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Energy Consumption and Emissions of Diesel-CNG Dual Fuel Engine at High Load Operation

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Abstract: Global warming and energy sustainability issues are among the major world concern. Malaysian National Green Technology Policy 2009 and Thailand Power Development Plan 2015-2036 (PDP 2015) were launched to enhance the green and sustainable energy usage. Meanwhile in the transportation sector, National Automotive Policy (NAP) has been implemented and revised to enhance the usage of the green energy, in order to achieve a low carbon emission and energy efficient vehicle. Researchers keep striving to find alternative solutions to power vehicles by cleaner energy efficiently. Compressed Natural Gas (CNG) has lower carbon emission and higher energy density compared to common petroleum fuel. It provides an opportunity to power the vehicle cleanly. Thus, it has been used as an alternative for fueling gasoline engine. However, CNG fuel is difficult to be applied on diesel engine. Unlike gasoline engine, diesel engine does not have spark plug and its fuel is combusted through compression in cylinder. Since CNG has high octane number, it is difficult to self-ignite in diesel engine. Therefore, Diesel-CNG Dual Fuel (DDF) system is applied. The system use CNG as part fuel and certain amount of diesel pilot fuel is injected into the cylinder to ignite the combustion. DDF engine may potentially reduce Carbon Dioxide (CO_2) emission. However, high fuel consumption and Nitrogen Oxide (NO_X) emission have been observed at high load engine operation due to improper fuel ratio. In this study, four ratios of DDF were tested and compared with 100% diesel: 90D10G, 80D20G, 70D30G, 60D40G. It was found that each of the fuel ratio behaved differently in terms of brake specific energy consumption (BSEC) and exhaust emissions.

Keywords: Alternative Fuel, Green Energy, Diesel CNG Dual Fuel

1. Introduction

Global warming and energy sustainability issues were being mainstreamed recently. It makes a big splash to transport sector which most relative to these matters. Motor vehicles have been powered by unsustainable fuel resource and emits harmful pollution from combustion. They are main contributor of black carbon and greenhouse gas emission.

In 2009, Malaysian National Green Technology Policy had been launched. According to the policy, the 'green technology' should minimize environmental degradation, lower greenhouse gas emission, and conserving energy and natural resources (KeTTHA, 2009). The policy was supported by National Automotive Policy 2009 (NAP 2009), which provides a better incentive and opportunity for green technology practitioner in the ecosystem from manufacturer to the end user (MITI, 2009). The NAP 2009 had been revised in 2014 and aims to be the regional automotive hub of Energy

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Efficient Vehicle (EEV) by 2020 (MITI, 2014). The EEV is specified by the type of vehicle that meets a certain level of carbon emission or fuel consumption. As long as the vehicle meets either condition, it can be claimed as an EEV.

In the energy sector, PDP 2015 was launched in Thailand to mitigate greenhouse gas emission from power generation. This plan targets to reduce the utilization of natural gas power plant, eliminate an existing diesel power plant and replaced with renewable energy power plant in 2026 (Ministry of Energy Thailand, 2015). In transition of renewable energy deployment, an improvement on the diesel power plant is possible to reduce greenhouse gas emission using an alternative fuel.

CNG fuel has been the alternative since over a few decades. It is abundant and has a lowest greenhouse gas emission. Although it is non-renewable resource, the existence of natural gas derived from biomass brings sustainability on the CNG engine. CNG from Palm Oil Mill Effluent (POME) has been used in Malaysia and its utilization potentials reduce the growth of CO_2 emission (SEDA, 2017). Malaysia is committed to increase the number of biogas capture facilities on palm oil mills and targets to reach 500 units of the facilities with 3,000 ktCO_2eq of biogas in 2020 (Ministry of Natural Resource & Environment Malaysia, 2015). As Indonesia, Malaysia and Thailand are the top rank of palm oil production, the increment of oil palm plantation projects a positive growth of biogas production and assure the energy security [7–9].

CNG has a good potential to replace the existing fuel such as gasoline and diesel (Doppelbauer, Penz, Renner, Masser, & Dorfer, 2013). However, it is difficult to be applied on existing diesel engine because it demands a source of ignition to combust. Besides the installation of ignition and gas fuel system, modification on compression ratio is needed in order to cope with the fuel properties. Therefore, the Diesel-CNG Dual Fuel (DDF) system is preferred to be applied without any modification on existing diesel engine. CNG is directly injected into the intake manifold and ignited by a certain amount of diesel fuel. The conversion is can be made by installing a gas fuel system on the diesel engine without affecting the original system and engine components physical. The fuel mode is interchangeable between the DDF and diesel fuel and more practical compared to the other method.

