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Experimental Investigation On Thermal Efficiency Of Diesel Engine With Jatropha-Diesel Blend With Biogas

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Abstract

This work presents technical performance measurements of field biogas with pure jatropha oil-diesel blends in a dual fuel diesel engine generator. Experimental tests of three performance parameters (thermal efficiency, volumetric efficiency and air excess ratio) were conducted by using biogas and jatropha oil - diesel blends (i.e. 5%, 10%, 20%, 30%, 40% and 50% jatropha oil/diesel). Accordingly, reference performance measurements of using diesel and the blends showed similar performance results in all the measured parameters. In the subsequent dual fuel operation, the thermal efficiency of all blends performs on an average of 31% at higher loads in similar result with the diesel (31.5%). The volumetric efficiency of J10 +Biogas is 92% among the blends which is comparable to that of the diesel and the other blends with biogas are in ranges of 80% at lower load and about 60% at higher loads, where the diesel has got 96% and 81% at lower and higher loads respectively. Air excess ratio of blends showed high reduction than the diesel: the highest ratio (4.37) is observed at lower load by using J10+Biogas and the lowest ratio (1) is resulted by J40+Biogas at higher load. The highest value for diesel is 6.17 at lower load and 1.8 at higher load.

Key Words: Actual biogas, Blends, Biodiesel, pure plant oil, Jatropha oil, Dual fuel, Pilot fuel,

1. Introduction

Since most of the energy resources are limited in nature, thus, the need for different energy resources mixing utilizations has been proposed as an alternative solution to the problem. The ‘‘dual-fuel concept’’ is one of them that uses liquid and gaseous fuels in an engine. This so-called dual fuel operation was studied by many others, using various fuels: [1, 2] indicates that, it is possible to operate most of the dual-fuel engines, either on gaseous fuels, such as biogas/natural gas with diesel/biodiesel or wholly on liquid fuel injection as a diesel engine, thus tends to retain most of the positive features of the diesel operation at full load. Dual-fuel engines achieved higher efficiency without significant particulates and NOx emission [3, 4]. Duc and Wattanavichien [5] reviewed and concluded as several studies are not conclusive on the difference in engine performance between diesel operation and dual fuel operation. To minimize the contradictory results of the dual-fuel diesel engine, [1, 5] recommends more researches on selection of types of fuel, operating and design parameters.

Most studies indicate as almost all combustion devices are easily adaptable to the use of gaseous fuels, such as biogas for power production [1, 5–6]. The biogas in combination with other liquid pilot fuels is studied by many others: biogas and biodiesel dual fuel technology can achieve overall efficiencies typical of diesel engines with a cleaner exhaust emission [7]. But, to utilize the biogas in engines, it is necessary to minimize/eliminate some harmful components such as CO_2, H_2S and water vapor by appropriate cleaning systems. The use of biogas introduces CO_2, which could influence the combustion process [2, 8]. However, up to 40% CO_2 in biogas did not deteriorate engine performance [9], the engine performance is not deteriorated much with 40% CO_2 in biogas, but the performance improves with 30% CO_2 in biogas [1]. Luijten and Kerkhof [2] were also used synthetic biogas (CH_4/CO_2 ratios) and reported a high performance that is comparable with previous works of Edwin Geo et al. [10] and Senthil Kumar et al. [11].

However, in using Biogas as a fuel in engine, it is not auto-ignite at the end of compression, therefore a pilot injection that covers 10% to 20% of the total heat release is required to start ignition [12, 13]. In this regard, fossil diesel and biodiesel are the common and safe pilot (liquid) fuel in the dual fuel engines [1, 14, 15-20], but plant oils are also reported to be used in some cases. Among them, Luijten and Kerkhof [2], have utilized pure jatropha oil without the esterification and reported promising results as the first dual fuel utilization measurements.

The using of the pure plant oil in engine system applications can be a noble idea for developing countries like Ethiopia. However, the utilization of the pure plant oil (PPO) also raised serious concerns by some studies. Spray atomization problem due to larger viscosity and deposit formation due to the larger molecule size on injector holes and piston bowl, reduction of thermodynamic efficiency, an increase in soot emissions and particle [2, 21, 7, 22]. Thus, several studies used different PPO in various ways and suggested that PPO can be used safely in the diesel engine, at least in small blending ratios with some deposit- limiting additives [2, 7, 16-19,21]. Pramanik [16] used blends of jatropha oil and diesel. Narayana Reddy and Ramesh [17] used jatropha oil with optimization of injection rate and timing. Sivakumar et al [18] reported 20% of jatropha oil blend with preheating to a maximum temperature of 47 ^{0}C as a better substitute for diesel. Up to 20% of jatropha oil blend with diesel gives the same result as fossil diesel [16-18, 20].

