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PERFORMANCE OF A BIOGAS RUN STIRLING GENERATOR

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ABSTRACT
New technologies for harnessing power and heat from biomass are being developed to widen such applications. Multi-fuel capabilities, continuous combustion, improved torque and emission characteristics and better part load efficiency are advantages of a Stirling cycle engine. By factoring in the pollution-related environmental and social costs associated with fossil and nuclear fuels, bioelectricity is becoming a competitive energy alternative. A Stirling generator developed by DEKA Research and Development Corp., USA was studied to for small scale (1 kW DC) electricity production using biogas fuel. The project was situated in Manikganj in Bangladesh. Biogas produced from a fixed-dome digester was used as fuel for the Stirling-generator charged with Helium as working fluid. The study focused on performance parameters such as: air-fuel ratio, brake specific fuel consumption, overall efficiency, regenerator heat input, different temperatures, engine speed, and exhaust emissions – at different power levels. The study revealed that the generator performed most efficiently at about 60-70% of the maximum rated load. The overall efficiency ranged 14-24%, which was higher compared to typical petrol engine generators used in small scale power generation. The temperature attained in the hot end was reasonable, although it showed some drop in internal fluid pressure with time, indicating need of improvements in seal durability.

Keywords: Stirling-Generator, Stirling Engine, Small Scale Power Generation, Biogas, Alternative fuel

1. INTRODUCTION
Stirling engines operate on the principle of compression and expansion of working fluid at two different temperature levels. It incorporates a regenerator heat exchanger, alternately accepting and rejecting heat to and from a working fluid and thus recycling a major fraction of the energy flow from one cycle to the next. The flow of working fluid is controlled by volume changes, so that there is a net conversion of heat energy to work and vice versa. Because of the use of regenerator, Stirling engines can have high thermal efficiencies[1]. A number of attempts have been made to use Stirling technology in small scale power generation, specially for rural areas [2,3,4,5]. The multi-fuel capability, better part load efficiency and less environmental pollution due to continuous combustion are advantages of using a Stirling engine for such applications. DEKA, a technology development company of USA is currently developing a Stirling generator prototype, which was tested for small scale electrical power generation in the rural area of Bangladesh (Tangail and Manikganj) using biogas in 2005. The DEKA Stirling generator was designed to produce up to 1kW of electricity for four hours using biogas generated daily from a 400cft fixed dome digester. The objective of this project was - to evaluate the field level performance of the prototype using biogas and to promote the use of renewable biomass energy for rural power generation.

2. EXPERIMENTAL SETUP
The setup consisted of the DEKA Stirling Generator, Biogas fuel supply system and a distributed electrical load bank grid system, as shown in figure 1.

2.1 Stirling Generator
The 1 kW prototype was an external combustion Stirling engine. Helium was used as the working fluid inside the engine. There are two parts in the generator - the core chassis, which consisted of the engine, and the auxiliary chassis, which consisted of the electrical parts and the radiator. The external combustion Stirling engine had two pistons, each having a connecting rod and each undergoing reciprocating linear motion along respective rod axes within respective cylinders and each having a displacement with respect to fixed points along the respective rod axes. Additionally, the engine had a harmonic drive linkage characterized by a net angular momentum. The engine working fluid (Helium gas) was contained within the first and second cylinders, the working fluid undergoing successive closed cycles of heating, expansion, cooling and compression. The engine also had a primary crankshaft, an eccentric crankshaft disposed internally to the primary crankshaft, the eccentric crankshaft was coupled to both the first connecting rod and the second connecting rod, and an epicyclic gear set coupling the eccentric crankshaft to the primary crankshaft in such a manner that the eccentric

crankshaft and the primary crankshaft counter rotate, the eccentric crankshaft is characterized by a forward angular momentum and the primary crankshaft is characterized by a backward angular momentum. The linkage also had a flywheel coupled to the eccentric shaft such that the net angular momentum of the harmonic drive linkage is substantially zero.

Fig 1. Experimental Set-up of DEKA Stirling Gen-set

Fig 2. Components of the Stirling Engine

As shown in figure 2 the engine had the generator coupled to the primary crankshaft for converting mechanical to electrical energy and a processor for controlling a current load on the generator in such a manner as to provide a substantially constant torque on the primary crankshaft. The first and second connecting rods are flexible with respect to bending in a direction transverse to the respective rod axes. The engine also have a heat exchanger for transferring thermal energy across a manifold from a first fluid (combustion gasses) to a second fluid (Helium), the heat exchanger comprising a plurality of pins extending from the manifold into the first and second fluid. The engine was fitted with a burner, which heats the combustion chamber. The burner burns any gaseous fuel and the heat is transferred to the piston-cylinder combination across a extended surface heat-exchanger. The hot end temperature of the burner was kept about 1000°C at full load. Type-K thermocouples were used for measurement of the temperatures. The intake manifold has a conduit having axial symmetry about the combustion axis with an inlet and an outlet for conveying radially inwardly flowing air. There is an air swirler disposed within the passageway for imparting a rotational component to the inwardly flowing air.