Previous studies have reported that DDF combustion has great potential to reduce more than 20 % of CO_2 emission [10-11]. It is because the natural gas has the lowest carbon content among other hydrocarbons. Thus, the combustion of DDF engine is cleaner and produces less CO_2 emission compared to another petroleum fuels. In actual practice, DDF engine showed high fuel consumption and emissions at high load engine operation, especially at 1500 rpm [12-13]. It may be resulted by uncontrolled blending ratio between diesel and CNG fuel. Therefore, further attention on the fuel ratio for DDF engine needs to be paid to minimize fuel consumption and exhaust emissions.

Performance of DDF engine varied and depend on engine operating load. Brake Specific Fuel Consumption (BSFC) is used to compare fuel consumed by the engine to produce 1 kW of power output. At 1500 rpm engine speed, several studies showed that BSFC of DDF engine was higher than the diesel engine at low load engine operation [12-13]. As engine load increased, BSFC of DDF engine is still higher than the diesel engine. However, a study done by Lounici et al. showed that BSFC of DDF engine was lower than the diesel engine at high load engine operation using different diesel-CNG fuel ratio (Lounici et al., 2014). Although the BSFC was able to be reduced, high concentration of NO_X has been observed.

2. Methodology

A 2.5 litre common-rail direct injection diesel engine vehicle was used as a platform for dual fuel test. The chosen engine has electronic fuel delivery system and able to supply a high pressurize of diesel consistently at any engine speed. Therefore, the dual fuel ratio was able to be controlled by reducing diesel fuel quantity without affecting its pressure. Specification of the test engine is presented in

Table **1**.

Table 1 - Specification of test engine

Parameter	Value
Engine Code	2KD-FTV
No. of Cylinder & Displacement	4 in-line & 2494 cc
Fuel System	Common-rail Direct Injection
Bore x Stroke / Compression Ratio	92 mm x 93.8 mm / 17.4 : 1
Maximum Torque	325 Nm @2000 rpm

The experiment was conducted in a dynamometer room with ambient temperature and pressure around 35 °C - 40 °C and 1.010 bar - 1.015 bar respectively. The experiment setup is shown in Fig. 1. Details on the engine conversion has been described in the author's previous work (Ismail, Zulkifli, Fawzi, & Osman, 2016). A steady-state dynamometer test was conducted with various fuel ratios. The fuel ratio was set using CNG programming software via a piggyback CNG ECU to control the CNG fuel quantity while the diesel fuel quantity was controlled using the original diesel ECU. Engine load was controlled using a Bosch KTS-540 Diagnostic Tool which directly connected to original 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 installed before the gas injector to measure CNG fuel mass flow rate. Two CNG injectors were installed at the intake manifold so that it premixed with air before it drawn into the engine cylinder. Thus, the CNG injection timing was neglected. A Dynapack 4WD Chassis Dynamometer was used to measure the engine power and torque and an Autocheck Gas & Smoke Analyzer was used to analyse the exhaust emissions. A piezo-electric pressure transducer was installed at the engine first cylinder and its signal was amplified by Kistler Charge Amplifier. A Dewetron Crank Angle CPU was used to determine the engine crank angle and the engine combustion was recorded using National Instruments Data Acquisition (CompactDAQ). Diesel fuel used was diesel B7 purchased from a local petrol station, which blended with 7% biodiesel from palm oil base while CNG used was from petroleum source. The specification of fuel used is tabulated in Table 2.

