JJMIE

Volume 16, Number 3, June. 2022
ISSN 1995-6665
Pages 353 - 359

Jordan Journal of Mechanical and Industrial Engineering

An Experimental Investigation of Raw Biogas Combustion in a Small Spark Ignition Engine using Cow Manure in Algeria

Ibrahim Rahmouni*, Belkacem Adouane[1]

Department of Physics, Faculty of Matter Sciences, University of Batna 1, Batna, 05000, Algeria.
Laboratory of Applied Energetic Physics (LPEA)

Received 6 Dec 2021 *Accepted 24 Mar 2022*

Abstract

Biogas from organic waste has a good potential to substitute fossil-based fuels. It is a good example of the circular bioeconomy where low quality waste is turned into a high-quality fuel, while bio-nutrients are recovered at the end of the digestion process. This renewable gas can play a vital role for future energy needs. In this study, an experimental investigation has been carried out on a 5 hp single cylinder Honda GX140 gasoline engine coupled to a TD115 Hydraulic Dynamometer, operating with raw biogas and gasoline. The biogas used to fuel the engine is produced from cow manure at mesophilic conditions. Under two engine loading conditions; 0 and 3.5 N.m, the engine performance characteristics were investigated. A significant increase in the exhaust gases' temperature and fuel mass flow rate was observed for the case of raw biogas. The results also revealed that raw biogas generated higher brake thermal efficiency and brake specific fuel consumption compared to gasoline. This will open the door for biogas to substitute partially fossil-based fuels and give positive societal effects in rural areas.

© 2022 Jordan Journal of Mechanical and Industrial Engineering. All rights reserved

Keywords: anaerobic digestion, raw biogas, spark ignition engine, combustion, waste to energy.

1. Introduction

Globally each year, over 105 billion tons of organic wastes are generated by human activities, in two approaches: directly or indirectly. If they were treated more effectively, 10% of the global greenhouse gas GHG emissions can be removed by 2030. For instance, methane has a contribution of about 20% to the total increase in GHG emissions, and we can cut 25% of all man-made methane emissions by treating them through anaerobic digestion [1].

Under anaerobic digestion, without oxygen, the microorganisms in a series of biological processes degrade the organic material for generating two products. The first is biogas, which is a raw gas that consists of methane CH_4 (50-70%), carbon dioxide CO_2 (30-50%) and other traces of gases like: H_2S, H_2, N_2, O_2, NH_3 and H_2O. Its density of 1.15 kg/m^3 is higher than methane density of 0.75 kg/m^3 at normal temperature and pressure because of its CO_2 Content [2], and due to the fact that the amount of 1 m^3 biogas produces around 5.8 kWh of electrical energy [3]. This renewable energy source can be used for heat and electricity generation, or as traffic fuel. It can also be injected in existing natural gas grids after being upgraded to biomethane. The second product is Digestate which is an excellent fertilizer that consists of useful nutrients, such as nitrogen, phosphorous and potassium [4].

Gaseous fuels for internal combustion engines have long been proposed as a way to keep engine efficiency and performance while lowering emissions [5]. For instance, substituting fossil fuels by biogas for vehicles, can reduce between 75% and 200% of CO_2 emissions [6]. Biogas has many advantageous like: high octane number, small flammability limits, high self-ignition temperature and high anti-knock index, which are desirable in SI engines [7].

Many researchers are working on enhancing the use of this alternative fuel in SI engines. Increasing the compression ratio, advancing spark timing, CO_2 content variations, biogas upgrading, and blending biogas with gasoline, are all subjects dealt with in the biogas field. In the following paragraphs, we find a number of relevant selected works.

Hotta et al., examined a single cylinder spark ignition engine using gasoline and raw biogas at a compression ratio of 10 under wide open and half throttle settings. When compared to gasoline, they discovered an 18% loss in brake power, a 66% rise in brake specific fuel consumption BSFC, and a 12% drop in brake thermal efficiency BTE when the engine is fuelled with raw biogas [8]. Sudarsono et al., studied the influence of compression ratio on the performance of a 3 kW gen-set fuelled by raw biogas. They found that the optimum compression ratio for the gen-set fueled with raw biogas is 9.5. At the optimum compression ratio, maximum brake power, brake torque,

* Corresponding author e-mail: ibrahim.rahmouni@univ-batna.dz.

