An Experimental Comparison of Enriched Biogas and CNG on Dual Fuel Operation of a Diesel Engine

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Abstract. In the present work CNG and enriched biogas (93% CH4 by vol.) have been experimentally compared for performance and emission characteristics in a dual fuel diesel engine. The diesel is used as the pilot fuel, which is directly injected into the engine cylinder. The CNG and biogas are used as the main fuels, which are inducted with the intake air in the intake manifold. The experimental observations are taken for steady state conditions at varying engine loads for maximum pilot fuel substitution conditions. The performance of the engine is evaluated based on energy and exergy analyses. The emission characteristics are shown for oxides of nitrogen (NOx), hydrocarbon (HC), carbon monoxide (CO) and smoke emissions. It was found that enriched biogas showed the performance similar to that with CNG, whereas slight variations in the emissions were observed. The exergy efficiencies of 27.8% and 26.9% were calculated for CNG and biogas dual fuel operations respectively at the full load. Similarly, maximum pilot fuel substitutions were found 73.4% and 71.4% for the above conditions respectively.

1. Introduction
Increasing the utilization of alternative and renewable fuels in the internal combustion engines (ICEs) is an important aspect towards energy security and environmental stability. In this context, compressed natural gas (CNG) is a suitable alternative to conventional petroleum fuels due to its rich natural resources and established infrastructure throughout the world. The CNG is mainly composed of methane (CH$_4$) that is compressed to high pressures and distributed in many forms. The utilization of the gaseous fuels in the internal combustion engines offer potential benefits of low emission and a range of improved performances. Biogas (BG) can be considered as a renewable route for the production of natural gas. Biogas is generated by the anaerobic digestion of organic matters and mainly consists of methane (CH$_4$) and carbon dioxide (CO$_2$). It also has small traces of nitrogen (N$_2$), hydrogen sulfide (H$_2$S), hydrogen (H$_2$) and oxygen (O$_2$). It is possible to remove the CO$_2$ and other trace compounds to enrich the biogas with methane (CH$_4$) which improves its properties as a fuel. One of the easiest ways to utilize gaseous fuels in the existing diesel engines is using Dual Fuel (DF) technology. In the DF technology, the conventional compression ignition process is retained along with the combustion of gaseous fuel, premixed with air. In this mode, the diesel fuel is used as the pilot fuel or secondary fuel that is used in small amount and its main purpose is to act as an ignition source. The gaseous fuel is used as the main fuel or primary fuel which is mixed with the intake air and compressed in the engine cylinder. The pilot diesel fuel is injected conventionally that initiates the combustion and gas-air mixture supports the main combustion process. One of the biggest advantages of DF technology is that very little modification is required in the conventional diesel engine, which
makes it technically and economically viable. In addition to that DF technology offers fuel flexibility so that it can be used in the DF as well as single fuel modes depending of the availability of the fuels.

Researchers have investigated CNG as the fuel in the DF mode and some important results have been reported. Nirendra et al. [1] studied diesel-natural gas DF operation and found considerably high specific fuel consumptions at low load compared to diesel only operation. On the emission side, diesel-natural gas DF operations showed higher HC and CO emissions. Liu et al. [2] studied CNG/diesel DF mode of combustion in a multi-cylinder diesel engine for emission investigation. It was found that DF operation resulted in incomplete combustion causing high amount of HC emissions. However, NOx emissions were around 30% lower than the diesel only operation. Alla et al. [3] argued that by advancing the pilot fuel injection timing, the thermal efficiency can be improved at low load and the emissions can also be lowered. Similarly, Yang et al. [4] analysed the diesel-natural gas DF engine with advanced pilot fuel injection timing and found 50% and 60% reductions in HC and CO emissions. They also found that the brake thermal efficiency can be improved by 30% compared to the standard pilot injection timing. Ryu [5] studied the DF operation with CNG as the main fuel and biodiesel as the pilot fuel and similar results were reported. Similarly, some researchers have also investigated on biogas in the DF engine, however, due to variation in biogas composition, these studies have shown diverse results. Verma et al. [6] studied the diesel-biogas DF operation with varying composition of biogas. It was found that with higher percentage of CO₂ in the biogas, the engine performance and emission characteristics are significantly affected. Barik and Murugan [7] studied the production and utilization of biogas with diesel in DF mode. Utilizing of biogas in DF mode caused 49% and 39% decrease in smoke and nitric oxide (NOₓ) emissions respectively compared to diesel only operation. However, thermal efficiency was decreased by 6.2% at full load condition. Luijten and Kerkhof [8] investigated biogas as the main fuel in DF operation with Jatropha as the pilot fuel. They found 10% decrease in thermal efficiency at low loads, however, at high loads, thermal efficiency similar to the diesel operation was observed.

