International Journal of Automotive Technology, Vol. 8, No. 4, pp. 421−428 (2007)

1229−9138/2007/035−04

COMPARATIVE STUDY OF GAS-TO-LIQUID (GTL) AS AN ALTERNATIVE FUEL USED IN A DIRECT INJECTION COMPRESSION IGNITION ENGINE

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(Received 20 December 2006; Revised 3 April 2007)

ABSTRACT−This paper investigates the combustion and emission characteristics of a compression ignition engine fueled with neat and blended Shell's gas-to-liquid (GTL) fuel, which was derived from natural gas through the Fischer-Tropsch process. The experiments were conducted in a 6-cylinder DI diesel engine with pump timing settings of 6°, 9°and 12°crank angle before TDC over ECE R49 and US 13-mode cycles separately and compared to a conventional diesel fuel. The results show that GTL exhibited almost the same power and torque output, improved fuel economy and effective thermal efficiency. It was found that GTL displayed lower peak in-cylinder combustion pressure and maximum heat release rate (HRR), the timings of the peak pressure and the maximum HRR were generally delayed, and the combustion durations were almost equivalent for diesel and GTL under the same speed-load condition. The results also indicate that, compared to diesel fuel, GTL blends showed a trend forward decreasing four regulated emissions simultaneously and a higher GTL fraction in blends contributing to further reductions in the emissions. In particular and on average, neat GTL significantly reduced HC, CO, NOx and PM by 16.4%, 17.8%, 18.3% and 32.4%, respectively, for all cases.

KEY WORDS : Gas-to-liquid (GTL), Fischer-Tropsch, Alternative fuel, Engine performance, Combustion, Emission, Compression ignition engine

NOMENCLATURE

BMEP : brake mean effective pressure (MPa)
BSFC, *sbe*: brake specific fuel consumption (g/kW·h)
ETE, η_{et} : effective thermal efficiency (%)
Hu : mass lower heating value (MJ/kg)
BTDC : before top dead centre
CA : crank angle (degree)
CO : carbon monoxide
GTL : gas-to-liquid
G10 : mixed GTL-diesel fuel in a volume ratio of 10 per cent GTL
G20 : mixed GTL-diesel fuel in a volume ratio of 20 per cent GTL
G30 : mixed GTL-diesel fuel in a volume ratio of 30 per cent GTL
G50 : mixed GTL-diesel fuel in a volume ratio of 50 per cent GTL
G70 : mixed GTL-diesel fuel in a volume ratio of 70 per cent GTL
G100 : neat GTL fuel
HC : hydrocarbon
n : engine speed (r/min)
NOx : nitric oxides
PM : particulate matter
T90 : temperature of fuel 90% distillation (°C)
θ_{pt} : pump timing (°CA BTDC)
θ_{it} : fuel injection timing (°CA BTDC)
θ_x : injection lag (°CA)

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1. INTRODUCTION

The Fischer-Tropsch (F-T) catalytic conversion process can be used to synthesize alternative diesel-like fuels from a variety of feedstocks, including coal, natural gas and biomass (Anton, 2001; Hock *et al.*, 2004).

The Shell's SMDS (Shell Middle Distillate Synthesis) process can convert natural gas into gas-to-liquid (GTL) fuel via synthesis gas by combining a modern, improved F-T synthesis and a special hydro-conversion process, which is schematically illustrated in Figure 1 (Clark *et al.*, 2005).

Currently, the use of GTL as an alternative diesel fuel is receiving considerable attention due to its attractive properties, such as its high cetane rating, near zero sulfur and ultra low aromatic contents. Several papers have

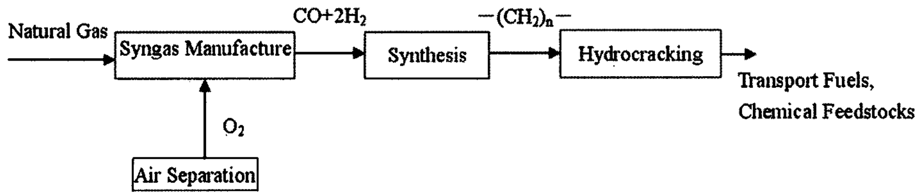


Figure 1. Schematic illustration of shell SMDS process.

documented GTL behavior and experiments have involved the study of engine and vehicle emissions running with GTL. The trends observed in those studies were a reduction in emissions using different kinds of GTL fuels compared to conventional fossil based diesel fuel (Leo *et al.*, 2000; Nigel *et al.*, 1999; Paul *et al.*, 1997; Thomas *et al.*, 2001).

