Investigation of Emission Characteristics of Diesel Dual Fuel (DDF) Engine with Multi-Point Natural Gas Injection System.

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Abstract
The present research had been done to investigate the emission characteristics of dual fuel engine using natural gas and diesel fuel in which diesel engine has been modified to diesel dual fuel (DDF) engine using multi-point electronic gas injection system. Electronic control unit (ECU) was used for controlling the injection amount of natural gas more accurately into the intake port of engine. Experiments were performed at different engine power output of 19 kW, 27 kW and 32 kW corresponding with engine speeds of 1500 rpm, 2000 rpm and 2500 rpm respectively maintaining constant load of 75% of that of standard diesel engine specification at all speeds. The results show an increase in maximum mixing ratio (Z) up to 92% and diesel reduction rate (ΔD) up to 88 % on increasing the engine power output and engine speed. Energy contribution of natural gas in DDF engine increases up to 89% on increasing the power output. Brake thermal efficiency for DDF engine comes out to be lower than diesel engine for all engine speed and power output. Unfortunately the total unburned hydrocarbon (THC) as well as CO emission is more for DDF engine as compared to that of diesel engine emission at all speed and power output but NO_x is less for DDF engine as compared to diesel engine.
Keyword: Diesel Dual Fuel (DDF), Natural Gas for Vehicle (NGV), Electronic Control Unit (ECU)

1.Introduction

In the current scenario of the world the demand for energy is increasing day by day. The reason for this is the increase in industry and transport activities all over the world. By 2030 total population has been estimated to be around 8.3 billion [1] and the primary energy demand is projected to be 734 Exajoules (EJ) per year [2].The other problem that has come into picture is the increase of emission like total unburned hydrocarbon (THC), CO and NO_x from the vehicles exhaust. An alternative fuel which has been find out to be more environmentally friendly with less emission can be used to replace conventional fuel e.g. gasoline and diesel. An alternative fuel like natural gas, hydrogen, ethanol, methane and propane has been interesting fuels during past decades.

Particularly natural gas had been considered as primary fuel to replace from low to high proportions of diesel. It is easily available and its reserves are large. At the end of year 2011, total natural gas reserves of the world was 208.4 trillion cubic meters [3]. Moreover the natural gas is cheaper than the diesel and gasoline. This is the reason that natural gas is attractive fuel in market nowadays. However the auto ignition temperature of natural gas is very high and cannot self-ignite at conventional diesel engine, small amount of diesel fuel was used to initiate the combustion in the engine while natural gas was injected into the engine as primary fuel. This type of engine is called diesel dual fuel (DDF) engine where diesel fuel is used to initiate combustion in the primary fuel used in the engine.

Modification of DDF system from the conventional diesel engine is not very complicated. DDF engine reduces the use of diesel fuel and therefore cost of running engine. Conventional natural gas is more clean fuel as compared to diesel and gasoline as it has low carbon intensity, thus reducing emission of CO [4]. However some works have shown higher CO emission using natural gas [5-6]. Natural gas also has very little non-carbon emission. Moreover by using DDF engine emission of NO_x also reduces. However as the proportion of natural gas increases to replace diesel fuel, it causes problem as higher amount of natural gas can reduce the engine output and increase tendency of engine knock [7].

Several experiments have been done in order to investigate the exhaust gas emission characteristic in case of dual fuel engine. However tendency of emission in dual fuel engine can be varied by various parameters e.g. engine speed, load, type of injection system, intake air temperature, equivalence ratio (Φ). Work of Yusuf et al. [8] had shown that in case of single cylinder dual fuel engine, at full load NO_x, CO and CO_2 emission was around 54%, 59% and 31% less as compared to that of diesel fueled engine respectively. Emission of CO was less because at full load DDF engine runs smoother than diesel engine. However at no load condition emission of NO_x at higher speed was higher for dual fuel engine than diesel engine. Also CO emission was more as compared to diesel engine but CO_2emission was less for dual fuel engine at no load condition. Papagiannakis et al. [6] showed that in single cylinder engine, as brake mean effective pressure (BMEP) vary from 1.2 bar to 4.9 bar at each engine speed of 1500 rpm and 2500 rpm, the THC and CO emission for DDF engine always remains greater than diesel engine and their difference decreases on increasing BMEP. NO_x at low load was lower than diesel engine and as load increases the difference in its value from diesel engine start increasing. BSFC value was also higher for DDF engine than diesel engine.

