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Effect of Compression Ratio on the Performance and Emission of Diesel Dual Fuel Engine Using Biogas

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Abstract: *In this paper, a single cylinder, 4 stroke diesel engine was modified to operate as a dual fuel engine using biogas as the primary fuel and diesel as the pilot fuel. The engine was operated at different compression ratios; 14:1, 16:1 and 18:1 and the performance and emission characteristics were studied. Brake thermal efficiency and mechanical efficiency were found to be highest at compression ratio of 18:1.Brake specific fuel consumption was also found to be lowest at compression ratio of 18:1. Engine exhaust gases were measures for different compression ratios. It was found that NOx and* CO_2 *emission increased with the increase in compression ratio and was highest at compression ratio of 18:1. HC and CO emissions reduced with increase in compression ratio and were highest at the compression ratio of 14:1. This study found that at compression ratio of 18:1, the dual fuel engine had superior performance and emission characteristics.*

Keywords: *Biogas, Compression Ratio, Dual fuel engine, Emission, Engine performance*

I. Introduction

Fossil fuels contribute more than 80% of the world total energy [1]. This over dependence on fossil fuels has caused a worldwide threat to the environment due to pollution from burning of fossil fuels because of their high greenhouse gas emissions. Currently petroleum fuels are also faced with challenges of unreliability due to global price fluctuations. More stringent environmental regulations have also been set to reduce the contribution of fossil fuels to emission of the greenhouse gases in the process of addressing climate change[2], [3]. Therefore, a need to utilize alternative energy sources is increasingly becoming viable in the process of reducing the challenges caused by fossil fuels. For decades, researchers have taken into consideration the use of biogas as gaseous sources of energy in internal combustion engines [4]–[9].

Gaseous fuels are considered to be good for internal combustion engines because of their good mixing characteristics with air. They have wide flammability limits and high self-ignition temperature enables them to operate with lean mixtures and higher compression ratios, resulting in an improvement in the thermal efficiency and reduction in emissions mostly HC, CO_2, NO_x, SO_x and particulate matter. Gaseous fuels include natural gas or (compressed natural gas), hydrogen, biogas and other gaseous fuels that can be used in internal combustion engines [10]–[13].

Considering the predicted depletion of fossil fuels and their effects on the global climate change, there is a need to utilize renewable source of fuel for internal combustion engine. Biogas has been studied by different researchers as the effective alternative fuel in internal combustion engines under dual fuel engine operation[14] .

Biogas is a renewable gaseous fuel produced by anaerobic fermentation of organic material. It can be produced from animal manure waste, waste water, municipal waste and solid wastes [15]. The primary contents of a typical biogas are methane and carbon-dioxide and other gases are in smaller quantities: methane – CH_4 (50-75 %), carbon dioxide CO_2 (25-50%), nitrogen N_2 (0-10%), hydrogen – H_2 (0-1%), hydrogen sulphide – H_2S (0-3%) and oxygen– O_2 (0-2%) [16]. It can be used in compression ignition (CI) engines in the dual fuel mode due to its high methane content. Methane CH_4 is the main constituent of biogas, and the proportion varies from feed stock to feed stock.

Research has been carried out for the use of biogas and diesel in dual fuel engine operation. Here biogas is inducted through the intake manifold and compressed along with air in a conventional diesel engine but since the self-ignition temperature of biogas is high, a small amount of diesel (pilot fuel) is injected just like in diesel engine. This pilot fuel self-ignites and causes the already compressed biogas to ignite [6], [9], [15], [17], [18].

The other mode of biogas utilization in internal combustion engines is homogeneous charge compression ignition (HCCI). In this engine operation, a nearly homogeneous lean mixture of fuel (biogas) and air is ignited by compression. This homogeneous charge compression ignition operation gives high thermal efficiency, extra low NO_x high and low particulate matter emission [19]–[21].

Dual-fuel engine operation combines the use of liquid fossil fuel and gaseous fuel which improves fuel economy and minimizes the emissions especially of NO_x and particulate matter (PM) which makes it one way of curbing the challenges posed by the use of fossil fuels in conventional internal combustion engines [14], [21]–[23].

A lot of research has been on the use of biogas in CI dual fuel engine [4], [6], [24], [25]. This research is therefore influenced by the previous work done on the use of biogas in internal combustion engines. The paper therefore seeks to study in details the effect of compression ratio on the performance and emission of dual fuel engine using biogas and diesel.

II. Experimental Setup And Procedure

2.1 Experimental Setup

The experiments were carried out on a 3.5 kW single cylinder, water cooled, four-stroke, multi-fuel, variable compression ratio CI research engine with specifications in Table 1. The CI engine was modified to operate as a dual fuel engine by introducing biogas with air as the main charge.