Alleman *et al.* (Alleman and MaCormick, 2003) reviewed the Fischer-Tropsch diesel fuel's properties and exhaust emissions, then concluded that in almost every case, NOx, CO, and PM emissions were reduced with neat F-T diesel fuel except HC emissions, which were variable.

Christopher *et al.* (Christopher *et al.*, 1999) found that at all operating conditions, when compared to D2 diesel (a commercially available low sulfur diesel fuel approved for on-highway use by the U.S. Environmental Protection Agency) GTL yielded an approximately 14% longer combustion duration; exhibited an average 3.4% lower peak combustion pressure t and a 35% average lower maximum burn rate; and the location of the peak pressure was generally later for the GTL at the same speed and load.

Studies on GTL spray characteristics were also performed by some researchers. Jeong *et al.* found the penetrations of GTL increased with the pressure of common rail increasing and slightly larger than diesel at the same condition (Jeong *et al.*, 2005). Koji *et al.* investigated the spray characteristics of different GTL fuels and concluded that spray penetration lengths for all GTL fuels were similar, the spray angle was widened and SMD was reduced as fuel viscosity decreased (Koji *et al.*, 2005).

The goal of this work is to study in detail the engine performance, fuel economy, and combustion and emission characteristics of plentiful GTL blends with diesel in a 6-cylinder, turbocharged, direct injection compression ignition engine over steady 13-mode cycles in both Europe and the USA at three different pump timing settings. Furthermore, a comparison was conducted between GTL and diesel to explore the essential mechanisms that directly influence the combustion process and pollutant emissions.

2. TEST FUELS

Test fuels in this study were a conventional automobile diesel fuel, Shell GTL fuel derived from natural gas and several blends of these two fuels. G10, G20, G30, G50, and G70 represent blends with GTL volume fractions covering 10%, 20%, 30%, 50%, and 70%, respectively. Similarly, neat GTL fuel is labeled G100. The main physical and chemical properties of the total seven kinds of fuels are presented in Table 1.

3. TEST EQUIPMENTS AND PROCEDURE

The experimental set-up consists of a diesel engine, a hydraulic dynamometer and some other measuring instruments, shown in Figure 2.

The engine used in this study was a turbocharged, intercooled, direct injection, heavy-duty diesel engine. Major specifications of the engine are listed in Table 2.

The engine torque and power were measured by a hydraulic dynamometer, and fuel consumption was recorded

Table 1. Physical and chemical parameters of diesel and GTL fuels.

Property	Diesel	G10	G20	G30	G50	G70	G100
Density@15 (g/cm^3)	0.8392	0.833	0.8278	0.8207	0.807	0.792	0.779
Cetane number	51.7	53.3	56	59.1	64.8	70.6	75
Sulfur (%(m/m))	0.0403	0.0371	0.0331	0.0286	0.0196	0.0091	0.0003
Lower heating value (kJ/kg)	42868	42940	43003	43082	43237	43405	43555
Total aromatics (%(m/m))	27.7	24.9	23	19.7	13.5	6.4	1.4
90% V/V recovery T90 (°C)	330.8	329.2	326.2	323.7	320.4	316.4	310.1
Kinematic viscosity@40°C (mm^2/s)	2.665	2.657	2.679	2.664	2.649	2.725	2.74
Carbon (%(m/m))	86.32	85.85	86.01	85.18	85.48	84.81	84.9
Hydrogen (%(m/m))	13.32	13.94	13.64	14.5	14.25	14.8	15.1

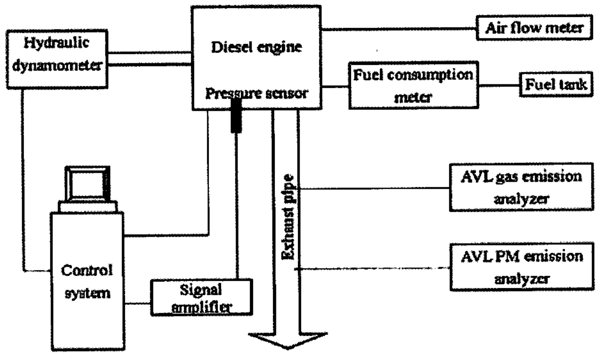


Figure 2. Schematic diagram of the experimental system.

Table 2. Engine specifications.