Various researches have been done in order to improve exhaust gas emission of dual fuel engine. Kusaka et al. [9] in their work showed that heating intake gas up to 210 ˚C and using optimum EGR of 50% in 4-cylinder DDF engine can reduce THC as well as NO_x emission by 91.02% and 92.81% respectively compared to baseline condition (intake gas temperature- 20 ˚C and using no EGR) and also improve thermal efficiency. Difference in thermal efficiency with baseline condition was 8.8%.Mizushima et al. [10] showed that decreasing the number of cylinders from 4 to 2 for DDF engine improve combustion and thermal efficiency, reduce CO and unburned hydrocarbon emission but increase NO_x emission because of increase in natural gas concentration per cylinder provided load condition remains same.

Previous research work used gas fumigation system for filling natural gas in engine [9-11].Zhang et al. [11] compared the emission of HC and CO between single point and multi-point injection system using ECU system. They found out that emission in case of single point injection system is more as compared to multi-point system. Also average substitution of natural gas in DDF engine was over 85%.

In this research work electronic control unit (ECU) was proposed for controlling natural gas flow in the engine combustion chamber and multi point gas injector had been used for injecting natural gas in each cylinder as it delivers gas more uniformly in all cylinders as compared to single point gas injector. Here the main purpose of this research is to study engine characteristics e.g. engine efficiency and emission characteristic of diesel dual fuel engine with multi-point gas injector system and ECU and compared with diesel engine.

2. Experimental Section

2.1 Experimental setup

The experimental work was performed on 4 cylinder, 4 stroke diesel engine, ISUZU-4JA1. The specification of original engine is mentioned in Table 1. Engine was modified to run on dual fuel. Amount of natural gas injection in engine was controlled by electronic control unit (ECU) while pilot diesel fuel was controlled by using distribution pump. The specification of distribution pump is given in Table 2.

Eddy current dynamometer was used for measuring and controlling the engine power output. Exhaust gases like O_2, CO_2, CO, NO, NO_2 and unburned hydrocarbon were measured by using exhaust system (MRU Model SWG 200^{-1}). Amount of diesel input was measured manually by using digital weight. Gas flow rate measurement was taken by the indirect weighting method. The lost weight of natural gas tank was measured by balancing the weight. The lost weight was measured by load cell and then convert it into electrical signal which was measured by data acquisition system. The schematic diagram of experiment setup is shown in Fig. 1.

Table. 1 Specification of original diesel engine

Model	ISUZU-4JA1
Engine type	4 stroke four cylinder
Combustion chamber type	Direct injection
Bore × Stroke	93mm × 92mm
Displacement Volume	624.95 cm^3
Compression Ratio	18.4:1
Compression pressure	31 kg/cm^2 at 2000 rpm
Power (JIS)	85 hp at 4000 rpm
Torque (JIS)	17.5 kgf.m at 2000 rpm
Cooling system	Water cooled

Table. 2 Specification of distribution pump

Injection pump type	BOSCH distributor VE type
Governor type	Mechanical
Injection timing	12 degree BTDC
Injection nozzle opening pressure	185 kgf/cm^2
Fuel injection order	1-3-4-2
Plunger diameter	11 mm

2.2 Experimental Procedure

The typical natural gas which is called the east gas was used in this experiment and its composition has been given in Table 3 [12]. Lower Heating Value (LHV) for diesel fuel and Natural gas is estimate to 45.13 MJ/kg and 34.53 MJ/kg respectively. During experiment torque was maintained at constant value of 75% of that of original diesel engine power output from the given engine performance curve. Constant torque was maintained at all power output by controlling the amount of natural gas in engine using ECU. ECU was actually controlling throttle position. As engine started

