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Effect of load on the performance of a family scale biogas-fuelled electricity generator

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Abstract. Biogas is a renewable fuel that can be used for many applications, such as fuel for kitchen stove, heating and drying system, electricity generation engine, and fuel to run farm tractor. The biogas used in this research was produced from tapioca wastewater treatment equipped with covered lagoon digester. Gasoline generator set having rated capacity 2500-W was modified in such a way that is able to run with 100% biogas. The experiment was performed by running generator set at different loads with incremental of 100-W. Three replications were conducted to get the average values. Performance parameters to be evaluated include biogas consumption, speed of engine (RPM), output power, and thermal efficiency. Results showed that generator set is able to work with raw biogas with methane content of 53%. The generator set reached a maximum load of 1300 W (52% of rated capacity). Biogas consumption increased with load from 1.40 $kg{\cdot}h^{-1}$ (no load) to 2.56 $kg{\cdot}h^{-1}$ at a load of 1300-W. Biogas specific consumption decreased with load from 16.4 $g{\cdot}W^{-1}{\cdot}h^{-1}$ at load 100 W to 2.2 $g{\cdot}W^{-1}{\cdot}h^{-1}$ at load 1300 W. Output power also increased with load from 0.04 to 0.49 ampere, respectively at a load od 100-W and 1300-W. Engine speed, on the other hand, decreased with load from 3686 RPM (no load) to 2413 RPM (load 1300-W). With biogas methane content of 53%, the maximum thermal efficiency of the generator set was calculated to be 11%.

1. Introduction

Biogas is a renewable energy source produced from anaerobic decomposition of organic materials. Indonesia has so many source of organic matter that can be explored as substrate for biogas production such as livestock waste (poultry dropping, cattle dung, and swine manure), liquid and solid waste from agricultural industries (cassava, palm oil mill, sugar cane), slaughterhouse, and energy crops. Wastewater from cassava mills is one of promising substrate for biogas. In addition to tapioca as main product, cassava mills also produce a large volume of wastewater ranging from 2.82 m3·ton [1] in big, efficient cassava mills to 4.94 m3·ton [1] in small cassava industries [1] and even to 7.0 m3·ton [1] [2]. Wastewater in small scale tapioca industries is resulted from fresh root washing, grating process, tapioca settling pond, and juice of cassava pulp (*onggok*) pressing. The wastewater contains high organic matter with COD (Chemical Oxygen Demand) from 9.01 $g{\cdot}L^{-1}$ [3] to 20.00 $g{\cdot}L^{-1}$ [4]. This high organic matter has caused stingy smell resulted from its decomposition that increasing health and aesthetic problems in the vicinity of the mills. The high organic matter, on the other side, can be utilized as substrate in anaerobic digestion process [5,6]. The process produces biogas that can be used for fuel and digestate or effluent that can be developed for organic fertilizer.

Other organic materials that have great potential to be used as a substrate for the biogas process are animal manure. This waste can be employed for community or household scale biogas development. So

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far, household scale biogas development has been focused on the main goal of producing biogas to replace LPG as household cooking fuel. This focus, however, gains low success because of the low economic benefits from biogas fuel. We have reported that each family consumes one bottle of LPG @ 3 kg per week, so that at a price of 20,000 IDR/bottle the economic benefits of household scale biogas is only IDR 80,000 per month [7]. This is considered as low economic benefit compared to the man hour devoted to operate and maintain the digester.

Biogas is a smart fuel that can be used for multifunction applications. In developing countries, biogas is used for cooking fuel to replace LPG and woodfuels [8–11]. Biogas can also be used for substituting gasoline and diesel fuels to run transportation vehicles [12–16] and agricultural machineries like tractor and water pump [17,18]. Methane content in biogas can be further upgraded to reach a quality of natural gas (75–99% methane content). The upgraded biogas can be injected into a natural gas grid or used as a transport fuel [10]. In developed countriest, biogas is mainly used as fuel for generating electricity [19]. Recently, household size generator engine is reported with promising success [20–26].