2.2 The Electrical System

The following components consisted the electrical system of the Stirling Gen-set:

Motor / Generator : Normally used as a generator to extract electric power from the Stirling Engine. Also used initially as motor to start the Stirling Engine.

Motor Drive : Used to control the phasing of currents through the motor / generator.

Boost / Buck Regulator : Used to boost voltage from battery to HV Bus. This was also used as buck converter when charging battery from HV bus.

Battery : Provided power to start stirling engine. Used as a hybrid to briefly power loads exceeding the maximum engine power .

Shunt : A heating element immersed in the radiator is used to dissipate excess power on the HV Bus when load is suddenly dropped.

Output DC/DC Converter : Provides conditioned power output to the user.

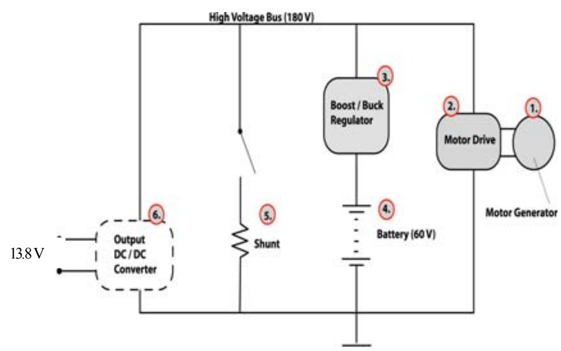

Fig 3. Electrical Block Diagram of Stirling Gen-set

The output terminal of the generator was then connected with 5×100 AH 12 volt deep cycle (Lead-Acid) battery and also with the customer load. So, the Stirling generator at the same time charged the batteries and gave power to the customer loads as shown in figure 3. The engine also has a radiator and a shunt, which is a resistive load immersed in the radiator. If there was any sudden drop in load, heat energy of the engine would be excessive, this was compensated by the shunt connected with the system. The shunt acted as the artificial load during this transition. The shunt is practically a resistive load cooled by water supply in the radiator. The Shunt could handle all of the output (approx 1kW). The radiator cools the shunt and transfers heat from the engine and motor (via the helium) not the burner. The shunt was also used when the unit is idling and the battery is charged, since some power is being produced and it must be dissipated. It also acts as a buffer between the time when load is removed and the engine rpm is reduced.

2.3 Small Distributed Grid System

A mini grid was designed of DC 12 Volt to transmit power to different households and shops were used. Individual wiring lengths from the centrally located generator set was limited to 300 feed. Accessories included - Fuse, Charge Controller and Distribution box.

Fig 4. Grid system (Fuse, Charge controller and Distribution box)

2.4 The Fuel System

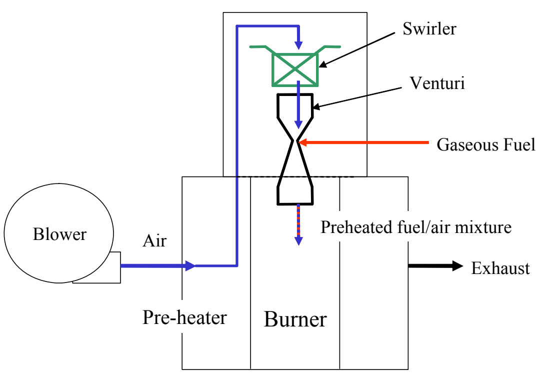

Fig 5. Venturi Fuel System Schematic

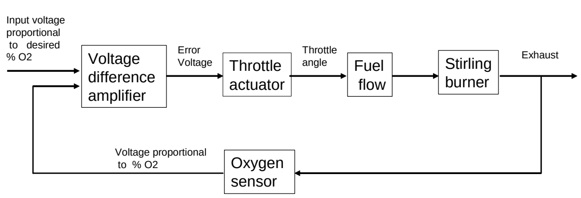

Fig 6. Fuel/Air control strategy.

The burner system was designed for any gaseous fuel. For this study biogas supply from a concrete fixed dome digester, already constructed at the site was used as fuel. The biogas fuel system consisted of a carburetor-type arrangement. With this system vacuum was created at the venturi restriction by air flow through the venturi (driven by the blower) as shown in figure 5. This vacuum was used to pull the fuel into the combustion chamber. The biogas was obtained from fermentation of cow dung. The bio-digester was fed with 10000 kg cow dung initially and then 400 kg cow dung daily. The peak generation of biogas was found to be about 500 cubic feet, with a hydraulic retention time (HRT) of 40 days.