© 2022 Jordan Journal of Mechanical and Industrial Engineering. All rights reserved - Volume 16, Number 3 (ISSN 1995-6665)

BTE and BSFC are 450.37 W, 1.66 Nm, 46.93%, and 0.59 kg/kWh, respectively [9].

Samanta et al., examined the effect of spark timing in spark ignition on a single zone SI engine model. They observed that at 27° before top dead center BTDC, spark timing gives the best performance: BTE is 24% and BSFC is 0.29 m^3/kWh [10]. Sendzikiene et al., evaluated experimentally an impact of bio-methane gas with a composition of 65% CH_4 and 35% CO_2 to Nissan Qashqai HR 16DE SI engine on performance characteristics with the engine throttle 15% open, a constant stoichiometric fuel mixture, and various ignition advance angles compared to petrol. They found that in order to obtain optimal engine thermal efficiency, the ignition angle must be advanced by 4°CA [11].

Kim et al., used a mini co-generation engine system to test biogas fuels of various compositions, and the intake air and fuel flow rates were varied to change the equivalence ratio. The results showed that for a given engine load, the CO_2 level increased the ignition delay, fuel consumption, and combustion duration while decreasing the combustion speed. However, using a lean burn strategy improves thermal efficiency, and using biogas with a stoichiometric air/fuel ratio can enhance fuel economy at higher loads [12]. Kriaučiunas et al., tested the effect of different biogas mixtures containing on four-cylinder NISSAN's HR16DE spark ignition engine under two separate spark timings (constant and optimum) at 2000 rpm and with a stoichiometric air and biogas mixture. According to the results, raising the CO_2 concentration and using the fixed spark timing increased the mass burned fraction combustion duration by 90%, and reduced in-cylinder pressure and BTE. On the other hand, the authors stated that optimum spark timing selection increases BTE [13].

Simsek et al., performed the impacts of the utilization biogas/gasoline fuel mixtures in different volumetric ratios on a single cylinder Honda GX390 model SI engine, with an increased compression ratio at six different engine loads and constant engine speed, in terms of performance and combustion indicators compared with the gasoline operation. They found that the lowest BTE and the highest BSFC were obtained with 100% biogas. Compared to gasoline, a decrease of 16.04% and an increase of 75.52% were observed, respectively [14]. Awogbemi et al., tested a 5 hp single cylinder Honda GX 140 SI engine using a 20:80 biogas petrol blend at speeds ranging from 1000 to 3500 rpm. The results of the testing revealed that the biogas/petrol mix produced more torque, brake power, indicated power, BTE, and brake mean effective pressure than petrol, but with lower fuel consumption and exhaust gas temperature [15].

Haryanto et al., evaluated the performance parameters on a 2.5 kVA gasoline generator run with 100% biogas at different loads with an incremental of 100 W. Results showed that the generator set can function with raw biogas with 53 % CH_4 content, and it was able to handle a maximum load of 1300 W. With load, output power and biogas consumption increased, on the other hand, biogas specific consumption and engine speed decreased. The maximum thermal efficiency of the generator set was calculated to be 11% [16]. Muhajir et al., investigated on SI generator set performances fueled with gasoline, biogas, and LPG at various electric load. The performances of the generator in terms of brake power and torque are almost similar when fed by gasoline, biogas, or LPG. Brake power and thermal efficiency also enhanced when O_2 level in biogas increases [17].

Back to our contribution in this paper, in the light of all results seen in the extended literature review above, we present here the first experiments using a lab-made biogas in a small SI engine. The preliminary results are shown and discussed and they are very encouraging. More advanced work is planned in the near future in order to investigate parameters not covered here. A simulation study is in its way to validate our results and investigate parameters we cannot deal with experimentally.

2. The Experimental Investigation and Methodology:

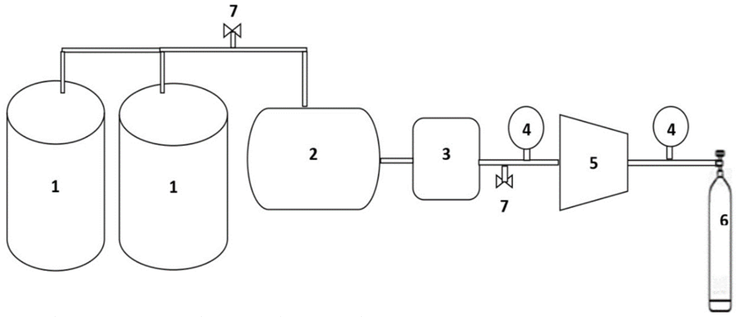
2.1. Experimental Raw Biogas Production Set-up

Figure 1, shows the schematic diagram of the experimental raw biogas production setup used in this experiment. The work was conducted in the Applied Energy Physics Laboratory (LPEA), faculty of Matter Sciences at the University of Batna 1.

