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Effects of Fuel Ratio on Performance and Emission of Diesel-Compressed Natural Gas (CNG) Dual Fuel Engine

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Abstract – *Recent research breakthrough reveals that diesel-CNG dual fuel (DDF) combustion can potentially reduce exhaust emission of internal combustion engines. However, problem arises when knock phenomenon occurs producing high carbon monoxide (CO) and hydrocarbon (HC) emission due to uncontrolled blending ratio of diesel-CNG fuel on specific engine load. This study will determine the limit of dual fuel ratio before knock occurrence while analysing performance and exhaust emission of an engine operating with diesel and DDF fuel mode. A 2.5 litre 4-cylinder direct injection common-rail diesel engine was utilised as a test platform. The models tested were 100% Diesel, 90% DDF, 80% DDF and 70% DDF, representing diesel to CNG mass ratio of 100:0, 90:10, 80:20 and 70:30 respectively. It was found that DDF engine performance was lower compared to diesel engine at 1500 rpm engine speed. At higher engine speed, the 70% DDF showed engine performance comparable to diesel engine. However, high HC emission with knock onset and a decrease of Nitrogen Oxide (NO_X) emission were recorded. This study suggests the preferred limit of dual fuel ratio should not be lower than 70% DDF which will be able to operate at high engine speed without the occurrence of knock and poor exhaust emission.*

Keywords: Alternative fuel, CNG-diesel, dual fuel, common rail, diesel engine

1.0 INTRODUCTION

The issue of global warming continues to be hotly debated ever since the turn of century. In addition, human daily activities including the use of fossil fuel in transportation which contributes to black carbon and certain ozone precursors, have further aggravated such a situation. Hence, stringent vehicle exhaust emission regulations are being implemented to mitigate the problem. At the same time, engine development technology has evolved to lower carbon emissions as a means to curb global warming.

One initiative is to shift to a cleaner fuel such natural gas which has higher hydrogen-carbon ratio (H/C) and produces less greenhouse gases compared to diesel fuel. Natural gas also has higher octane number and is suitable for high compression ratio engines. Therefore, natural gas which is found in abundance may be considered as the best alternative because it is clean and less polluting compared to other common fossil fuels. In short, substituting diesel with natural gas can be considered as part of the low carbon initiatives to potentially save the environment.

The use of Compressed Natural Gas (CNG) in any gasoline engine is straight-forward, where both fuel uses spark ignition to combust and generate power. The use of CNG in a diesel engine also requires a source of ignition, although the spark plug is unavailable in diesel engine. A diesel-CNG dual fuel or DDF system is one of the methods to apply CNG in diesel engine. DDF system operates by injecting a controlled amount of CNG fuel into the intake manifold as substitute fuel while another portion of diesel is directly injected into the combustion chamber as pilot to ignite combustion.

This method is more practical and economical compared to installation of fuel and ignition system through major modification to the diesel engine. It is believed that DDF engine may provide benefits with better fuel economy and exhaust emission. Addy et al., (2000) found that Nitrogen Oxide (NO_X), Carbon Dioxide (CO_2) and Particulate Matter (PM) emission of DDF was lower compared to diesel engine. However, Papagiannakis & Hountalas, (2004) argued that DDF showed poor combustion efficiency, poor brake power, high CO and HC emission at particular engine operating conditions.

In actual practice, the dual fuel ratio of diesel to CNG should not be kept constant but should be dependent on specific engine load. Hakim et al., (2015) revealed that DDF can be operated using diesel to CNG ratio of 30:70. CNG substitution is possible to be obtained up to 90% with greater power output compared to diesel engine (Dahodwala et al., 2014). However, excessive amount of CNG fuel may lead to knocking which would cause engine damage. Therefore, further assessment and optimization with respect to the dual fuel ratio over specific engine operating are needed.