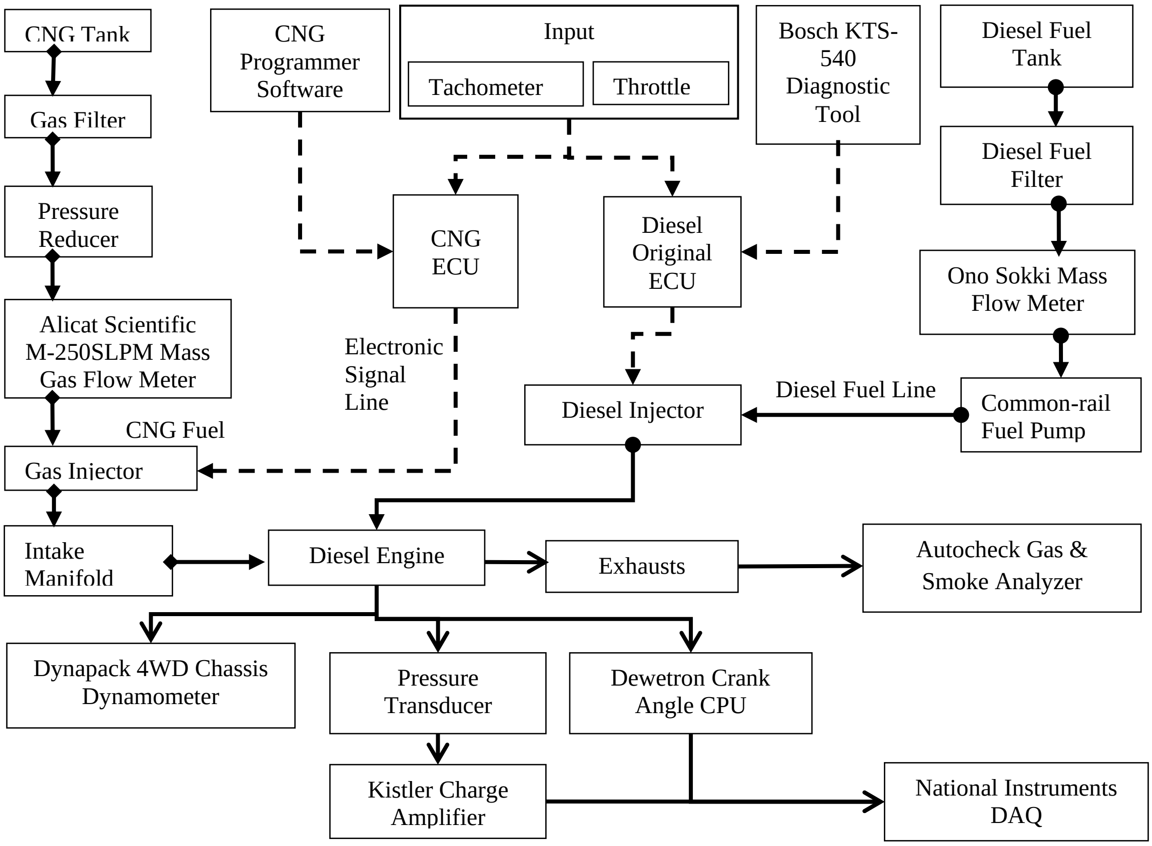

Fig. 1 - Test bed setup

Table 2 - Fuel Specification [15-16]

Diesel	
Density at 15 °C	0.8314 kg/liter
Sulfur Content	330 ppm
Cetane Number	54
Fatty Acid Methyl Ester Content	7.0 %
Flash Point	63 °C
Kinematic Viscosity at 40 °C	2.9 cSt
CNG	
Methane Content	92.73 %
Ethane Content	4.07 %
Other Hydrocarbons Content	3.20 %
Flash Point	-187 °C
Auto Ignition Temperature	537 °C

Based on previous studies, high fuel consumption and poor exhaust emission occurred during high load engine operation at 1500 rpm engine speed (Ismail et al., 2018). Thus, a steady-state dynamometer test was conducted at 1500 rpm engine speed. Air Fuel Ratio (AFR) was kept constant by controlling air and fuel mass flow rate. Since diesel engine operates in wide open throttle, air mass flow rate is proportional to engine speed. Thus, the air mass flow rate for overall test condition at 1500 rpm was constant. The fuel mass flow rate was kept constant at 6.74 kg/h which derived from 45 mm^3 of diesel fuel injection per engine cycle. Engine speed increased as the fuel was injected into the cylinder. Thus, brake load was applied to the engine using dynamometer in order to keep the engine speed constant at 1500 rpm. Conforming these settings, diesel ECU was read to indicate 100 % of engine load at 1500 rpm engine speed. The fuel ratio was set by the percentages of diesel fuel to the CNG fuel mass flow rate as tabulated in Table 3.