Raw biogas was generated from cow manure from two digesters of 500 L of each, with a total solid (TS) concentration of 7%, at mesophilic conditions of 35°C, and collected in a storage bag. The raw biogas was analyzed by Biogas 5000 Geotech Analyzer. The raw biogas produced is saturated with moisture, and its composition is shown in Table 1.

Table.1. Biogas composition

Component	Value
CH_4	61.3%
CO_2	32.6%
O_2	1.3%
H_2S	245 ppm
BAL	4.7%



1- Digester of 500 L volume, 2- Storage bag, 3- Biogas analyzer, 4- Manometer, 5- Gas compressor, 6- Bottle, 7- Valve

Figure 1. Schematic diagram of the experimental biogas setup

In order to fill-in the produced biogas in bottles, a small compressor, the FN43GY model, was used. Two check valves and two manometers upstream and downstream of the compressor are used for safety reasons. The bottle pressure was maintained at 10 bar, in gaseous phase. This pressure allowed the delivery of the gas to the engine at a constant pressure of about 100 KPa.

2.2. Experimental Engine Test Rig

Figure 2, shows the schematic diagram of the experimental engine test rig used in this work. The experiments were carried out in the “Motor Laboratory”, at the Department of Mechanical Engineering, University of Batna 2.

The present study was conducted on a 5 hp single cylinder Honda GX140 gasoline engine. This is a four strokes engine with a compression ratio of 8.7:1. The main specifications of the engine are shown in table 2.

The engine was connected to a hydraulic dynamometer, which can adjust the speed and torque using a header tank's water supply. A pulse counting system measures the engine speed electronically. The resulting pulse train is electronically processed to provide a readout of the engine speed. The tachometer optical head is connected to the instrumentation unit through a 5-pin cannon plug/socket.

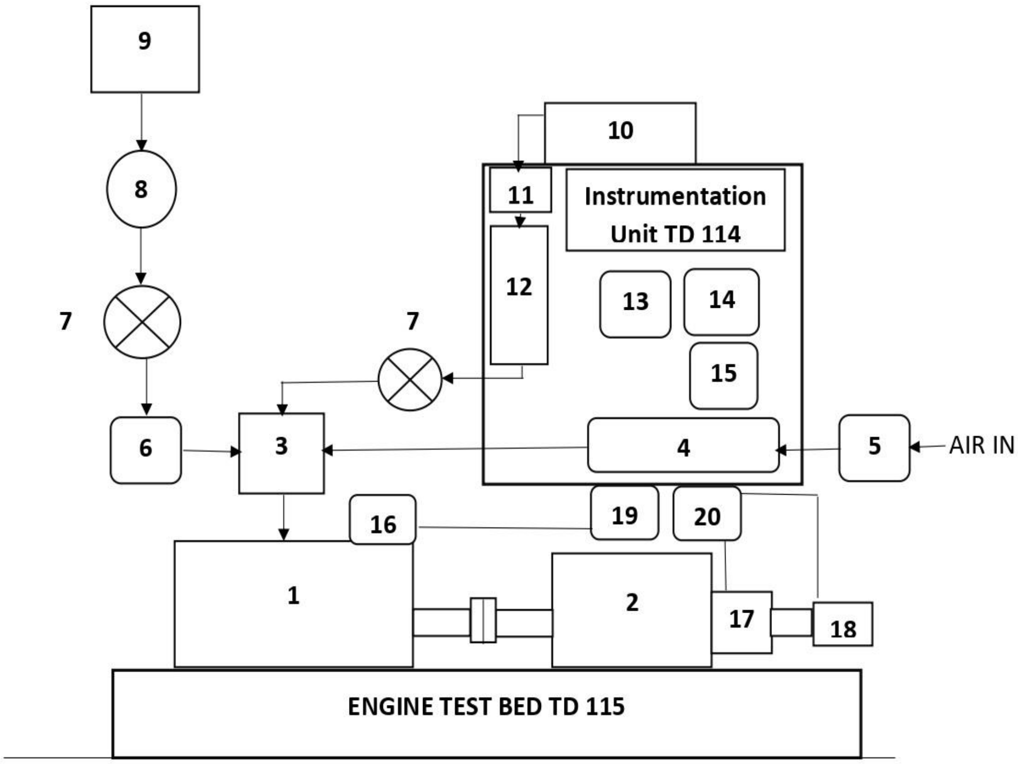
The engine torque is measured by a rotary potentiometer and transmitted to a torque transducer through a 4-pin cannon plug/socket.