One way to develop household biogas in a more attractive way is to use biogas as fuel to generate household electricity by using small generator set (genset). Electricity is a basic necessity of the society. Even, development and welfare status of the community can be evaluated from the level of accessibility of the people to electricity. Accessibility to electricity is important to support community activities in many sectors such as economy, production, service business, and communication. The development of household-scale electricity using biogas fuel is also very important for remote communities that are characterized by the absence of industrial activities, poor infrastructure and off-grid electricity from the Government-owned Electricity Company or PLN [27]. Small scale biogas generators can potentially be explored to generate electricity in remote microgrids. Biogas-fueled genset can be modified easily from the existing gasoline genset [26]. In addition, small-scale biogas gensets with a power range of 750 to 5000 W are commercially available currently. This power range is very suitable for household electricity needs from minimum applications to micro economic industries. This study aims to determine the performance of household scale biogas power plants as a way to generate electricity for remote households.

2. Materials and methods

2.1. Description of the Tapioca Wastewater Treatment System

Research was conducted at the biogas digester facility of PD. Semangat Jaya, a community-based cassava mill with a daily capacity of 30 to 80 ton fresh tubers in the village of Bangun Sari, District of Negri Katon, Pesawaran Regency, Lampung Province (figure 1). Tapioca extraction process produces a lot wastewater, specifically 4.94 $m^3 \cdot ton^{-1}$ fresh cassava [1]. Wastewater comes from cassava washing step, grating process, tapioca settling pond, and juice of cassava pulp (*onggok*) pressing. After passing through the sedimentation basin, all waste water is flowed into the biogas digester in order to undergo anaerobic decomposition process and produces biogas fuel. The digester is a lagoon covered by black geo-membrane High-Density Poly Ethylene (HDPE) plastic sheet (figure 2). The lagoon was constructed by excavating the earth with a depth of 6 m and surface area of 35 m x 70 m. With a side slope 3:1 and freeboard of 40 cm, the pond is able to store wastewater 12,500 m^3. The hydraulic retention time (HRT), therefore, is 32 days during low milling season to 84 days during peak season. The biogas is used for drying tapioca flour and/or shelled corn.

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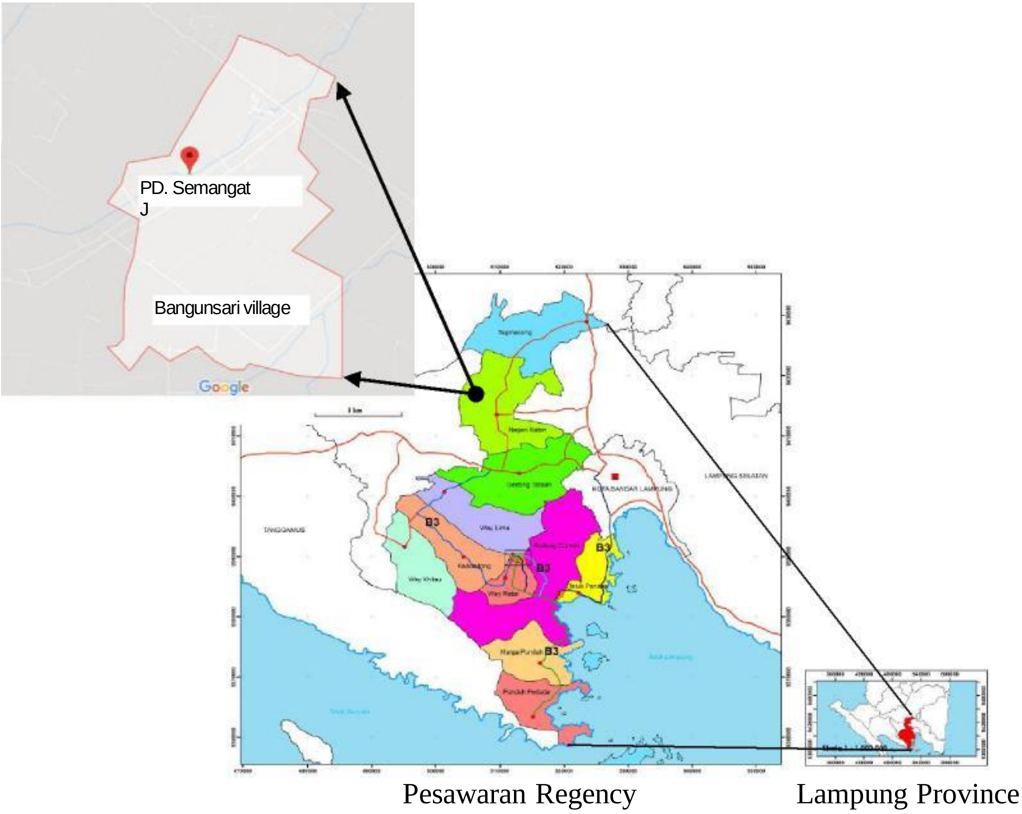

Figure 1. Location of the research (PD. Semangat Jaya, Bangun Sari Village, District of Negeri Katon, Pesawaran Regency, Lampung Province).