As seen in the literature review, most of the dual fuel engine performances studied by using diesel, biodiesel or their blends with NG or biogas. In addition, the recent study of pure jatropha oil with synthetic biogas by Luijten and Kerkhof [2] is also claimed as the first work in this regard. Thus, as the most studies, including [2], reported more problems of using PPO in CI engine and actual biogas has also additional chemical compositions than the synthetic biogas: CH_4, CO_2, unavoidable content of 2-8% water vapor and traces of O_2 N2, NH_3, H_2, and H_2S [23]. Therefore, the present work is focused to assess the technical performances of pure jatropha oil-diesel blending with actual field biogas in a modified dual fuel diesel generator, and hence, this work presents the first measured results on combination of jatropha oil-diesel blends and the actual biogas to the author's knowledge.

2. Experimental Materials and procedure

The experiment was conducted on naturally aspirated, single cylinder direct injection diesel engine generator. The engine specification is shown in Table 1. The Engine is directly coupled to electrical generator of 9kw. Locally produced jatropha seed was pressed by locally made device and used in the study along with fossil diesel in blending. The liquid fuels (diesel and the blends) consumption was quantified by externally combined two-tank system one for each fuels.

A 16m^3 biogas plant was used as the biogas source. Simple biogas and air mixing chambers and cleaning systems were constructed and used. The amount of gas is regulated with a control valve based on the optimum engine operation and the flow rate is measured by using known water volume displacement method. Manometer was used for gas pressure measurement.

A load board consisted of 5 lamplights of 1000W and 8 lamplights of 200W each and 1 hot plate cooking stove of 2500W was constructed and used for the electrical power output measurement. Multi-meter was also used in Current-Voltage-resistance measurements. By using the load bank, series measurements were made from 0 kw to 8 kW with steps of 1 kW. Here, although the maximum rated power of the engine is 9kw, but only about 90% of its capacity (8kw) was used. A constructed air box and manometer are used to measure the intake air and the output is used to determine the volumetric efficiency as well as the excess air ratio. The air box method of measuring air consumption involves drawing the air through some form of measuring orifice and measuring the pressure drop across the orifice with manometer [24]. Figure 1 shows all experimental set up with components and instruments.

Table 1. Generator set specifications

LOMBARDINI 7LD663/I	
No of cylinder	1
Number of stroke	4
Bore	95mm
Stroke	94
Volume displacement	666cm3
Compression ratio	17.8:1
Rated output	9kw
Rated speed (rpm)	3000
Power KVA	7 / 5 / 2
Voltage v	380/ 220/ 110
COS	0.8
Frequency HZ	50

2.1. Chemical / physical property of blends

The locally pressed jatropha oil is filtered, blended and used in the engine. The engine's operational conditions were observed and investigated in advance to select the blend levels for laboratory chemical testing. The cylinder head of the engine was repeatedly dismantled and observed for deposit and injection valve clogging. As the observations results showed insignificant quantity of deposits only in higher jatropha oil in the blends (20%-50%), thus, to confirm it, a sample of pure jatropha oil and three samples of blends (5%, 10% and 20%) were tested at Ethiopian petroleum enterprise fuel laboratory for their chemical and physical properties characterization. The laboratory test results are obtained and some of the results are utilized for this study. Since J30, J40 and J50 blend levels were not tested, therefore, some properties of these blends were also utilized from literatures as input in this work.

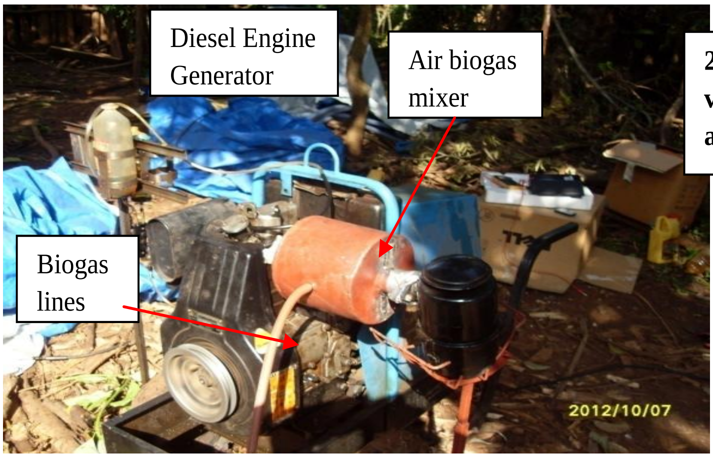
2.2. Reference performance measurements

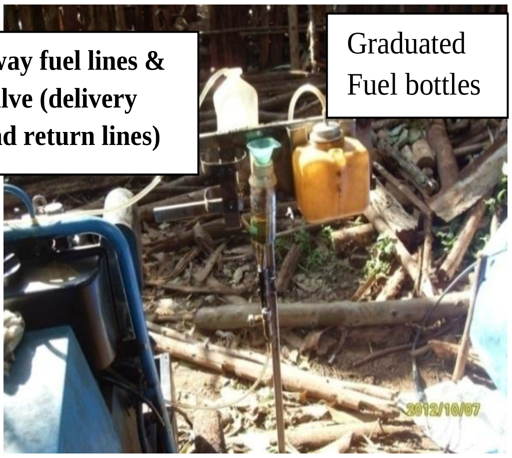
The purpose of this test is to determine differences between the Jatropha oil–diesel blends operation and diesel operation and also to set reference comparison measurements for dual fuel operation. Accordingly, Engine was operated with diesel alone and with jatropha oil-diesel blends. Air box was used for air flow measurement to determine volumetric efficiency and air-excess ratio. Here, the electrical load and the diesel were input variables, but for the operation with blends, the percentages of the blends are also used as variable inputs. During the test, for each load determined volume fuel (diesel or blend) use is measured over time; each measurement takes approximately 15 minutes. With measuring the total range of the generator's electrical output a characteristic for thermal efficiency is obtained.

