Performance and Exhaust Emission Studies of a Large LNG-Diesel Engine Operating with Different Gas Injector's Characteristics

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Abstract
This research article reports the performances and emissions of a 12-litre LNG-diesel dual-fuelled engine when equipped with two different gas injectors. Natural gas is used as main fuel with a pilot amount of diesel for the ignition source. The main objective of this study is to replace the imported injector by the local product, while maintaining the performance compatibility. This means an economical benefit is obtained. Both gas injectors' characteristics are investigated and found that characteristic of local product is relatively different from the imported one. The results show that injectors' characteristic analysis must be separated into two ranges, including lower and higher engine speed ranges. Thus, the local injector must be then electronically adjusted in order to attain the engine performance and emission compatibilities. Consequently, it can operate satisfyingly, while no engine knocking is observed. The engine performance results show minor differences between two injectors, which are averagely less than 0.43%. The exhaust emissions also show small differences. The graphical presentations, the discussions and conclusions are also presented in this paper.

Keywords: *Gas injector, LNG, Diesel, Performance, Emission*

1 Introduction

In the present situation of rapid depletion of fossil fuel resources and the coming up of environmental issues are main motives for the growth of alternative fuels. Many alternative fuels have been tested successfully in the engine with or without modifications. Natural gas has been drawing many people attention since it is one of the most interesting alternative fuels with high hydrogen to carbon (H/C) ratio which minimizes the greenhouse gas, carbon dioxide (CO_2).

Natural gas is a blend of hydrocarbon fuels mainly methane. According to its low density, it is compressed under high pressure of approximately 200 to 250 bars, so called "Compressed Natural Gas" (CNG). Normally, the price of CNG is around one-third of conventional fuels which really draws many people attention. In liquefied form, the volume of liquefied natural gas (LNG) becomes 600 times less than the same amount of natural gas at room temperature. The energy density is about 2.4 times comparing to that of CNG. The capital cost of LNG is also less than CNG due to non-electricity consumption. Therefore, LNG presents special benefits over CNG in the terms of transportation, storage and energy density [1].

Two applications of natural gas in diesel engines have been implemented. First, the diesel engine is dedicated to operate as a spark ignition engine by modified the pistons and replacing the diesel fuel injectors with spark plugs and some other modules. The other method is to operate the engine with both diesel and natural gas which is called "Dual Fuel".

Natural gas is used as the main fuel while a pilot amount of diesel is injected into the cylinders for the starting of combustion.

The difference between the diesel engine and LNG-diesel dual-fuel engine is the addition of gas vaporizer and natural gas injectors into the intake manifold. Hence, the gas injector plays an important role here. An appropriate amount of gas must be injected accurately and timely in order to obtain a proper distribution of air and fuel. This is one of the most important key points for keeping away from the abnormal combustion [2-3].

Previous studies have completed a variety of issues about the gas injection in diesel-gas dual-fuel engines. Appropriate portion of injected gas for each specific engine condition has been reported by literatures [4-5]. Literatures [6-7] also tried to investigate the effect of gas injection timing. While there are some other issues, which focus on the injector durability [8] and control system [9-10]. It can be understood that these literatures are mainly aimed to reveal the effect of process parameters on the response parameters in laboratory scale because most of literatures are conducted in a single cylinder engine and they do not show any incentives in commercial or business viewpoints. These points became the most two important research gaps.

This research is performed in order to fulfil the research gaps as discussed above. Firstly, knocking is a main problem in small dual-fuel engines, as reported in literatures [6,11-12]. This problem is even more pronounced for the utilization of gaseous fuel in large engines [13]. However, this experiment is conducted in a 12-litre heavy-duty commercial engine.

Secondly, this investigation came up with the economical reason. The engine needed six imported gas injectors for the multipoint injection system. Practically, imported natural gas injectors cost approximately twice comparing to the local product. Thus, the main objective of this research is to substitute the imported injectors with the local products. Both injectors' characteristics must be verified and controlled electronically in order to obtain compatible engine performances and emissions without any knocking phenomena.