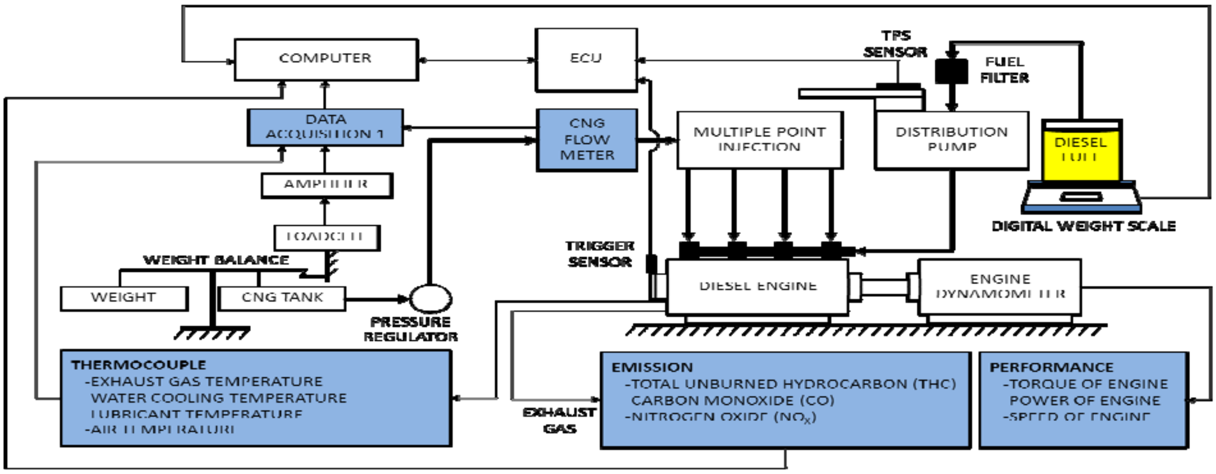


Fig. 1 Schematic diagram of experimental setup

ECU optimizes the throttle position in such a way that the amount of natural gas-air mixture entering the engine produced the desired amount of torque.

Experiment was performed at three different engine power outputs of 19 kW, 27 kW and 32 kW at engine speeds of 1500 rpm, 2000 rpm and 2500 rpm respectively for both diesel and DDF case. In DDF condition amount of diesel was reduced and natural gas was adjusted and added to the engine until desired engine power output was achieved at particular engine speed. In order to compare between diesel and DDF case with the same engine output the equivalence ratio could not be easily controlled. Hence cannot obtain same equivalence ratio to compare between diesel and DDF case. Instead mixing ratio (Z) and the diesel reduction rate (ΔD) was considered. Mixing ratio (Z) for diesel dual fuel (DDF) engine is defined as the amount of natural gas that can be replaced by diesel to produce same power output as that when using only diesel as fuel. Z is calculated by using Eq. (1).

$$Z(\%) = \frac{\dot{m}_{gas}}{(\dot{m}_{gas} + \dot{m}_{diesel})} \times 100 \qquad (1)$$

The term ΔD is defined as diesel that gets reduced by using DDF engine as compared to when using pure diesel engine. It is calculated by using Eq. (2).

$$\Delta D(\%) = \frac{\dot{m}_{diesel} - \dot{m}_{diesel.in.DDF}}{\dot{m}_{diesel}} \times 100 \qquad (2)$$

During experiment at each speed, data of exhaust gas was measured and then it was averaged for the interval of 180 seconds at steady exhaust gas temperature. This was done to avoid fluctuations.

The present investigation was done to measure the relative changes in exhaust emission like total unburned hydrocarbon (THC), CO and NO_x, thermal efficiency, brake specific fuel consumption (BSFC), mixing ratio (Z), Diesel reduction rate (ΔD) and exhaust temperature with increasing engine speed and power output maintaining constant load of 75% of the original engine specification and compare it with the emission of diesel engine.

Table. 3 Typical natural gas composition of east gas in Thailand

Composition	**Amount in % by mole**
CH_4	76.57
C_2H_6	5.14
C_3H_8	1.67
C_4H_{10}	0.37
C_5H_{12}	0.14
C_6H_{14}	0.06
N_2	1.99
CO_2	13.76

3. Results and discussion

3.1. Energy Contribution

From Table 4 it can be seen that as engine power output increases from 19 kW, 27 kW and 32 kW the maximum amount of natural gas that can be replaced by diesel increases from 72.86%, 80.93% and 91.57% respectively. This means at higher power output more and more amount of natural gas can replace diesel fuel leading to decrease in the cost of running engine.

In this experiment as power output increases from 19 kW, 27 kW and 32 kW value of ΔD also increases from 62.21%, 73.09% to 88.03% respectively shown in Table 4.

Energy contribution is the amount of energy contributed from different fuels input for running the engine to produce the fixed power output. Energy contribution for diesel engine and DDF engine for different fuels has been reported in table 5.As can be seen from table 5, as power output increases the contribution of natural gas for producing desired output also increases up to 89%.

3.2. Engine efficiency

As can be seen from Fig.2, break thermal efficiency (BTE) of diesel engine are 42.2%, 41.99 %, 42.47 % at engine power output of 19 kW, 27 kW and 32 kW respectively while break thermal efficiency of diesel duel fuel engine are 36.56 % , 36.75 %, 38.08% at 19 kW, 27 kW and 32 kW respectively. It is obvious that thermal efficiency for diesel dual fuel (DDF) engine is lower as compared to that of diesel fuel engine. On increasing engine power output from 19 kW, 27 kW to 32 kW change in efficiency of diesel dual fuel (DDF) engine from diesel engine decreases from 13.36%, 12.5% to 10.32% respectively.