2.0 DDF ENGINE COMBUSTION

Combustion of DDF engine is combination of Diesel cycle and Otto cycle (Weaver & Turner, 1994). Its in-cylinder pressure is lower compared to diesel fuel combustion (Aroonsrisopon et al., 2009; Hakim et al., 2015; Selim, 2001). At low load engine operation, combustion duration of a DDF engine is longer than diesel engine. In contrast, the combustion duration of DDF engine becomes shorter than diesel engine at high load operation. The NO_X emission of DDF engine shows a reduction, but the CO and HC emission shows increment. However, the CO and HC emission can be reduced using an exhaust catalyst (Aroonsrisopon et al., 2009; Dishy et al., 1995)

According to Shioji et al. (2001), HC emission can be reduced by increasing diesel pilot fuel quantity and advancing the pilot injection timing. However, NO_X emission is increased along with increment of diesel fuel quantity. A study conducted by Ryu (2013) showed the IMEP and NO_X emission increase as the pilot injection timing was advanced from -11°CA to -20°CA. In addition, Aroonsrisopon et al. (2009) showed NO_X concentration can be reduced by advancing the pilot injection timing more than -20°CA. When the pilot injection timing is over advanced, IMEP is decreased drastically with occurrence of misfiring. Therefore, the suggested optimum injection timing was -40°CA because the IMEP also decreased when the injection timing was retarded below than -20°CA.

3.0 KNOCK PHENOMENON ON DDF ENGINE

An uncontrolled combustion in DDF on compression ignition engine is similar to the knocking phenomenon in spark ignition engine. The knock phenomenon in DDF engine can be described by a high peak pressure gradient of the charge in cylinder. It occurs due to the auto-ignition of CNG fuel and drastically raise the in-cylinder pressure (Wannatong et al., 2007). The heat releases abruption of air and gaseous fuel mixture resulted from the abnormally high reaction rates (Saidi et al., 2005).

Among the causes of knock phenomenon is the preheated air-fuel mixture in the intake manifold (Jun et al., 2003; Ryu, 2013; Saidi et al., 2005). During combustion, heat energy from the combustion chamber is transferred to the intake manifold where the CNG is injected. As consequence, the air-fuel mixture goes into the preheating process before it gets sucked into the cylinder. Preheating of the CNG tends to auto-ignite as it reaches the auto-ignition pressure and temperature.

Jun et al. (2003) state that the auto-ignition pressure and temperature of CNG fuel are dependent on equivalence ratio. As the equivalence ratio decreases, the auto-ignition pressure and temperature are increased. As the pressure, temperature and equivalence ratio reach a certain limit, knocking combustion occurs. However, increment of equivalence ratio is not the only reason of knock onset (Saidi et al., 2005). Higher intake temperature and advanced pilot injection timing also affect occurrence of knock. Shioji et al. (2001) demonstrated that the knock limit of equivalence ratio can be reduced by pilot injection timing retardation.

4.0 EXPERIMENTAL SETUP

A Toyota Hilux 2.5L common-rail direct injection diesel engine was used in this study and its specification is as shown in Table 1. Its fuel delivery system uses common-rail direct injection system which is suitable for DDF system (Stålhammar et al., 2011). The high pressure diesel fuel is supplied constantly at lower engine speed and the electronic controlled fuel system is able to control injection pressure, timing, and duration. Therefore, this system offers more flexible control compared to the conventional system which is mechanically controlled and the mechanism is dependent on geometry (Bunes & Einang, 2000).

Table 1 : Specification of test engine (Toyota Motor Corporation, 2007)

Parameter	**Value**
Engine Code	2KD-FTV
No. of Cylinder & Displacement	4 *In-line* & 2494 cc
Fuel Delivery	Diesel Direct Injection with Common-rail System
Bore x Stroke / Compression Ratio	92 mm x 93.8 mm / 17.4 : 1
Maximum Power & Torque (120 DIN)	80 kW/3600 rpm & 325 Nm/2000 rpm
Fuel Consumption: (Based on EU Directive 80/1268-2004/3/EC)	*Combined*: 8.3 L/100 km *Extra Urban*: 7.2 L/100 km *Urban*: 10.1 L/100 km
Carbon Dioxide Emission (CO_2)	219 g/km

The experiment setup is shown in Figure 1 while details of the engine conversion has been described in this author’s previous work (Ismail et al., 2016). In this study, a steady state dynamometer test was conducted with various dual fuel ratios. The dual fuel ratio was set using CNG programming software via a piggyback CNG ECU to control CNG fuel quantity while the diesel fuel quantity was controlled using the original diesel ECU. An Ono Sokki Mass Flow Meter (FZ-2100) was installed before the common-rail fuel pump to measure diesel mass flow rate during the test. An Alicat Scientific M-250 SLPM Mass Gas Flow Meter was used to measure the CNG fuel mass flow rate. A Dynapack 4WD Chassis Dynamometer was used to measure engine power and torque. An Autocheck Gas & Smoke Analyzer was used to measure exhaust emissions.