2 Experimental Setup

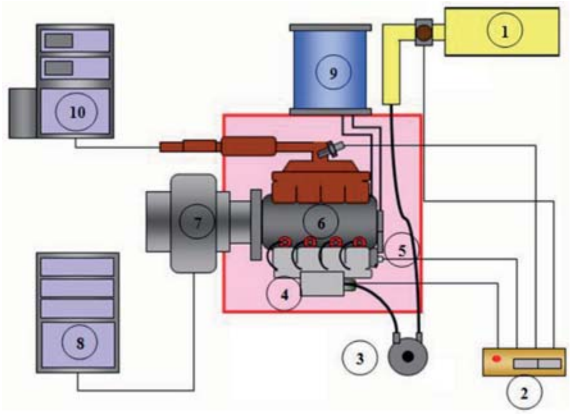
As mentioned earlier, the primary objective of this experimental investigation was to substitute the imported injectors (so called "Injector A") with the local product (so called "Injector B") in a large LNG-diesel engine. However, it is found that the difference in electronic characteristic between two injectors was the main obstacle. Hence, the investigation tried to control injector B electronically in order to meet the compatible output engine performance and exhaust emissions to those of injector A. The engine control module, TEMS LNG Dual Fuel ECU was connected to all injectors together with top dead center sensor and crank angle sensor. Hence, the researcher can control both injection timing and injection duration via this equipment.

The engine used in the study was a Hyundai D6CA (Direct Injection). The specifications of tested engine are shown in Table 1. Literatures found that knocking phenomena usually occurred in dual-fuel operating mode [6,11,13]. Thus, two knock sensors were attached at the engine block to observe knocking. The engine was connected to an AVL AC-Dynamometer rated at 2500 Nm and a maximum speed of 7500 rpm. The Horiba Mexa-7100 D gas analyzer was equipped to measure the emissions. THC and NO_x were analyzed using a flame ionization detector and a chemi-luminescent detector, respectively. While CO and CO_2 were analyzed using the non-dispersive infrared technique.

Table 1: Specifications of the tested engine

Model	D6CA
Displacement (cc)	12,920
Bore x Stroke (mm)	133 × 155
Cooling Type	Water Cooling
Fuel Supply System	Direct Injection
Cylinders	6 in Line
Compression Ratio	17 : 1
Aspiration	Turbocharge Intercooler

The experimental setup is shown in Figure 1. The engine was dual-fuel operated at full load with speeds between 1100 and 2000 rpm. A set of injector A was first installed to the engine, using multipoint port gas injection method, while a pilot amount of diesel fuel was still used as an ignition source. After the test, gas injector A was also replaced with injector B as shown in Figure 2 and Figure 3. The engine was tested under the same operating condition. Consequently, researcher can compare the results between injector A and injector B operations.



1. LNG Tank
2. Electronic Control Unit
3. LNG Vaporizer
4. Gas Injection System
5. Diesel Injection System
6. Tested Engine
7. Dynamometer
8. Dynamometer Controller
9. Cooling System
10. Exhaust Gas analyzer

Figure 1: The experimental setup.

Figure 2: Installation of injector A.

Figure 3: Installation of injector B.

Brake thermal efficiency and brake specific fuel consumption (BSFC) were calculated using Equations (1) and (2).

$$\eta_{th} = \frac{Power \times 100\%}{\dot{m}_f \times Fuel\ Heating\ Value} \tag{1}$$

$$BSFC = \frac{\dot{m}_f}{Power} \tag{2}$$

Where $\dot{m}_f$ = Fuel flow rate (kg/hr)

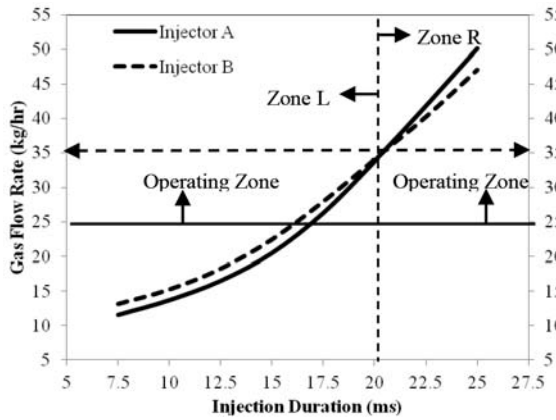


Figure 4: Relation between injection duration and gas flow rate.