Fig. 3 shows that for diesel dual fuel (DDF) engine brake specific fuel consumption is more compared to diesel engine. Brake specific fuel consumption for diesel dual fuel (DDF) are 15.42%, 14.28% and 11.50% more compared to

Table. 4 Maximum mixing ratio (Z) and diesel reduction rate(ΔD) for DDF engine

Power output (kW)	DDF	
	Z (%)	ΔD (%)
19	72.86	62.21
27	80.93	73.09
32	91.57	88.03

Table. 5 Energy contributions of fuels in case of diesel engine and DDF engine

Power output (kW)	Diesel contribution (%)	DDF	
		Diesel contribution (%)	Natural gas contribution (%)
19	100	32.74	67.26
27	100	23.55	76.45
32	100	10.74	89.26

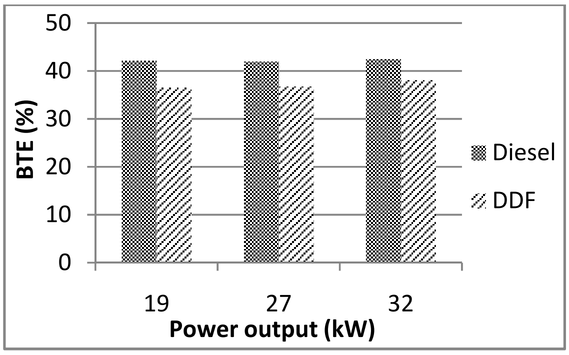


Fig. 2 Brake thermal efficiency (BTE) in case of diesel dual fuel (DDF) engine and diesel engine at 19 kW, 27 kW and 32 kW power output

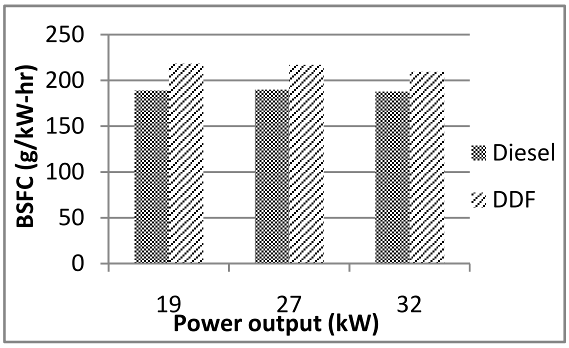


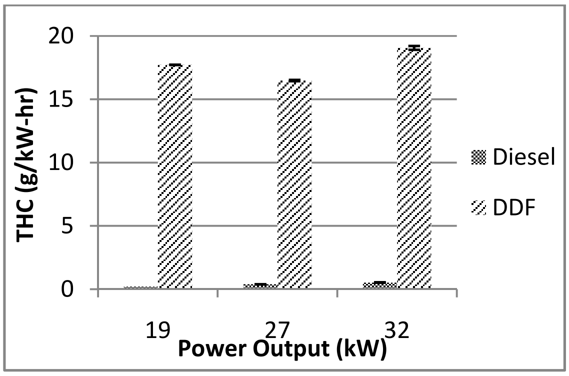
Fig. 3 BSFC in case of diesel dual fuel (DDF) engine and diesel engine at 19 kW, 27 kW and 32 kW power output

diesel engine at 19 kW, 27 kW and 32 kW power output respectively. In DDF engine due to natural gas substitution the amount of air available for combustion decreases. This reduces combustion efficiency and volumetric efficiency. For lower power, combustion efficiency of DDF engine is lower than diesel engine [13].Therefore lower thermal efficiency and higher BSFC for DDF engine at lower power output than diesel engine [13].

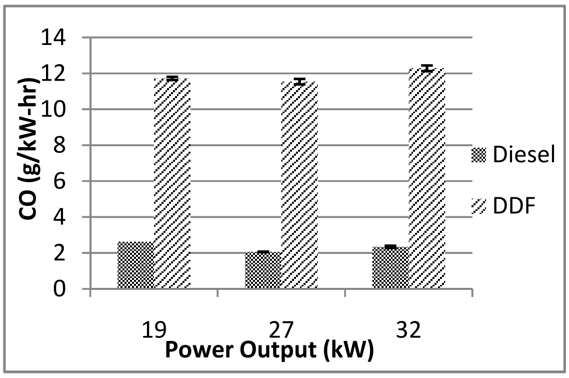
The trends of BSFC are also similar to the work previously done in this topic [5-6]. At low load the BSFC for DDF engine is more than diesel engine. The difference in BSFC between DDF engine and diesel engine is more at low load but on increasing load this difference starts decreasing [6].