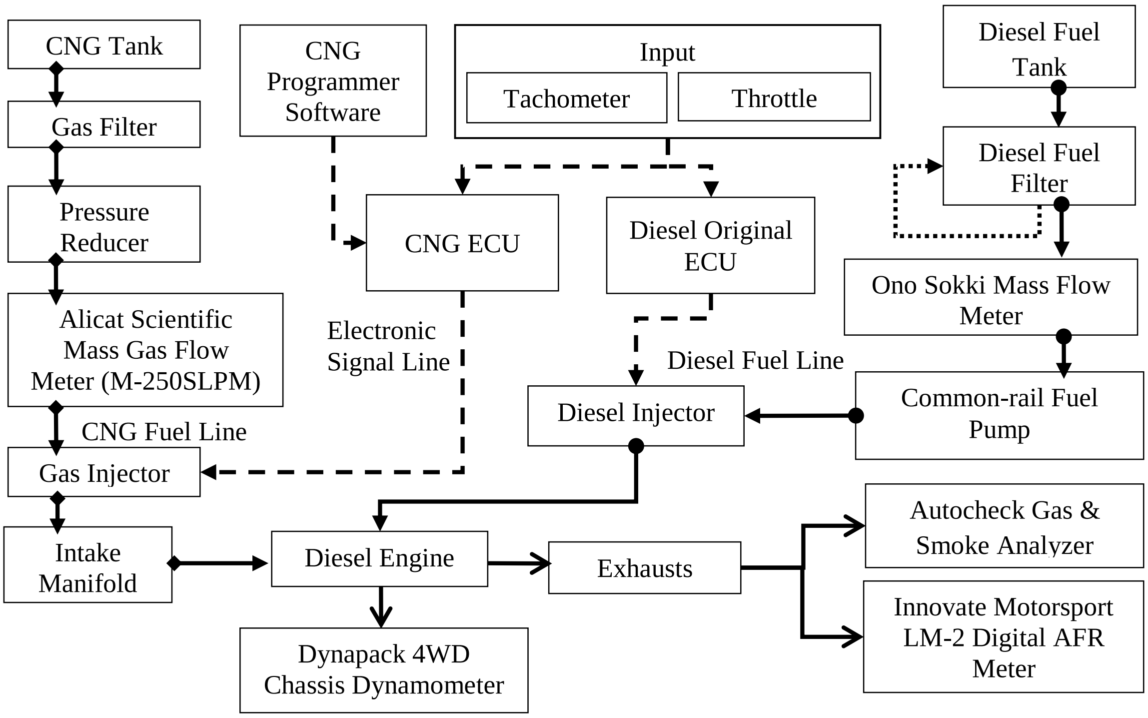


Figure 1: Test bed setup

The dual fuel ratio refers to the percentage of diesel fuel mass to the CNG fuel mass. The selected ratios of diesel to CNG were 90:10, 80:20 and 70:30. The term of 100% Diesel, 90% DDF, 80% DDF and 70% DDF represent the value of dual fuel ratios. It is defined as the percentage value from 0.0374175 grams/cycle which represents 100% of diesel fuel. The experiment matrix for mass flow rate ratio is tabulated in Table 2.