2.3. Dual fuel performance measurements

Here the engine was run with jatropha oil–diesel blends as liquid fuel and biogas as gaseous fuel.In the dual fuel measurement, in addition to the loads and blends, the amount of biogas used by the engine at each load is also used as an input variable.
The engine was started on diesel and then it is switched to blends and biogas running mode. The other process includes, switching on the first 1000W lamplight, increase biogas flow by control valve and decrease pilot fuel to adjust an optimum engine operation position to obtain the required output voltage with fixed resistance and current. The biogas valve the optimum position is marked and the flow rate of the biogas is measured by means of known water volume displacement for every load.

Since the dual fuel volumetric efficiency was not measured here directly, thus it is obtained with the gas flow measurement and the assumption that the volume of intake mixture is constant as measured in the reference performance measurement. Therefore, as the total volume of the intake mixture is known and volume of the biogas is measured, together, this results in the volume (and mass) of the intake air and dual fuel volumetric efficiency is computed. Since, this study is the first actual biogas and jatropha-diesel test, so that, other related fuels' previous test results: jatropha and other vegetables biodiesel with biogas/Natural gas (NG) is used here for comparison purpose.





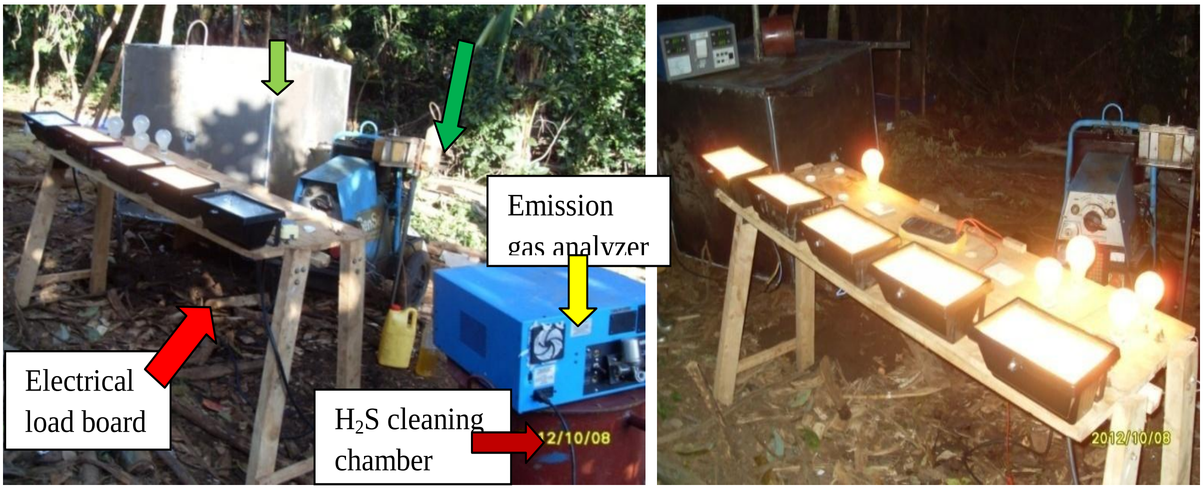


Figure 1. Experimental set up of engine and test components (Top and bottom)

2.4 Engine Performance parameters

In order to define the process of measuring and data analysis of the fuel operation performance, the engine performance is described here with three parameters:

2.4.1 **Air-excess ratio (λ).**This is measured to determine if the engine is starved for oxygen at given load operations. The mass of air that is taken in per second is calculated in terms of the manometer reading which is fitted at the bottom of the air box. The known volume (mass) of fuel (diesel and blends) that is used by the engine is measured in second. These two values give the actual air-fuel ratio and the stoichiometric air-fuel ratios for diesel and different blend ratios are calculated on basis of balancing their reaction equations.