3.3. Exhaust emission

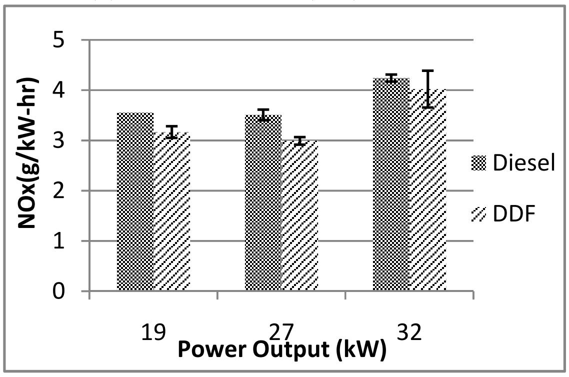
From Fig. 4(a) and Fig. 4 (b) it can be observed that at all power outputs emission of total unburned hydrocarbon (THC) and CO in case of diesel dual fuel engine is more as compared to that of diesel fuel. At 19 kW, 27 kW and 32 kW power output, emission of THC for diesel engine is 98.83%, 97.63% and 97.2% respectively less compared to that of diesel dual fuel engine emission. Emission of CO for diesel engine is 77.5%, 82.13% and 80.9% less compared to DDF engine at19 kW, 27 kW and 32kW power output respectively. This trend of THC and CO is due to lower volumetric efficiency and combustion efficiency of high amount of natural gas especially at high engine speed. From the previous results as power output increases value of %Z increases which indicates that amount of air intake decreases due to high amount of natural gas substitution. This high amount of THC and CO emission is also related with lower brake thermal efficiency compared with diesel engine. Emission trend resembles with the work [14].



(a) Total unburned hydrocarbon (THC) emissions



(b) Carbondioxide (CO) emissions



(c) Nitrous oxide (NO_x) emissions

Fig. 4 Exhaust emission of (a) THC, (b) CO and (c) NO_x in case of diesel dual fuel (DDF) engine and diesel engine at 19 kW, 27 kW and 32 kW power output

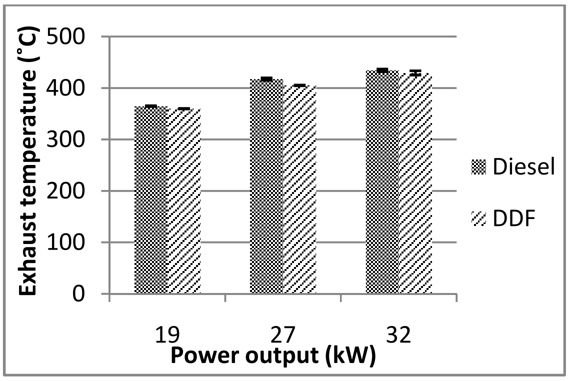


Fig. 5 Exhaust temperature in case of Diesel dual fuel (DDF) engine and Diesel engine at 19 kW, 27 kW and 32 kW power output

Trend of NO_x emission is opposite to that of THC and CO emission. Emission of NO_x directly depends on the in-cylinder temperature. For this experiment emission of NO_x for diesel engine is 12.19%, 17.27% and 5.47% more compared to DDF engine at 19 kW, 27 kW and 32 kW power output respectively shown in Fig. 4 (c). This co-relation is justified by Fig.5.It shows that exhaust temperature for diesel dual fuel engine is always lower than diesel engine.

4. Conclusion

The main focus of this research work is the use of ECU and multi-point gas injector system. ECU was used for controlling amount of gas flow and multi-point gas injector for injecting gas in combustion chamber. From the results obtained it can be concluded that:

- In DDF engine as the engine speed and power output increases the amount of natural gas substitution (%Z) increases up to 92%. Diesel reduction rate (ΔD)also increases up to 88%.As engine power output increases energy contribution of natural gas increases up to 89%.
- Thermal efficiency for DDF engine is lower than diesel engine at all power outputs because of reduced combustion efficiency and volumetric efficiency.
- Because of such lower volumetric efficiency and combustion efficiency, emission of THC and CO becomes more than diesel engine. Inefficient combustion leads to lower in-cylinder temperature. Therefore NO_x emission is less than diesel at all power output.

For improving thermal efficiency and emissions at low load pre-heating of fuel air mixture can be done. EGR can be used to reduce NO_x level from DDF engine. At part load thermal efficiency can also be increased by increasing the amount of pilot diesel fuel and also by increasing the amount of air input in combustion chamber.

5. Acknowledgement

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