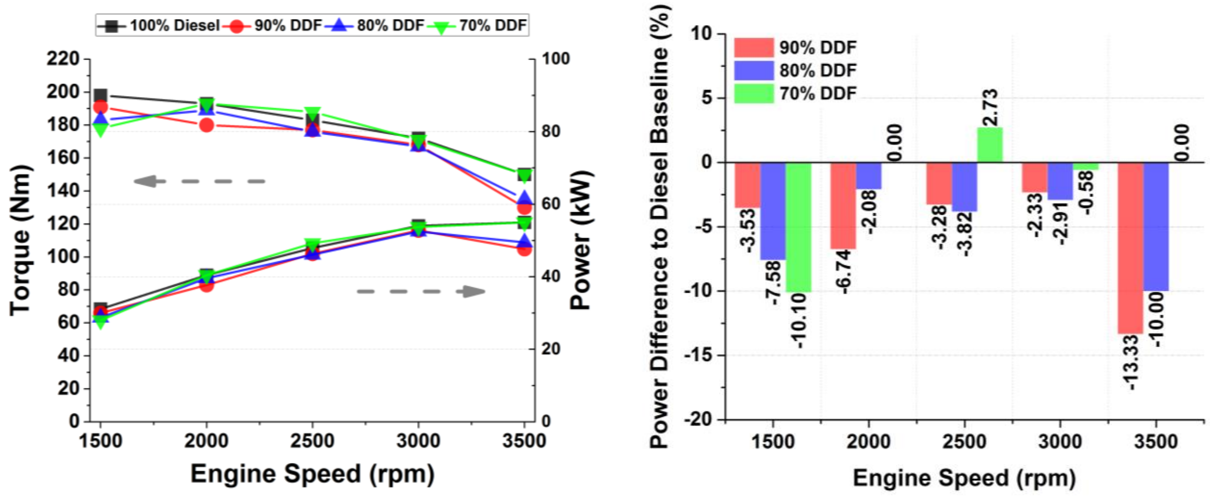
Table 2: Diesel and CNG fuel mass flow ratio

Engine Speed (rpm)	**100% Diesel**	**90% DDF**		**80% DDF**		**70% DDF**	
	Diesel (kg/h)	**Diesel (kg/h)**	**CNG (kg/h)**	**Diesel (kg/h)**	**CNG (kg/h)**	**Diesel (kg/h)**	**CNG (kg/h)**
1500	6.7352	6.0616	0.6735	5.4630	1.2722	4.7146	2.0205
2000	8.9802	8.0822	0.8980	7.2839	1.6963	6.2861	2.6941
2500	11.2253	10.1027	1.1225	9.1049	2.1203	7.8577	3.3676
3000	13.4703	12.1233	1.3470	10.9259	2.5444	9.4292	4.0411
3500	15.7154	14.1438	1.5715	12.7469	2.9685	11.0007	4.7146

5.0 RESULTS AND DISCUSSION

Based on the experiment conducted, engine torque for DDF engine was lower than the diesel engine. The engine torque for 70% DDF was lower compared to the 90% DDF at 1500 rpm engine speed. As the engine speed was increased to 3500 rpm, the engine torque for 70% DDF was similar to 100% Diesel while the 80% DDF and 90% DDF were lower. The collected data is illustrated through a graph in

Figure **2**(a).

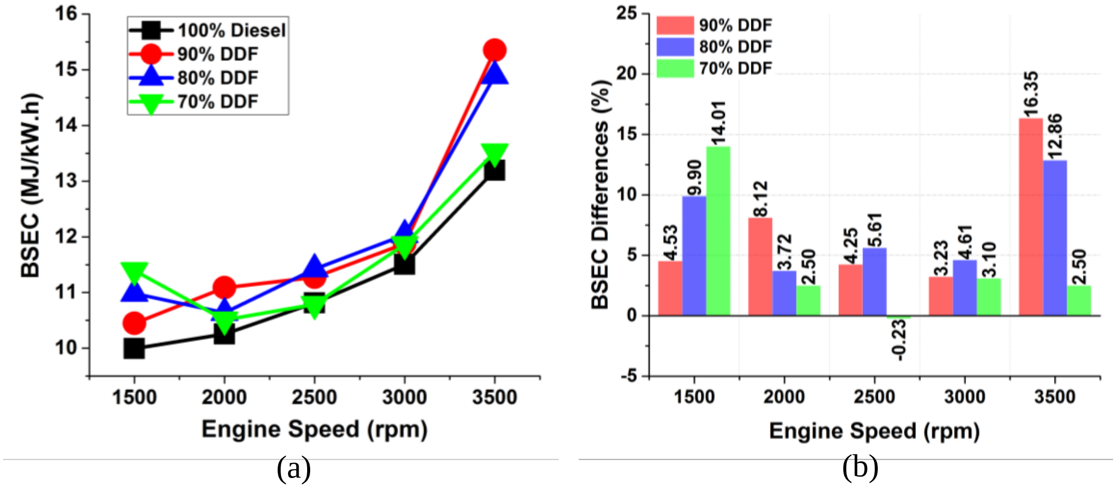


(a) (b)