Figure 2. Covered lagoon biogas digester facility in PD. Semangat Jaya at different times and views.

2.2. Experiment procedure

The experiment used a biogas-fueled generator set (genset). It is a four-stroke, single cylinder, air-cooled, gasoline engine with rated capacity of 2500 W (maximum 2800 W), 220 V and 50 Hz (figure 3). The engine has been modified for running with biogas by adding a fuel converter system. The fuel converter system consists of (1) connector with three holes to hose biogas flow into the mixing chamber, (2) air filter, (3) valve to regulate the mixture of air and biogas, (4) mixing chamber to mix air and biogas, (5) two bolt holes to attach the converter on the engine carburetor. The generator was electrically started using starter motor setup. A 12 V battery is provided to start the engine electrically. In case the battery is not good, the generator can also be started manually using a rope to rotate the cranksaft.

Raw biogas from the digester was flowed into a 2m □ 2m □ 3m storage box made of 0.8-mm HDPE sheet. It is expected that the biogas is dehumidified and water vapor contained in the biogas will be condensed in order to get relatively dry biogas. The biogas was then filled into a plastic pouch having capacity of 200 L by using a hand pump. From this pouch, the biogas was then hosed into the fuel converter. The biogas was used as it was without any further treatment. Its composition was analyzed using a gas chromatograph (Shimadzu GC2014) with TCD detector and zinc carbon column.

Figure 3. Biogas-fueled genset used in the experiment. Boxed numbers: 1. Ignition key, 2. DC 12 Volt output, 3. Volt meter, 4. AC output plug, 5. Battery 12 V, 6. Circuit breaker, 7. Three leg AC output plug.

A load board was prepared with 20 load points to parallely plug100-W light bulbs. The genset was run by using 100-L biogas stored in the pouch. The engine was turned on until the biogas in the pouch finished and the time was measured by using stopwatch. The experiment was conducted by varying load with increment 100 W and replicated three times. It is important to note that the battery should be in good condition in order to ease the genset ignition (starting). During starting, the biogas storage pouch needs to be slightly pressed to increase biogas flow. In addition, the mixture of biogas fuel and air entering the engine carburetor must be regulated through a valve. Either too poor or too rich the fuel mixture is not good for the engine. Too poor mixture causes misfire, whereas too rich mixture causes the engine become inefficient [22].

During the experiment, important parameters were measured, including: engine speed (RPM), voltage (V), electric current (A), and time duration (*t*). Engine speed was measured using digital tachometer (Ono Soki HT-341) and electric current was measured using a digital clamp meter (Kyoritsu KEW SNAP 2007A). Voltage was monitored from the volt meter attached on the front panel of the genset. Genset performance includes brake power (P_b), brake specific fuel consumption (*BSFC*), and brake thermal efficiency (*BTE*) calculated as in the following [28]:

$$P_b = V \times I \tag{1}$$

$$BSFC = \frac{FC}{P_b} \tag{2}$$

$$BTE = \frac{3600 \times V \times A}{SFC \times LHV} \times 100\% \tag{3}$$

where *FC* is fuel consumption and *LHV* is biogas low heating value that is estimated from its CH_4 content.

3. Results and discussion

3.1. Biogas and Genset Characteristic

Biogas used in this experiment has a composition of 52.8% methane (CH_4), 28.6% carbondioxide (CO_2), and 18.1% nitrogen (N_2). With this composition, biogas is easy to burn. Using low heating value 191.76 kcal·mole^{-1} for methane or 35.82 MJ·Nm^{-3} [29], the biogas has calorific value of 18.9 MJ·Nm^{-3}. Nitrogen content of the biogas in this experimentis is high as compared to typical biogas composition. High nitrogen content in the biogas, however, was also reported using Sudan grass as substrate [30]. The effect of high nitrogen content in the biogas includes decreasing calorific value, anti-knock properties of engines and corrosion [31].

During the experiment the genset worked well with stable engine sound and voltage up to power load of 1200 W. The light bulbs were bright and stable, but they began to fade and eventually died when the biogas in the pouch run out. At power load of 1300 W the genset become unstable and at 1400 W the genset completely failed to run.