The reference air-excess ratio of this study is calculated by using equation (1).

$$\lambda = \frac{AF_{actual}}{AF_{st,oich}} = \frac{\left\{\frac{A}{F}\right\}_{actual}}{\left\{\frac{A}{F}\right\}_{stoich}} \qquad (1)$$

The air to-fuel ratio AF_{dual} can be written for dual fuel operation as;

$$\lambda_{dual} = \frac{AF_{dual}}{AF_{st,dual}} = \frac{m_{air}}{m_{blend}\left\{\frac{A}{F}\right\}_{blend} + m_{CH4}\left\{\frac{A}{F}\right\}_{CH4}} \qquad (.2)$$

An empirical formula used to calculate the mass flow rate of the air from the air box is obtained from [24],

$$\dot{m}air = Cd * A\sqrt{2 * \rho * \Delta p} \qquad (3)$$

2.4.2.Volumetric Efficiency. Volumetric efficiency has a direct influence on power output and consequently on thermal efficiency. It is defined as:"the volume flow rate of air into the intake system divided by the rate at which volume is displaced by the system" [5].

$$\eta v = \frac{m_{air}}{\rho_{ref}\, V_d} \qquad (4)$$

In dual fuel operation biogas replaces air in the inlet mixture, therefore, eqn. (4) can be written for the dual operation as:

$$\eta v, ref = \frac{m_{air}}{\rho_{ref}\, V_d} = \frac{m_{air}}{\rho_{ref}\, V_d\, N} \qquad (5)$$

where V_d is the displacement volume N the number of cycles per minute (rpm) and ρ_{ref} the density of air at ambient conditions during the reference measurements. Values of ηv,ref are straightforwardly obtained from the reference measurements.

The reference volumetric efficiency as expressed in equation (5) is the volumetric efficiency of a fuel (example diesel) operation at a certain rotational speed (RPM). It is assumed that the total volume of the intake mixture does not change when biogas is added; therefore the reference volumetric efficiency does not change when biogas is added. But, biogas in the intake mixture replaces air and will therefore influence engine performance parameters.Thus for the dual fuel operation, equation (4) can be converted in to;

$$\eta v, ref = \frac{(m_{air})_{dual}}{\rho_{a+b} * V_{d.} * CPS} =$$

$$\frac{m_{air} + m_b}{\rho_{dual} * V_{d.}\ CPS} \text{ X } \frac{m_{air}}{m_{air} + m_b} \text{ X } \frac{\rho_{dual}}{\rho_{a+b}} \qquad (6)$$

Where, ρ_{a+b} is density of air and biogas

2.4.3. **Thermal efficiency**

Thermal efficiency is considered the overall system efficiency. Thermal efficiency is defined as the ratio between power output and power input by means of heat release of the fuels (LHV) as expressed in equation (2.7);

$$\eta th = \frac{P_{out}}{P_{in}} = \frac{P_{elec}}{m_{blend} \cdot LHV_{blend} \cdot + m_{CH\,4}\, LHV_{CH\,4.}} \qquad (7)$$

$P_{ele\,c}$= electrical power output
LHV= lower heating value of the fuels
m_{CH4} LHV_{CH4} is used during dual fuel measurement.

3. Results and Discussion

3.1 Chemical and physical properties tests

The test results was done by the American Standard Test Method (ASTM) in relative to the AGO (diesel) limit. For the three blends (J5, J10 and J20), corresponding viscosity was found to be 3.71, 4.01, and 5.31 cSt respectively, while that of the pure oil is 36.92 at the same test condition. Thus, the viscosity of J5 and J10 was within the (AGO) limit.

3.2 Reference measurements

3.2.1 Thermal efficiency. During these tests electrical loads are used and engine characteristic for thermal efficiency is obtained over the complete output range of the generator. Figure 2. show thermal efficiency as a function of power output.