Figure 2: Performance versus engine speed by different fuel ratios

The graph of power differences for performance comparison between DDF and diesel engine is depicted in Figure 2(b). Because power was calculated by the function of torque and engine speed, the percentages of power differences were equal to torque differences. The power difference for a DDF engine fluctuated as the engine speed increased. At 1500 rpm engine speed, the power dropped with a dual fuel ratio from 90% DDF to 70% DDF. However, the graph shows 2.73% improvement of power for 70% DDF as the engine speed was increased to 2500 rpm, while the power dropped for both 90% DDF and 80% DDF. When engine speed was increased to 3500 rpm, the power for 90% DDF and 80% DDF drastically dropped 13.33% and 10.00 % respectively. The power for 70% DDF dropped slightly at 3000 rpm engine speed and remain unchanged at 3500 rpm engine speed.

Brake Specific Energy Consumption (BSEC) was calculated to compare the amount of energy consumed by 100% Diesel, 90% DDF, 80% DDF and 70% DDF. This parameter is useful for comparing performance of the different fuels. Figure 3(a) shows the trend of energy consumed increased as the engine speed was increased. The 100% Diesel consumed less energy than DDF engine for the overall engine speed. At 1500 rpm engine speed, the BSEC showed an increment as the dual fuel ratio changes from 90% DDF to 70% DDF. However, it increased inconsistently when the engine speed was increased beyond 2000 rpm. Comparison between the BSEC of DDF to diesel baseline is shown in Figure 3(b), whereby the DDF consumed more energy to produce 1 kWh for overall engine speed. This is because the CNG fuel was partially burned. This was also indicated by the relatively high HC emission. However, the 70% DDF showed lower BSEC compared to 90% DDF and 80% DDF with a slight reduction of BSEC was shown at 2500 rpm engine speed.



(a) (b)

Figure 3: BSEC versus engine speed by different fuel ratios

Exhaust emissions against engine speed by different dual ratios were plotted in the graph as shown in Figure 4. In most cases, CO emissions were below 0.1%. The CO emission for DDF combustion was lower than the diesel combustion at 2500 rpm to 3500 rpm engine speed. The high concentration of CO emission presented in the exhaust emission was due to the engine running in a relatively rich air-fuel ratio (Pulkrabek, 2004). The rise of CO emission for 70% DDF at 1500 rpm and 80% DDF at 2000 rpm engine speed were probably caused by relatively rich combustion since all the combustion were lean. Such trends suggest that the CO emission will increase as the combustion reaches stoichiometric value.

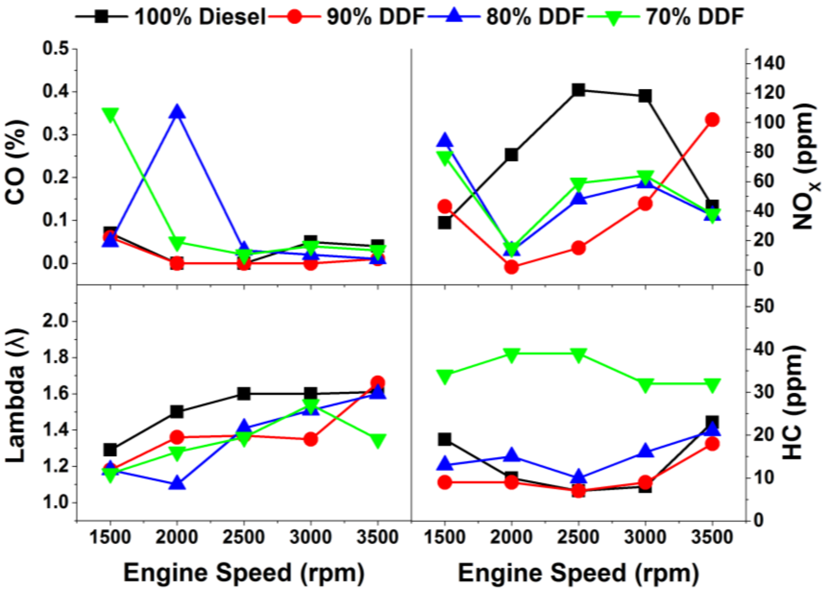


Figure 4: Emission versus engine speed by different fuel ratios

As shown in Figure 4, NO_X emission for 100% Diesel engine was greater than DDF engine. At 1500 rpm, NO_X for 100% Diesel was about 30 ppm which was lower than the rest. At this engine speed, NO_X increased as the diesel fuel ratio decreased. When the engine speed was increased to 2000 rpm, NO_X emission for DDF significantly decreased. Meanwhile, the

NO_X of 100% Diesel rose to the peak when engine speed reached 2500 rpm. In between 2000 rpm and 3000 rpm, the pattern of NO_X emission was almost similar. The 90% DDF showed a greater reduction of NO_X emission than 100% Diesel, but it increased as the dual fuel ratio reached 80% DDF and 70% DDF.