Engine type	D6114Z_LQB
Configuration	inline 6 cylinders
Aspiration	turbocharged, intercooled
Bore (mm)×Stroke (mm)	114×135
Engine displacement (L)	8.27
Compression ratio	18
Rated power (kW)/Speed (r/min)	184 /2200
Maximum torque ((N·m)/Speed (r/min)	1000/1400
Pump timing settings (°CA BTDC)	6, 9, 12
Nozzle number×Orifice diameter (mm)	6×0.24

by a transient fuel consumption meter. The history of the combustion pressure in the cylinder was logged by a Kistler 6125A type piezoelectric sensor, a Kistler 5015A charge amplifier and a Yokogawa GP-1B data acquisition apparatus. An AVL PROVIT5600 gas emission analyzer was used to measure the concentration of nitrogen oxide (NOx), total hydrocarbon (HC) and carbon monoxide (CO). The particulate matter (PM) mass was tested using a PM emission analyzer model AVL 472 Smart Sampler PC. Emissions experiments were performed over ECE R49 and US 13-mode cycles respectively.

As the diesel engine used in this study was equipped with a mechanically controlled pump-line-nozzle type fuel injection system, the start of injection can hardly be controlled directly, because it depends on sophisticated transport phenomena in the pump, high-pressure tubes, and the injector. However, the start of fuel injection is closely related to the start of pump fuel delivery, which can be set easily to any desired value. In this paper, the start of injection-pump delivery, namely, pump timing (θ_{pl}), was set at 6, 9 and 12°CA (degree crank angle) before top dead center (BTDC), respectively.

4. RESULTS AND DICUSSION

4.1. Engine Power, Torque, Fuel Consumption and Thermal Efficiency

Figure 3 shows torque and power of the engine operating neat diesel and GTL fuels with 6°, 9° and 12°CA BTDC pump timings. It can be clearly observed that there is very little difference in torque and power between diesel and GTL, which indicates that GTL can be used in prototype diesel engines without compromising engine power output.

Curves of the brake specific fuel consumption (BSFC) and the effective thermal efficiency (ETE) of diesel and G100 fuels are plotted in Figure 4. Formulation (1) and (2) are BSFC be and effective thermal efficiency η_{et}, where B is practical fuel mass consumption per hour, P_e is effective power of the engine, Hu is lower heating value.

$$be = \frac{B}{P_e} \times 10^3 \ \text{(g/kW·h)} \tag{1}$$

$$\eta_{et} = \frac{3.6 \times 10^6}{beHu} \times 100\% \tag{2}$$

It can be seen from Figure 4 that the BSFC of G100 is lower than diesel by 2.9% and the ETE of G100 is slightly higher than that of diesel by 1.4% on average at three different pump timings. The reason for this is that G100 has a higher mass-lower-heating value than diesel (Table 1).

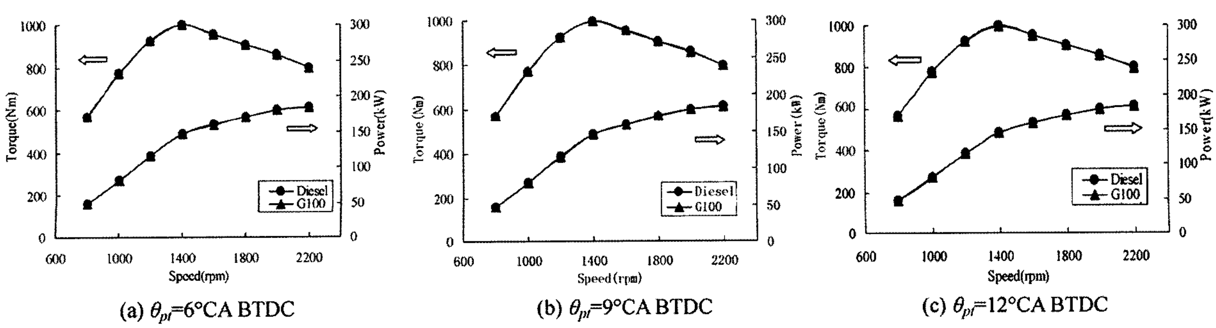
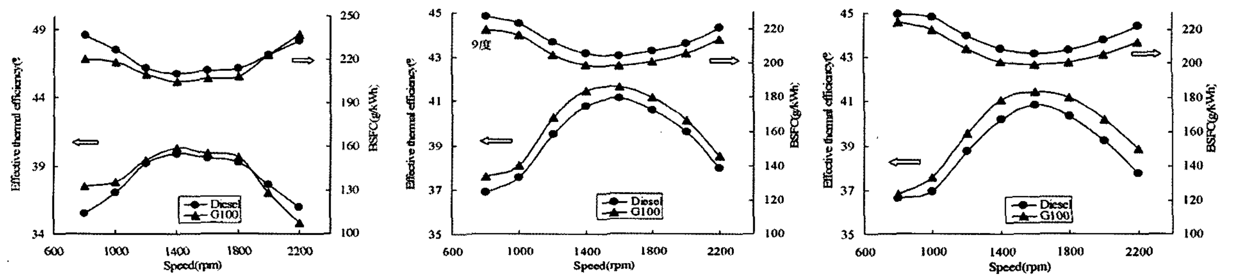


Figure 3. Torque and power of the engine at full load versus engine speed.



