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Performance and emissions analysis of natural gas-diesel dual fuel mode

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ABSTRACT

Towards the effort of reducing emissions, especially nitrogen oxides (NO_X) from direct injection diesel engines, researchers have come with various alternatives, one of which is the use of a gaseous fuel as a partial alternative for diesel fuel. These engines are known as dual fuel (DF) combustion engines, which uses both conventional diesel fuel and a gaseous fuel. The use of compressed natural gas (CNG) as a replacement fuel is a promising solution. The potential benefits of using natural gas in diesel engines were both economic and environmental. The high auto-ignition temperature of natural gas is a serious advantage since the compression ratio of conventional diesel engines is maintained.

The present work describes an experimental investigations performed on a single cylinder, four-stroke, naturally aspirated, air-cooled, direct injection diesel engine with a compression ratio of 17.5, which has been suitably modified to operate under dual fuel (DF) mode. The CNG is the primary fuel, which is ignited by pilot diesel fuel. Experiments were conducted for various operating CNG energy ratios ranging from 0% to 79.3% at a fixed brake mean effective pressure (BMEP) of 5.3 bar. It was noticed through an experimentation that at higher CNG energy ratio, the thermal efficiency was found to be lower as compared to conventional compression ignition (CI) mode of operation. The level of NO_X and smoke emissions are significantly low. However, the concentration of hydrocarbons (HC) and carbon monoxide (CO) emissions were higher than the CI mode.

KEY WORDS: Dual fuel, Diesel engine, Emissions, Compressed natural gas (CNG), Pilot injection.

1. INTRODUCTION

According to popular surveys it's a matter of time that fossil fuels are going to extinct in not more than 35 years. So with ever growing population and with their energy demands, it is no longer safer to rely on crude oil resource for energy purposes (Mendes Justino and Morais, 2012). Apart from it, rise in average temperature in the last few years because of harmful emissions like NO_x, CO emitted from the engines made researchers aware to step towards cleaner energy sources. Economical edge that renewable sources have against fossil fuels also became a key reason to promote cleaner fuels in energy market (Nirendra and Robert Raine, 2008).

Among the bio-fuels like natural gas, biogas, liquid petroleum gas (LPG) have great potential to replace the existing fossil fuels in internal combustion (IC) engines (Nayan Mirgal, 2017). The key advantage of natural gas was its easy availability and presence of lower alkane like methane as its major composition where as crude oil sources consists of higher alkanes, so natural gas emits significantly fewer NO_x, particulate matter (PM) into the surrounding air (Debabrata Barik and Murugan Sivalingam, 2013). Gaseous fuel also mix with air uniformly which leads to better combustion and least possible emissions.

Natural gas, which is formed from the decayed matter of plants and animals can also be produced from waste matter treatment plant where it is called as "biogas" when natural gas is stored at increased pressure it results in compressed natural gas which majorly consists of methane, higher alkanes like ethane, propane etc. other than hydrocarbons hydrogen sulphide, nitrogen also present in natural gas. Because of presence of lower alkane like methane auto-ignition temperature of natural gas was very high in the order of 540˚C as compared to various kinds of liquid fuels (Christopher Weaver and Sean Turner, 1994). Hence, attaining that much higher temperature inside the cylinder is not possible in the case of compression ignition (CI) engine. A pilot amount of diesel fuel or any other higher alkane fuel is always required to reach the combustion stage. Moreover, researchers are making their effort to study dual fuel (DF) mode in internal combustion (IC) engines by employing natural gas as primary fuel along with pilot amounts of any liquid fuels (Jorge Barata, 1995).

When the engine combusts in dual fuel mode with natural gas as fuel, thermal efficiency is expected to be less compared to neat liquid fuel because of low in-cylinder combustion temperature due to gaseous fuel characteristics like high auto ignition temperature, low carbon percent and also due to the slower burning rate due to the slower flame propagation speed increases the heat loss during the combustion process, resulting decline in thermal efficiency (Silvana, 2016). On the other side the effect of knocking can be eliminated due to high octane number of natural gas.

