

Performance Assessment of a Small Biogas-fuelled Power Generator Prototype

M Himabindu* and R V Ravikrishna

Department of Mechanical Engineering, Indian Institute of Science, Bangalore-560012

Received 7 March 2013; revised 8 December 2013; accepted 30 September 2014

This study reports the development and performance evaluation of prototypes of biogas-fuelled stationary power generators in the range of 1 kW. Strategies to achieve high engine efficiency namely pulsed manifold injection, electronic throttle control and dual spark plugs, have been incorporated in the prototype. A complete closed-loop control of the engine operation to maintain a steady engine speed of 3000 rpm ($\pm 5\%$) across the entire load range while maintaining an optimum fuel-air equivalence ratio is made possible by an electronic control unit (ECU) controlling the injection duration, ignition timing and throttle position. This study specifically focuses on the response of the generator to transient loads, and the overall efficiency obtained. The results obtained from testing the prototype have been found to be satisfactory and show that biogas power generators for low power applications can be made efficient (overall efficiency of 19% at electrical load of 640 W) using the strategies of biogas fuel injection.

Introduction

Biogas is a renewable fuel produced by anaerobic fermentation of organic material. Worldwide, various sources are being used for biogas production: residuals from beverage production, animal waste, vegetable wastes, household waste and waste from the food and fodder industry among others. It primarily contains methane (CH_4) and carbon dioxide (CO_2). Table 1 shows typical properties of biogas compared to other gaseous fuels. In developing countries of Asia and Africa, the respective Governments are promoting household biogas plants which are fed by kitchen waste, animal dung and other organic matter. There are an estimated six million biogas plants in India alone. The power requirements of a typical house or a cluster of households in rural areas of these countries is typically of the order of 1000 W. Currently, there are no products and technologies available that can generate electric power from the biogas generated from these plants. Huang and Crookes¹ assessed the performance of simulated biogas in spark ignition engine and concluded that the compression ratio can be increased up to 13:1 without knocking, leading to high power and thermal efficiencies for relative air-fuel ratios between 1.05 and 0.95. Porpatham *et al.*² found that the reduction in concentration of CO_2 in biogas leads to higher efficiency and power output in S.I. engines. With increase in CO_2

concentration, maximum brake power shifts toward the leaner side. Similar effect of CO_2 on power and emissions were observed by other researchers³⁻⁴. Various high efficiency strategies for power generation in biogas fuelled small SI engine were investigated and found stable operation in low power range of 450W-1000W⁵⁻⁷. Experiments on the performance and exhaust gas emissions of a commercial large generator modified to operate with 100% syngas at different syngas flows were investigated and the results were compared with gasoline operation at same electrical power⁸. Similar studies are done to understand the effect of biogas hydrogen blends⁹. The main aim of this study was to develop a prototype of a biogas-fuelled power generator based on the knowledge generated during the experiments on the performance of very small engines ($\sim 100\text{cc}$ capacity) operating on biogas

Experimental Setup and Procedure

The prototype comprised of an electronically-controlled gas injection system, dual spark plugs, throttle controller and a closed-loop ECU. The overall system consisted of a biogas-fuelled single-cylinder air-cooled engine coupled to the alternator mounted on a metal chassis. One of the objectives of the present study is to evaluate performance of the prototype biogas-fuelled generator under realistic electrical loading conditions. This was achieved by estimating the overall efficiency

* Author for Correspondence
E-mail: himabindu@mecheng.iisc.ernet.in

(chemical-to-electrical) over the entire load range. Figure 1 represents the prototype of test layout. Overall efficiency is defined as brake thermal efficiency (η_{bte}) x generator efficiency (η_g), whereas generator efficiency is defined as ratio of the electrical power output to the mechanical power input.