(a) θ_{pt}=6°CA BTDC (b) θ_{pt}=9°CA BTDC (c) θ_{pt}=12°CA BTDC

Figure 4. Brake specific fuel consumption and effective thermal efficiency of the engine at full load versus engine speed.

4.2. Combustion Pressure and Heat Release Rate

Comparisons of combustion pressure in cylinder and the heat release rate (HRR) at 1400 rpm, 1.52 MPa BMEP (brake mean effective pressure), with 6°, 9° and 12° pump timings are shown in Figure 5. Traces of combustion pressure were averaged over 50 cycles. The HRR was calculated using the first law of thermodynamics and a zero dimensional model (Heywood, 1988). It can be seen that the maximum combustion pressure of G100 is lower than diesel by 4.6%, 2.9% and 3.2% at three angles, respectively. This is due to the significantly high cetane number of GTL shortening ignition delay period during which time less combustible mixture formed and the maximum combustion pressure dropped. The location of the maximum pressure is slightly later for GTL. Lower peak combustion pressures, resulting in lower in-cylinder gas temperatures, would contribute to reduce NOx emission of GTL.

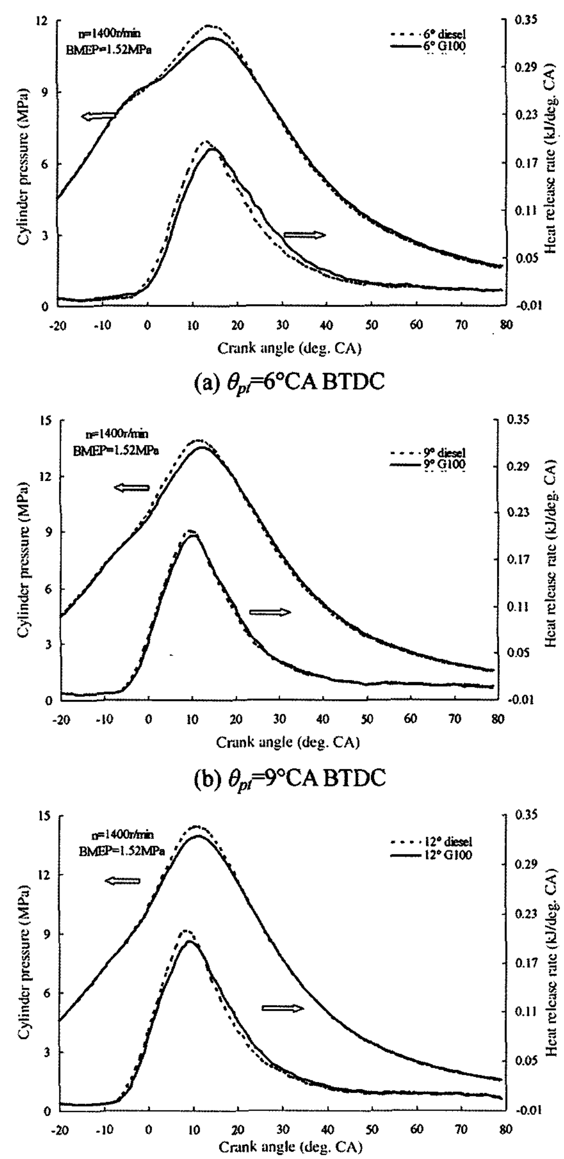
It also can be seen that the peak value of the HRR with G100 is lower than diesel at each of the three angles by 4.8%, 2.8% and 5.4%, respectively. The location of GTL heat release rate peak value is slightly retarded in comparison with diesel.

4.3. Ignition Time and Combustion Duration

The ignition time and combustion duration of G100 and diesel at the maximum torque operating point are described in Figure 6. Ignition time, namely, the start of combustion, is defined as the crank angle that 10 per cent of the total amount of combustion heat has released, and the combustion end point is defined as 90% of that. Combustion duration is defined as the difference between the above two angles.