This study is conducted in the context of analysing biogas as a renewable source of methane and its utilization in the internal combustion engines in DF mode. In the present work CNG and enriched biogas (93% CH₄ by vol.) have been experimentally compared for performance and emissions characteristics in a DF diesel engine. The performance of the engine is evaluated based on energy and exergy analyses. The emission characteristics are shown for oxides of nitrogen (NOₓ), hydrocarbon (HC), carbon monoxide (CO) and smoke emissions.

2. Experimental setup and procedures

The experiments were performed in a four-stroke, single cylinder, diesel engine. The engine has 87.5 mm bore and 110 mm stroke, and 17.5 compression ratio. It also has a Bosch diesel injector for pilot fuel injection and gaseous fuel is fumigated in the intake manifold. The intake manifold was slightly modified by incorporating a gas mixture for gaseous fuel induction. The engine operates on natural inspiration and an air-box was used to damp-out air fluctuations. The gaseous fuels (CNG and biogas) were stored in the high pressure gas cylinders and the operating pressure was achieved with the help of pressure regulators. A flame trap was also used as a safety device against possible backfire; in addition to that it also helped in pressure stabilization. The control valve was used for gas flow control and a digital flow meter was used for the flow measurements. The conventional diesel injector was used for pilot fuel injection; the pilot fuel was stored at an overhead tank. The schematic diagram of the experimental test setup for DF operation is illustrated in Figure 1(a).

There are three cases: diesel (single fuel), BG-diesel DF and CNG-diesel DF. Firstly, the engine operation was studied with the single fuel operations that is only diesel as the fuel. The engine load was varied from no load to full load during the tests. In case of DF operations, the gaseous fuel was fumigated with the intake air. As a result of additional incoming energy to the engine, the engine speed was slightly increased that was controlled by the mechanical governor. As a result of this, the pilot diesel injection is slightly decreased and engine speed is controlled. The input of gaseous fuel was gradually increased to reach the maximum substitution level (DS), which is denoted by:
\[ DS(\%) = \left[ \frac{m_D - m_{DF}}{m_D} \right] \times 100 \] (1)

where, maximum diesel substitution (DS) is the maximum pilot fuel substituted by the gaseous fuel. In equation 1, \( m_D \) and \( m_{DF} \) are the pilot fuel flow rates at single fuel and DF operations respectively. At this point the engine was allowed to run for some times for thermal stability and then the measurements were taken for both performance and emission analyses. The energy efficiency (\( \eta_I \)) and exergy efficiency (\( \eta_{II} \)) are defined as following:

\[ \eta_I = \left( \frac{E_W}{E_{in}} \right) \times 100 \] (2)
\[ \eta_{II} = \left( \frac{X_W}{X_{in}} \right) \times 100 \] (3)

where, \( E_{in} \) is the energy input to the system that is comprised of fuel energies (sum of the pilot fuel and main fuel) and \( E_W \) is the energy output from the engine as brake power respectively. In equation (3), \( X_{in} \) and \( X_W \) are the exergy input to the engine and exergy output as the useful works respectively.

The measurements of HC, CO and NOx emissions were performed with the help of AVL DIGAS exhaust analyzer. The AVL smoke meter was used for the measurement of smoke emission from the exhaust gases.

### 3. Results and discussion

The variations in diesel substitution and diesel energy share with the engine load for diesel-BG and diesel-CNG DF operations are shown in Figure 1(b). It can be seen that diesel substitution decreases with the increase in engine load for DF operations. This is due to the higher combustion rates required at high loads that need higher amount of pilot fuel as compared to at the low loads. Therefore, due to higher pilot fuel flow rates at higher loads, lower diesel substitutions were observed. The diesel substitution was found to vary between about 90%-70% as the engine load was varied during DF operation of the diesel engine. It was also found that BG and CNG did not significantly affected the diesel substitution and similar trend was observed. However, CNG as the main fuel showed slightly higher diesel substitution as compared to BG in the DF operations. At full load, diesel substitutions were found 73.4% and 71.4% for CNG and BG DF operations respectively.

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**Figure 1.** (a) Schematic diagram of the dual fuel experimental setup. (b) Variation of diesel substitution and diesel energy share with the engine load for diesel-BG and diesel-CNG DF operations.
The energy and exergy efficiencies are given in Figure 2(a) and Figure 2(b) respectively for diesel, diesel-BG and diesel-CNG DF operations with the engine load. It was found that DF operations showed lower efficiencies at low to medium engine load as compared to diesel operation, however, equivalent engine operations were achieved at the high loads. This is because of leaning (air to fuel ratio) of DF operation at low loads that caused lower combustion rates and lower conversion efficiency. Also, lengthened ignition delay shifts most of the combustion process far from TDC that also contributes to lower efficiency. In addition to that the higher HC emissions (See Figure 3(a)) indicates poor combustion as compared to diesel operation and contribute to lower efficiencies. On the other hand at high loads, a rich homogenous air-gas mixture helps in achieving higher combustion rates and produces better efficiencies. Furthermore, slightly lower exergy efficiencies as compared to energy efficiencies can be observed for all the engine loads. This is because of higher exergetic potentials of liquid and gaseous fuels as compared to their energy potentials (heating values). The exergy efficiencies of 27.7% and 26.9% were calculated for CNG and biogas DF operations respectively at the full load, whereas 27.45% for diesel operation. This is mainly because of higher heating value of CNG as compared to BG, which provides higher combustion rates and higher efficiency. Whereas, due to presence of small amount of CO₂ in biogas, slower combustion causes lower efficiency compared to CNG.