The genset has nameplate capacity of 2500 W and maximum power of 2800 W. However, from the experiment can only be operated with maximum load of 1300 W or 52% of the rated power. The genset is designed to run using gasoline with a calorific value of 42.8 MJ·kg^{-1}. On the other hand, biogas fuel used in this experiment has a calorific value of 18.1 MJ·Nm^{-3}. The low calorific value of working fuel explains the low power loading that can be borne by the genset. [21] revealed that 1500-W engine was able to run at maximum load (100%) by using petrol fuel but only a maximum 800 W by using biogas with 55% CH_4 content. For biogas with lower methane-content, higher fuel flow rate was required to supply enough heat input to support the applied load. In case of a constant speed engine, the air flow becomes limited to accommodate this higher fuel flow rate. The maximum load that the engine is capable to support, therefore, decreases when the engine run by using biogas with low CH_4 content [21].

The wide difference between the rated capacity and the actual capacity of the biogas genset suggests the need to improve biogas quality by increasing methane content and reducing CO_2 and other impurities, especially H_2S. [26] concluded that higher performance of engine using biogas can be achieved by completely removing the H_2S and H_2O from biogas [26]. It was reported that biogas with CO_2 content up to 40% do not cause fuel starvation problem and no significant decrease in overall efficiency of the engine [32]. [33] however, showed that maximum power of the engine increase with the decreasing CO_2 in the biogas and that alkalines solvent such as NaOH, KOH, $Ca(OH)_2$, Na_2CO_3, K_2CO_3, $CaCO_3$ can be used to absorb CO_2 [33]. [34] also reported that lime ($Ca(OH)_2$ can be used to absorb CO_2 in the biogas and the engine produced higher brake thermal efficiency when using mixture of treated biogas and diesel fuel as compared to those using mixture of swamp biogas and diesel fuel [34].

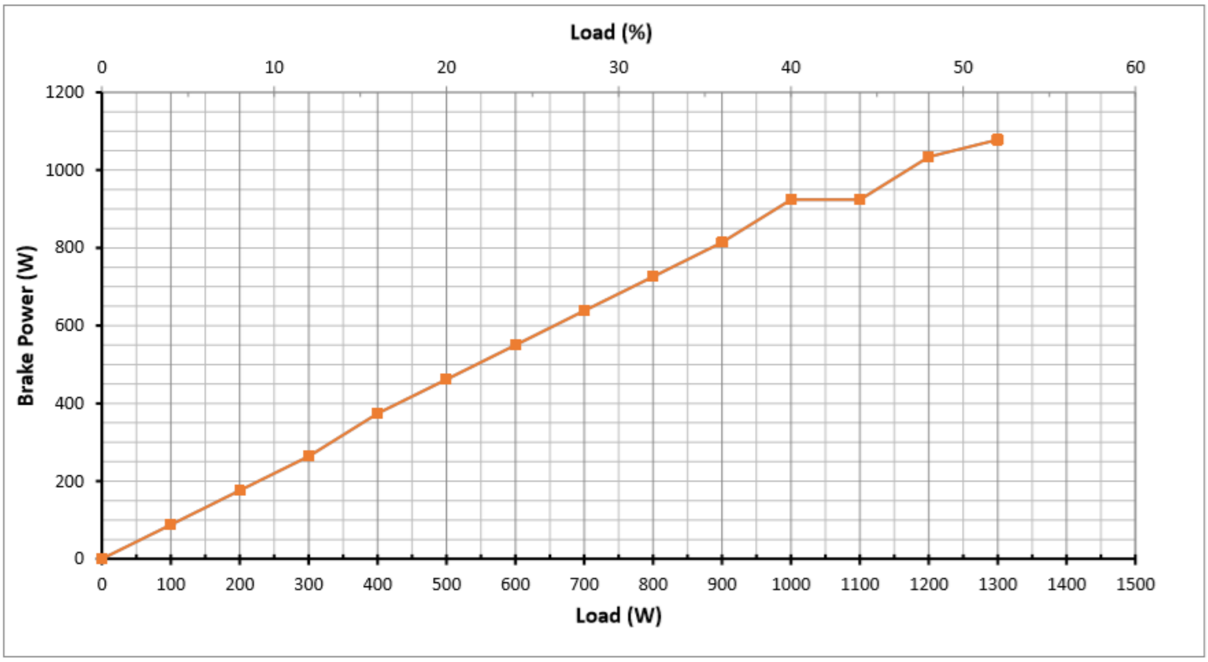

Figure 4. Effect of power load on the brake power of the generator engine.

