 shows the maximum allowable values of some of the recommended components of gasoline. As the category number increases, the fractions by volume of each component decreases significantly.

Olefin is not even defined in Category 1, but it is less

Table 1. Comparison of experimental fuel properties.

Category Item	I	II	III	IV
Olefins content Vol. (%)	–	20	10	10
Aromatics content Vol. (%)	50	40	35	35
Benzene content Vol. (%)	5	2.5	1	1

Table 2. Maximum values of fuel contents from World Wide Fuel Charter.

	Gasoline	RM 30	RM 50	Test method
Fuel composition Vol. (%)	Gasoline 100%	Methanol 24% Aromatic 28% Non-aromatic 48%	Methanol 54% Aromatic 23% Non-aromatic 23%	
Benzene content Vol. (%)	0.86	0.16	0.04	
Olefin content Vol. (%)	17.5	1.50	0.30	
Carbon fraction Wt. (%)	84.46	75.42	62.89	
Hydrogen fraction Wt. (%)	13.89	13.02	12.59	
Oxygen fraction Wt. (%)	1.65	11.56	24.53	
Vapor pressure (kPa)	68.65	67.67	71.59	ASTM D323
Specific gravity (15/4°C)	0.7228	0.7613	0.7797	ASTM D4052
Octane number (RON)	92.2	96.2	121.0	ASTM D2699
LHV(kJ/kg)	41993	36760	31024	KS M 2057-97

than 10% by volume in Category 4. Fuel as well as emissions regulations are becoming more stringent. The components of the reformulated fuels (RM30 and RM50) are well within th boundaries of Category 4.

The fuel consists of the various components of different molecular weights, which will vaporize at different temperatures. Small molecular weights boil at lower temperatures and larger molecular weights at higher temperatures. Generally one way to describe fuel volatility is to use three temperatures at which 10%, 50% and 90% of the fuel are vaporized. Fuel volatility plays an important role in liquid evaporation. At the point where 90% of the liquid is evaporated, maximum power is achieved relating the deposit of combustion chamber or spark plug and the engine oil dilution. The initial 10% point relates to cold starts and the mid point relates to accelerating performance.

Figure 1 shows the characteristics of distillation curves for each fuel used. At the vicinity of the 10% and 90% point, there is not much difference for each evaporated point. But at the 50–70% evaporated point, which is related to acceleration performance, the RM50 fuel has recognizable differences from other fuels. From the distillation curve, it will be predicted that the acceleration performance of RM 50 will be worse than that of other fuels.

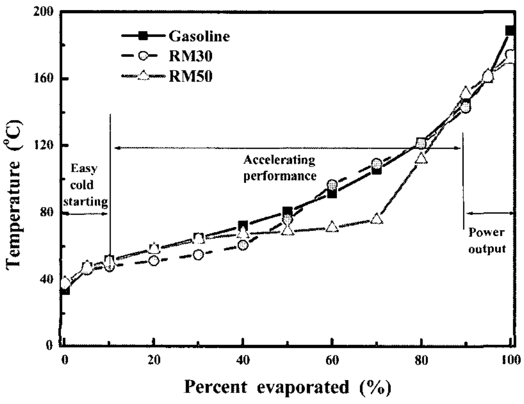


Figure 1. Distillation curves of experimental fuels.

Table 3. Specifications of experimental engine.

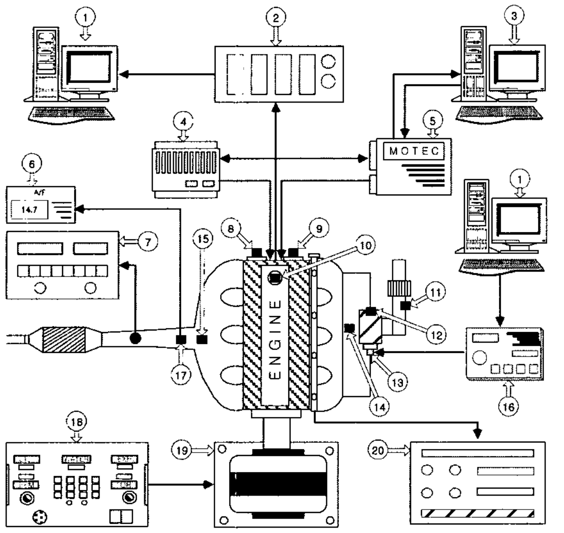
Item	Specification
Engine type	In-line 4 cylinder, SI engine
Valve mechanism	DOHC
Displacement (cc)	1799
Bore Stroke (mm)	81.6×86
Compression ratio	9.8

2.2. Apparatus and Methods

Table 3 shows the specifications of the modern production engine used in this study. The schematic diagram of the experimental setup is shown in Figure 2. Band O_2 sensor signal, the intake air temperature and exhaust gas temperature are taken simultaneously by a data acquisition board.