The exhaust gas temperature is measured by a chrome/alumel thermocouple conforming to BS1827. The thermocouple is located into the exhaust pipe close to the cylinder block of the engine. Color-coded leads from the thermocouple are connected to terminals underneath the instrumentation unit. The gasoline consumption is determined by measuring the time (t) taken for the engine to consume 8 ml in the graduated flow pipette.

The raw biogas consumption is also determined by measuring the time (t) taken for the engine to consume 0.01 m^3 of biogas using an (AC-5M) gas meter model.

Table.2. Engine specifications [21].

Item	Specification
Type	Four strokes, air cooled, single cylinder, OHV
Bore × Stroke	64 × 45 mm
Total Displacement	144 cm^3
Compression Ratio	8.7:1
Max. Power	3.6 KW @ 4000 RPM
Max. Torque	9.8 N.m @ 2500 RPM



1- Engine, **2**- Hydraulic dynamometer, **3**- Carburetor, **4**- Inclined tube manometer, **5**- Airbox/viscous flowmeter, **6**- Gas meter, **7**- Control valve, **8**- Biogas flow manometer, **9**- Biogas bottle, **10**- Gasoline tank, **11**-Gasoline tank level, **12**- Graduated flow pipette, **13**- Tachometer, **14**- Torque meter, **15**- Exhaust temperature meter, **16**- C/A Thermocouple, **17**- Rotary potentiometer, **18**- Pulse counting system, **19**- Thermocouple sockets, **20**- 4/5 Pin canon (tachometer/torque transducer).

Figure 2. Schematic diagram of the experimental engine test rig

 © 2022 Jordan Journal of Mechanical and Industrial Engineering. All rights reserved - Volume 16, Number 3 (ISSN 1995-6665)

Front Interface Back Interface

Figure 3. Experimental engine test rig.

For the adaption of the biogas fuel for the given engine, the fueling system of the engine was modified. The petrol carburetor was replaced with LPG/CNG gasoline dual fuel carburetor. In this carburetor, the air and raw biogas get mixed in appropriate proportions, before entering the engine cylinder.

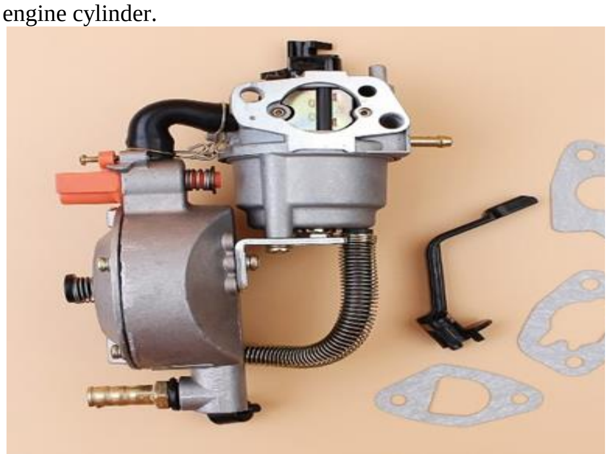


Figure 4. LPG/CNG gasoline dual fuel carburetor [19].

2.3. Experimental Procedure and Mathematical Formulas

The objective of these experiments is to study the variations of the engine performance characteristics, such as exhaust gas temperature, fuel mass flowrate, brake specific fuel consumption and brake thermal efficiency. Under two engine loading conditions, 0 & 3.5 N.m using the hydraulic dynamometer coupled to a single cylinder gasoline engine. The engine was tested with four speed settings: 2000, 2500, 3000 and 3500 rpm. The experiments were conducted for the two fuels, i.e., raw biogas and gasoline.

At each engine speed, the required values such as fuel flowrate, torque and exhaust gas temperature will be recorded to calculate the performance characteristics of the engine. A stop watch and a thermometer were also used for the experiment.

Applying the output value from the experiments and with the help of mathematical formulas, brake power (BP), fuel mass flowrate ($\dot{m}_f$), brake specific fuel consumption (BSFC), and brake thermal efficiency (η_{Bt}) were measured.