![Figure 2. (a) Variation of energy efficiency (b) Variation of exergy efficiency with the engine load for diesel, diesel-BG and diesel-CNG DF operations.](image)

The variation of nitrogen oxides (NOx) emissions with the engine load for diesel, diesel-BG and diesel-CNG DF operations is shown in Figure 3(a). The DF operations showed lower NOx emission at low to medium load, however, only at higher loads, higher NOx emissions (compared to diesel operation) were observed. It is primarily because of lean air-fuel ratio at low load, which causes lower combustion temperature and hence lower NOx emissions. Whereas, premixed gas-air mixture produces significantly higher temperature at high loads and hence high NOx emissions. The CNG showed slightly higher NOx emissions as compared to BG from medium to high loads. The slight amount of CO₂ may perhaps cause this effect. The variation in HC emission is shown in Figure 3(b) for diesel and DF operations with the engine loads. The results show significantly higher HC emissions in DF operations as compared to diesel operation at low loads. It shows incomplete combustion of hydrocarbon fuels due to over-leaning effect at low load. The small quantity of diesel (pilot fuel) is not able to properly ignite the mixture causing unburned fuel to exhaust in the atmosphere. This is disadvantageous not only from the environmental point-of-view but also to the engine performance. However, as the engine load was increased, the HC emissions were significantly decreased but remains higher than the diesel operation. CNG DF operation showed slightly lower HC
emission as compared to BG DF operation.

![Figure 3](image1.png)

**Figure 3.** (a) Variation of nitrogen oxides (NO\textsubscript{x}) emissions (b) Variation of hydrocarbon (HC) emissions with the engine load for diesel, diesel-BG and diesel-CNG DF operations.

The variation in CO emissions from diesel and DF engines are shown Figure 4(a) with the engine loads. The trend of CO emission was found similar to HC emission in which DF operations showed higher emissions as compared to diesel operation. The BG showed slightly higher emission compared to CNG. However, CO emission was found to be increased with the engine load for diesel and DF operations. This could be due to fuel richness in the engine cylinder increases with the engine load. The formation of CO is significantly governed by the local fuel richness and combustion temperature. At high load, higher amount of pilot fuel injection may also contribute to higher CO emissions. The variation of smoke emissions with the engine load for diesel, diesel-BG and diesel-CNG DF operations are shown in Figure 4(b). Both the DF operations indicated significantly lower smoke emission compared to diesel only operation for all the engine loads. The smoke emission increases with the engine load, however for DF operation the variation was found lesser. CNG and BG showed similar smoke emissions for DF engine, however, BG was found little lesser polluting than CNG. This could be due to the presence of small amount of CO\textsubscript{2} in the biogas that forms active radicles and helps in smoke inhabitation.

![Figure 4](image2.png)

**Figure 4.** (a) Variation of carbon monoxide (CO) emissions (b) Variation of smoke emissions with the engine load for diesel, diesel-BG and diesel-CNG DF operations.
4. Conclusions
An experimental comparison of BG and CNG as the main fuels in DF operations is presented in this article with diesel as the pilot fuel. The tests were performed in a single cylinder, four stroke, diesel engine, which was modified to work with the gaseous fuels in the DF mode. The comparison is presented for performance including energy and exergy efficiencies and emission characteristics of HC, CO, NOx and smoke emissions for diesel and DF operations. It was observed that both BG and CNG showed similar engine performance as the main fuels in DF operations, however, CNG showed slightly better performance. The exergy efficiencies of 27.8% and 26.9% were calculated for CNG and biogas DF operations respectively at the full load. On the emissions side, both the DF operations showed lower smoke and NOx emissions, however higher CO and HC emissions as compared to diesel operation. Nevertheless, the NOx emissions were higher for DF operations only at the peak loads. CNG as the main gaseous fuel showed slight advantage over BG with slightly lower levels of emissions. Nevertheless, enriched BG can be effectively used as an alternative to CNG for transportation and power. This renewable methane form BG can be a prominent fuel for future transportation and energy mix.

Acknowledgments
We would like to acknowledge the support of Council of Scientific & Industrial Research (CSIR), New Delhi, India. Research facility provided by Indian Institute of Technology Delhi (IITD) is also gratefully acknowledged.

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