GTL's ignition should be earlier than diesel, due to its much higher cetane number. However, what is in fact shown in Figure 6 is neat GTL igniting about 1 degree later than diesel. This can be explained by the following pump timing θ_{pt} and a fuel injection timing θ_{it} have the relationship seen in formula (2), where θ_x is fuel injection delay.

$$\theta_{pt} = \theta_{it} + \theta_x \quad (2)$$



(a) θ_{pt}=6°CA BTDC

(b) θ_{pt}=9°CA BTDC

(c) θ_{pt}=12°CA BTDC

Figure 5. Comparison of combustion pressure in cylinder and heat release rate.

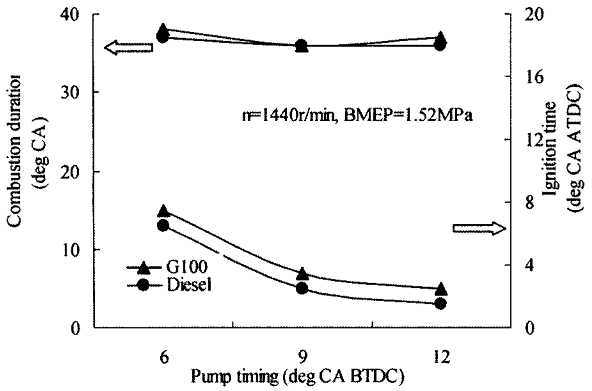


Figure 6. Comparison of ignition time and combustion duration.

The use of GTL fuel delayed the pump-line-nozzle type fuel injection system timing compared to diesel, because of the different densities and bulk modulus of the compressibility of the fuels (Boehman *et al.*, 2004; Szybist *et al.*, 2005). Szybist *et al.* found that the fuel line pressure of F-T diesel was lower than a conventional diesel BP325 (325 ppm low sulfur diesel fuel from BP) and F-T diesel caused a delay of the start of injection timing of 1.2-2.4 deg CA at 3600 rpm, 75% load (Szybist *et al.*, 2005). GTL with lower density and bulk modulus is more compressible than diesel fuel, so the pressure in the fuel injection system develops more slowly; pressure waves propagate later, leading to larger θ_x. As a result, the injection timing θ_{it} of GTL fuel starts later with lower pressure and rate than diesel at the same nominal pump timing θ_{pt}. Therefore, this may result in subsequently late ignition for GTL. The reason may also be for the delay of the maximum pressure and peak value of HRR for GTL in Figure 5.

It also can be observed from Figure 6 that there is nearly no significant difference in the combustion duration between diesel and G100. GTL with high cetane number should have a prompt combustion, however the injection delay of GTL leads to more fuel being injected in the cylinder after TDC, then, combustion efficiency was diminished and the end of combustion was delayed, therefore, the combustion duration for both fuels are comparable in the test.

4.4. Pollutant Emissions

Effects of GTL concentration in blends on HC, CO, NOx and PM emissions over ECE R49 13-mode cycles at 6°CA BTDC are presented in Figure 7. It is apparent that, compared to diesel, GTL blends offer reductions in the four regulated pollutant emissions simultaneously. Trend lines show there is a good relationship between the magnitude of reductions in emissions and the amount of GTL in blends. Typically, neat GTL (G100) shows the greatest reduction of 12.9% in HC, 16.6% in CO, 23.7% in NOx and 27.6% in PM in comparison with diesel.