2.3.1. Brake power

The brake power is given by:

$$BP = (2\times\pi\times N\times T) / 60000 \quad (1)$$

where BP is the brake power (kW), N is the engine speed (Rev/min), and T is the torque (N.m).

With correction to standard condition of pressure and temperature:

$$BPc = BP \times Ps/P \times T/Ts \quad (2)$$

where BPc is the corrected brake power (kW), Ps and Ts are the pressure and temperature at standard conditions respectively, P and T are the measured pressure and temperature respectively.

2.3.2. Fuel mass flowrate

For gasoline, the formula below is used:

$$\dot{m}f = (Sg_f \times V \times 3600) / (t) \quad (3)$$

where $\dot{m}_f$ is the fuel mass flowrate (Kg/hr), S_{gf} is the specific gravity of fuel, V is volume of fuel (m^3), and t is time (sec), where S_{gf} for gasoline: 0.74.

To calculate the mass flowrate of biogas, the following formula is used:

$$\dot{m}f = \rho(\text{actual biogas}) \times V/t \quad (4)$$

where ρ is the density of the raw biogas(Kg/m^3).

After pursuing an analytical calculation, the actual density of our biogas is found to be 1.02 Kg/m^3.

2.3.3. Brake specific fuel consumption

The brake specific fuel consumption is given by:

$$BSFC = \dot{m}_f / BPc \quad (5)$$

where, BSFC is the brake specific fuel consumption (Kg/kWh).

2.3.4. Brake thermal efficiency

The brake thermal efficiency is given by:

$$\eta Bt = (BPc \times 3600) / (\dot{m}_f \times LCV) \times 100 \quad (6)$$

where, η_{Bt} is the brake thermal efficiency (%), and LCV is the lower calorific value (kJ/Kg).

where, the LCV of gasoline is 44000 kJ/Kg, and the LCV of our raw biogas is 20283.09 kJ/Kg.

3. Results and Discussion

The engine performance characteristics on gasoline and raw biogas for two different load conditions at various speed were investigated. The results of performance parameters are presented below:

3.1. Exhaust Gas Temperature

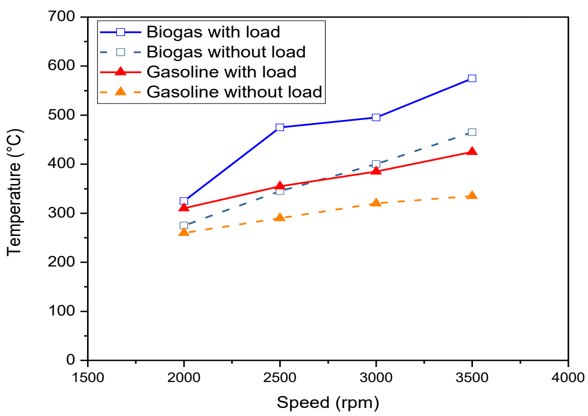


Figure 5. Exhaust gas temperature versus engine speed with load and without load for both gasoline and raw biogas.

Figure 5, shows the exhaust gas temperature variation in the two cases (with and without load) fueled with raw biogas and gasoline for different speeds.

It was found that with the increase of speed, the exhaust gas temperature increases gradually for all cases. The case of "load" was usually higher than the case of "without load". This is because the increase of in-cylinder temperature and pressure reaches a maximum of 575°C at 3500 rpm in the case of raw biogas with load compared to 465°C without load. For gasoline, 425°C at 3500 rpm are attained in the case of load compared to 335°C without load.

The reason for the higher exhaust temperature in the case of raw biogas is mainly because of the carburetor used to mix air and biogas, where it is likely that the engine is operating near stoichiometry. Mariani et al., suggested a solution by recycling uncooled exhaust gas (EGR) and mixed with the fresh charge, an air-biogas mixture, to control in-cylinder gas temperature. Depending on the amount of adopted EGR, the intake charge temperature consequently increases [20].