3. PERFORMANCE OF THE GENSET

The DEKA Stirling engine outfitted with a venturi fuel system and performance was tested in the rural area of Bangladesh. "APU controller" converts the 3-phase power from the brushless generator into DC power, which is dissipated into loads. Output power, water temperature and engine head temperatures were recorded using software embedded in the DEKA motor controller. A BACHARACH portable gas analyzer was used to monitor combustion products such as CO, CO_2, and O_2. Engine head temperature, swirler temperature, speed, DC load, engine gross power was also measured. Biogas analysis was done from BCSIR (Bangladesh Council for Scientific and Industrial Research) and flow from the digester was measured daily. Biogas methane content was found to vary between 50 – 60% by volume. Air flow rate, fuel flow rate, air-fuel ratios, specific fuel consumption, overall efficiency, exhaust emission components, engine speed, power produced by the generator and temperature of the engine were the main parameters measured. The tests were carried out with a range of variable loads from 400 watt to about 900 watt. The engine was very quite in operation in respect with other internal combustion engine of same capacity. It was found 72dB at 3 meter distance. Table-1 shows the performance parameters when run with biogas having 50% methane content and table-2 the same for biogas with 60% methane content.

Table 1: Parameters at loads, 50% CH_4 content Biogas

Avg. Power (watt)	$\dot{m}_{Biogas}$ *(kg/hr)*	$\dot{m}_{Air}$ *(kg/hr)*	*Bsfc (g/ kW-hr)*	Q_{reg}/Q_{in}	*Overall Efficiency (%)*
902	0.55	24.12	610	1.3	14.1
848	0.49	23.2	578	1.4	14.2
780	0.43	19.54	551	1.4	15.3
721	0.37	16.1	513	1.3	16.8
654	0.31	11.88	474	1.2	19.5
553	0.24	8.71	434	1.1	22.0
404	0.24	7.98	594	1	16.8

Table 2: Parameters with load, 60% CH_4 content Biogas

Avg. Power (watt)	$\dot{m}_{Biogas}$ *Kg/hr)*	$\dot{m}_{Air}$ *(kg/hr)*	*Bsfc (g/ kW-hr)*	*Qreg/ Qin*	*Overall Efficienc. (%)*
902	0.61	24.12	676.3	1.7	15.45
848	0.54	23.2	636.8	1.8	15.55
780	0.47	19.54	602.6	1.74	16.77
721	0.41	16.1	568.7	1.6	18.44
654	0.34	11.88	519.9	1.5	21.66
553	0.27	8.71	488.3	1.3	24.15
404	0.27	7.98	668.3	1.2	18.53

3.1 Air and Fuel Flows

The increment of air flow rate with load was almost linear for biogas. The air flow rate was controlled by the blower rpm. The fuel flow was decreased and increased by decreasing and increasing the air flow rate through the venturi and it was done with the demand of the load. The air flow rate varied from 24.1 Kg/hr to 8 Kg/hr with the variation of load of 400 to 900 watt (approximately). Air flow rate was measured with the approximation made with the blower speed of the Stirling generator. Figure 7 shows the variation of the air flow rate and fuel flow rate with load for biogas.

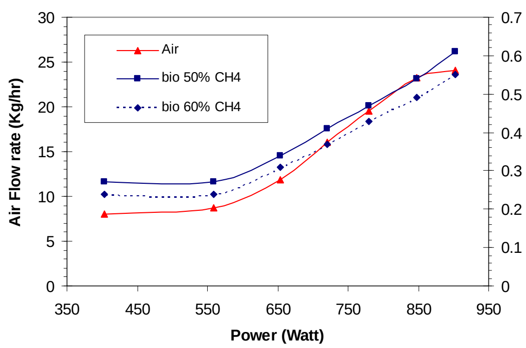

Fig 7. Power vs Flow rate for Biogas.

Figure 7 also shows the variation of the fuel flow rate with load for biogas. The variation of fuel flow rate with load was almost linear. Since the fuel flow measurement was made from system pressure, the calculated mass flow rate is influenced by the value of gas constant (R), which is a function of gas composition. For biogas it was found to vary from 0.27 Kg/hr to 0.61 Kg/hr considering 50% CH_4 content Biogas and 0.3 Kg/hr to 0.55 Kg/hr considering 60% CH_4 content Biogas with the variation of load from 400 to about 900 watt. Fuel flow rate both for 50% and 60% CH_4 content Methane content of the Biogas produced was found to be from 50% to 60%.