3 Results and Discussions

3.1 *Characteristic of gas injectors*

The relations between injection durations and gas flow rates of both injectors are investigated. It is found that, injector B can supply higher gas flow rate at the injection duration below around 20 milliseconds (marked as "Zone L" on the left side of the vertical dashed line) but it is vice versa when the duration is over 20 milliseconds (marked as "Zone R" on the right side of the vertical dashed line) as shown in Figure 4. Researchers have done a preliminary experiment in order to identify the approximate gas flow rate of the tested engine. The test reveals that the smallest amount of gas flow rate is approximately 25 kg/hr. Thus, the operating zone is located above the horizontal solid line, as seen in Figure 4. This data will be further discussed in section 3.2.

The key point of this research is the gas injectors. Hence, characteristics of gas injectors, while operating in zone R, are further investigated and are shown in Figures 5 and 6. When injector A is stimulated, the current approaches to the peak with faster actuation time than that of injector B. There is also a small period of hold peak current which maintains injector A in open position, while injector B does not show this period according to the slower response. Consequently, in zone R, injector A can inject a certain amount of natural gas more precisely and accurately than that of injector B.

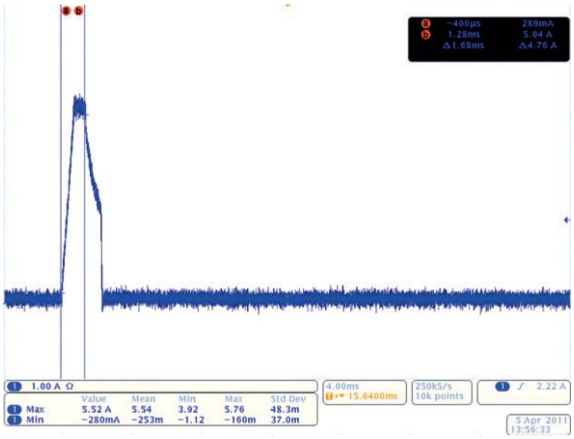


Figure 5: Electronic characteristic of injector A.

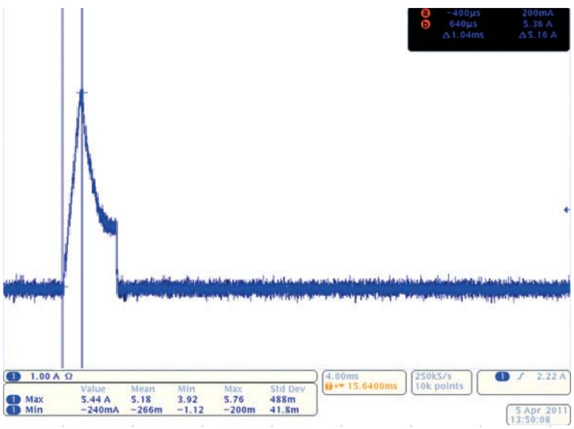


Figure 6: Electronic characteristic of injector B.

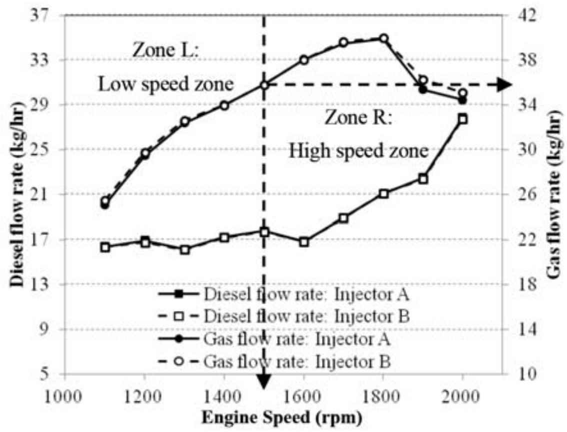


Figure 7: Fuel flow rates versus engine speed.

