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Modelling of the Operation of a Small Generator Set Powered by Scrubbed Biogas from Cow Dung

J. K. Tangka[1*], C. T. Ketuma[2], N. Ajaga[3] and C. T. Viyoi[4]

[1]*Renewable Energy Laboratory, Department of Agricultural Engineering, University of Dschang, Cameroon.*
[2]*Department of Agricultural Engineering, University of Bamemda, Cameroon.*
[3]*Department of Rural Sociology, University of Dschang, Cameroon.*
[4]*Department of Anthropology and Sociology, University of Maroua, Cameroon.*

Authors' contributions

This work was carried out in collaboration between all authors. Author JKT designed the study, performed the statistical analysis and wrote the protocol. Author CTK carried out the practical experimentation in the field and data collection, wrote the first draft of the manuscript. Author NA supervised and co financed the research. Author CTV managed literature searches and did the final proof reading. All authors read and approved the final manuscript.

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ABSTRACT

This study involved investigation of the impact of the various factors affecting the use of biogas in a modified gasoline generator. A 1.5 kW gasoline generator was modified to function with biogas by advancing the engine timing and installing a Bernoulli suction device in the carburetor. Biogas produced was purified by removing carbon dioxide, hydrogen sulphide and water vapor in this sequence before introduction into the engine of the generator. Various factors associated with engine performance were investigated including, biogas fuel consumption rate, maximum power output, NOx emissions, CO emissions and the overall efficiency. Results indicated a biogas fuel consumption of 6 litres per minute or 3.6 m 3 per hour. The maximum power output was 0.91 kW giving a power drop of about 39%/ The maximum overall efficiency of the biogas fuelled generator set was 15%. NO_x and CO emissions were 742 and 30 ppm respectively.

**Corresponding author: E-mail: tangkajkfr@juliustangka.org;*

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1. INTRODUCTION

Electricity access in rural areas in developing countries continues to be a myth. It has been estimated that in sub-Saharan Africa, up to 80 percent of the rural population has no access to electricity and other forms of modern energy sources such as cooking gas. The situation is further aggravated by the rapidly increasing population accompanied by little or no expansion in grid electricity connection as well as rapid dilapidation of existing energy infrastructure. The poor road infrastructure in developing countries and the seasonal nature of many of such roads makes the transport and distribution of modern energy sources difficult and in some cases impossible. As a result of this, many people in developing countries rely on biomass exploitation using crude and inefficient technology for heating and lighting. The consequences of using these crude technologies are sometimes disastrous to their health conditions. The use of fuel wood caused many respiratory and ophthalmological diseases in the rural populations as well as caused serious pressure on ecological resources. In Cameroon the number of deaths caused by accidents from temporary energy solutions during blackouts like forgotten lighted candles, and suffocation from charcoal are steadily on the rise. Other problems associated with energy shortage include the devotion of over 30 percent of the useful time to the search for daily energy needs. Also, extensive deforestation has been blamed on fuel wood and agricultural activities of the rural population. In Cameroon, energy supply remains unsatisfactory and the rate of access to modern energies is still very low, about 15% for electricity and of 18% for domestic gas. Access to electricity is less than 5% in rural zones against 50% in urban zones [1]. The rural population in Cameroon is highly dependent on biomass resources for their energy supply. Almost 99% of the rural households cook with firewood, which causes serious respiratory and eye illnesses, especially for women and children [2]. Giant structural projects such as the Lom Pangar hydroelectric dam will further increase the national supply by 200 MW but distribution into the hinterlands will still remain a major problem because of the lack of the necessary infrastructure.

While the population suffers from energy crises there are always cheap and affordable alternatives that are even environmentally friendlier than conventional energy sources. Biogas technology remains one of the simplest and easily affordable energy sources to the rural populations. This is because there is organic waste everywhere there is human settlement and this can be used in biogas plants. In many communities in developing countries, people live with animals such as cows, pigs, donkeys, and goats that generate considerable waste which can be exploited for biogas and subsequently for electricity generation. Such simple technologies would create significant impact on the quality of life, decreasing the incidence of some diseases, and even helping in the mitigation of global warming. Methane the main component of biogas is about 25 times worse as a greenhouse gas than carbon dioxide produced during its combustion, [3]. Biogas technology enables the capture and burning of this gas to produce less toxic gases to the environment with the use of electricity generator sets amongst other power appliances. This technology has been extensively used in many European countries for centuries [4], and South East Asia, [5].