Volumetric efficiency is defined as the volume flow rate of air into the intake system divided by the rate at which volume is displaced by the piston.

$$\eta_v = m_a / \rho_{a,i} V_d$$

where m_a is mass of air inducted into the cylinder per cycle
 $\rho_{a,i}$ is the inlet air density

V_d is the displacement volume

Biogas at a constant pressure (0.1 bar) was fed into the fuel rail, and the ECU was used to calculate the required amount of fuel and the right time to ignite the mixture based on information from various sensors which controls the injector, ignition coils and throttle body. The biogas is stored in high pressure cylinders and the composition of the synthetic biogas used was of 65% methane (CH_4) and 35% carbon dioxide (CO_2) for the experiments. In addition, the alternator operation demanded that the engine speed be maintained within 5% of 3000 rpm. Therefore, it was also necessary to monitor the fluctuations in speed during load transients. After having fine-tuned the ECU injection map to maintain an equivalence ratio of 0.7-0.75 over the entire load range, overall efficiencies were measured. Speed fluctuations were then measured by obtaining the signal from the ECU crankshaft position sensor and recording it with a NI Data Acquisition Unit. The resulting engine speed

versus time data at various loads is then processed using MATLAB. The engine and alternator specifications are presented in Tables 2 (a) and 2 (b). Before the performance of the prototype could be evaluated, it was necessary to optimize the injection parameters, since electronic fuel injection is one of the important features of the prototype. This was done using a commercially available software developed by Race Dynamics Pvt Ltd., India. This software mainly allows control of parameters such as the injection duration, ignition timing, throttle position and also mode of operation (Open loop or Closed loop). Table 3 shows the actual injection map generated for the prototype experiments. The values in the fuel map are the injector open time in milliseconds which were generated for specific engine conditions of speed (top row, especially in the range of 2750-3250 rpm) and load (left column).

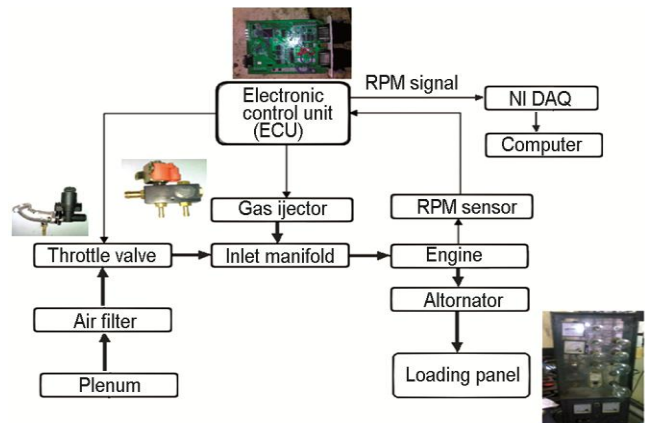


Fig. 1—Prototype Test Layout

Table1—Biogas fuel Properties

PROPERTY	LPG	Natural Gas	Hydrogen	Biogas	Producer Gas
Lower Heating Value at 1 atm & 15°C (MJ/kg)	45.7	50	120	17	3500-6000 kJ/m ³
Density at 1 atm & 15°C (kg/m ³)	2.26	0.79	0.08	1.2	1.05
Flame Speed (cm/s)	38.25	34	275	25	20-30
Stoichiometric A/F (kg of air/kg of fuel)	15.5	17.3	34.2	11 (6 Nm ³ air/Nm ³ gas)	1.2 (0.95 - 1.3Nm ³ air/Nm ³ gas)
Flammability Limits (vol.% in air)					
Leaner	2.15	5	4	7.5	7
Richer	9.6	15	75	14	21.6
Octane Number					
Research	103-105	120	130	130	100-105
Motor	90-97	120	130	-	-
Auto-Ignition Temperature (°C)	405-450	540	585	650	625

Results and Discussion

Overall efficiency

After generating the optimum fuel injection map, the prototype was tested for assessing performance. The biogas-fuelled power generator prototype was operated in a lean mode for improved engine efficiency. Too lean or too rich mixtures cause the engine to either misfire or become inefficient. From