3.2 Air-Fuel Ratio

The variation of the fuel flow rate is shown in figure 8. The air-fuel ratios varied during the range of loads. Mass basis AF ratio varied within a range from 40 to about 30 for 50% CH_4 content Biogas and 33 to about 44 for 60% CH_4 content Biogas with load variation from 400 watt to about 900 watt as shown in figure 5 for biogas. The stoichiometric AF ratio for natural gas is 17.2, and for biogas it is only about 5. So the mixture for combustion was very lean. It was due to the fact that the fuel intake system was venturi type, so to draw more fuel it required higher airflow rate.

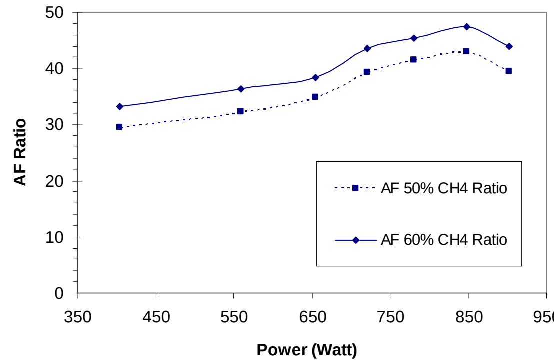

Fig 8. Power vs AF Ratio for Biogas.

3.3 Sfc and Overall Efficiency

The specific fuel consumption (sfc) for biogas varied from 676.3 g/kW-hr to 488 g/kW-hr for 50% CH_4 content biogas and 609.7 g/kW-hr to 594 g/kW-hr for 60% CH_4 content biogas, the overall efficiency varied from 24.1% to 15.4% for 50% CH_4 content biogas and 22% to 14.1% for 60% CH_4 content biogas with a variation of load from 400 watt to about 900 watt. The sfc took a greater value for the highest load and also for the lowest load. The sfc had the lowest value i.e. 488 g/kW-hr for 50% CH_4 content biogas and 434 g/kW-hr for 60% CH_4 content biogas at 550 watt (approximately) and at the same load had the highest overall efficiency i.e. 24.1% for 50% CH_4 content biogas and 22% for 60% CH_4 content biogas. So, it can be said that the generator works best in the region of 550 to 650 watt load and has less efficiency in the higher and lower loads than that range. As for the Stirling engine a considerable amount of heat is recovered from the regenerator and fed again in to the system. The regenerator heat input, Q_{reg} was also accounted for calculation of overall efficiency. For comparison a petrol equivalent of biogas consumption was also. For 50% CH_4 content biogas it was in the range from 146.7 g/kW-hr to 204 g/kW-hr and for 60% CH_4 content biogas it was 180.8 g/kW-hr to 255 g/kW-hr with load variation of 400 watt to about 900 watt.

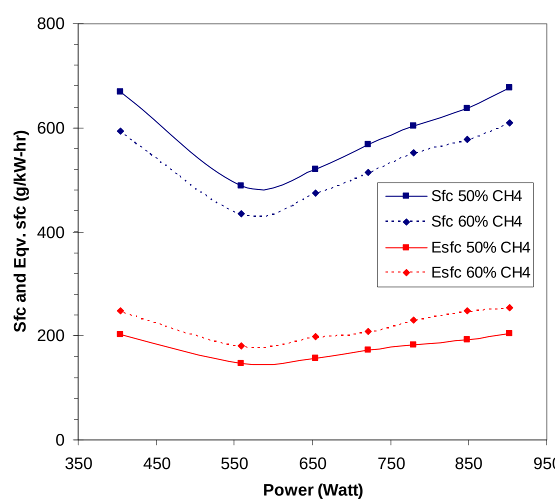

Fig 9. Power vs Bsfc and Eqv. Bsfc for Biogas.