Table 3 - Diesel and CNG fuel mass ratio

Fuel Label	Diesel : CNG	Diesel (kg/h)	CNG (kg/h)
100D	100:0	6.74	-
90D10G	90:10	6.07	0.67
80D20G	80:20	5.39	1.35
70D30G	70:30	4.72	2.02
60D40G	60:40	4.04	2.70

In order to compare the engine performance between two types of fuel, Brake Specific Fuel Consumption (BSFC) was used. Since the study uses two types of fuel with a different state (liquid and gas) concurrently, Brake Specific Energy Consumption (BSEC) was calculated by taking account fuel calorific value [18-20]. Thus, BSEC was calculated using equation (1) and equation (2) below:

$$BSFC = \frac{\dot{m}_{Fuel}}{Power} \quad (1)$$

$$BSEC = \frac{\left(\dot{m}_{Diesel.} \times CV_{Diesel}\right) + \left(\dot{m}_{CNG} \times CV_{CNG}\right)}{Power} \quad (2)$$

$\dot{m}$ = Mass flow rate
CV = Calorific value

Heat release rate was calculated using single zone model to analyze energy released during combustion. The heat release rate, $dQ_{net}/d\theta$ was derived as shown in equation (3) where P is cylinder pressure, V is cylinder volume, θ is crank angle degree and γ is specific heat ratio.

$$\frac{dQ_{net}}{d\theta} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dP}{d\theta} \quad (3)$$

3. Results and Discussion

Although the total fuel mass flow rate was constantly set as 6.74 kg/h, different calorific value for each fuel affects the total energy flow rate for each fuel ratio. Thus, the energy flow rate was calculated to determine the energy input into the system. The calorific value used were 46.165 MJ/kg for diesel fuel and 50.009 MJ/kg for CNG fuel [21-22]. The calculated energy flow rate, BSEC and measured results were laid in Table 4.

Table 4 - Experiment results

Fuel Label	Measured				Calculated	
	Torque (Nm)	Power (kW)	CO_2 (%)	NO_X (ppm)	Energy Flow Rate (MJ/h)	BSEC (MJ/kW.h)
100D	178	27.96	9.27	802	310.93	11.12
90D10G	199	31.26	10.07	785	313.52	10.03
80D20G	188	29.53	6.39	154	316.11	10.70
70D30G	190	29.85	8.55	677	318.70	10.68
60D40G	180	28.28	8.56	958	321.28	11.36

Based on the results, DDF showed higher power compared to diesel fuel. The highest power was recorded by 90D10G and followed by 70D30G, 80D20G, 60D40G and diesel fuel respectively. Because CNG has higher energy density compared to diesel, the calculated energy flow rate for DDF was higher than diesel. However, the increment of energy flow rate was not in the same order to increment of power. Therefore, the BSEC was calculated to determine the specific energy consumption and a graph was plotted in Fig. 2.

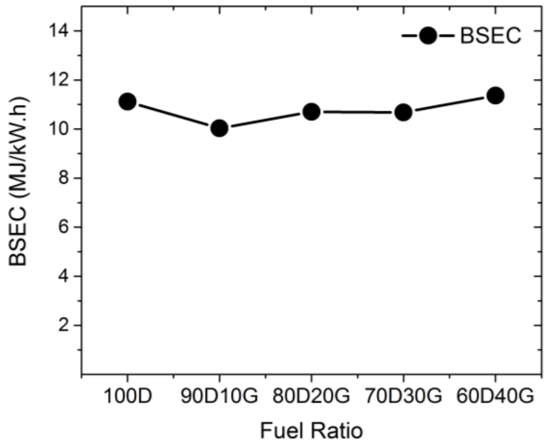

Fig. 2 - BSEC by various fuel ratio

According to Fig. 2, BSEC for 90D10G is the lowest while 60D40G is the highest. 90D10G, 80D20G and 70D30G showed lower BSEC compared to diesel fuel. It shows that 90D10G was most efficient which consumed less energy to produce a power. The highest power was recorded by 90D10G with the lowest energy flow rate among DDF. On the other hand, 60D40G was not efficient since it consumed the highest energy to produce usable power. The highest energy flow rate was recorded by 60D40G with the lowest power among DDF.

A graph of exhaust emissions was plotted as shown in Fig. 3. 90D10G showed higher CO_2 and slightly lower NO_X emissions compared to diesel fuel. The 80D20G showed decrement on the exhaust emissions with the lowest CO_2 and NO_X emissions. CO_2 and NO_X emissions were increased continuously from 80D20G to 60D40G and the highest NO_X emission was recorded on 60D40G.