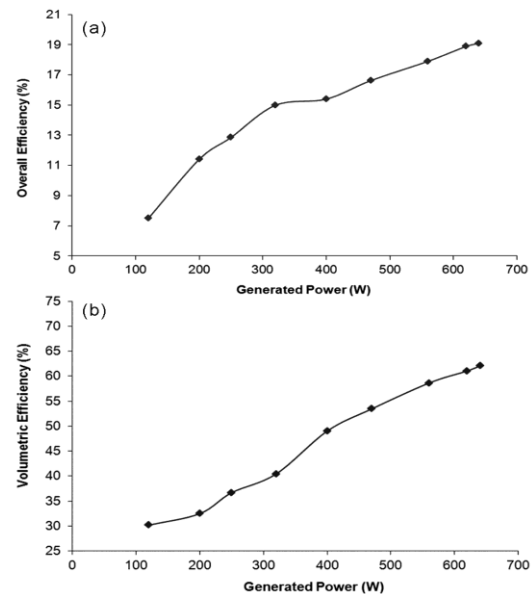
Table 2 (a)—Engine specifications

Type	4-Stroke, single cylinder, forced air cooled
Displacement	95.4 cc
Ignition	Digital with 2 spark plugs
Compression ratio	9.2:1
Max. Power	7bhp at 7000 rpm with petrol
Max. Torque	0.8kg-m at 5500rpm

Table 2(b)—Alternator Specifications

Make and Model	Fuji, FA-3000
Type	Brushless
Phase	Single
AC Voltage	220V
AC Output	3kVA
Frequency	50Hz
Speed	3000rpm
Prime Mover	6~7 HP

Figs. 2 (a) and 2(b), it is observed that overall efficiencies as high 19% have been achieved at high loads (in between 80-85% throttle opening) using the current strategy of pulsed manifold injection. The



Note: 640W represents 88% throttle opening, 560W represents 77% of throttle, 400W indicates 55% of throttle opening and 200W represents 27% of throttle opening.

Figs. 2(a)—Overall Efficiency vs Electrical Power Generated; 2(b)—Volumetric Efficiency vs Electrical Power Generated (W).

Table 3—Fuel injection map indicating the fuel injection duration in milliseconds for various speed-load cases.