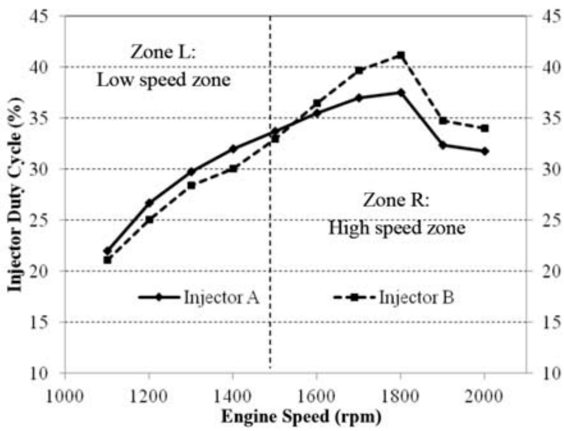


Figure 8: Injector duty cycle versus engine speed.

Therefore, Figures 4 to 6 can be concluded that the performance of injector A is higher when it operates in zone R. On the other hand, injector B shows a higher performance in zone L.

In order to replace injector A (imported product) with injector B (local product) and still maintain the compatible engine performances without abnormal combustion, zone R is unquestionably the critical area. In this zone, natural gas must be accurately and timely injected by a proper controlling. Researchers adjusted two parameters including, gas injection timing and injection duration by increase the duty cycle of injector B electronically.

For simplicity, it is important to notify that the intersection point in Figure 4 is taking place at around 35 kg/hr, as shown by the horizontal dashed line. Concurrently, the gas flow rate of 35 kg/hr occurs at the speed of 1,500 rpm as shown in Figure 7. Then, this engine speed becomes the border line between zone L and zone R. In other words, injectors operate in zone L when the engine speed is below 1,500 rpm and if the engine speed is over 1,500 rpm, they are operating in zone R. It is clearly seen, in Figure 7, that the amount of diesel injection is fixed, while researchers try to introduce the same amount of natural gas into the tested engine.

In Figure 8, injector B does not have any problem to operate in zone L because of its higher performance. However, its duty cycle must be decreased in order to attain the equivalent amount of natural gas, which alleviates knocking problems [13]. The duty cycle of injector B is increased in zone R in order to supply an adequate amount of natural gas since it presents a lower performance, as already shown in Figure 4.

According to the adjustment of the duty cycles,

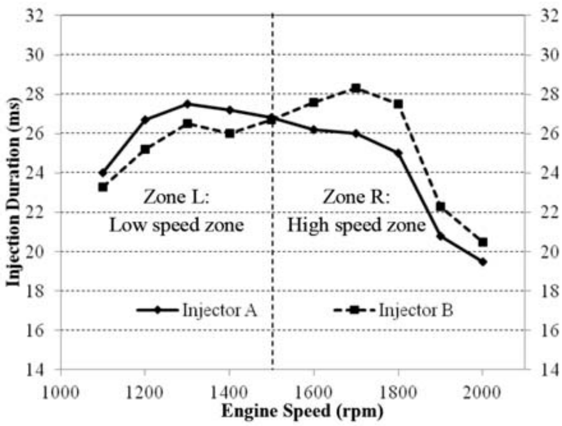


Figure 9: Injection duration versus engine speed.

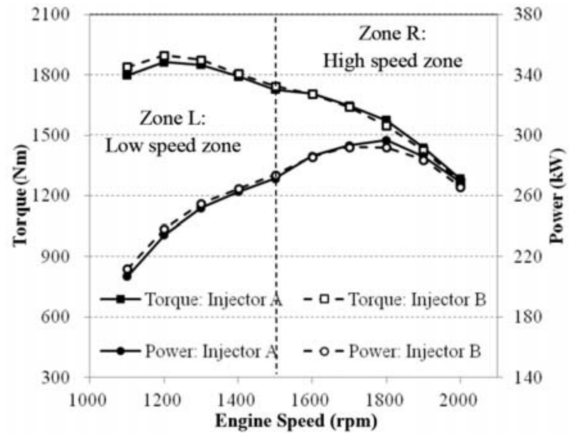


Figure 10: Torque and power versus engine speed.

gas flow rate of both injectors are very identical. Preliminary, both injectors are predicted to generate a compatible engine performance. These results will be shown in section 3.2.

Figures 8 and 9 present a clear proportional relation of duty cycles and injection duration of both injectors A and B. Figure 9 also reveals that the operating curve of injector A has smoother gradient than that of injector B. This means that the engine with injector A can run more consistently, smoothly and precisely especially in the transient operating condition.