To measure the air/fuel ratio during cranking mode, a wide-band oxygen sensor is mounted at the exhaust pipe. In the acceleration test, a stepping motor is installed at the throttle body to control the throttle valve-opening ratio.

To evaluate each fuel while cranking, the engine is operated by a conventional ECU and engine speed, fuel injection time, air/fuel ratio, oxygen sensor voltage and engine-out exhaust emission gases are measured. Repeatability of engine cranking is affected by the coolant water and the intake air temperature. During the experiment the coolant water temperature ranges between 22 and 24°C and the air intake temperature between 23 and 25°C.



1. Computer
2. Data acquisition system
3. Programmable ECU control PC
4. ECU
5. Programmable ECU
6. A/F ratio displayer
7. Exhaust gas analyzer
8. Encoder
9. Cam sensor
10. Pressure sensor
11. AT sensor
12. TP sensor
13. Stepping motor
14. MAP sensor
15. Oxygen sensor
16. Stepping motor interface
17. Wide range oxygen sensor
18. Dynamometer controller
19. Dynamometer
20. Fuel measuring system

Figure 2. Schematic diagram of experimental apparatus.

The acceleration test uses a the conventional ECU and an rpm accelating range that is typical of driving (1500 up to 3000).

The load is 4.6 kg-m, which is a quarter of a full load for this engine. The throttle valve opening times are 0.5 and 3 seconds, which represent rapid and slow acceleration modes and the opening ratio is 20±1° for each fuel. The engine-out exhaust gases in terms of CO, HC and NOx are analyzed by I/M 2000, which is able to detect data per second. The calibration is conducted with standard gases.

3. RESULTS AND DISCUSSIONS

3.1. Cold-start Mode

Figure 3 shows the engine speed and the injection duration with the elapsed time after engine start for the different fuels. After cranking, the engine undergoes two transient processes: it accelerates to a high speed, and then it decelerates to the idle.

At the early stage of the cold-start, the engine speed using RM30 is in similar to gasoline fuel, and the engine accelerated from 185 rpm to 1500 rpm in about six revolutions. RM50 has a somewhat higher engine speed, accelerating up to 1750 rpm. During the cold-start, accelation is governed by an open loop control that has the same injection quantity for each fuel. The uncertainty of maximum engine revolution for RM50 is 3.01% and the uncertainty of the time to arrive the maximum engine revolution is 13.23%. Although 13.23% is a large value, the average time to maximum rpm is 1.5 seconds and the standard deviation is 0.198 seconds respectively. Other fuels have lower uncertainty value than RM50.

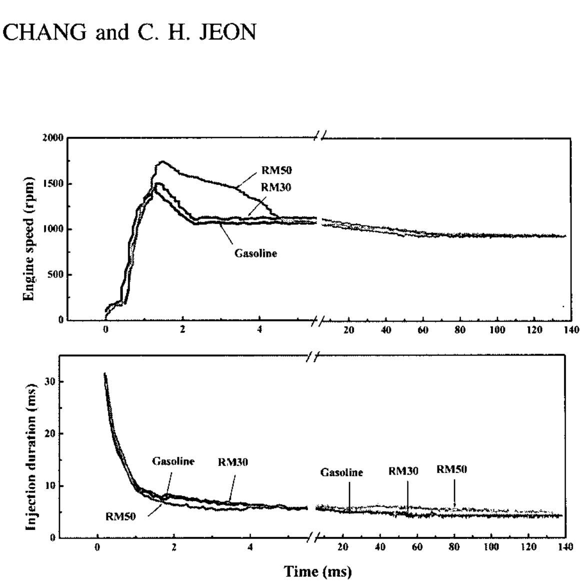


Figure 3. Comparison of engine speed and injection duration under cranking mode.