Table 1: Research Engine Specification

Parameter	Value
Displacement(cm^3)	661
Number of Cylinders	1
Number of Strokes	4
Power(kW)	3.5
Compression Ratio	VCR(18-12)
Torque(Nm)	11.5

Biogas was introduced to the engine's air intake system by flexible rubber tubes through a desulphuriser, dehydrator and to a gas pump that was used pump it to the engine. The purpose of the desulphuriser was to reduce the hydrogen sulphide (H_2S) levels by precipitation of sulphur using iron salt such as iron II chloride. Hydrogen sulphide was removed before combustion to prevent corrosion of the equipment and for environmental concerns. The volume flow rate of the biogas was controlled by the valves and measured with a positive displacement gas flow meter as shown in Fig. 1.

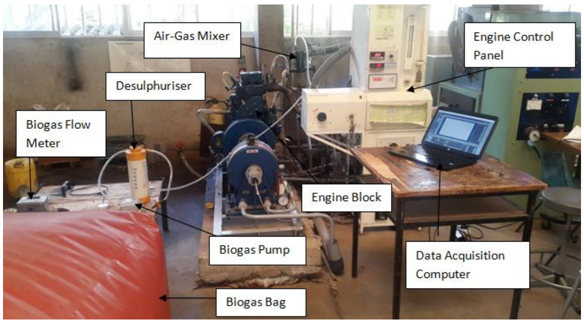

Figure 1: The Experimental Setup

The diesel fuel consumed by the CI engine was measured by determining the volume flow of the fuel in a given time interval during each test. The volume flow was measured using a glass burette having graduations in milliliters (ml). During each test, the volume flow was measured for a particular time, (one minute for each engine loading) and then using the diesel density (837 kg/m^3), fuel consumption in (kg/hour) was calculated by multiplying the volume flow rate with the diesel density.

The fuel air mixing unit was designed to allow proper mixing of biogas and air before the mixture was introduced into the combustion chamber as the main charge for combustion. The volumetric capacity of the engine that was used in this research was 661cc so the volume of the mixing chamber was designed to be more than 661cc so that adequate air was supplied into the combustion chamber [26].Using a cylindrical steel pipe of an internal diameter of 86 mm, the length that would give the volume of the mixing chamber greater than 661cc and length greater than 158 mm. A length of 200 mm was selected due to the considerations of installation to the modified engine.

1.2 Experimental PROCEDURE

The variable compression ratio engine used the tilting block mechanism to vary the compression ratio without changing the geometry of the combustion chamber. The tilting block mechanism works by varying the TDC position of the piston [27], [28]

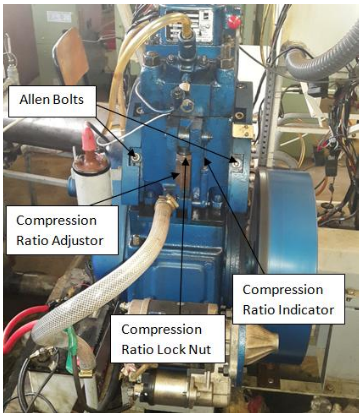

Figure 2: Mechanism for Adjusting Engine Compression Ratio

The mechanism is provided with the compression ratio indicator as shown in Fig.1 which indicates the compression ratio marks of 18, 17, 16, 15, 14 and 12. To change the compression ratio, the allen bolts on both sides of the block were loosened, the compression ratio lock nut was also loosened to enable the compression ratio adjustor to rotate and move to a specific compression ratio mark on the CR indicator. After adjusting to the required CR, the lock nut was then tightened and all the allen bolts tightened. The new compression ratio was then configured in the software and the tests carried out. The tests were carried out on compression ratio of 18, 16 and 14. On each compression ratio, engine was load was increased from 3kg (25%) to 12kg (100%) and the speed was maintained constant. Engine performance and emission characteristics were then studied on each load for various compression ratios.

Exhaust gases; HC, CO_2, NO_x, SO_x and CO were measured using a Testo 350-S flue gas analyser which comprised of a control unit and a testo 350-S/-XL flue gas analyser. An opening was created in the exhaust pipe to allow the insertion of the flue gas analyser probe. The probe and the sampling tube were connected to the gas analyser to measure the content of the exhaust gas for each test.