3.2. Brake Power

Figure 4 shows the effect of electric load on the brake power developed by the genset while operating on raw biogas. The engine run well and produced brake power (= $V \times I$) that increasing linearly up to a load of 1300 W (52%), but then failed at load of 1400 W. Even though biogas (being a gaseous fuel) had better mixing with air and improving the combustion and maintaining the overall efficiency, the maximum load capacity had decreased as compared to, for example, petrol [21]. Reddy et al. reported similar trend wher the brake power developed by the engine is found to be increasing with increase in electric load. Using 1.4-kVA single cylinder, four stroke, air cooled LPG fueled generator engine using raw biogas they found that at biogas flow rate of 20 LPM the brake power increase from around 250 W at load of 200 W (14.3%) to a maximum of 812 W at load 1400 W (100%) [28]. Increase in electric loading has resulted in the increasing combustion quality of the fuel thus increasing the power output.

3.3. Biogas Consumption

Figure 5 shows the effect of load on the biogas consumption and biogas specific consumption. The variation of biogas consumption with respect to applied load was almost linear. In general, biogas consumption increased from 0.32 $L \cdot s^{-1}$ (1.40 $kg \cdot h^{-1}$) at no load condition, to 0.33 $L \cdot s^{-1}$ (1.45 $kg \cdot h^{-1}$) at a load of 100 W, and to 0.59 L s^{-1} (2.56 $kg \cdot h^{-1}$) at maximum load of 1300 W. Similar trend was reported by [21] where fuel consumption of 1.5-kW electric generator increase from 1.25 $kg \cdot h^{-1}$ at load 100 W (6.7%) to 1.94 $kg \cdot h^{-1}$ at load 800 W (53.3%) using biogas with 55% CH4 [21]. The biogas consumption is affected by engine size. The work of [21] that was just referred to has proven that smaler size engine consumes lower biogas than that of biger one (our case). The biogas consumed by the engine is also influenced by biogas quality (methane content). For example, [21] showed that by using biogas with CH4 content 70%, biogas consumption decrease to around 0.82 kg/h at load 100 W [21].