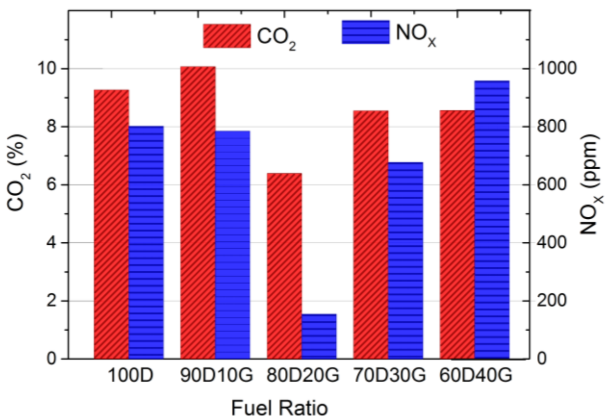

Fig. 3 – CO_2 and NO_X emission by various fuel ratio

Fig. 4 shows a plot of heat release rate by various fuel ratios to present the energy reaction rate during combustion. The point between A and B is known as ignition delay, which is the common phenomena in diesel combustion. On this process, diesel fuel absorbs the heat energy from surrounding before it self-ignited. As it was ignited, flame propagation led the rapid combustion occurred from B to C. During this process, cylinder pressure and heat release rate were drastically raised and being stable from C to D which is known as controlled combustion. Lastly, final combustion occurred with the decrement of cylinder pressure and heat release rate during the expansion stroke.

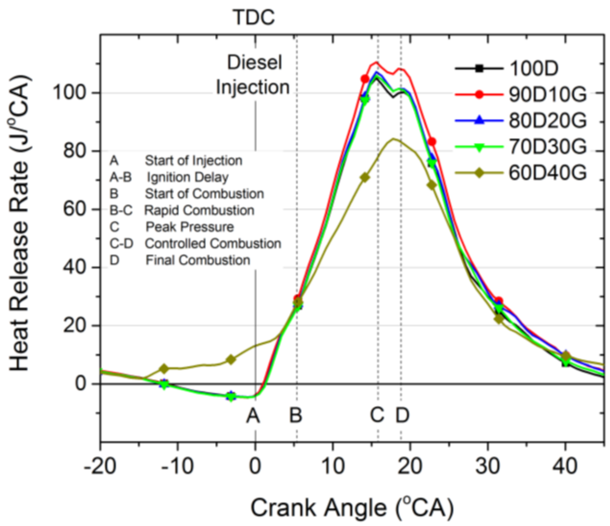

Fig. 4 - Heat release rate of test fuel ratios

According to Fig. 4, 90D10G showed the highest heat release rate while 60D40G was the lowest. Diesel, 90D10G, 80D20G and 70D30G showed similar trend during ignition delay. Because of heat release rate was differentiated using dθ equal to 1 °CA, the energy absorption during ignition delay is hard to be seen. As combustion started, 90D10G showed the highest heat release rate and followed by 80D20G, 70D30G and diesel. Early combustion occurred on 60D40G and showed by the increment of heat release rate before 0 °CA. CNG fuel of 60D40G was self-ignited and led the increment of heat release rate before diesel pilot fuel injection. After the diesel pilot fuel was injected, heat release rate for 60D40G was the lowest. The lowest heat release rate came from the diesel pilot fuel combustion since the CNG fuel was combust before 0 °CA.

Based on BSEC, exhaust emissions and heat release rate analysis, it showed that good combustion occurred on 90D10G. The improvement of CO_2 emission on the 90D10G showed most of fuel was completely burned. Thus, heat release rate for 90D10G was the highest. A good combustion enhances heat released and led an improvement to the power output. It shows that 90D10G is most efficient which consumes the lowest energy to produce 1 kW of power output with a slight reduction of NO_X emission.

The 80D20G showed lower BSEC, CO_2 and NO_X emissions compared to diesel fuel. It shows that NO_X emission was able to be reduced more than 80 % compared to diesel fuel. The 80D20G showed lower power output and led the higher BSEC compared to 90D10G. The lowest CO_2 and NO_X emissions for 80D20G was due to the reduction of diesel fuel, partial burning of CNG fuel and led to the retardation of thermal NO_X occurrence. According to Fig. 4, the heat release rate for 80D20G was lower than 90D10G. The declination shows that less energy was able to be released by 80D20G and led to higher energy consumption compared to the 90D10G. Compared to diesel fuel, 80D20G showed better performance with lower BSEC and the lowest CO_2 and NO_X emission. Therefore, 80D20G has a good potential to replace diesel fuel in order to lower carbon emission and energy consumption.