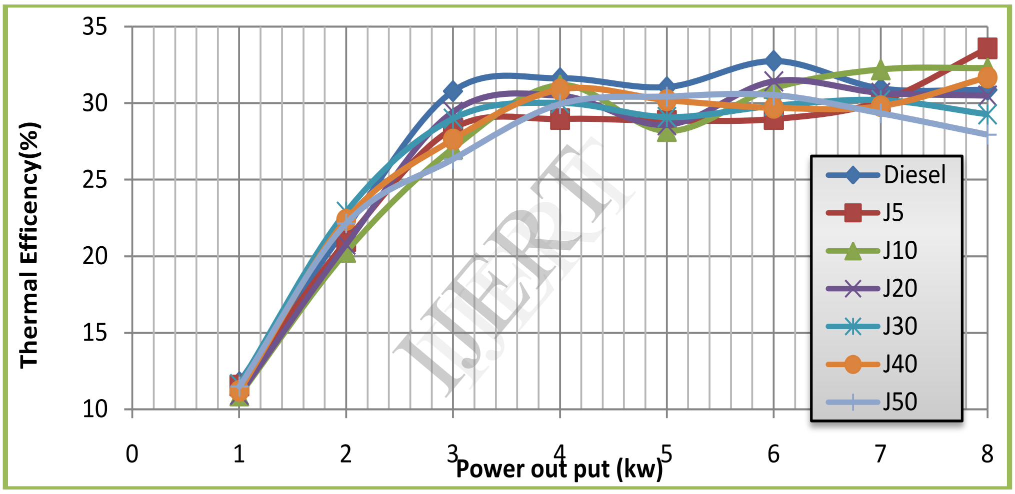


Figure 2. Thermal efficiency reference measurements

Here, the thermal efficiency decreases under half load conditions in all blends and diesel with the lower value of 11% at lower load. Similarly, it increased with increasing of engine loading at about 29.27% - 33.58%. In general, the above results showed similar thermal efficiency of all the used fuels at all engine load conditions, where the blends' results are even higher than the diesel (30%) in some cases (33.58% and 32.31 for J5 and J10 respectively). In the same way, Narayana Reddy and Ramesh [17] used jatropha oil and report 29% for jatropha oil efficiency (after optimization of injection rate and timing) and 32% for diesel in the same engine. But [16] Pramanik reports 18% thermal efficiency at full load for jatropha oil and diesel and 27% for diesel at full load. V.R. Sivakumar et.al, [18] also reported break thermal efficiency decreases from 20% to 18.7% for the increase in blend from 0% to 20%. The only test of pure jatropha oil by [2], also reported 32.5% thermal efficiency for the jatropha oil and diesel. In general, this result is consistent with the works of [16-18, 20], which indicates that up to 20% of jatropha oil blend with diesel gives the same result as fossil diesel.

3.2.2 Volumetric efficiency. Reference volumetric efficiency was measured as a function of engine electrical output load both for jatropha oil-diesel blends and diesel operation. For the reference tests the volumetric efficiency is obtained by air box flow measurement, as described in section 2.4.

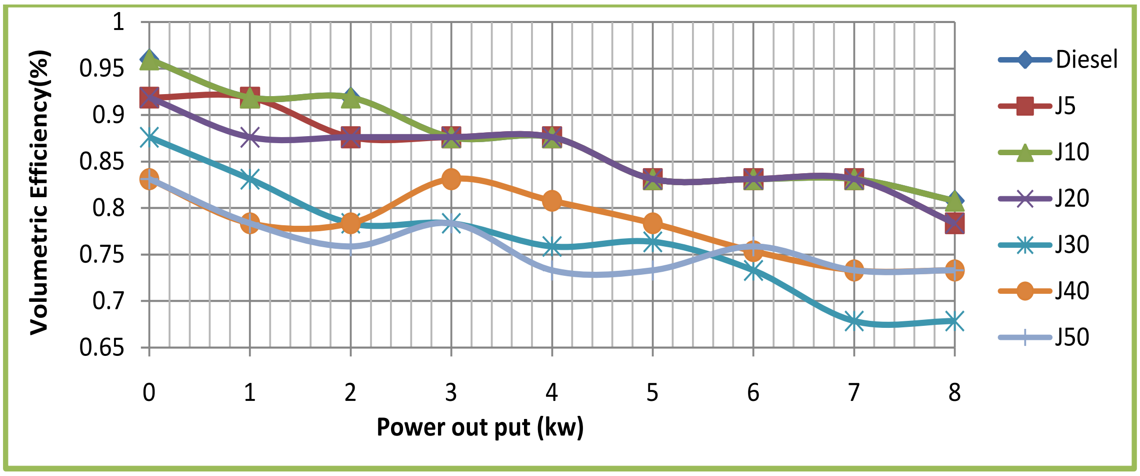


Figure 3. Reference volumetric efficiency measurements

The reference volumetric efficiency results in figure 3. shows that the engine has almost similar volumetric efficiency when using J5-J20 and diesel (92%-96% in lower load and about 80% at higher), but with slight reduction is seen in using J30-J50 (83%-88% in lower load and about 70% in higher loads). But, in general the volumetric efficiency shows slight reduction with the increasing loads, which is consistent with [2], that uses 100% Jatropha oil and reported the average result of 95.1% and 95.7% for diesel. But, here the average result is somewhat, lower than what is reported at 87% for diesel and between 87%- 76% for J10 and J50 respectively. However, this result shows, still the they are on the high end of the diesel volumetric efficiency range, as it is between 80% and 90% [3].

3.2.3 Air-excess ratio. Figure4. shows reference air-excess ratios of different fuels. Here, the results are decreased from 6.8 at no load to 1.78 at full load for diesel fuel. This means that there is still 78% excess air. Excess air factor of the blends are also comparatively similar to that of the diesel at lower engine loads (0-4 kw). The lowest ratio is recorded for J50 at higher load of 8 kw which is 1.52 and indicates that still it is greater than minimum requirement (1.4) for diesel engine optimum operation [3]. Here, values of J10 and J20 indicate that, the air excess ratios of the blends are even higher than the diesel in some load conditions. In the 100% jatropha oil and diesel study, Air excess ratios are reported by [2] as range from 1.4 at full load to as high as 5.7 for minimum (about 10% of full) load. Elango, T. et al [25] indicates that, an engine can ran leaner with *Jatropha* oil and blends than diesel.