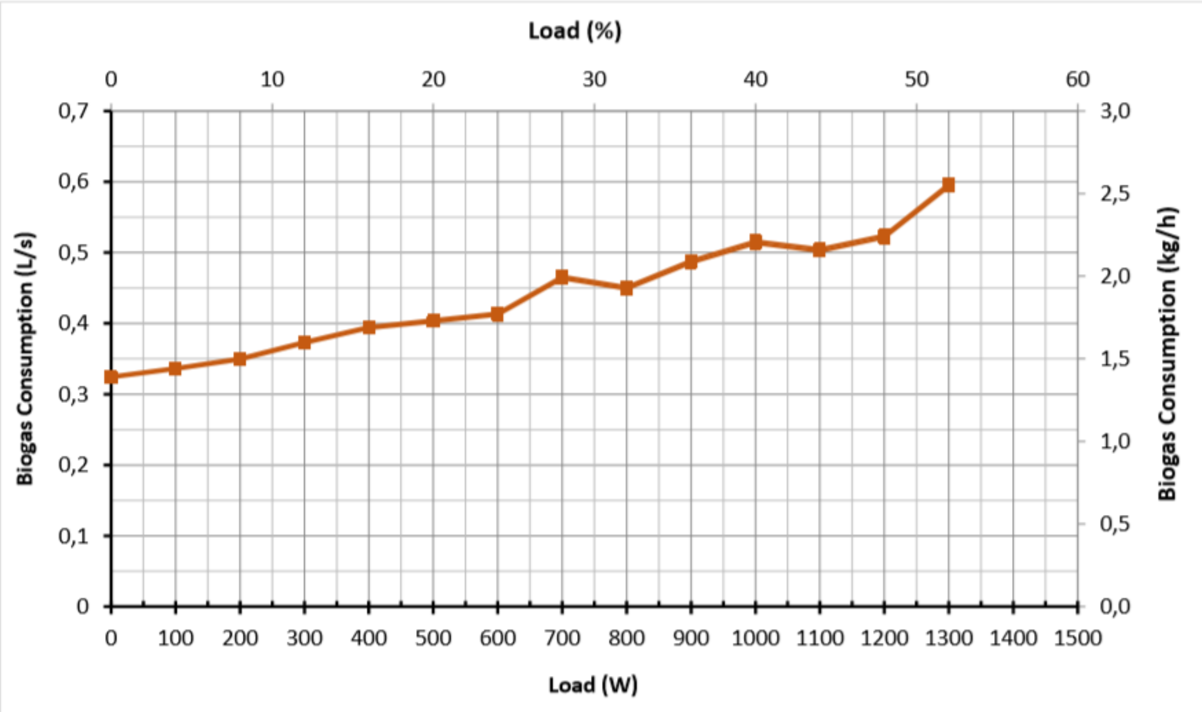

Figure 5. Effect of power load on the biogas concumption and specific biogas consumption.

The brake specific fuel consumption (BSFC) of the engine was found to be high at low loads, decreased sharply at load of 16% and then further decrease slowly to a minimum near the rated capacity as depicted in figure 6. BSFC is a measure of effectiveness of engine to convert chemical energy into useful work, depends on the fuel flow rate, engine speed and brake power. BSFC depend mainly on fuel consumption rate (FC) and power output. Based on Equation (2) BSFC depends inversely on brake power which increases with increase in electric load. The BSFC of the engine was around (16.4 $g \cdot W^{-1} \cdot h^{-1}$) at 100W load and decreased to a value 4.5 $g \cdot W^{-1} \cdot h^{-1}$ at 400W load. Since then then BSFC decreased slowly to 2.2 $g \cdot W^{-1} \cdot h^{-1}$ at high loading (1100 to 1300 W). Similar trend was reported by [21] using 1.5kW generator engine. Using biogas with 55% CH4 content, BSFC from 13.5 $g \cdot W^{-1} \cdot h^{-1}$ at 100W load decrease sharply to 4.0 $g \cdot W^{-1} \cdot h^{-1}$ at 370W and slowly diminish to about 2.4 g/kWh at 800W load [21]. [35] also reported BSFC of 1.3kW (peak) generator engine running on biogas which ranged from 16 g/WH at 100W load to around 4.1 at 500W load [35]. All heat engines attains best performance including specific fuel consumption at rated (design, nominal) power. Therefore, as we increase the load, better specific fuel consumption is reached. Under low load the BSFC is high because of low mechanical efficiency. At high engine load (close to the rated power), the combustion is improved due to higher temperature (inside the cylinder) following successive working of the engine which improves fuel atomization and fuel-air mixing process as well [28].