2.3 Performance Characteristics

Engine performance characteristics were studied under dual fuel operation. The tests were done on compression ratio of 18, 16 and 14. For each compression ratio, the engine load was increased from 3, 6, 8 10 and 12kg. Performance characteristics that were analysed for the varying compression ratio were brake thermal efficiency, brake specific fuel consumption, and mechanical efficiency of the engine. For the dual fuel engine, the brake thermal efficiency was calculated as in equation (1) and the brake specific fuel consumption (BSFC) was calculated as in equation (2)

$$\eta_{ther} = \frac{\dot{W}_b}{CV_b \dot{m}f_b + CV_d \dot{m}f_d}. \tag{1}$$

$$BSFC = \frac{\dot{m}f_b + \dot{m}f_d}{\dot{W}_b} \tag{2}$$

Where η_{ther} is the brake thermal efficiency, $\dot{W}_b$ is the engine brake power, $\dot{m}f_b$ is the mass flow rate of biogas to the engine, $\dot{m}f_d$ is the mass flow rate of diesel into the engine, and CV_d and CV_b are calorific values of diesel and biogas respectively.

1.3 Emission Analysis

Exhaust gas from combustion was analysed using the flue gas analyser to test the concentration of unburned HC, CO_2, NO_x, SO_x and CO. All the tests were carried out with the engine running at 1500 rpm with varying load. The content of the exhaust gas was measured in particles per million (ppm) or volume percentages (%vol).

III. Results And Discussion

This section presents and discusses the results of the experiments. Variation in performance characteristic and emission characteristics with respect to the compression ratios are shown. The attributes of the variations are also discussed.

3.1 Performance Characteristics

3.1.1 Brake Thermal Efficiency

Fig. 3 shows the variation of brake thermal efficiency with the engine load at different compression ratios. Brake thermal efficiency increases as the load increases for all the compression ratios and for both dual fuel operation and diesel fuel operation. The increase in thermal efficiency with increase in the load is attributed to the higher power produced at higher loads [29]. There was a 19% increase in the thermal efficiency when the compression ratio was increased from 16 to 18. The increase in thermal efficiency with compression ratio is attributed to the rise in temperature and pressure in the combustion chamber that increases with the increase in compression ratio [8] [30]. The increase in temperature and pressure in turn leads to increased combustion of biogas in the combustion chamber. It is also observed from the figure that the thermal efficiency of the dual fuel engine at all loads under dual fuel operation is lower than that of the diesel engine. On average, the thermal efficiency dropped by 17% between the diesel operation and dual fuel operation at CR 18. The drop between the thermal efficiency under dual fuel was due to the fact that biogas contains carbon-dioxide which replaces oxygen in the combustion chamber thus causing incomplete combustion in dual fuel engine [31].

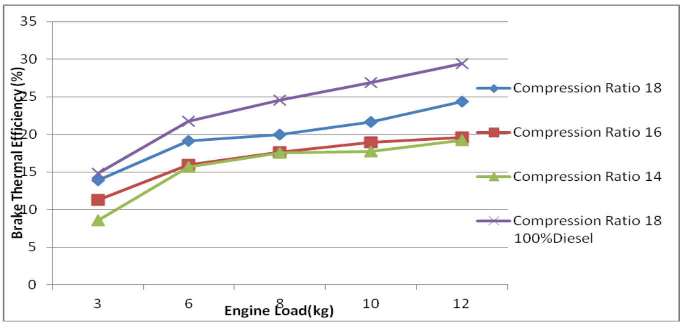

Figure 3: Variation of brake thermal efficiency with load

3.1.2 Brake Specific Fuel Consumption

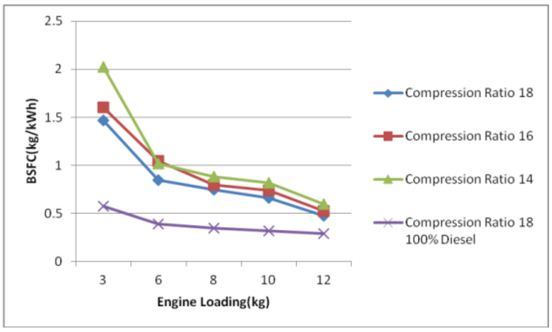

Figure 4: Variation in brake specific fuel consumption with load

Brake specific fuel consumption variation is shown in Fig.4. It can be observed that the brake specific fuel consumption of the dual fuel engine was higher than that under diesel fuel operation. The increase in brake specific fuel consumption of a dual fuel engine is caused by lower heating value (calorific value) of biogas [32]. Another reason for the increased brake specific fuel consumption under dual fuel operation is the presence of CO_2 in biogas that leads to low fuel conversion efficiency [31]. Fig.4 also shows the reduction on BSCF for both diesel and dual fuel operations with increase in the engine loading. This is attributed to the incomplete combustion and slow burning that lead to low fuel conversion efficiency of dual fuel at low loads [5].