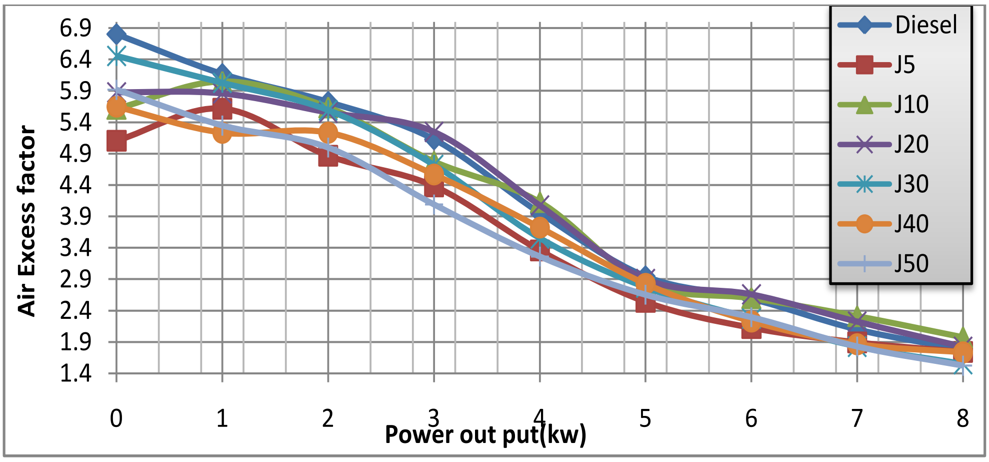


Figure 4.Reference Air-excess ratios

Table 2. dual fuel thermal efficiencies

Power (kw)	Thermal efficiency (%)							Diesel only
	Diesel+B	J5+B	J10+B	J20+B	J30+B	J40+B	J50+B	
1	0.13	0.19	0.19	0.18	0.18	0.20	0.15	11.76
2	0.30	0.26	0.33	0.30	0.34	0.22	0.17	21.84
3	0.33	0.28	0.28	0.37	0.33	0.26	0.25	30.78
4	0.33	0.26	0.27	0.33	0.33	0.34	0.24	31.62
5	0.32	0.32	0.33	0.34	0.30	0.30	0.27	31.06
6	0.28	0.31	0.30	0.30	0.29	0.28	0.28	32.75
7	0.33	0.35	0.35	0.29	0.31	0.28	0.33	30.96
8	0.31	0.32	0.33	0.33	0.30	0.30	0.32	30.87

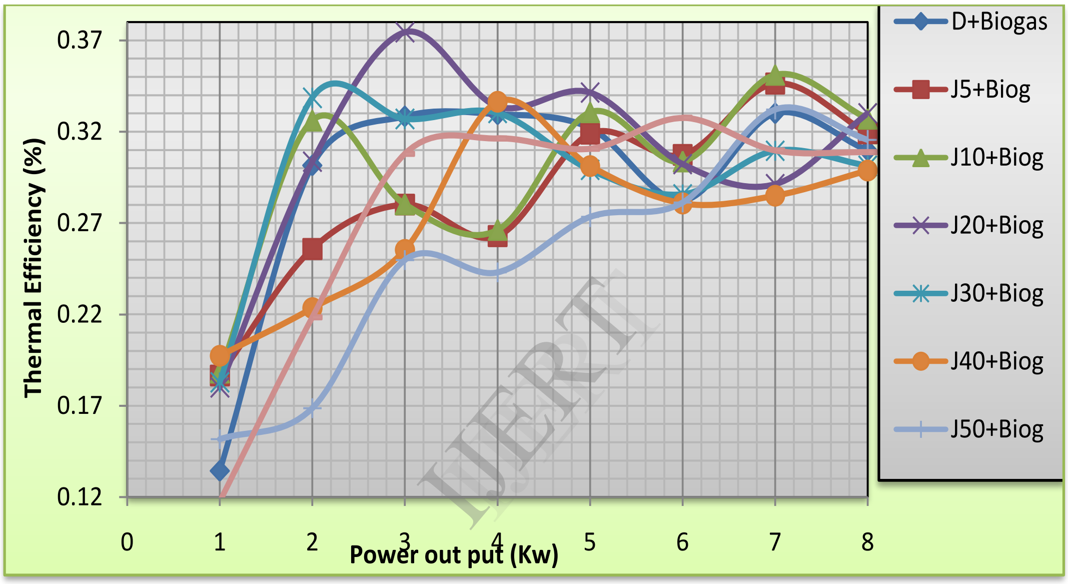


Figure 5. Dual fuels vs diesel thermal efficiency

3.3 Dual fuel Engine performance measurement

3.3.1Thermal efficiency. The dual fuel test measurement efficiency is obtained from the test results of the used fuels (both bio gas and blends) and power output. As it can be seen from Table 2 and figure 5, thermal efficiencies increased with increasing engine load for the dual fuels. Despite some irregularities (Sudden increasing and decreasing) observed between 4kw and 6kw, the thermal efficiencies remains increasing and unchanged for the higher load of 8kW. This results showed that, the dual blends are performed the same to/ or slightly better than the diesel, except in the case of J50+B.