3.2. Fuel Mass Flowrate

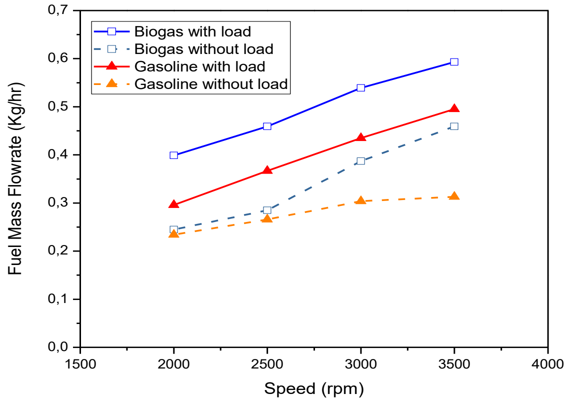


Figure 6. Fuel mass flowrate versus engine speed with load and without load for both gasoline and raw biogas.

Figure 6, indicates the variation of fuel mass flowrate in the two cases (with and without load) fueled with raw biogas and gasoline for different speeds.

As expected, it was found that with increasing speed, the fuel mass flowrate increases for all cases. For both fuels, the variation in fuel mass flowrate with load was nearly linear and the cases with load are usually higher than that without load. For the raw biogas, it reached, at a speed of 3500 rpm, 0.593 Kg/hr with load, and 0.459 Kg/hr without load. For gasoline, it reached, at 3500 rpm, 0.495 Kg/hr with load and 0.313 Kg/hr without load.

To create adequate heat input to sustain the load applied to the raw biogas, a larger fuel mass flowrate was required, to compensate for the non-combustible components in the raw biogas, like CO_2 and N_2, because they have a great impact on the overall performance of the engine. Furthermore, because of the lower density of biogas compared to gasoline, it flows more easily [15].

3.3. Brake Specific Fuel Consumption

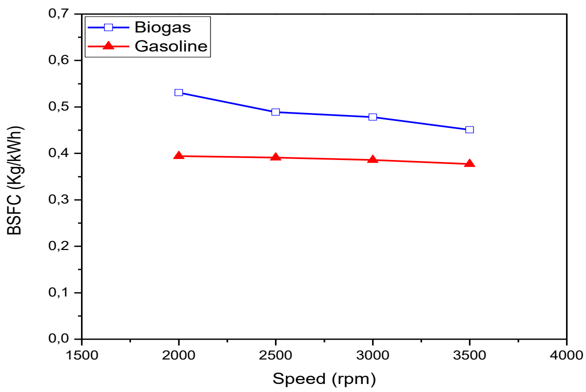


Figure 7. Brake specific fuel consumption versus engine speed with load for both gasoline and raw biogas.

From Figure 7, we can see that the BSFC decreases slightly with the speed increase at a constant load. For the case of gasoline, the BSFC is lower than that of the raw biogas, and remains almost constant with speed increasing, with a small decrease at the highest speed. The BSFC falls from 0.531 Kg/kWh to 0.451 Kg/kWh when the speed is raised from 2000 rpm to 3500 rpm for the raw biogas. The BSFC falls from 0.394 Kg/kWh to 0.377 Kg/kWh when the speed is raised from 2000 rpm to 3500 rpm for gasoline.

 © 2022 Jordan Journal of Mechanical and Industrial Engineering. All rights reserved - Volume 16, Number 3 (ISSN 1995-6665)

The lower heating value of biogas compared to gasoline causes the BSFC of biogas to be higher than that of gasoline. It reduces the combustion and flame propagation speed, this means more fuel to achieve the same power. Furthermore, a large amount of CO_2 gas present in the raw biogas does significantly increase BSFC values. Using raw biogas with a lower CO_2 concentration increases the peak in-cylinder pressure and reduces the BSFC.

The BSFC decrease at higher speeds is very clear for the case of biogas compared to gasoline; this means that approaching the nominal speed, which corresponds to the highest effectiveness of the engine, biogas is more effective in terms of BSFC than gasoline, this is another positive point to be added to biogas. Simsek et al., found also the BSFC value increased with the use of biogas compared to gasoline [14]. Therefore, one can see that to produce the same power output for a certain time lapse, the engine consumes much more raw biogas than gasoline in terms of flowrate only.

3.4. Brake Thermal Efficiency

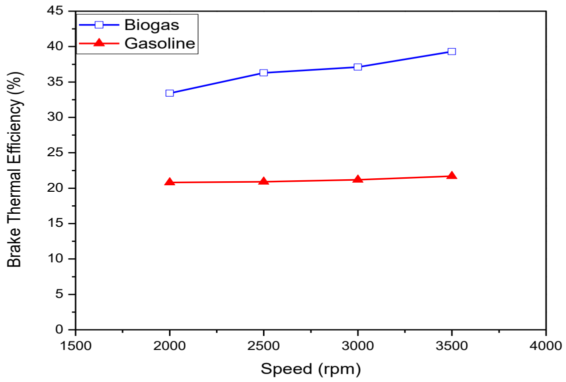


Figure 8. Brake thermal efficiency versus engine speed with load for both gasoline and raw biogas.