It can also be observed from Fig.4 that the BSFC lowers with increasing compression ratio. There was about 26% drop at a load of 3kg for the increase of compression ratio from 14 to 18. This trend is pointed to the better combustion at higher compression ratios [33]. Similar results were also observed by V. Hariram *et al.,* [29] in their research that investigated the influence of compression ratio on combustion and performance characteristics of direct injection compression ignition engine.

3.1.3 Mechanical Efficiency

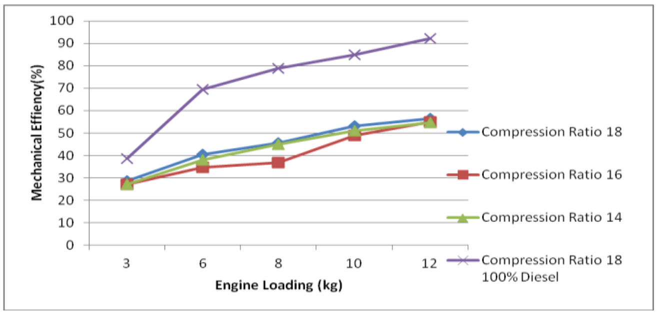

Figure 5: Variation in mechanical efficiency with load

Variations in mechanical efficiency of the dual fuel engine with compression ratio and engine loading is shown in Fig.5. For the dual fuel engine, the mechanical efficiency was lower than that of the purely diesel operated engine. However its also observed that for both the dual fuel engine at all compression ratios and diesel engine, the mechanical efficiency increased with the increase in the engine loading.

3.2 Emisson Analysis

3.2.1 Carbon Monoxide Emission

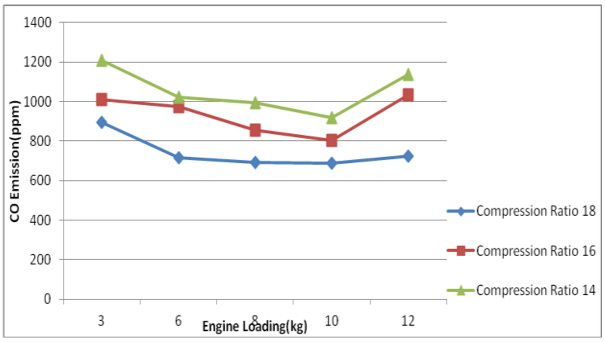

Figure 6: Variation of the CO emission with engine load

The effect of compression ratio on carbonmonoxide (CO) emission is illustrated in the Fig. 6. It can be observed in the figure that high compression ratios have low CO emissions. The exisitance of high CO emissions at low compression ratio describes the incomplete combustion of the biogas-air mixture in the combustion hamber [34]. The figure also shows that at low loads, the emission of CO was high for all the compression ratios and reduces as the load increased. This is attributed to the dilution of the charge with CO_2 in biogas that leads to low temperatures in the combustion chamber that subsequently reduces the oxidation of CO and increases CO emission at low loads. Increasing the load also causes increase in temperatures thus increasing combustion and reducing CO emission [35].

3.2.2 Carbondioxide Emission

Fig. 7 shows the variation in the carbondioxide (CO_2) emission with the engine loading at different compression ratios. At high compression ratios, CO_2 emission in the exhaust increased. The reason for the increased amounts of CO_2 with increase in compression ratio is that at high compression ratios, the clearance volume of the combustion chamber reduces which leads to increase in temperatures of combustion and thus better combustion. Better combustion leads to high CO_2 emission in the combustion exhaust. Similar results were obtained by Bora *et al.*, in the experiment to optimize the injection timing and compression ratio of a raw biogas powered dual fuel engine [6].