The major advantage with dual fuel setting is it helps in reducing overall emissions. Usually NOx, CO, UHC are the harmful gases that disperses into air. NO_x is greatly influenced by in-cylinder temperature and oxygen concentration. NO_x formation occurs when temperature is above about 1800 K and the formation rate increases exponentially with combustion. So due to lower combustion temperature leads to the reduction of NO_x formation (Papagiannakis & Hountalas, 2004). Similarly, the formation of CO_2 strongly depends on in-cylinder temperature and oxygen concentration as carbon monoxide (CO) is a product of hydrocarbon fuels completely burning. Hydro carbons first oxidized to CO and then if the in-cylinder temperature is high enough and with the presence of oxygen, CO was oxidized to form CO_2 consecutively. Coming to HC emissions, emissions observed to be higher with the increasing substitution ratio of natural gas to diesel fuel. It is difficult for combustion to propagate throughout the charge and the unburned mixture may result in higher HC emission (Lijiang Wei, Peng Geng, 2015).

Dual fuel technology using natural gas-diesel is a promising method. It reduces toxic emissions like NO_x, CO, CO_2 than those emitted by diesel engines. With dual fuel technology it is observed that both PM and NO_x can be reduced significantly (Yusaf and Al-Atabi, 2001).

The present experimental work aimed at investigating the influence of compressed natural gas (CNG) energy ratio on performance and emission characteristics and compared the results with neat diesel mode of combustion. The results signifies that the level of NO_x and smoke emissions were drastically reduced as compared to the CI mode.

2. EXPERIMENTAL SETUP AND METHODOLOGY

Test fuel: The natural gas was used in the present study as primary fuel to run the diesel engine in dual fuel mode. The liquid fuel injected into the combustion chamber (pilot fuel), which acts as the ignition source, conventional diesel fuel. The fuel properties are depicted in Table.1.

Table.1. Fuel properties

Fuel properties	CNG	Diesel
Auto ignition properties (C)	540	220
Flash point	150	52-96
Cetane number	-	52
Octane number	130	-
Low heating value (MJ/KG)	48	42.5
Carbon content %	75	87
Stoichiometric air-fuel ratio	17.3	14.3

Experimental setup: In the present investigation, a constant speed, stationary, single cylinder, four stroke, air cooled, DI diesel engine with a rated power output of 4.4 kW at 1500 rpm was used to operate as a dual fuel engine using CNG and diesel as a primary and injected fuel respectively. Table.2, indicates the specifications of test engine used. For loading the engine and eddy current dynamometer was coupled with the engine shaft. Table.3, indicates Dynamometer specifications. A surge tank was used to damp out the pulsations produced by diesel engine, for ensuring steady flow of air through the intake manifold. A non-contact type sensor was connected to measure the engine speed. The schematic of the experimental setup for natural gas-diesel dual fuel mode is depicted in Fig.1.

The fuel measuring system consists of a vertical burette. The mass flow rate of diesel consumed was measured on volume basis. The time taken for consumption of fuel for a fixed volume was calculated and the mass flow rate of diesel is calculated.

The air flow to the engine was monitored by passing the intake air through an air box with manometers incorporated in the intake manifold. The flow rate of gas was monitored by venturimeter which was installed near intake manifold and flow rate was measured by manometer which was attached to venturimeter.

Table.2. Specifications of test engine

Parameter	Description
Make/model	Kirloskar TAF 1
Engine type	Vertical, four stroke, single cylinder, air cooled, CI engine
Brake power, kW	4.4
Rated speed, rpm	1500
Number of cylinder	One
Cooling system	Air cooled
Air intake system	Naturally aspirated
Bore, mm	87.5
Stroke, mm	110
Nozzle opening pressure, bar	200
Injection timing, ^{o}BTDC	23