A rich air/fuel ratio is needed to start an engine with gasoline. Theoretically RM50 has a lower air/fuel ratio than gasoline, but it is injected in the same quantity as the gasoline. Thus RM50 has a less rich combustion condition than other fuels. For this reason, RM50 achieves a higher engine speed. Fuel injection duration for each fuel is dramatically reduced within several seconds after starting and then returns to almost the same level within 20 seconds. As mentioned previously, the oxygen sensor does not work in this region, so acceleration is governed by an open loop control.

In this study, two oxygen sensors are used to check the air/fuel ratio. One is the oxygen sensor which is used typically in conventional engines and works at temperatures over 250. The other is the wide band oxygen sensor, which monitors the excess air ratio and even works well in cold conditions. The oxygen sensor provides feedback control, but the wide band oxygen sensor monitors the

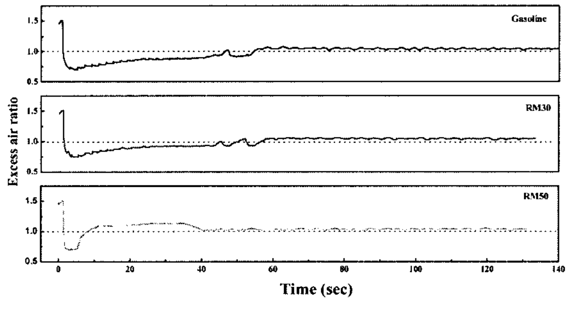


Figure 4. Excess air ratio with wide band O_2 sensor at craking mode.

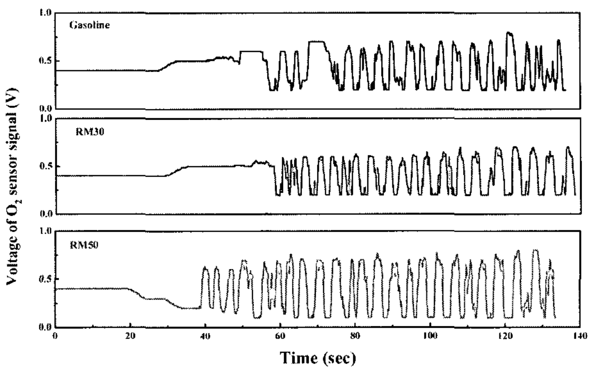


Figure 5. Feedback signal from O_2 sensor output under cranking mode.

excess air ratio for each fuel.

Figure 4 shows the excess air ratio measured by the wide band oxygen sensor. RM 50 has a lean the excess air ratio ($\lambda \fallingdotseq 1.1$) for 10 to 37 seconds. During this period, NOx has a lower value than the stoichiometric air/fuel ratio due to the lean combustion and lower LHV of RM 50. After 40 seconds, feedback control starts and the engine runs at the theoretical air/fuel ratio. This is well within the range of results of the oxygen sensor voltage for RM 50 as shown in Figure 5.

Figure 5 shows the results of the oxygen sensor signal. In the early stage the oxygen sensor did not work. As the exhaust temperature increased, the normal signal of the oxygen sensor appears. For gasoline and RM30, the oxygen sensor signal is varied about 30 seconds after cranking and full-scale feedback control began after about 60 seconds. But for RM50, the sensor output voltage is generated after about 20 seconds and feedback control started after 40 seconds. The earlier feedback control had positive effects on the exhaust emission characteristics.

Figure 6 shows the variation of exhaust emissions of HC, CO and NOx for each fuel by time. On the whole RM50 shows good exhaust characteristics. Generally, about 60–80% of the total HC emissions during the New European Dirving Cycle (NEDC) and FTP-75 cycles are emitted within the first 200 seconds of a the cold-start (Koltsakis *et al.*, 1999; Shin, 1997; Crane *et al.*, 1997; Son *et al.*, 1999).

In the early stage of a gasoline cold-start, combustion occurs under very rich conditions, so a larger amount of HC is emitted than is for the reformulated-fuels. RM50 stabilized earlier than the other fuels when HC emissions are maintained during idling conditions. This is because RM50 had the fastest feedback control as can be seen in Figure 5.

For RM50 a small amount of CO is emitted because combustion occurs under relatively lean conditions.