In general, in the figure 5, increasing of thermal efficiency is observed with increasing of engine loads, this trend is also reported in dual fuel measurements by other fuels: combination of jatropha oil and simulated biogas by [2] and for diesel with natural gas, dual fuel by [5], whereas the efficiency was found to be lower than for the pure oil for combinations of pure plant oils with producer gas by [26]. For lower load, reduction of thermal efficiency is observed with biogas addition, in line with most reported dual fuel measurements including [2, 5, 26]. The reason for this condition is speculates by some as, the mixture becomes too lean and burns too slowly, resulting in lower thermal efficiency under these conditions.

3.3.2 Volumetric efficiency. Figure 6 gives the test results for volumetric efficiency for jatropha oil-diesel blends and biogas as a function of power output.

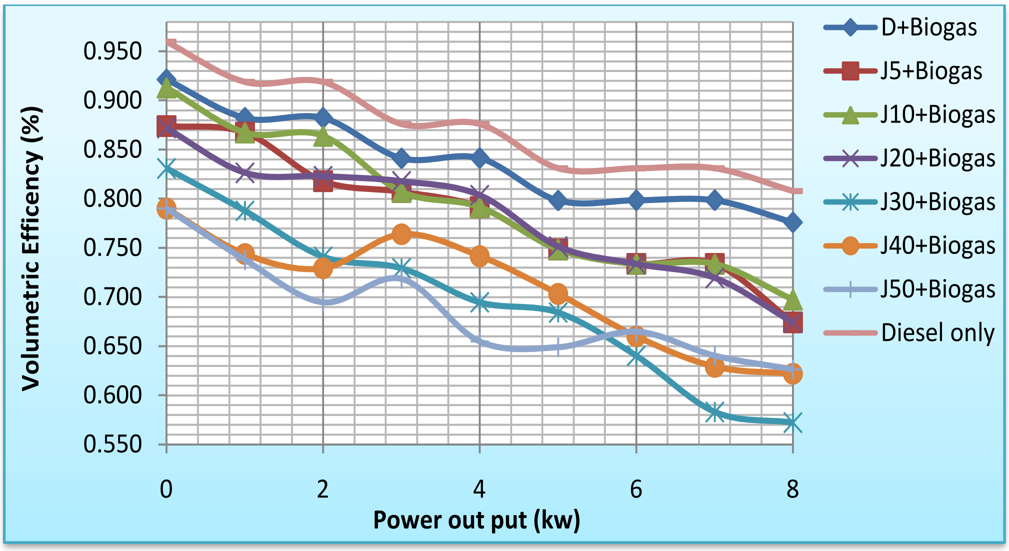


Figure 6. Dual fuels volumetric efficiency

Here, the overall decrease in volumetric efficiency is shown with increasing engine loads. The volumetric efficiency of J10 +Biogas among the blends is 92% which is comparable to that of the diesel and the other blends with biogas are in arrange of 80% at lower load (1kw) and in arrange of about 60% at higher loads, where the diesel has got 96% and 81% at lower and higher loads respectively. In comparison with the reference measurements of diesel and blends, the volumetric efficiencies are reduced at about quarter of the results obtained in the references in lower loads (95%). Significant reduction of the volumetric efficiency is observed, especially in J30, J40 and J50 in the order of 20-29% under higher engine loading. Such strong reduction of the volumetric efficiency was also reported by Senthil Kumar et al. [15], in a study of vegetable oil and hydrogen in CI, which is also similar to Edwin Geo et al. [10], who studied dual fuel operation of rubber seed oil and its bio-diesel with hydrogen. But, a modest volumetric efficiency reduction is reported for pure jatropha oil with biogas in CI for maximum simulated biogas substitution [2].

3.3.3 Air-excess ratio. Values for actual air ratio of the air-excess ratio are obtained with the air box measurement from the reference measurements. Figure 7, Presents the results of dual fuel operation air-excess ratio.