The purpose of this study was to investigate the factors affecting the sustainable use of a small gasoline generator on a biogas, the overall efficiency of the system, the emission/pollution characteristics and the per hour per kilowatt consumption rate. Some literature has been published that sometimes does not hold in field operations for particular cases especially on small generators common in remote areas. The GTZ, [5] gives the amount of biogas consumed per HP as 0.5m3 of gas per HP per hour. Such information would help in modelling the fuelling of small generators with biogas and also guide in energy policy.

2. METHODOLOGY

A 1000 liters polyvinyl (plastic) container was first transformed into a fixed-dome biogas digester. This involved an installation of a dung inlet, slurry outlet, a 10 mm gas collection pipe and a slurry mixer that was introduced through the slurry inlet pipe. A sensible analog manometer was introduced at the top to read the biogas pressure. The 1000l biogas digester is shown on Fig. 1. It was painted black to improve on solar radiation absorption characteristics thereby enhancing some warming of the digester. This waste/water ratio was maintained at 1:1. Cow dung was well mixed with water and the slurry used to fill the digester. The digester was placed under sunlight with average ambient temperature of 22 to 24 *C.

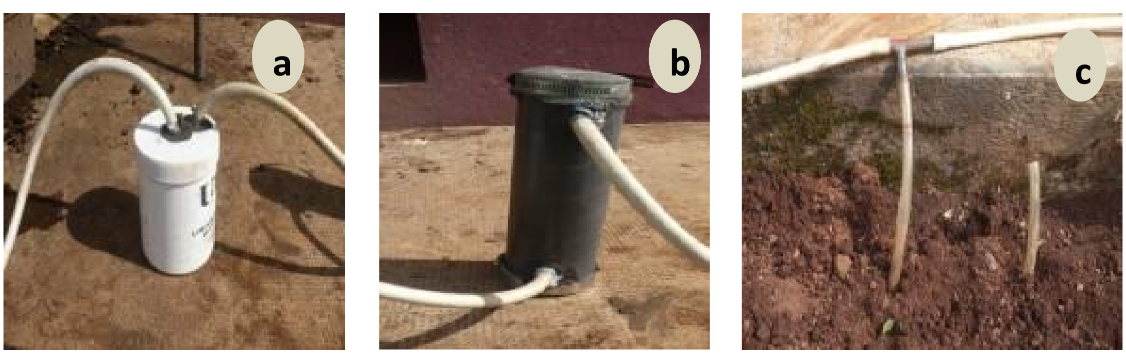
2.1 Biogas Scrubbing

Flammable biogas was produced as from the third day of fermentation. The biogas produced was purified by removing carbon dioxide, hydrogen sulphide (H_2S) and water vapor in this sequence. The purification system was designed to be simple enough to be replicated with village technology. To eliminate carbon dioxide, the gas was bubbled in a 1 liter solution of lime water in a plastic container Fig. 2(a). To eliminate H2S, the gas was passed through a 1.5l column of iron fillings in a pipe of diameter 80 mm, Fig. 2(b). The average size of the iron fillings was 2.5 mm. Moisture was removed from the gas with the use of a simple U shaped moisture trap located on the gas pipeline as shown on Fig. 2(c). The resulting scrubbed biogas was analyzed using a Micro Clip gas detector capable of detecting O_2, CO_2, H_2S and CH_4.

2.2 Conversion of the Gasoline Fuelled Generator Set to Biogas Fuelled Generator Set

The gen-set that was used was the Japan made KING MAX©, KM4500DX model. It is a single cylinder, four-stroke engine having a rated power output of 1000-1500 W at 1500 rpm and registered with the ISO9002 certificate. A biogas metering device designed for the experimentation was T-shaped, with the biogas pipe perpendicular to the gasoline

Fig. 1. A 1000l biogas digester for cowdung



(a) (b) (c)

Fig. 2. The simple low cost biogas scrubbing sequence used. (a) Bubbling through lime water, (b) Passing through a column of iron filings and (c) Moisture trap

pipe as seen in Fig. 3. This enabled the biogas to move under the suction of the engine into the carburetor causing its mixing with air. A Hand Controlled Valve (HCV) and fuel filter was connected before the T-junction. This valve enabled the mechanical control (throttle) of the quantity of biogas entering the engine depending on the required fuel consumption. The lower calorific value in kJ/m^3 of the gas was estimated using the following equation 1.

$$H_{u,act} = \frac{V_{CH_4}}{V_{tot}} \cdot \rho_{CH_4,act} \cdot H_{u,n} \quad (1)$$

Where: $H_{u,act}$ is the actual lower calorific value in kJ/m^3,

V_{CH_4} is the volume of methane in m^3,

V_{tot} is the volume of biogas in m^3,

$\rho_{CH_4,act}$ is the actual density of methane in kg/m^3,

$H_{u,n}$ *is* the standard lower calorific value in kJ/m^3.