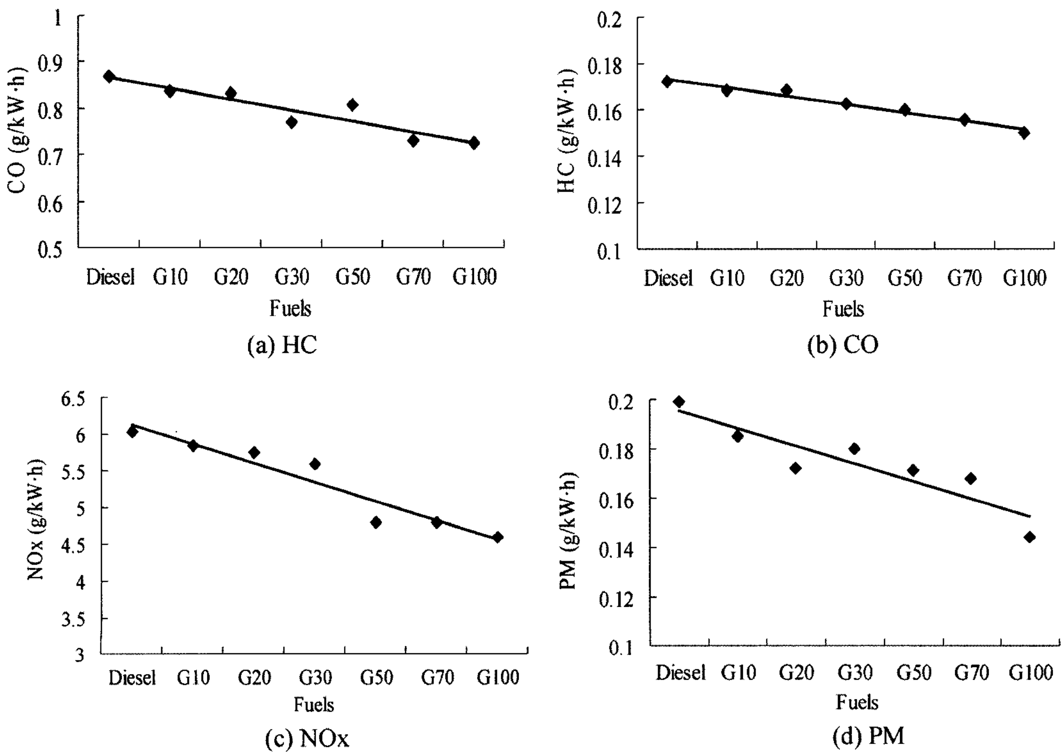


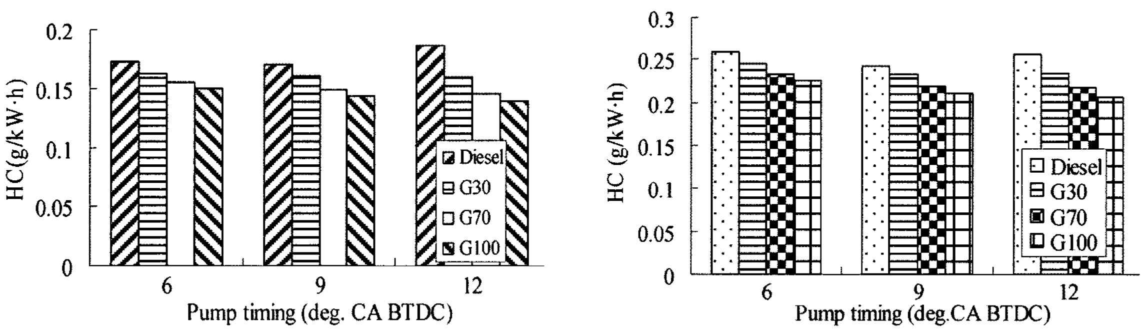
Figure 7. Pollutant emissions over ECE R49 13-mode cycles at 6°CA BTDC pump timing.

In addition to data shown in the above Figure 7, more runs of tests were also conducted in order to identify absolute GTL emission benefits under different test conditions. Emission performances of diesel, G30, G70 and G100 for both ECE R49 and US 13-mode cycles at 6°, 9° and 12°CA BTDC pump timings are described with histograms in Figure 8~Figure 11.

As expected, GTL fuels still have showed significant benefits in reducing emissions with the two 13-mode procedures and at the three different pump timings. Generally, reductions in four pollutant emissions are proportional to the amount of GTL in blends.

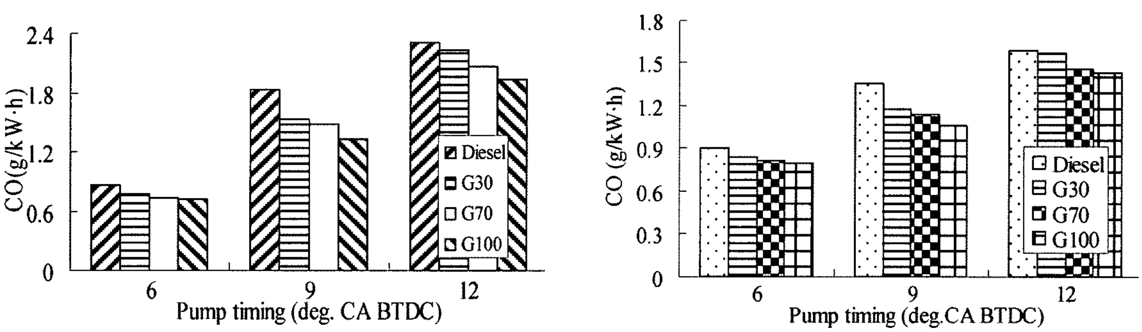
Figure 8 and Figure 9 show HC and CO emissions with diesel and GTL fuels, which are at very low level. GTL blends reduce HC and CO emissions at different pump timings; especially, G100 reduces 16.4% in HC and 17.8% in CO when compared to diesel. Amounts of intake air and combustion efficiency are the key factors affecting HC and CO emissions. Generally, the excess air coefficient of GTL is higher than diesel in the test, for instance, 0.1%~3% higher with GTL at 6 deg CA over ECE R49 13-mode cycle. With high cetane ratings and being an extremely low aromatic, GTL should have higher combustion efficiency leading to lower BSFC than diesel (described in Figure 4). Therefore GTL produced relatively low HC and CO emissions compared to diesel for its higher air-fuel ratio and lower BSFC. Lower T90 of GTL (shown in Table 1) than diesel indicates that GTL has a less heavy distillation, which suggests GTL easily evaporates and mixes with air, forming a more homogenous charge. So, part of the reductions in HC and CO emissions is also attributed to the lower T90 of GTL.