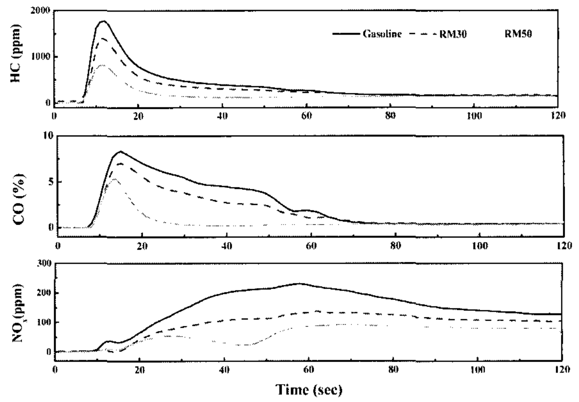


Figure 6. Comparison of exhaust emission response for cranking mode.

Thus RM50 has better combustion characteristics than others in cranking modes and it is well within the results of engine revolution as shown in Figure 3.

During the first 10 seconds of the early stage, the NOx emission does not vary, but as time progresses, the amount of NOx increased. Gasoline and RM30 have the same tendencies, but RM50 has somewhat different inclinations around 40 to 50 seconds. This is caused by the rapid change of the air-fuel ratio due to feedback control as shown in Figures 4 and 5. This reconfirms that fast feedback control is very important in reducing exhaust emissions.

Figure 7 shows the relative emissions ratio and the reference values for each exhaust emission for gasoline from start to 120 seconds. The emission ratios of the reformulated fuels have a lower level than those of gasoline.

HC emissions, are reduced by 15.7% and 51.2% for RM30 and RM50, respectively. CO emissions are reduced by 24.3% and 72.9%, respectively and NOx emissions are reduced by 35.3% and 58.9%, respectively. On the whole the emissions of RM50 are about a half of those for gasoline. As stated above, the starting problems can be solved using reformulated-fuels without using other devices.

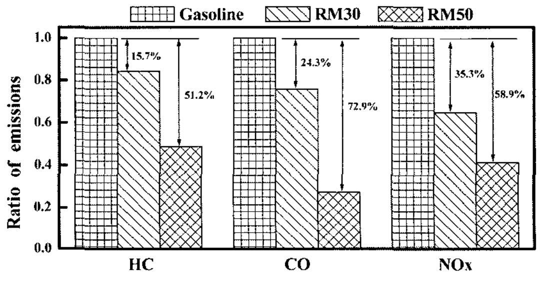
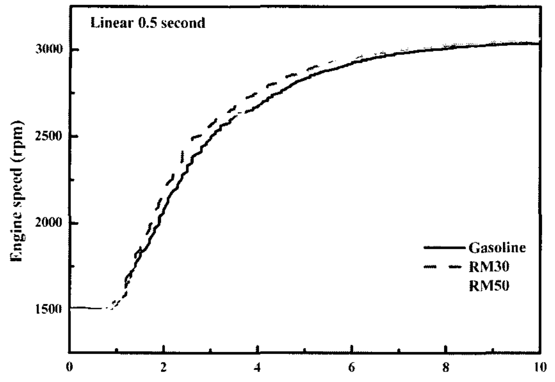
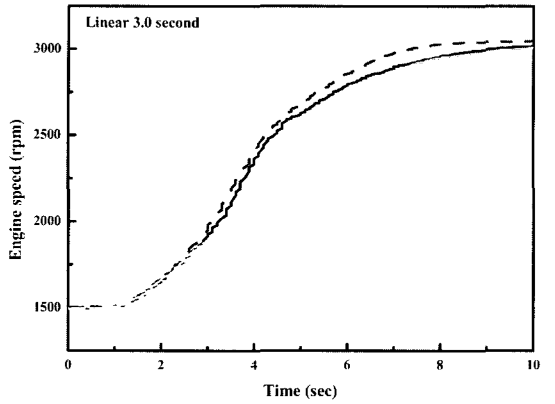


Figure 7. Relative emission ratio of exhaust emission based on gasoline for cranking mode.