INJECTION MAP

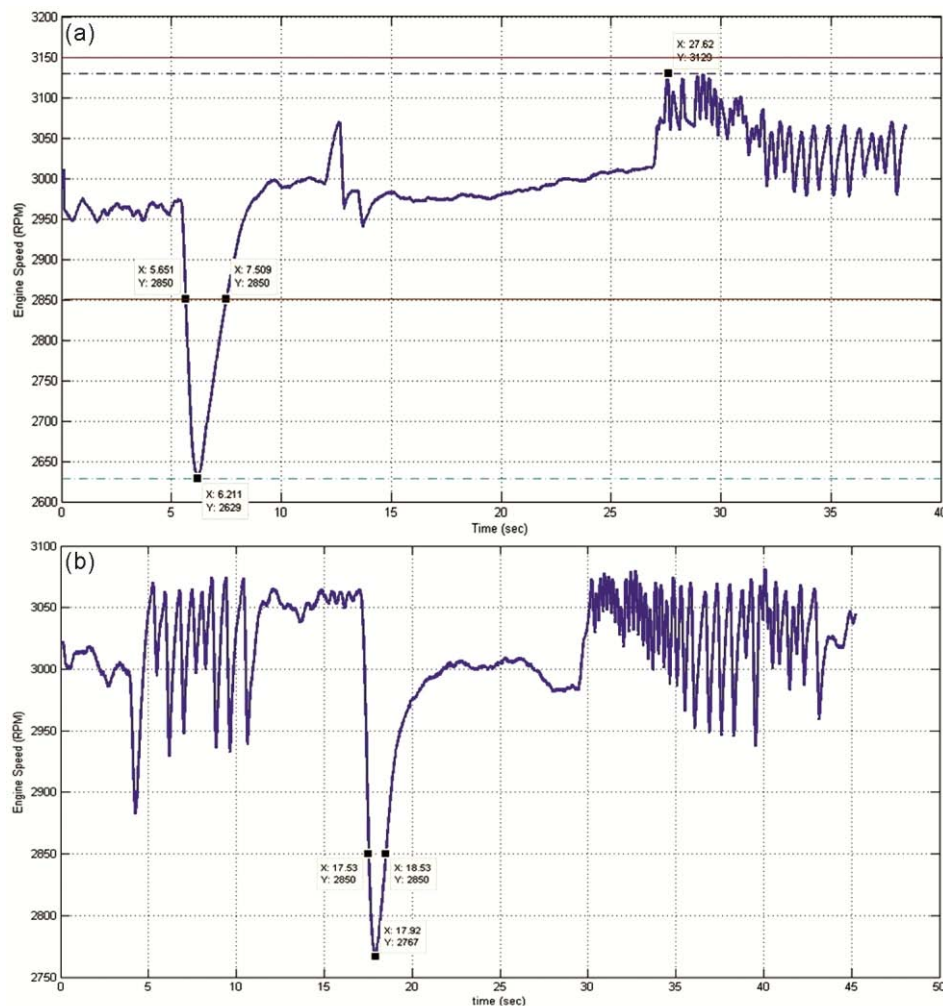
Speed	250	500	750	1000	1250	1500	1750	2000	2250	2500	2750	3000	3250	3500	3750	4000	4250	4500
16	11	15	15	40	40	40	40	35	35	35	35	30	30	36	35	35	35	20
15	15	14	14	40	40	40	40	35	33	34	35	29	29	34	33	25	19	16
14	22	35	35	35	40	40	40	30	30	33	29	29	29	31	32	17	17	16
13	22	35	35	35	23	35	24	35	35	32	28	28	28	30	30	30	16	16
12	22	22	22	22	23	24	24	28	30	31	27	27	27	30	30	30	30	30
11	22	22	22	22	23	24	24	25	30	30	26	26	26	30	30	30	10	14
10	22	22	22	22	23	24	24	25	30	30	24	21	21	28	28	10	10	11
9	18	18	18	22	23	24	22	25	30	30	22	12	12	7	6	10	10	10
8	16	16	15	15	9	10	22	25	23	23	13	13	14	23	6	12	10	11
7	16	16	9	9	8	10	24	27	30	20	7	7	7	20	20	20	10	8
6	16	16	9	9	16	9	20	20	20	18	12	8	8	8	16	16	9	9
5	16	16	9	9	16	9	15	20	20	16	8	7	7	5	0	14	1	10
4	9	9	5	5	9	9	15	25	16	14	0	0	0	11	11	16	7	8
3	9	9	5	5	9	9	15	13	7	12	0	0	0	8	8	13	13	9
2	8	8	9	9	8	8	5	5	5	12	0	0	0	12	12	12	12	9
1	8	8	9	9	8	8	5	5	5	12	0	0	0	5	5	10	3	9
Load	*Load is indicated by percentage of throttle opening (1-16 corresponds to 0-100% throttle opening)															All values are specified in ms of injector open time		

volumetric efficiency (referred to engine cylinder) is around 65% at high throttle. As expected, the same injection strategy is quite inefficient at low loads (in between 25-27% throttle opening), with efficiencies dropping to around 7.5%. However, the engine operation is reasonably stable even at low loads due to superior closed loop control technology of the ECU. Thus, such prototypes based on small engines are equipped with fuel injection and electronic engine controls are observed to deliver reasonably high overall efficiencies in the power range of around 1 kW.