A comparison of diesel and GTL NOx emission is depicted in Figure 10. As the pump timing decreases from 12° to 6°CA BTDC, NOx emissions decrease gradually for all fuels. At a given angle, NOx emissions with diesel-GTL blends are lower than those of diesel; furthermore, more NOx emissions decrease with increasing GTL in blends. In terms of neat GTL, an 18.8% reduction in NOx is observed when compared to diesel. Late injection timing caused by late fuel delivering results in relatively higher temperature and pressure in cylinder and shortens the ignition delay period of fuels. Therefore, this short delay, which leads to less combustible mixture and lower maximum temperature, hinders the production of partial NOx. These histograms display that GTL can reduce NOx significantly and show that the approach of retarding injection timing is effective to reduce more NOx emissions. There is a good linear correlation between total aromatics in fuels and NOx emission (Nylund *et al.*, 1997), so lower NOx emission is also attributed to lower aromatics content of GTL.



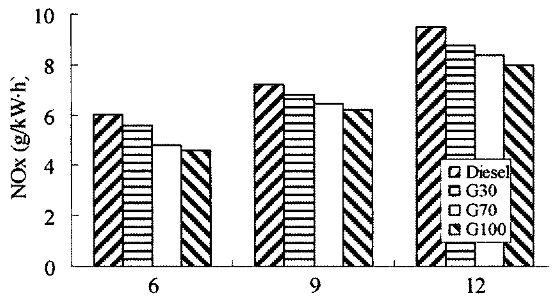
(a) ECE R49 13-mode cycle (b) US 13-mode cycle

Figure 8. HC emission over ECE R49 and US 13-mode cycles at different pump timings.

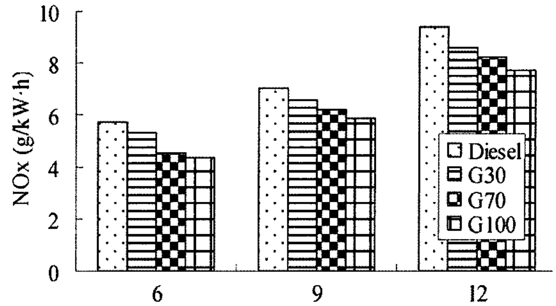


(a) ECE R49 13-mode cycle (b) US 13-mode cycle

Figure 9. CO emission over ECE R49 and US 13-mode cycles at different pump timings.

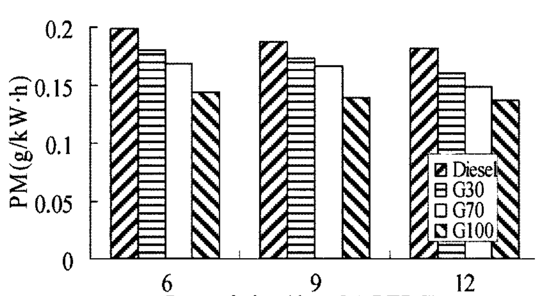


(a) ECE R49 13-mode cycle

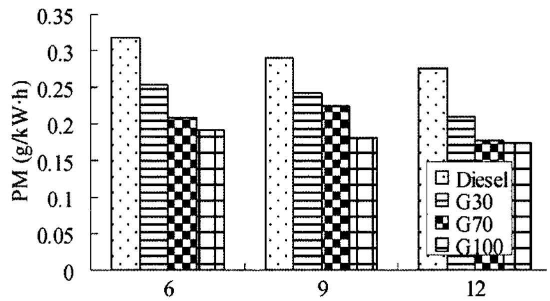


(b) US 13-mode cycle

Figure 10. NOx emission over ECE R49 and US 13-mode cycles at different pump timings.



(a) ECE R49 13-mode cycle



(b) US 13-mode cycle

Figure 11. PM emission over ECE R49 and US 13-mode cycles at different pump timings.