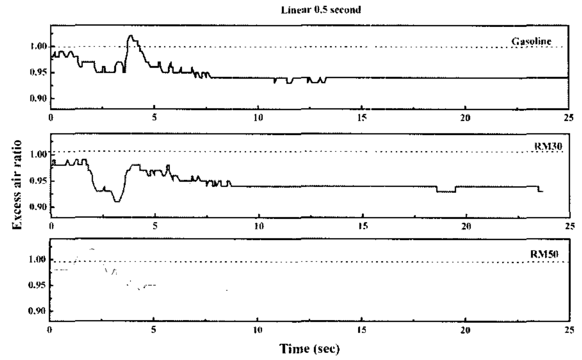


(a) Linear 0.5 second

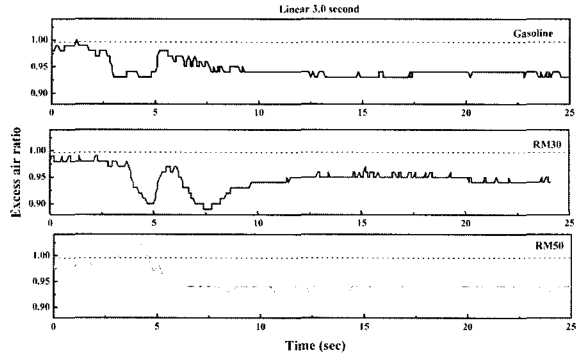


(b) Linear 3.0 second

Figure 8. Engine speed response for acceleration mode.



(a) Linear 0.5 second



(b) Linear 3.0 second

Figure 9. Excess air ratio for acceleration mode.

3.2. Acceleration Mode

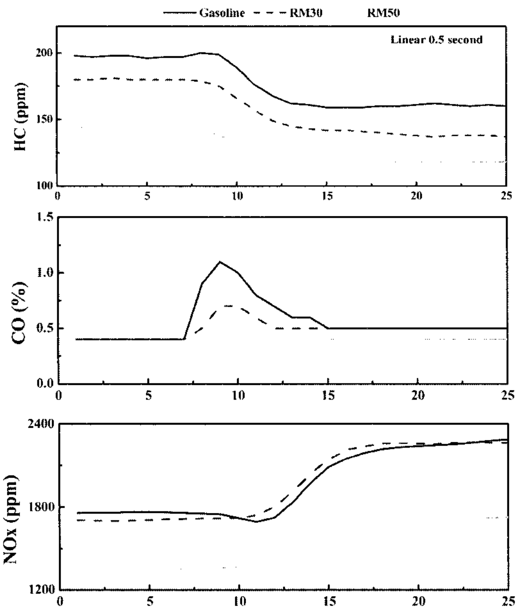
Figure 8 shows engine behaviors when revolutions vary from 1500 rpm to 3000 rpm with varying throttle valve opening times under a load of 4.6 kg·m. The accelerating times are 0.5 (rapid or fast acceleration) and 3 (slow acceleration) seconds respectively. RM30 has a faster revolution response than gasoline. The RM50 has the slowest response.

In the electronic controlled MPI (multi-point injection) type engine, the fuel is injected and enters the combustion chamber. In actuality, some of the fuel attaches to the intake port and some enters the combustion chamber. If the throttle valve is opened rapidly to improve power, the injection rate is insufficient, so the air-fuel mixture is lean for a while. To correct this problem, the throttle position sensor is used to increase the quantity of fuel when the throttle valve changes rapidly. Due to the instantaneous lean condition of RM50 after accelerating as shown in Figure 9, the feedback control increases the quantity of fuel, and the feedback response becomes much slower than other fuels. It is as if RM50 engine revolutions are slower than those of other fuels. This result is well with in the distillation curve at the 50% point as shown in Figure 1. From the distillation results, the acceleration performance could be predicted without conducting engine experiments.

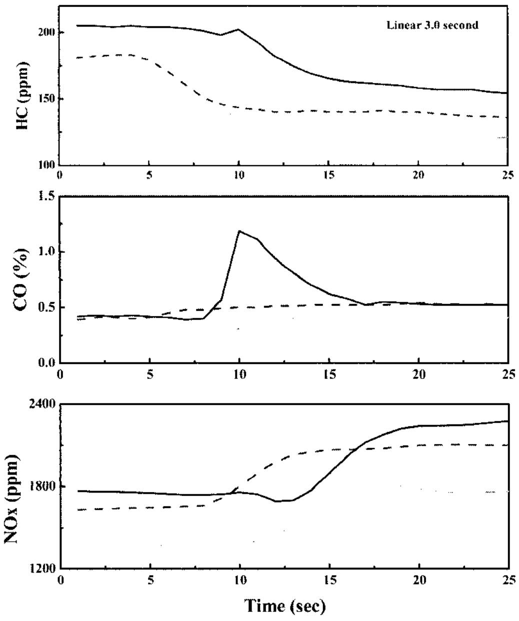
Figure 10 shows the results of the exhaust emissions for fast and slow accelerating conditions. In both cases, RM50 has good exhaust emission characteristics. In the slow acceleration mode, the changing points of emission levels for each exhaust gas are different. This means that the combustion characteristics of each fuel are well represented because the acceleration time is relatively long compared with the fast acceleration mode. On the contrary the changing points for the fast acceleration mode are almost the same for each exhaust gas.