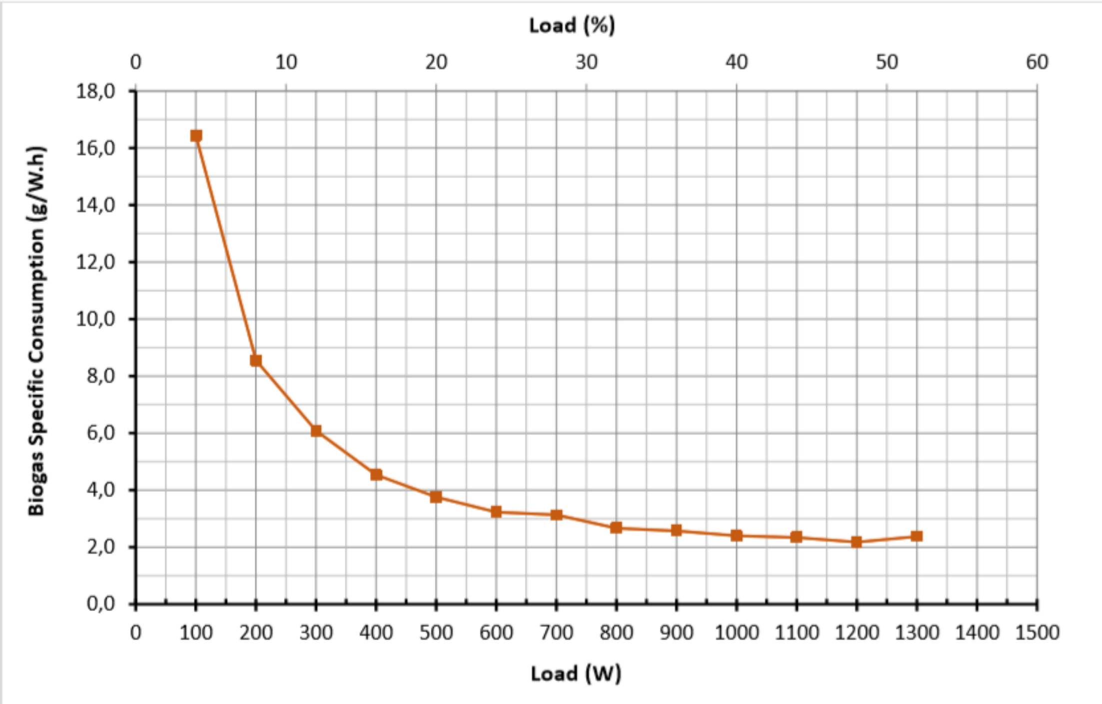

Figure 6. Effect of power load on the brake specific biogas consumption.

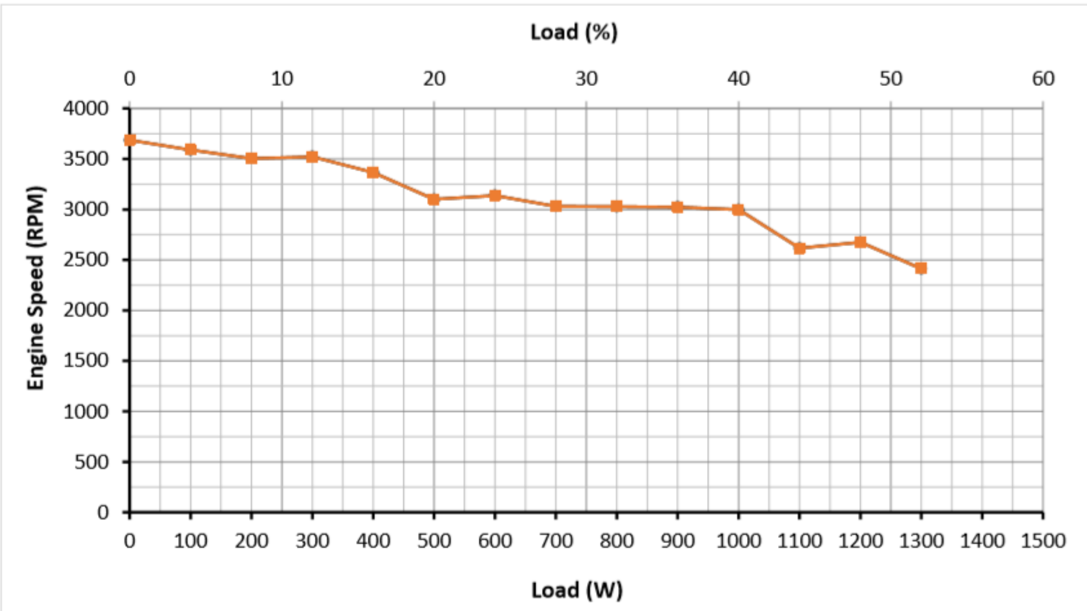

Figure 7. Variation of engine speed (RPM) with respect to electric load.

3.4. Engine Speed

Genset consists of a prime mower (engine) that producing mechanical work and a generator that producing electricity. The generator is a coil made of copper that converts the mechanical energy produced by the engine into electrical energy through electromagnetic induction process. The amount of electrical energy produced by the generator depends on the rotation speed of the engine shaft. Variation of engine speed with respect to applied electric load is presented in figure 7. Engine speed decreases with the increase in load. Without loading, engine speed was 3686 RPM and decrease to 2413 RPM at 1300W load. Below the maximum capacity of the generator's prime mover (engine) the current output of a generator is determined by its load. As the load on the engine increases, the speed decreases to keep up with the stability of the system. To compensate this loss in engine speed, as we previously discussed more fuel is supplied to the engine as the load increase (figure 5). Adding more, load the engine will slow down until a point that the engine actually stalls. In our study, the genset was completely stalled at a load of 1400W which is 56% of the rated paower capacity.

3.5. Thermal Efficiency

The second thermodynamics law dictates that there is no engine will have 100% thermal efficiency. Some of heat input into the engine should be removed. As clearly presented by equation (3), brake thermal efficiency depends on brake power, fuel consumption rate and calorific value of biogas. The variation of BTE with respect to electric load is presented in figure 8. The efficiency increased with load and reached maximum value of 11% at load of 1300W. Similar findings were reported in the literatures. [21] reported a maximum overall efficiency of 1.5kW generator set at around 13% by using biogas with CH_4 content of 60-70%. When CH_4 content in the biogas is reduced to 55% the engine efficiency declines to 8% [21]. [22] reported a prototype generator for low power application (1 kW) to have overall efficiency in the range of 7.5% at loading 120W to 19% at loading 580-620W by using biogas with CH_4 content of 65% [22].