Table.3. Dynamometer specification

Make	Power Mag
Maximum torque	7.5 HP @1500 RPM
Maximum power	10 kW

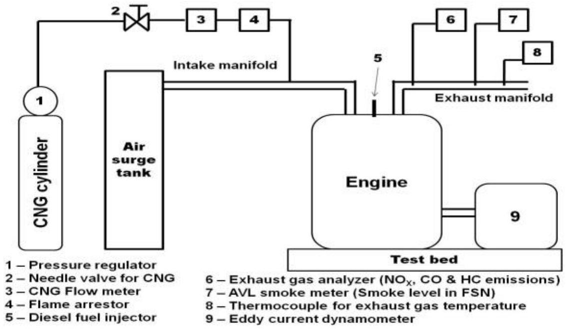

Figure.1. Schematic of experimental arrangement for natural gas-diesel DF engine

Table.4. List of instruments used

Loading	Eddy current dynamometer
Air flow rate	Orifice plate with U-tube manometer
Diesel consumption measurement	Burette and stopwatch
CNG consumption measurement	Manometer (connected to venturimeter)
Emission measurement	Qrotech gas analyzer

Regarding emissions, an exhaust gas analyser placed on the line of the engine, exhaust gas was used to detect the major pollutant gases. The level of NO_X, HC and CO emissions were detected using exhaust gas analyser (Make: QROTECH, Model: QRO-404). An AVL smoke meter (Make: AVL, Austria, Model: 415S) was used to measure smoke level in the exhaust gas.

Experimental methodology: Experiments were performed at constant engine speed of 1500 rpm and with a constant injection timing of 23°BTDC. At first the engine was operated with neat diesel and then subsequently run with natural gas in dual fuel mode. Two modes of steady state operation were chosen for experimentation: light load (1 BMEP) and high load (5.3 BMEP) which were about 25% and 100% of the rated output of engine at this engine speed. To ensure consistency in engine operations, the engine was initially operated with neat diesel until the exhaust gas temperature reached a fixed value of temperature indicating the engine reaches the stable operation. Then the measurements were recorded for this condition. The quantity of CNG was increased by adjusting fine control of needle valve. Subsequently, quantity of diesel that was injected reduces with help of governor. The CNG energy ratio was varied from 0% to maximum possible range until engine started to misfire.

To present the percentage of gaseous fuel, the following expression was used:

$$Z = \frac{\dot{m}_{Nat.Gas}}{\dot{m}_{Diesel} + \dot{m}_{Nat.Gas}} \times 100(\%)$$

Where, z=0% represents normal diesel operation and Z > 0% represents dual fuel operation.It varies from 63% to 80% depending on operating conditions.

3. RESULTS AND DISCUSSIONS

The results presented in this section were obtained with natural gas as the main fuel and diesel was injected in small quantity in order to sustain the combustion of natural gas in the DF mode. In this case, the CNG energy ratio was varied from 0% to the maximum possible operating range at a constant engine speed and BMEP.

Engine performance: Figure.2, depicts the variation of brake thermal efficiency with different CNG energy ratio at BMEPs of 1 bar and 5.3 bar. The BMEP of 5.3 bar indicates the full load operation i.e., rated power output of 4.4 kW. The brake thermal efficiency was decreases with introduction of natural gas. This is due to the poor ignition quality as the amount of diesel is relatively less in the DF mode. It has been reported that the cylinder charge has higher overall specific heat capacity as compared to the conventional diesel operation. It was also noticed that the ignition delay period is longer than the conventional diesel operation. Introduction of natural gas can lead to partial oxidation of fuel-air mixtures during the compression stroke. This has an increasing effet on the ignition delay period of the liquid diesel fuel.

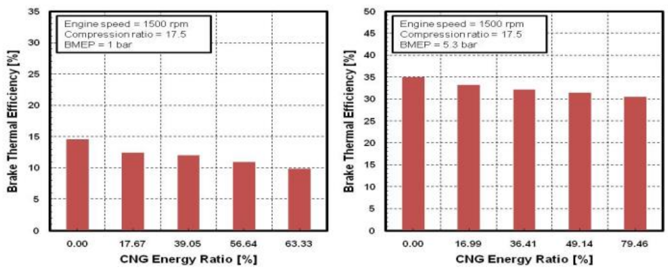

Figure.2. Variation of brake thermal efficiency with CNG energy ratio for BMEP of 1 bar and 5.3 bar at a constant engine speed

Emissions characteristics of natural gas-diesel DF mode at various BMEPs: The plot of NO_X emissions versus CNG energy ratio at a fixed BMEPs of 1 bar and 5.3 bar is shown in Fig.3. NO_X level were always lower than those observed for pure diesel operation. The formation of NO_X is primarily dependent on in-cylinder gas temperature, residence time and oxygen availability. Similar trends were followed at higher BMEPs.