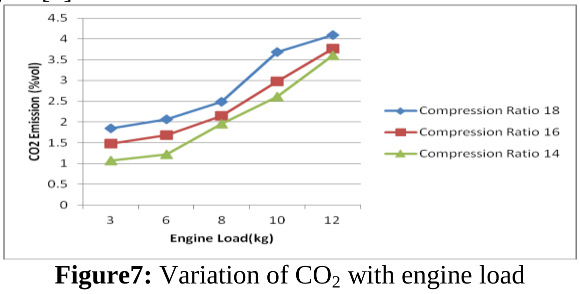

Figure7: Variation of CO_2 with engine load

3.2.3 No_x Emission

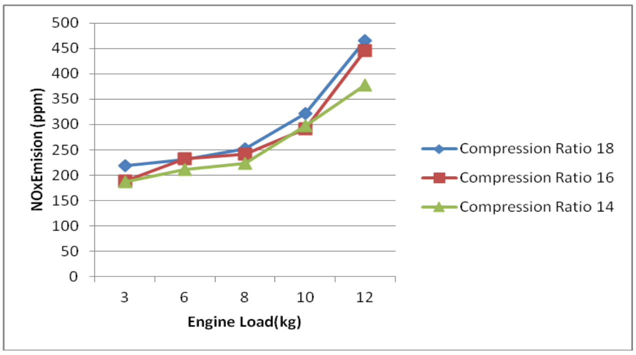

Figure 8: Variation of NOx with engine load

In Fig.8 the variation of the NOx emission with the engine load for different compression ratios is illustrated. It can be seen from Fig.8 that NOx emission increased as the compression ratio increased. On average, there was a 20% increase in NOx when compression ratio was increased from 14 to 18. The rise in NOx levels with compression ratio is attributed to the increase in cylinder temperature. At high compression ratios, the clearance volume reduces and thus the combustion temperatures increase leading to oxidation of nitrogen and high NOx emission. It can also be observed from the figure that for all the compression ratios, the NOx emission increases with increase in the engine load. One reason for this is that at high load, there is increased combustion temperature and pressure at high engine loads [36][5].

3.2.4 Unburnt Hydrocarbon Emission

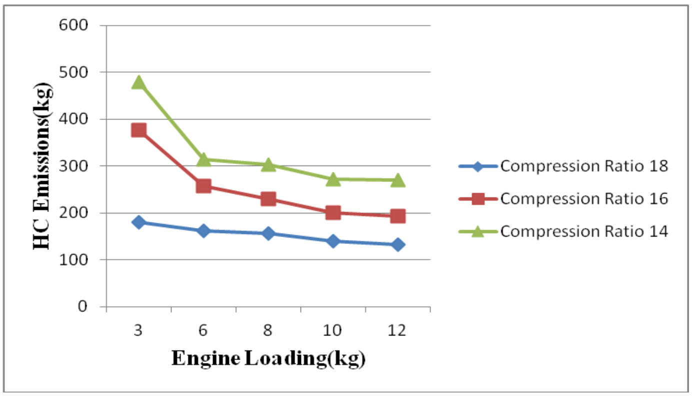

Figure 9: Variation of HC with load at different CR

The unburnt hydrocarbon (HC) is the product of incomplete combustion of fuel. Fig.9 illustrates that HC emission reduced with the increase in the compression ratio. In this study, on average the HC emission decreased by 60% with the increase in CR from 16 to 18. The reason behind this trend is that at high compression ratio, cylinder temperature increases and thus facilitates proper flame propagation and complete fuel combustion [6][8]. It can also be observed from the figure that HC emission also reduces as the engine load increases. This is also attributed to the rise in cylinder temperature at high loads that facilitates complete combustion.

IV. Conclusion

In this study, an experimental investigation was conducted to study the effect of compression ratio on the performance and emission characteristics of a dual fuel engine using biogas as the primary fuel ad diesel as the pilot fuel. A direct injection compression ignition engine was modified to operate under the dual fuel engine mode and its operation was studied. The following conclusions were drawn from the study;

1. Biogas is a relatively cheap renewable source of energy that can be used to substitute the use of fossil fuels in internal combustion engine.
2. The brake thermal efficiency of the dual fuel engine is lower than that of a single fuel diesel engine. This is due to the low calorific value of biogas. However, increasing the compression ratio increases the brake thermal efficiency of a dual fuel engine due to the increased combustion.
3. Increasing the compression ratio reduces the brake specific fuel consumption of a dual fuel engine. This is because there is better fuel energy conversion at high compression ratios. The brake specific fuel

consumption of a dual fuel engine is higher than that of the single fuel diesel engine due to presence of CO_2 in biogas.

4. Mechanical efficiency of a dual fuel engine increases with the increase in the compression ratio but it is lower than the mechanical efficiency of the single fuel diesel engine.
5. Emission of NOx and CO_2 increase with increase in compression ratio for the dual fuel engine. This is due to the increased combustion under high compression ratios. HC and CO reduces with the increase in the compression ratio. This is because at low compression ratios, there is incomplete combustion.

The performance of a dual fuel engine can be improved by operating at high compression ratio and high engine loads. At high compression ratio, there is better brake thermal efficiency, brake specific fuel consumption and higher mechanical efficiency compared to lower compression ratios.

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