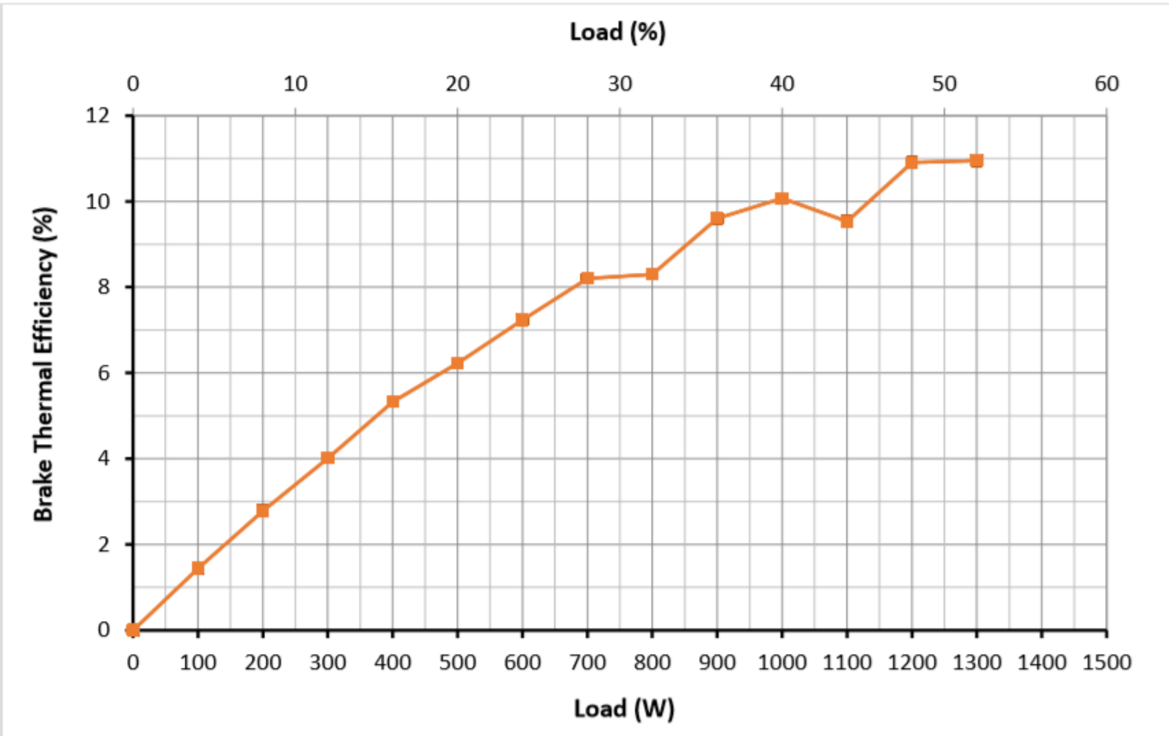

Figure 8. Effect of power load on the brake thermal efficiency.

4. Conclusion

This paper deals with the performance of a 2.5 kVA 4-stroke, spark ignition, single cylinder, air cooled generator engine using raw biogas at various power loading. The small-scale generator engine succesfully run on raw biogas with minimum modifications at the air intake system. Using biogas with CH_4 content 53%, the maximum power load is 1300W or 52% of the ratep power capacity. The small scale genset can be developed through decentralized energy systems to provide sustainable power production especially in rural areas. Based on experiment, biogas consumption rate increases with power loading from 0.32 $L \cdot s^{-1}$ (1.40 $kg \cdot h^{-1}$) at no load condition to 0.59 $L.s^{-1}$ (2.56 $kg \cdot h^{-1}$) at maximum load of 1300 W. Brake spesific fuel consumption decreses with load from 16.4 $g \cdot W^{-1} \cdot h^{-1}$ at power load of 100 W to 2.2 $g \cdot W^{-1} \cdot h^{-1}$ at high loading (1100 to 1300 W). The engine speed was 3686 RPM at no load and decrease to 2413 RPM at 1300W load. Brake thermal efficiency increase with load and achieved maximum value of 11% at power load of 1300 W.

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