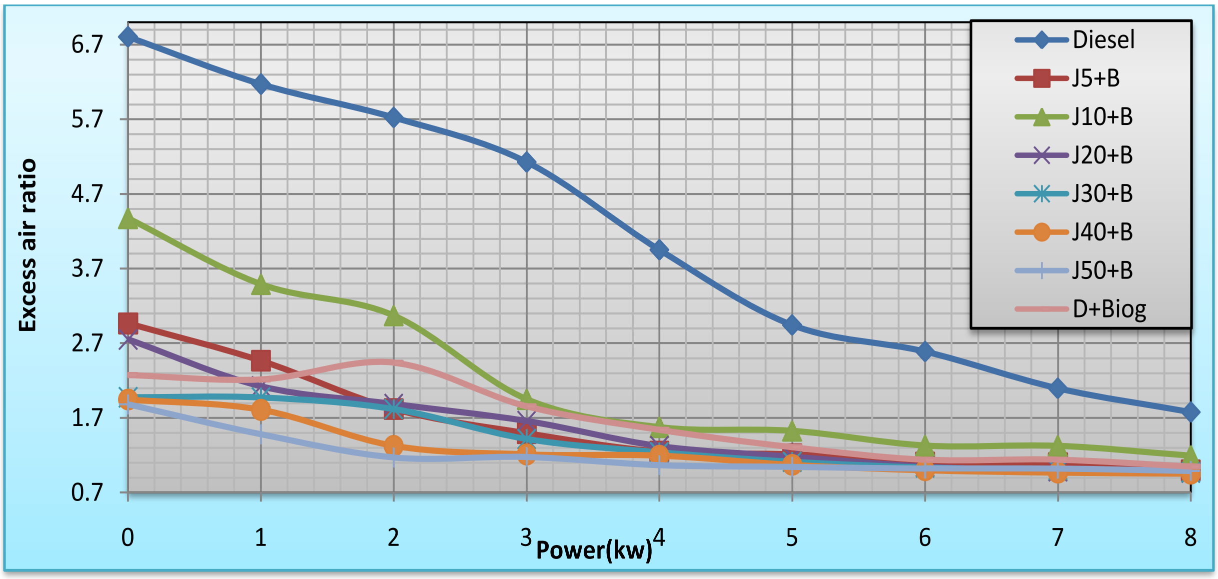


Figure 7. Dual fuel operations air-excess ratios

Here, the air excess ratio of blends showed high reduction ratios than that of the diesel. The highest ratio (4.37) is observed at lower load of 1kw by using J10+Biogas and the lowest ratio (1) is resulted by J40+Biogas at higher load of 8kw. But the highest value for diesel is 6.17 at lower load (1kw) and 1.8 at higher load. Such condition might be resulted in accordance with the expectations of an increase of the biogas fraction in the fuel mixture results in a decrease in air-excess ratio since biogas components (CH_4 and CO_2 and other traces) replaces air in the intake mixture.

Since, it is assumed that, the generator's intake mixture volume remains constant, so that, for dual fuel tests, air-excess ratio obtained from the air box measurements is also consistently decreased with increasing load in the same trends of the reference measurements, but here, in a significantly different than the reference tests. Here, although, some reduction of the air excess ratio is expectable in the dual fuel operations [2], however, the higher reduction of the values in the current work might be due to the used biogas lower quality, which would result in more air displacement and hence lower air excess ratio.

3.3.4. Additional observation result. Although it is not the interest of this study, the reference test as well the dual fuel tests Emmision analysis was done by Exhaust gas analyzer: similar emission in reference and increasing conditions in dual fuel operation were measured. Simple economic analysis of the system also shows 2-7 years pay back period in local condition.

4. Conclusions and Recommendations

As a first step of this study, diesel engine was modified to dual fuel system and other experimental setup and measuring components were also developed locally and successfully used in the study. Accordingly, reference performance measurements of diesel and the blends achieved similar performance results in the measured parameters (thermal and volumetric efficiencies and air excess ratio). So that, this study concluded that the use of the pure jatropha oil-diesel blends instead of diesel does not deteriorate the overall performances characteristics of the CI engine.

In the subsequent dual fuel (blends + biogas) tests, the thermal efficiencies are resulted in similar values to the diesel alone operation. But, the dual fuel volumetric efficiency results show some inconsistencies and reductions than the diesel operation and measurement of the air excess ratio of the dual fuel operation also showed higher reduction in comparing to the diesel. However, since such moderate to large reductions of results of the dual fuels performance parameters than the diesel are also reported as the common dual fuel system limitations in other fuel type studies, thus, this study also concludes as the problem is unavoidable issue due to the air replacement by biogas components and other factors.

In addition to the experimental tests, since, the laboratory level chemical and physical test of the jatropha oil– diesel blends were also shows results of improving some of the inherent drawbacks of the PPO and the physical engine part tests of the lower blends also shows insignificant effects to the engine with the field biogas. Therefore the study recommends the lower blends (J5-J20) with best due recognition, as possible substitutes of the fossil diesel fuels with the biogas. Although the higher blends (J30-J50) were not supported by the laboratory chemical tests, but as their experimental tests resulted in similar performances to the lower blends, so that, the higher blends are also recommended as a fuel for the CI engine, but with some precaution measurements such as periodical inspection of engine parts after using.

In the limiting factor identification of this study, quality of the biogas, which might be a cause for some performance results reduction, is labeled as one of the limitations in this study, and appropriate biogas cleaning mechanism is recommended in future works. In addition, as some of the blends (J30-J50) and few important parameters, such as Calorific Value (CV) were not tested due to limitations of the local laboratory facilities, so that, more tests are required for better understanding of the system.

Since, the main objective of the present work was to investigate the performance and possibility of using pure jatropha oil - diesel blends and actual biogas as a dual fuel in CI engine, therefore, this work has been achieved most of its goals and reported, to our knowledge, as the first dual fuel measurements using locally pressed jatropha oil blends with diesel and locally produced biogas as a fuel in CI engine generator, by utilizing essential instrumentations and components.

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