Figure 8, shows two positive aspects of using biogas as a fuel, first it has a brake thermal efficiency, BTE, higher than that of gasoline, it is almost double at the highest speed of 3500 rpm. Muhajir et al., reported also that the BTE of biogas fueled engine is higher than gasoline fueled engine [17]. On the other hand, the BTE for the case of biogas increases with increasing the engine speed, whereas it is almost constant for gasoline. Aguiar et al., observed that for lower loads, the engine operates with poor efficiency using gasoline [21]. For the raw biogas, with the increase of speed from 2000 rpm to 3500 rpm at a torque of 3.5 N.m, the BTE increases from 33.4% to 39.3%. For gasoline, with the increase of speed from 2000 rpm to 3500 rpm at 3.5 N.m, the BTE increases from 20.8% to 21.7%.

Raw biogas being a gaseous fuel had a better mix with air, improving the combustion process, in addition, a certain proportion of H_2 that might be contained in raw biogas can improve the fuel's volumetric burning velocity, which is beneficial to the combustion stability. Zhang et al., concluded that increasing H_2/CH_4 ratio in biogas composition increased the engine power output, especially under ultra-lean conditions [22]. Moreover, high resistance to knock permits engines to work at a high compression ratio, producing high thermal efficiency.

Conclusion

Raw biogas is used to fuel a Honda GX140 engine test rig. The experimental study shows interesting results for raw biogas compared to gasoline. The main conclusions are summarized below:

- The exhaust gas temperature increases by increasing the engine speed and load; for raw biogas, the exhaust gas temperature is higher. At 3500 rpm, the highest temperature was 575°C for raw biogas as a fuel with load, where the minimum temperature was 335°C for gasoline without load.
- The fuel mass flowrate rises sharply with the increase of speed for all cases. For instance, at 3500 rpm with load, the engine consumes 0.593 Kg/hr of raw biogas compared to 0.495 Kg/hr of gasoline.
- At the torque of 3.5 N.m, the BSFC of gasoline is lower than that of raw biogas. For gasoline, between 2000 rpm and 3500 rpm, there is a decrease of around 5%. For raw biogas, between 2000 rpm and 3500 rpm, there is a decrease of around 15%.
- At the torque of 3.5 N.m, the BTE of raw biogas is clearly higher that of gasoline. For raw biogas, between 2000 rpm and 3500 rpm, there is an increase of around 18%. For gasoline, between 2000 rpm and 3500 rpm, there is an increase of around 5%.
- The Brake thermal efficiency BTE of the engine using the two fuels, shows that biogas is performing highly better compared to gasoline; this shows that biogas has all the aspects to play the role of substitute fuel for gasoline and other fossil fuels.
- These preliminary experiments on biogas as a fuel in a small SI engine showed clearly that biogas is a very promising fuel, not only in terms of being CO_2 neutral, but also in terms of efficiency and effectiveness. It is clearly proved from the results that the engine is performing better when fueled with biogas.
- The experiments shown above are just an indication of the viability of biogas as a fuel for internal combustion engines, more work is planned to investigate further the impact of this fuel on the engine and its performance.

Acknowledgment

The authors would like to acknowledge the help and support of the "Motor Laboratory" at the Department of Mechanical Engineering, University of Batna 2.

References

[1] N. Primmer, "Biogas: Pathways to 2030";2021, World Biogas Association Report.

[2] P.J. Jørgensen, "Green energy"; 2009, Digisource Danmark A/S.

[3] B. Noche, A. Al Mansi, G. De La Torre, "Comparison of Biogas Supply Chains Using the Example of the Conditions of a Municipality". Jordan Journal of Mechanical and Industrial Engineering, Vol. 4, No. 1, 2010, 91-110.

[4] M. Fallde, M. Eklund, "Towards a sustainable socio-technical system of biogas for transport: the case of the city of Linkoping in Sweden". Journal of Cleaner Production, 2014.

[5] R. Ali, S.H. Raheemaha, N.N. Al-Mayyahi. "Numerical Analysis of Combustion Characteristics and Emission of Dual and Tri-Fuel Diesel Engine under Two Engine Speeds".