PM emission results are presented in Figure 11. As seen in the figure, from the later pump timing 6° to the earlier 12°CA, PM emission of each fuel decreases gradually. G100 produces 32.4% less average PM than diesel at three angles and with two test procedures. With early fuel delivering causing early fuel injection, the relatively low temperature and pressure in the cylinder makes the fuel ignition delay period relatively long, which is helpful for homogeneous charge forming, resulting in decreasing PM.

It is obvious that PM emissions with GTL fuels are lower than diesel at any given angle and a higher GTL percentage in blends contributes to more reductions in PM. Reductions in PM are due to the zero sulfur content, which eliminates the sulfate contribution to PM and ultra low aromatic content, which reduces the soot contribution to PM. The figure indicates GTL fuels can significantly reduce PM emission, and further reduction of PM can be obtained by coupling with a advanced injection timing.

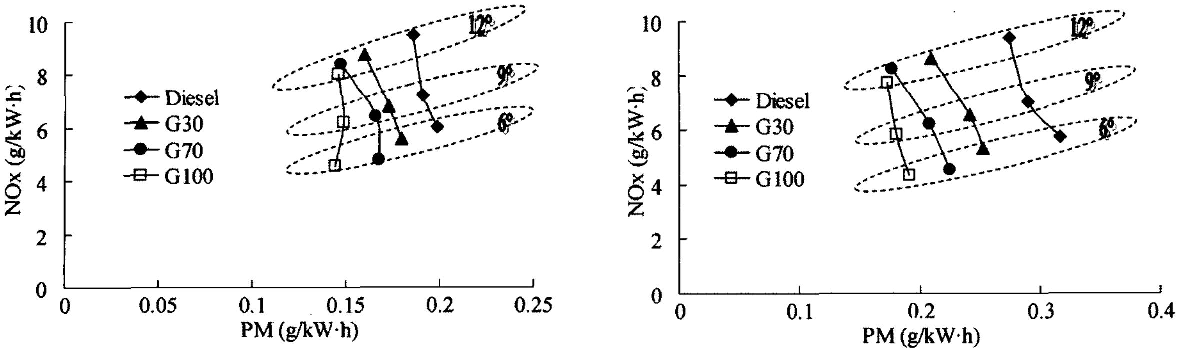
A correlation of NOx and PM emissions of diesel and GTL fuels over ECE R49 and US 13-mode cycles at three different pump timings is shown in Figure 12. It can be observed that GTL fuels have eliminated the tradeoff relation of PM and NOx emissions in some conditions. For all GTL fuels, both NOx and PM emissions are lower than diesel at the three angles, which suggests GTL can reduce these two emissions simultaneously. NOx and PM with G100 at 6°CA are lower than diesel at 12°CA by 31.1% and 38.2% in Figure 12(a), and by 53.9% and 30.4% in Figure 12(b), respectively. This shows that, compared to diesel, the use of GTL fuel coupled with the retardation of pump timings is an effective means to improve NOx emissions of CI engines without compromising PM emissions.

5. CONCLUSIONS

A study of combustion and emission performance of GTL blends compared to conventional diesel was conducted using a 6-cylinder, 4-stroke DI compression ignition engine, which was run over a couple of steady test cycles under multiple pump timing conditions. The main conclusions of the investigation can be drawn as follows:

(1) The neat GTL fuel exhibits almost the same power and torque output as diesel.

(2) The neat GTL has lower brake specific fuel consumption with 2.9% reduction, and slightly higher effective thermal efficiency of 1.4%, than diesel under the test conditions.



(a) ECE R49 13-mode cycle

(b) US 13-mode cycle

Figure 12. NOx-PM tradeoff for diesel and GTL fuels.

(3) The neat GTL displays lower maximum combustion pressure in the cylinder, as well as the peak value of heat release rate; the locations of the two peak values are generally retarded when compared to diesel.

(4) The ignition of neat GTL is slightly later than diesel by 1°CA. The combustion duration of GTL is almost equivalent to that of diesel.

(5) Compared to diesel fuel, four regulated emissions decrease with increasing GTL in diesel-GTL blends. Especially, neat GTL reduces HC, CO, NOx and PM, respectively, by 16.4%, 17.8%, 18.3% and 32.4% on average over ECE R49 and US 13-mode cycles at 6°, 9° and 12°CA BTDC pump timings due to its unique fuel properties.

(6) A tradeoff between NOx and PM emissions can be eliminated in some conditions by using GTL fuel coupling with optimum injection timing for diesel engines.

ACKNOWLEDGEMENT–The authors thank the Shanghai Science & Technology Commission (contract No. 043012015) and Shell International Gas Limited for financial support for this study. Shell also provided the GTL fuel and fuel property data.

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