According to Fig. 4, heat release rate for 70D30G was higher than diesel and lower than 80D20G. Although the heat release rate for 70D30G was lower, power output for 70D30G was slightly higher than 80D20G. It is because the heat release rate for 70D30G was higher than 80D20G during rapid combustion (process B-C). 70D30G showed lower BSEC compared to diesel and 80D20G. Thus, 70D30G is suitable to be applied due to lower BSEC, CO_2 and NO_X emissions compared to diesel. However, 70D30G showed higher CO_2 and NO_X emission compared to 80D20G. Therefore, 70D30G is should be the second option after 80D20G in order to improve exhaust emissions on a diesel engine for high load operation.

60D40G showed the highest BSEC and NO_X emission as shown in Fig. 2 and Fig. 3 respectively. It shows that 60D40G is not efficient and not suitable to be used on high load DDF engine at 1500 rpm engine speed. Although energy flow rate for 60D40G was the highest, its heat release rate was the lowest. In Fig. 5, ten cycles of 60D40G combustion were recorded and its combustion characteristic were observed. According to 60D40G combustion, an early combustion occurred before 0 °CA and showed by the rises of heat release rate and cylinder pressure as shown in Fig. 4 and Fig. 5. CNG was self-ignited before diesel pilot fuel injection and led to the occurrence of uncontrolled combustion as shown in Fig. 5. The uncontrolled combustion was able to be observed by the fluctuation of cylinder peak pressure between 6.5 and 8.0 MPa. Both early and unstable combustion events cause power loss and led to the poor energy efficiency on 60D40G. Therefore, 60D40G was not suitable to be applied on high load DDF engine at 1500 rpm engine speed.

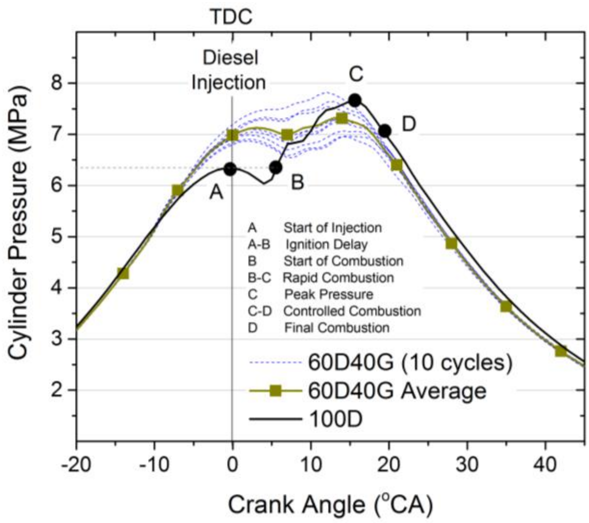

Fig. 5 - In-cylinder pressure of 60D40G fuel ratio

4. Conclusion

The performance and emissions by various dual fuel fuel ratio at1500 rpm engine speed and high load operation were analyzed, and the following conclusions were made;

1. Selected diesel-CNG dual fuel ratio was proven to have better BSEC than diesel at high load engine operation. All of 90D10G, 80D20G and 70D30G showed lower BSEC compared to diesel.
2. The 90D10G showed the lowest BSEC but produces highest CO_2 emission and moderate NO_X emissions.
3. 80D20G was found to be more efficient than diesel but less efficient than 90D10G. However, it showed the lowest CO_2 and NO_X emissions.
4. 60D40G showed the highest BSEC and NO_X emission. Therefore, it is not suitable to be applied on DDF engine at low engine speed and high load operation.
5. This study suggests 80D20G is the best setting for energy efficiency with lowest exhaust emission at low engine speed and high load operation.

DDF engine conversion has shown lower greenhouse gas emission and energy consumption compared to the diesel engine at certain diesel-CNG dual fuel ratio. As we move towards utilizing renewable energy usage such as biogas, DDF engine has the potential to help fulfil one of the objectives in Malaysia National Green Technology Policy and PDP 2015.

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