For this biogas with a 58% CH_4 content, the stoichiometric air/fuel ratio was 6.80:1 by volume. This meant that, for 1 unit of air, we require 0.15 unit of biogas for complete combustion. This diameter of the gas supply pipe was determined using equation 2:

$$d = \sqrt{\frac{4A_i}{\pi}} \quad (2)$$

Where: A_i is the cross-sectional area of the air/biogas nozzle in m^2.

This gave a diameter value of 0.006 m (6 mm).

The exhaust emissions: The flue gas was analyzed and the different quantities of pollutants were given to show the degree of GHGs emissions reductions.

The noise pollution characteristics were measured with a sound level meter and compared with conditions using only gasoline as the main fuel. A summary of model parameters by subset investigated are shown in Table 1.

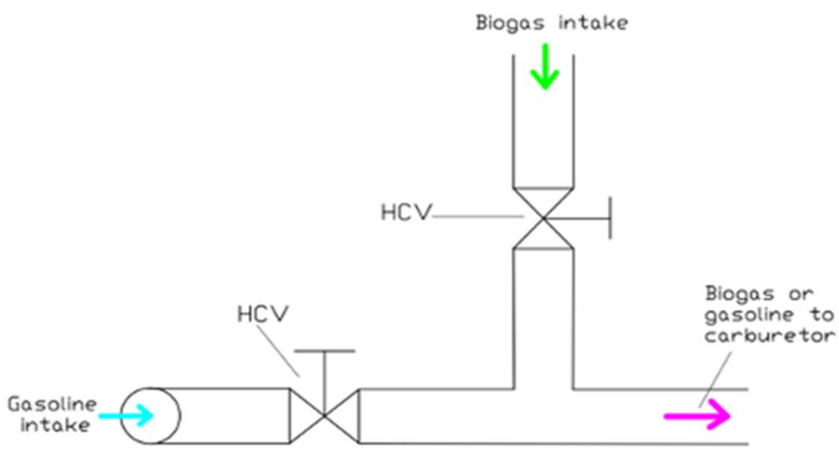


Fig. 3. A T-shaped gasoline/biogas metering device

Table 1. Model parameters by subset

Plastic biogas digester	Electricity generator set operation	Exhaust emissions
Size of digester	Specific biogas consumption	NO_x emission
Quantity of cow dung	Fuel or biogas consumption	CO emission
Temperature of digestion	Excess air ratio	O_2 in exhaust gas
Quantity of gas produced	Engine's temperature	Noise
Quality of biogas (methane content)	Engine coolant temperature	Flue gas temperature
Fresh biogas temperature	Lubricating oil temperature	
Calorific value of biogas	Engine efficiency	
Quantity of water	Overall efficiency	
	Actual electric power output	
	Operation duration	

3. RESULTS AND DISCUSSION

3.1 Digester Performance

The design biogas production was 214 ℓ/day and was stored in the volume above the waste in the plastic biogas digester with a capacity of 107 litres. However, biogas yield was 60 – 140 litres daily with an average digester temperature of 28.94°C. The biogas produced from cow dung was made up 58% CH_4, 41.5% CO_2. The actual calorific value was calculated from the lower calorific value to be 18038 kJ/m^3. The pressure during the experimental period increased from 0 mbar to 35 mbar. Biogas pressures of 1.3 mbars to 35 mbars enabled normal operation of the generator set. The pressure in the biogas digester dropped rapidly during the first five minutes and then gradually until the biogas was exhausted by the generator set. This means that for biogas exploitation at this scale it is necessary to use a small compressor to maintain gas pressure. In the village level where electricity can be very scarce, a small solar energy powered compressor attached to a battery can boast gas supply pressure to the engine. The average temperature of the biogas at the exit of the biogas digester was measured to be 28.5°C before introduction in to the engine.

Table 2 shows the different quantities of biogas before and after treatment with the purification system shown in Fig. 2. As can be seen the simple scrubbing system eliminated all the H2S and a greater percentage of the CO2 resulting in a gas 96 percent pure in Methane. Scrubbing is important because H2S is corrosive to the engine and CO2 and moisture lower the calorific value of the biogas.