Speed fluctuations during load transients

As mentioned earlier, stable electrical output demands that the rotational speed of the engine be maintained within a band of 2850 rpm and 3150 rpm (5% of rated speed of 3000 rpm) under all loading

conditions. To verify whether the developed prototype can meet this requirement, the engine speed was recorded for several sudden and gradual load transients as shown below. Figure 3 (a) shows the variation of engine speed with time for the case when the engine was idling at the start, and then subjected to full load in one single step. Subsequently, the engine was allowed to reach a steady state and then brought to its initial state (idling) in one single step. The region between the red lines shows the acceptable speed range. A downward spike can be observed when the prototype is suddenly loaded. The engine speed falls below 2850 rpm for just a period of 1.85 seconds. The minimum engine speed recorded is 2629 rpm. As the engine stabilizes, and the entire electrical load is suddenly removed, the maximum speed recorded is 3120 rpm, which is within the upper limit of 3150 rpm. Figure 3 (b) shows a similar



Figs. 3(a)—Engine speed vs time for zero to full load and vice versa in a single step load transient; 3(b)—Engine speed vs Time for zero to full load and vice versa in two equal steps of load transient.

variation of engine speed with time when the prototype was loaded and unloaded completely in two equal steps each. The two deepest downward spikes in the first half denote the two steps of the loading transient. It is observed that the engine speed drops below 2850 rpm on the second downward spike (mid to high throttle) for a period of 1 sec. The lowest speed recorded is 2767 rpm. Similar to the previous case, the engine speed does not exceed 3150 rpm during unloading. A similar variation was observed for the case when the prototype was loaded and unloaded completely in ten equal steps each. The engine speed does not cross the set boundaries at any point of time. Also, the prototype was loaded and unloaded randomly and the engine speed was recorded. The engine speed is noticed to have fallen below 2850 rpm for less than 1 sec.

Conclusions

The current work describes the performance evaluation of a prototype of a biogas-fuelled power generator for low power applications (1 kW) in terms of the overall efficiency and capability of the controller to maintain constant engine speed under load transients. The results obtained from testing the prototype show that biogas-fuelled power generators for low power applications (1 kW) can be made efficient (as high as 19%) using the strategies such as electronic fuel injection and lean operation. The performance of the electronic control unit (ECU) in maintaining the engine speed in a narrow band around 3000 rpm under various load transients is found to be satisfactory. It is believed that this overall efficiency can be further improved by

minimizing transmission losses from the engine to the alternator by incorporating a direct coupling between the engine and the alternator, and by using more efficient alternators.

References

- 1 Huang J & Crookes R J, Assessment of simulated biogas as a fuel for the spark ignition engine, *J Fuel*, **77**(1998) (15)1793–1801.
- 2 Porpatham E, Ramesh A & Nagalingam B, Investigation on the effect of concentration of methane in biogas when used as a fuel for a spark ignition engine, *J Fuel*, **87**(2007) 1651–1659.
- 3 Midkiff C K, Bell R S, Rathnam S. & Bhargava S, Fuel Composition Effects on Emissions from a Spark-Ignited Engine Operated on Simulated Biogases, *ASME J of Engg for Gas Turb and Pow*, **123**(2001) 132-138.
- 4 Shrestha B S O and Karim G A, Predicting the effects of diluents with methane on spark ignition engine performance, *Int J of Appl Ther Engg*, **21**(2001) 331–342.
- 5 Kapadia B, Development of SI engine for 100% biogas operation, *Thesis for the degree of Master of Science*, Department of Mechanical Engineering, Indian Institute of Science Bangalore, (2006).
- 6 Jatana G S, Himabindu M, Hari Thakur S & Ravikrishna R V, Strategies for high efficiency and stability in biogas-fuelled small engines, *J Expt Ther and Flu Sci*, **54**(2014) 189-195.
- 7 Meyer R C, Meyers D P, King S R & Liss W E, Effect of spark plug number and location in natural gas engines, *J of Engg Gas Tur and Pow*, **114**(1992) 475-479.
- 8 Shah A, Srinivasan R, Filip S D, & Columbus E P, Performance and emissions of a spark-ignited engine driven generator on biomass based syngas, *Biores Technol*, **101**(2010)4656–61.
- 9 Jeong C, Kim T, Lee K, Song S, & Chun Min K, Generating efficiency and emissions of a spark-ignition gas engine generator fuelled with bio-gas-hydrogen blends, *Int J Hyd Engy*, **34**(2009)9620–7.