In the fast acceleration mode, the changing points of the HC emission appears earlier than those of other exhaust gases. In the early stage, at 1500 rpm, the HC level is higher than that of the 3000 rpm. This is because the throttle valve-opening ratio increased and the charged air increased. The HC emissions of RM50 did not change much compared with the HC emissions of other fuels.

There are three mechanisms that are responsible for



(a) Linear 0.5 second



(b) Linear 3.0 second

Figure 10. Exhaust emission response for acceleration mode.

the production of NOx in the combustion process: the thermal or Zeldovich mechanism, the prompt or Fenimore mechanism, and the fuel NOx mechanism. The thermal mechanism is the most important during high-temperature combustion. The production of NOx needs residual time when it reacts at high temperatures. Therefore the changing point of NOx is later than that of other emissions.

Carbon monoxide is generated when the engine is operated under a fuel-rich condition. When there is not enough oxygen to convert all of the carbon to CO_2, some fuel does not get burned and some carbon ends up as CO. Not only is CO evidence of incomplete combustion, but it also represents lost chemical energy that is not fully utilized in the engine. The CO emission of RM50 changes just slightly in all acceleration modes. This is because the methanol fuel contains enough oxygen in itself.

During slow acceleration, the changing points of each exhaust gas are different, but the emissions have the same tendencies as during fast acceleration. As mentioned previously, RM50 seems to be a suitable clean fuel, which can be used in urban areas.

4. CONCLUSIONS

In this experimental research, the characteristics of the transient mode in SI engine were studied to compare pure gasoline and the alternative fuels RM30 and RM50 for performance and exhaust emissions without reconstructing of engine systems.

(1) In the distillation curve, in the vicinity of the 10% and 90% evaporation points, there was not much difference. At the 50–70% point, the characteristics of RM30 are similar to gasoline, but RM50 has a lower evaporation temperature than that of the other fuels and this affected acceleration. From the results of the distillation curve, engine performance could be predicted without experiments.

(2) In the cranking mode, the fuel injection duration is almost the same during the early stage, but the engine revolutions using RM50 behave differently due to a somewhat lean combustion. The emission characteristics of methanol-reformulated fuels are better than those of gasoline, especially RM50. From start to 120 seconds, HC emissions are reduced by 15.7% (RM30) and 51.2% (RM50), the CO emissions by 24.3% (RM30) and 72.9% (RM50), and the NOx emissions by 35.3% and 58.9%, respectively compared to the emissions for gasoline.

(3) In the acceleration mode, RM30 has the fastest response and RM50 had the slowest response. This is related to the response characteristics of the feedback control of fuel injection. The HC emissions of RM50 fuel do not vary as much within the range of 30 ppm. The CO concentrations for RM50 varys only a slightly during the acceleration.

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APPENDIX

The World-Wide Fuel Charter established both unleaded gasoline and diesel fuel to four different categories of fuel quality. These are described below.

Category 1: Markets with no or minimal requirements for emission control; based primarily on fundamental vehicle/engine performance concerns.

Category 2: Markets with stringent requirements for emission control or other market demands. For example, markets requiring US Tier 0 or Tier 1, EURO 1 and 2, or equivalent emission standards.

Category 3: Markets with advanced requirements for emission control or other market demands. For example, markets requiring US California LEV, ULEV and EURO 3 and 4, or equivalent emission standards.

Category 4: Markets with further advanced requirements for emission control, to enable sophisticated NOx and particulate matter after-treatment technologies. For example, markets requiring US California LEV-II, US EPA Tier 2, EURO 4 in conjunction with increased fuel efficiency constraints or equivalent emission standards.

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