3.2 *Comparisons of engine performances*

The consequences of two gas injector on the engine performances are presented in Figures 10 and 11. Figure 10 shows the relations between output torque and power at a wide range of engine speeds, while Figure 11 shows the relation between thermal efficiency and BSFC.

It is expected that torque increases as engine speed increases until it reaches a maximum point. After that, torque decreases at a higher speed because of the inability of the engine to intake a full charge of air. Since heavy-duty diesel engines are normally designed for high torque at a low speed range, the maximum torque is observed at the speed of 1200 rpm.

The power increases with engine speed and then significantly decreases at higher speeds of 1900 rpm. This is due to the fact that friction losses increase with speed and become a dominant factor at very high speeds.

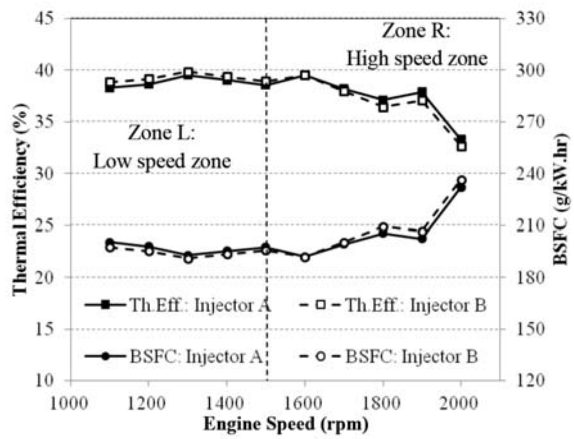


Figure 11: Thermal efficiency and BSFC versus engine speed.

In low speed range, the engine with injector B show a slightly higher torque and power than that of the injector A. while in high speed range, the engine with injector B has shown vaguely lower torque and power. However, these differences are approximately 1.42% and -0.47%, respectively.

Thermal efficiency and BSFC are calculated by equations (1) and (2). Thermal efficiency shows a similar trend to torque and power. The differences are only 0.43% in low speed zone and -0.33% in high speed zone. BSFC is usually inversely proportional to the thermal efficiency. The engine with high thermal efficiency normally means lower fuel consumption. Thus, BSFC has exactly same trend and gradient with thermal efficiency, as shown in Figure 11.

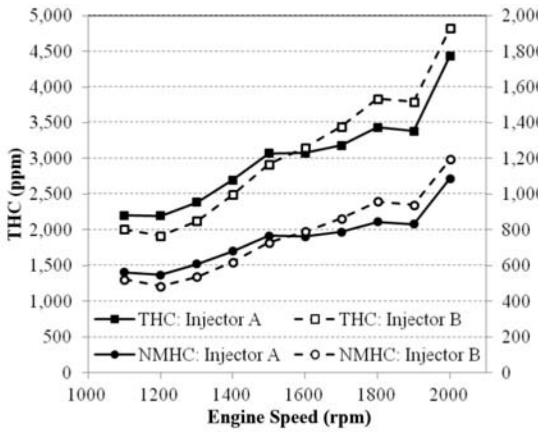


Figure 12: THC and NMHC versus engine speed.

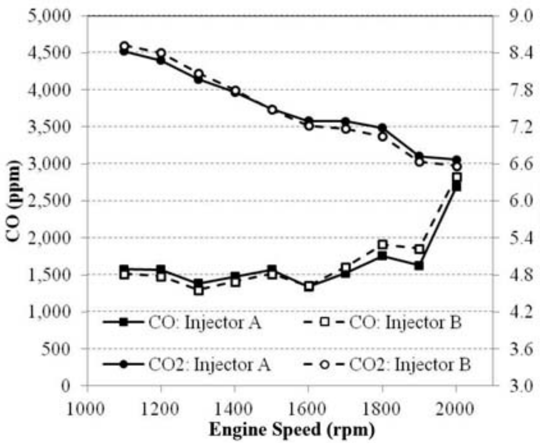


Figure 13: CO and CO_2 emissions versus engine speed.