3.2 Biogas Fuel Metering Set

The biogas metering set was made to separately meter gasoline and biogas into the engine. This device was designed to be adapted on the gasoline intake without the change of the gasoline stoichiometric air/fuel ratio since the generator set would be started with gasoline. This metering set was T-shaped, with a hand controlled valve (HCV) or throttle to control the flow of biogas into the engine. This device enabled the introduction of the quantity of biogas that corresponded to the engine's volumetric intake on mixing with air for normal working velocity of the engine as well as normal operation of the generator set. Maximum efficiency was obtained by fine tuning this metering set. To prevent wear and tear due to biogas pressure, this metering device was made up of galvanized pipes of 6 mm in diameter welded together.

Table 2. Quantity by volume of biogas components before and after scrubbing

Gas	Percentage composition before scrubbing	Percentage composition after scrubbing
H2S (ppm)	16	0
Methane content	58	96
Carbon dioxide	41.5	3.8

Fig. 4. Metering set mounted on the electricity generator set

3.2.1 Starting and fuelling the generator set with biogas fuel

The generator set was first hand-started with gasoline to enable heating of the engine and working of the generator set. The generator set was allowed to operate with gasoline for one minute after which the gasoline hand controlled valve was carefully closed and the biogas hand controlled valve was immediately and carefully opened to introduce the treated biogas into the engine. The generator set operated smoothly with biogas with careful adjustment of the crank angle or ignition timing to 11° before top dead center (BTDC) with the use of the adjustment knob. The compression ratio of the gasoline generator set was maintained for operation with biogas. The air/biogas mixing was done with the use of the gasoline carburetor. The butterfly valve next to the carburetor was exploited to suck or meter the right amount of fuel into the engine with respect to the engine's volumetric capacity.

3.3 Generator Set's Operation Parameters Results

3.3.1 Biogas fuel consumption

It was determined that the biogas consumption during the test period ranged from 5.2 litres per minute for loads of 100 W to minute to 5.4 litres per minute for loads of 820 W. Tuning the generator set for maximum efficiency led to a biogas fuel consumption of 6 litres per minute with the maximum power output of 0.91 kW from the 1.5 kW generator set.

The specific biogas fuel consumption at maximum power output of 0.91 kW for twenty-one minutes operating time was calculated to be 0.4 m^3/kWh. This means that the generator set consumes 4 m^3 per hour of biogas. The real biogas consumption for the 0.91 kW generated power was estimated at 0.36 m^3 per hour of operation of the generator set.

3.3.2 Electric power output with biogas fuel

Electrical power output monitoring during the experimental period showed that it varied between 0.84 kW to 0.91 kW optimum power output. Tuning the hand controlled valve for metering biogas and the change of the ignition timing to 11° before top dead center gradually led to the obtainment of a maximum electrical output of 0.91 kW.

3.3.3 Generator's efficiency and overall efficiency

The efficiency of the biogas fuelled generator was determined to be 60.6% with a maximum power output of 0.91 kW. This showed that the generator deviated in relation to the engine's running speed of 1 kW by 9% and in relation to the maximum engine output by 39.4%. Notwithstanding, this generator set operated with biogas fuel with little variation from the gasoline fuel. The overall efficiency of the generator set obtained during this test was 0.15 or 15 %. This was a little bit lower than some reports. Bhaskor J et al. [6] explored the potential of three different types of biodiesel viz. Rice bran oil methyl ester, Pongamia oil methyl ester, and Palm oil methyl ester as pilot fuels for a biogas run dual fuel diesel engine designed for power generation. They obtained maximum break fuel efficiencies ranging from 17.4% to 19.97%.

3.3.4 Excess air ratio and variation

The excess air was calculated to be 1.08. Literature, [7] also confirms a normal mixture at this value. This value meant that the actual air/biogas mixing was approximately equal to the Stoichiometric ratio or normal. This implied that no excess air was included in the fuel during combustion. This is because the diameter of the air intake of the gasoline fuelled generator set was 8mm and reduced to 4 mm for operation with biogas. In fact, the generator set at the point of biogas shortage stopped within five seconds. This period indicates the saturation of the biogas with air. The generator set finally stopped and it was assumed that the excess air at this point was 1.3 in conformity with what other researchers observed [8,9].

3.3.5 Gen-set operation temperatures variation

The engine's surface and lubricating oil temperatures attained maximum at 80.2°C and 59.3°C respectively. The flue gas temperature increased proportionately within ten minutes up to a maximum of 143.9°C which remained constant till the end of the operation time. The flue gas temperature for the operation with gasoline showed that it was higher than for operation with biogas. The engine's air coolant was measured to be 21.8°C. In fact, the coolant being air enabled the displacement of hot air from the engine surface thereby cooling it.