HC emission of 70% DDF was significantly the highest. Meanwhile 100% Diesel, 90% DDF and 80% DDF showed almost similar trends with value below 25 ppm. The presence of HC emission in exhaust gases was due to unburned fuel during combustion. It may be caused by valve overlap period that led the gaseous fuel being directly discharged during the scavenging process (Wei & Geng, 2016). Another source of HC may be contributed by trapped CNG in the piston crevices. HC emission may also result from incomplete combustion of CNG as indicated by the retardation of engine performance, increment of BSEC with respect to the increment of CNG fuel quantity.

Knock occurrence was observed at 70% DDF. The cycle to cycle combustion became unstable and might contribute to incomplete combustion. Besides, a part of the CNG fuel had been possibly ignited before the pilot fuel was injected. As suggested by Heywood (1988), the *'undermixing'* combustion might result in high HC emission. During combustion, the fuel ignition was fragmented into two phases in a cycle as illustrated in Figure 5.

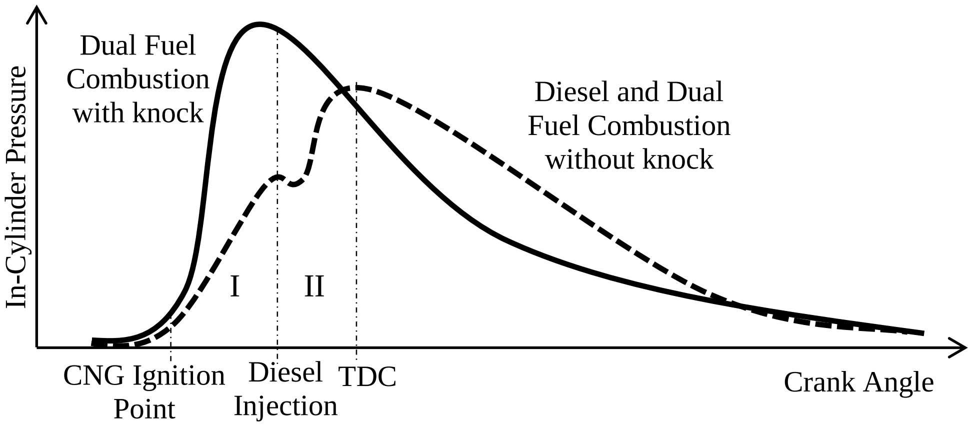


Figure 5: Illustration of the combustion phase during knock occurrence

When a large amount of CNG fuel mixture was drawn into the cylinder, the high increases of in-cylinder pressure and temperature caused CNG fuel mixture to auto-ignite (Jun et al., 2003). When it auto-ignited, the in-cylinder pressure was raised drastically before injection of diesel pilot fuel. When the diesel fuel is injected, poor atomization might occur due to slight pressure differences between the in-cylinder side and injector side. With regards to the study done by Jun et al., an earlier combustion with shorter duration might occur. An unwell atomized of diesel injection is burned with shorter and slower propagation. Therefore, combustion did not take place properly and a small volume of unburned fuel was left at the end of the combustion process.

6.0 CONCLUSION

Performance and emission results of these steady-state dynamometer tests by various dual fuel ratios substitutions were analysed and the following conclusions are reached:

(a) The DDF engine produced lower torque compared to a diesel engine at low engine speed.

(b) The DDF engine shows higher BSEC than diesel engine. This was caused by the partial combustion of CNG fuel.

(c) Combustion of DDF engine was relatively richer than a diesel engine. High CO emission was observed as the lambda value approaching stoichiometric.

(d) NO_X emission of DDF engine was lower than diesel engine. The 90% DDF showed greater reduction of NO_X emission and increased as it reached 70% DDF.

The maximum blending ratio for DDF engine was a 70% diesel and 30% CNG. It is the limit before the knock phenomenon and higher HC emission take place. However, it showed brake power comparable to diesel engine.

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