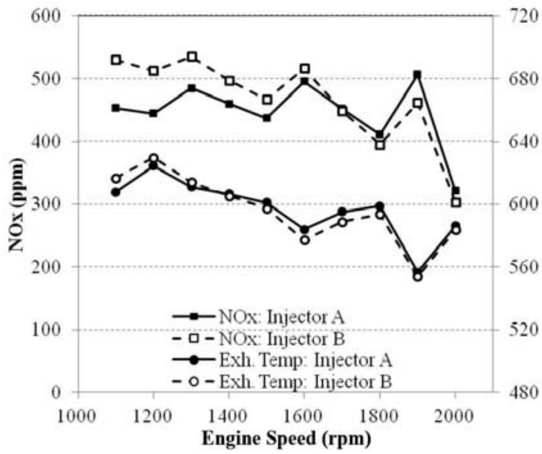


Figure 14: NO_x and exhaust temperature versus engine speed.

3.3 *Comparisons of engine emissions*

Figures 12 to 14 report the effects of injector characteristic on the exhaust emissions. To simplify the explanation, according to Figure 7, we can assume that diesel and natural gas flow rate are not significantly different. Nevertheless, the emission results still show the noticable variations between two injectors. It is verified that, not only the amount of injected fuel affects the exhuast emissions, but the technique of injection also influences.

As previously discussed in section 3.1, injector B operates more precisely and accurately in the low speed range, while injector A shows its potential in the high speed range. This reason can be the key explanation of Figures 12 to 14.

Theorethically, the complete combustion can totally convert hydrocarbon (HC) fuels into carbondioxide (CO_2) product. Thus, the exhaust gas consists of lower HC and higher CO_2. The existing of HC and carbonmonoxide (CO) in the exhaust gas indicates the incomplete combustion, since both of these emissions can be further combusted and releases some more output energy with a certain amount of CO_2.

In Figure 12, total hydrocarbon (THC) and non methane hydrocarbon (NMHC) are presented. These emissions are not much considered in the diesel operation [14] but it is very significant in gaseous engine [15-16]. These emissions indicate the level of incomplete combustion. The results show that engine with gas injector B can inject more accurately and timely. Thus, it combusts more efficiently and emits less hydrocarbon in low speed range. When the engine speed increases, injector B then shows a lower performance. The hydrocarbon emissions becomes higher than that of injector A in higher speed range.

Lower hydrocarbon emission from efficient combustion theorethically comes up with lower CO emission and higher CO_2 as seen in Figure 13. The result also shows this relation in both low and high engine speed ranges.

Figure 14 shows a relation of NO_x and exhaust temperature. NO_x emission is generated under the high combustion temperature conditions. In low speed range, injector B comes up with efficient combustion, which leads to the high combustion temperature. High exhaust temperature and high concentration of NO_x

emission are presented here. The result shows vice versa in the high speed range with the same explanation.

4 Conclusions and Recommendations

This research aims to investigate the effect of gas injector's characteristics on the performances and emissions of a heavy-duty LNG-diesel engine. This is to substitute the imported gas injector by the local product in order to obtain an economical benefit.

The results show that the local injector can operate more efficiently at low engine speed but it performs less efficiently at high engine speed. This is noticed from the injector's actuation time. Researchers try to maintain the same gas flow rate by adjusting the duty cycle. Consequently, the engine performances from both injectors are very similar. The difference is averagely around -0.33% to 0.43%.

Even the engine performances are not significantly different. It is also found that injector with faster actuation time can inject a certain amount of natural gas more precisely and accurately, which leads to an efficient combustion. Lower HC and CO emissions come up with higher CO_2 are the indicator for the complete combustion. High NO_x emission and high exhaust temperature also identify the complete combustion with high combustion pressure and temperature.

This experiment reveals the possibility of replacing the imported product with local product. This give a big advantage in economical aspect. However, it is important to mention that different injectors can supply same amount of natural gas by adjusting their duty-cycle, which results to a similar engine performance, but the exhaust emissions also depend on the actuation time or the quality of the injectors. Therefore, the limitation of this research is found that the engine is tested at steady conditions over a wide range of engine speeds. It is very interesting to compare the results of these two injectors while they operate under transient condition to investigate the effect of injector's actuation time. This makes the research more approaching the real application and present more impact.

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