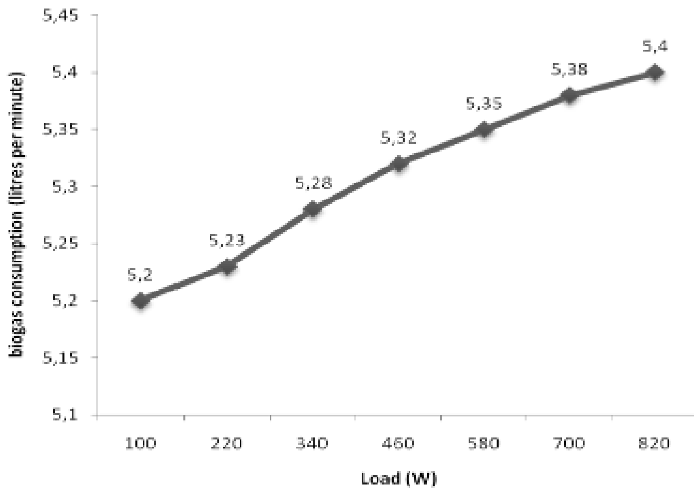


Fig. 5. Biogas consumption with electrical load

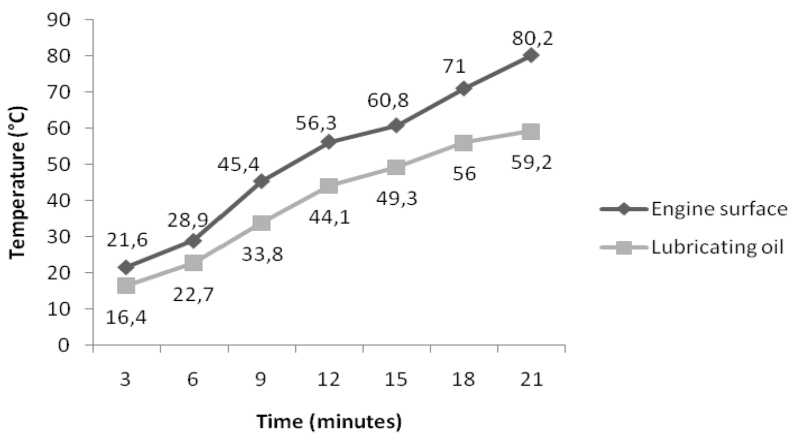


Fig. 6. Temperature variation of the engine surface and lubricating oil

This observation showed that when biogas is used to power a gasoline engine, there are possibilities of co-generation for heating other systems.

3.3.6 Exhaust emissions

The methane gas that is principally responsible for global warming has been captured and burnt while producing energy to release less polluting gases to the environment. Table 3 shows that the quantities of NO_2 and CO are far less than the quantities obtained from burning gasoline fuel. This enables the safeguarding of the environment against methane pollution.

The selection of the right equivalence ratio and spark timing allowed the achievement of efficiencies above the gasoline as confirmed by [10]. The performance and NO_x (nitrous oxide) emissions of a biogas-fueled turbocharged internal combustion engine were investigated using one-dimensional cycle simulation by [11]. They found out that a rise of CH_4 content in biogas causes high engine performance and NO_X emissions.

Noise emission from the generator set was just slightly equal to that obtained from operation with gasoline and equal to 64dB. This had also been confirmed by [12].

Table 3. Engine's exhaust emissions

Component	Quantity
NOx (ppm)	742
CO (ppm)	30
Oxygen (%)	4.1

4. CONCLUSIONS

The biogas digester is operated normally by producing biogas containing 58% methane at an average digester temperature of 29.8°C. The 1 m^3 biogas digester yielded biogas between 60 and 140 litres daily. Maximum biogas pressure obtained was 35 mbars. The biogas produced was purified by using a simple system by removing carbon dioxide, hydrogen sulphide and water vapor before introduction into the engine for normal generator set's operation.

The conversion of the previously fuelled gasoline generator set to a biogas fuelled generator set was achieved by designing, fabricating and mounting a T-shaped biogas metering set on the gasoline carburetor. The generator set's operation was possible with a maximum fuel consumption of 6 litres per minute. The specific biogas fuel consumption was calculated to be 0.4 m^3/kWh. The temperatures of the engine, lubricating oil and exhaust gas increased during operation. An excess air ratio of 1.08 was obtained. An overall generator set's efficiency of 15% was obtained for operation with biogas and the engine deviated by 9% from the running power of the generator set and by 39.4% from the maximum power of the generator set.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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