Jordan Journal of Mechanical and Industrial Engineering, Vol. 14, No. 2, 2020, 205-213.

[6] C.B. Pandya, R.S. Divyang, M.P. Tushar and P.R. Gaurav, "Performance Analysis of Enriched Biogas Fuelled Stationary Single Cylinder SI Engine". Journal of Mechanical and Civil Engineering (IOSR-JMCE), Vol. 13, No. 2, 2016, 21-27.

[7] K. Ravi, S. Mathew, J.P. Bhasker, E. Porpatham, "Gaseous Alternative fuels for Spark Ignition Engines-A technical review". Journal of Chemical and Pharmaceutical Sciences, Vol. 10, No. 1, 2017, 93–99.

[8] S.K. Hotta, N. Sahoo, K. Mohanty, "Comparative Assessment of a Spark Ignition Engine Fueled with Gasoline and Raw Biogas". Renewable Energy, 2018.

[9] Sudarsono, A.A.P. Susastriawan, I.G. Badrawada, H. Wibowo, D.L. Indrajati, "The Effect of Compression Ratio on Performance of Generator Set Fuelled with Raw Biogas". Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, Vol. 89, No. 01, 2022, 185-195.

[10] A. Samanta, S. Das, P.C. Roy, "Performance Analysis of a Biogas Engine". International Journal of Research in Engineering and Technology, Vol. 05, No. 01, 2018, 67-71.

[11] E. Sendzikiene, A. Rimkus, M. Melaika, V. Makareviciene, S. Pukalskas, "Impact of biomethane gas on energy and emission characteristics of a spark ignition engine fuelled with a stoichiometric mixture at various ignition advance angles". Fuel, Vol. 162, 2015,194-201.

[12] Y. Kim, N. Kawahara, K. Tsuboi and E. Tomita, "Combustion Characteristics and NOx Emissions of Biogas Fuels with Various CO_2 Contents in a Micro Co-Generation Spark Ignition engine". Applied Energy, Vol. 182, 2016, 539-547.

[13] D. Kriaučiunas, S. Pukalskas, A. Rimkus, D. Barta, "Analysis of the influence of CO_2 concentration on a spark ignition engine fueled with biogas". Applied Sciences, Vol. 11, No. 14, 2021, 63-79.

[14] S. Simsek, S. Uslu, H. Simsek, "Experimental study on the ability of different biogas level dual fuel spark ignition engine: Emission mitigation, performance, and combustion analysis". Oil & Gas Science and Technology - Revue d'IFP Energies Nouvelles, Vol. 76, No. 74, 2021.

[15] O. Awogbemi, Adeyemo, S. Babatunde, "Development and testing of biogas petrol blend as an alternative fuel for spark ignition engine". International journal of scientific and technology research, Vol. 4, No. 09, 2015, 179-186.

[16] A. Haryanto, T.G.T. Nindhia, W. Rahmawati, U. Hasanudin, T.W. Saputra, A.B. Santosa, S. Triyono, "Effect of load on the performance of a family scale biogasfuelled electricity generator". IOP Conference Series: Earth and Environmental Science, Vol. 355, No. 01, 2019.

[17] K. Muhajir, I. G. Badrawada, A. A. P. Susastriawan, "Utilization of biogas for generator set fuel: performance and emission characteristics". Biomass Conversion and Biorefinery, 2019.

[18] Honda Motor Company, L. HONDA GX140. Retrieved from https://www.wersis.net/honda/gx140.html

[19]Kit, GPL.NG. Retrieved from: https://www.slittpeg.com/index.php?main_page=product_info&products_id=267953.

[20] A. Mariani, M. Minale, A. Unich, "Use of biogas containing CH_4, H_2 and $C0_2$ in controlled auto-ignition engines to reduce NOx emissions". Fuel, Vol. 301, 2021.

[21] P.L. de Aguiar, P.H.S Diniz, L.R. da Costa, R.A. Rattes, A.T. Lopes, R.C. Leitão, W.M. Barcellos, "Performance evaluation of biogas fueled generator set". Journal of the Brazilian Society of Mechanical Sciences and Engineering, Vol. 43:409, 2021.

[22] Y. Zhang, M. Zhu, Z. Zhang, Y.L. Chan, D. Zhang, "Combustion and Emission Characteristics of Simulated Biogas from Two-Phase Anaerobic Digestion (T-PAD) in a Spark Ignition Engine". Applied Thermal Engineering, 2017.