At low BMEPs, the increase of the gaseous fuel concentration results in decrease of NO_X emissions. The effect was more pronounced at low BMEP where the reduction of the NO_X emission is just above 60%. This was due to the fact that low charge temperature caused by the poor quality of natural gas combustion. At highest possible BMEP of 5.3 bar i.e., full load condition, with rise in CNG energy ratio, volume percentage of diesel in combustion decreases which finally reduces in-cylinder temperature. Hence thermal NO gets reduces significantly whereas chemical NO remains same so overall reduction in NO observed at higher CNG energy ratio.

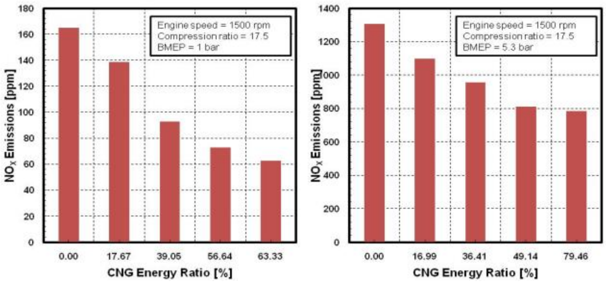

Figure.3. Variation of NO_X with CNG energy ratio for BMEP of 1 bar and 5.3 bar at a constant engine speed

Hydrocarbon (HC) and carbon monoxide (CO) emissions: Figure.4, illustrates the variation of the hydrocarbons with CNG energy ratio at a fixed BMEPs of 1 bar and 5.3 bar. As known, the variation of unburned hydrocarbons in the exhaust gases depends on the quality of the combustion process occurring inside the combustion chamber. Under dual fuel operating mode, combustion process was affected considerably by the total relative air–fuel ratio since this specific factor plays a significant role on the flame propagation mechanism. Hence, at higher energy ratios CNG retards the combustion which leads to misfire and lack of energy to complete combustion of these hydrocarbons. This results into more amount of hydrocarbons are emitted as unburnt hydrocarbons (UHC).

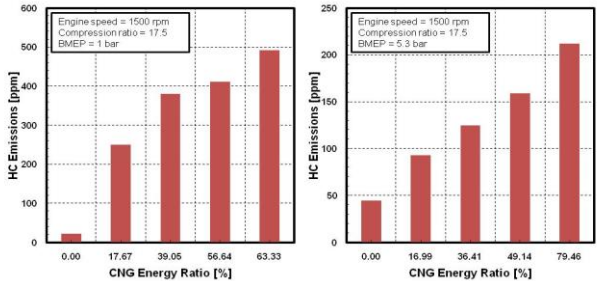

Figure.4. Variation of HC emissions with CNG energy ratio for BMEP of 1 bar and 5.3 bar at a constant engine speed

Figure.5, depicts variations of CO emissions with varying natural gas energy proportions. As known, the rate of CO formation was a function of the air-fuel ratio, the unburned gaseous fuel availability and also the cylinder charge temperature. The mentioned parameters control also the rate of decomposition and oxidation. For entire operating range in dual fuel operation the CO emissions are significantly higher compared to the normal diesel mode. This was due to increase in liquid fuel which was accompanied with a reduction of total relative air-fuel ratio, which favours CO formation. The effect was more pronounced at low load where the increase of the specific CO emission. This was due to the fact that the extremely poor quality of the gaseous fuel combustion contributes to a sharp increase of the unburned gaseous fuel availability, which combined with the low charge temperature and low oxygen concentration of the cylinder charge enhance the CO formation mechanism.

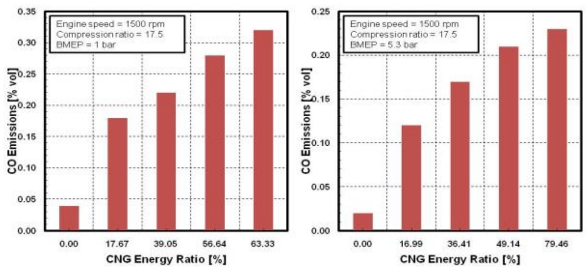

Figure.5. Variation of CO emissions with CNG energy ratio for BMEP of 1 bar and 5.3 bar at a constant engine speed

Smoke emissions: Figure.6, reveals smoke emissions with different CNG energy ratio. It was seen that the level of smoke emissions reduces with induction of natural gas. In dual fuel mode of operation, the contribution of diesel that was injected play a vital role in determining the level of smoke emissions. Smoke level reduces as the CNG energy ratio increases due to lesser quantity of diesel that was injected as compared to the neat diesel operation for both BMEPs of 1 bar and 5.3 bar respectively.

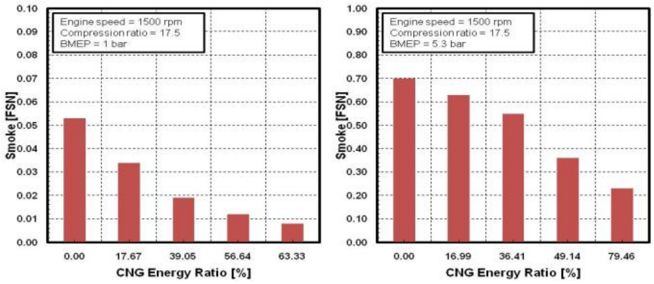

Figure.6. Variation of smoke emissions with CNG energy ratio for BMEP of 1 bar and 5.3 bar at a constant engine speed

Exhaust gas temperature: Figure 7 illustrates the variations of exhaust gas temperature with varying CNG energy ratio. It was revealed that at both the loads i.e., low and high loads, the total relative air-fuel ratio examined the increase of engine speed results to higher exhaust gas temperatures due to longer duration of combustion, due to this brake thermal efficiency also decreased. As the most of the produced energy inside the in-cylinder was absorbed by exhaust gases, exhaust gas temperature observed to be higher while in-cylinder gas temperature remain lower.

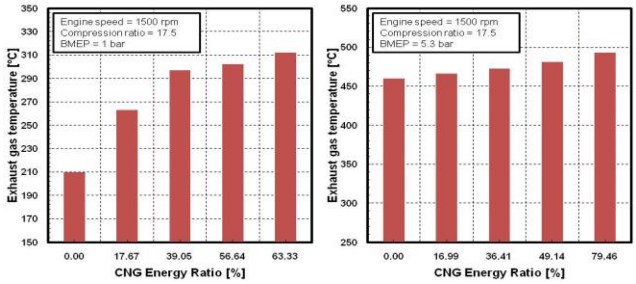

Figure.7. Variation of smoke emissions with CNG energy ratio for BMEP of 1 bar and 5.3 bar at a constant engine speed

4. CONCLUSIONS

An experimental investigation has been conducted in a single cylinder, constant speed, direct injection, naturally aspirated diesel engine with a compression ratio of 17.5. The engine has been suitably modified to operate under DF mode. Measurements have been taken at various CNG energy ratio under both normal diesel and dual fuel operating modes.

- From the experimental data, it was shown that decrease of total air-fuel ratio which was caused by the increase of natural gas, results to a lower brake thermal efficiency compared to diesel mode.
- For all combinations of engine operating range, the increase of CNG energy ratio results in lower nitric oxide emissions as compared to the respective ones observed under normal diesel operation.
- The increase of CNG energy ratio affects adversely (i.e. increase) the concentration of the carbon monoxide emissions. This effect becomes more evident at low and intermediate loads in comparison to the one observed at high load, since at high engine load and low total relative air–fuel ratios a slight decrease of the emitted carbon monoxide concentration was observed.
- Dual fuel operation results also in higher unburned hydrocarbon emissions compared to the ones observed under normal diesel operation. Taking into account all the findings of the experimental investigation, it was revealed that dual fuel combustion using natural gas as a supplement for liquid diesel fuel was a promising technique for controlling both NO_x and soot emissions on existing DI diesel engines, requiring only slight modifications of the engine structure. This is extremely important if one considers the difficulties of controlling both the main pollutants. The observed disadvantages concerning brake efficiency, HC and CO can be possibly mitigated by applying modifications of engine.

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