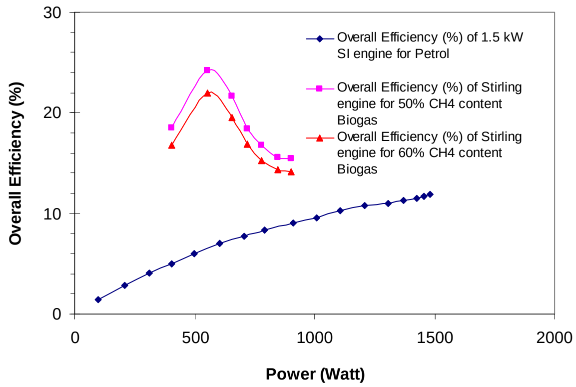

Fig 10. Comparison of Petrol and Stirling engine overall Efficiency

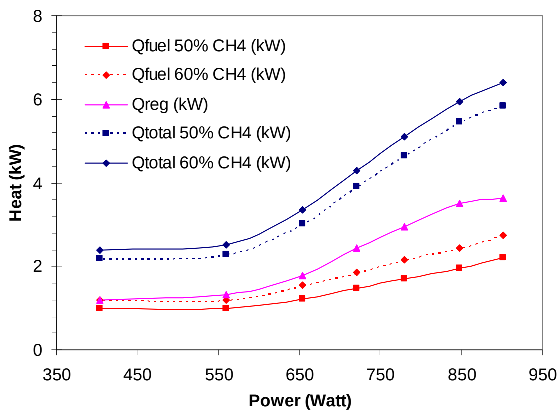

Fig 11. Power vs Heat inputs for Biogas.

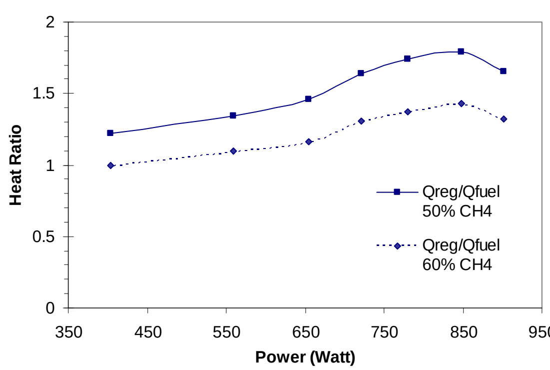

Fig 12. Power vs Heat Ratio for Biogas.

The electrical output of the generator was 13.8 volt dc. The output voltage was almost constant and didn't vary with load the only thing varied was the current. Current varied with the variation of load. As the load varied from 400 to about 900 watt, the current varied from 30 to 70 ampere (approximately). The wirings were designed accordingly.

3.4 Temperatures

Measurements of temperatures were at the burner body which was known as "Head Temp", in side the burner (near regenerator) which was known as "Swirler Temp", and the temperature of coolant (water was used as coolant and it cooled the engine and the radiator (shunt) in a closed loop circuit). Head temperature normally ranged from 700°C to 960°C depending on the load varied from 400 watt to about 900 watt and also on the ambient conditions for biogas. Swirler temperature varied in the range of 400°C to 665°C, but most of the time it was in the range of 500°C to 550°C for biogas. Coolant outlet temperature varied from 34°C to 45°C depending on the ambient conditions and load. But there was a sudden increase in coolant temp when the generator output was dumped into the shunt which was located in the radiator.

3.5 Speeds and Torques

There were two rotating components: (a) the Stirling engine and (b) the blower. The engine speed varied from 1400 to 2900 rpm for biogas depending on the load produced by the generator. The blower speed varied from 4,000 to 18,650 rpm for biogas depending on the air demand for combustion. The blower speed was higher for biogas operation as it required more air for combustion. The torque of the Stirling engine was almost flat over the variation of power. It varied from 2.71 N-m to 3.88 N-m in the range of power from 400 watt to about 900 watt. But in 550 watt to 900 watt range it varied between 3.58 to 3.88 N-m. Figure 10 describe Power vs Engine Speed & Torque for Biogas.

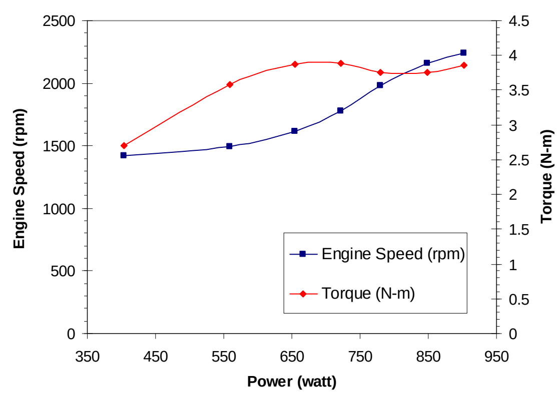

Fig 13. Power vs Engine Speed and Torque for Biogas.

3.5 Exhaust Emissions

The exhaust emission was tested by BACHARACH Portable Combustion Analyzer (PCA). Here percentage of O_2, CO_2, Excess air, Combustion efficiency and parts per million (ppm) of CO was measured. In the exhaust emission remaining oxygen was 2 to 15.2%, CO_2 was 3.8 to 12.6%, excess air was 4.8 to 24.2%, CO was 22 to 6000 ppm for biogas. The combustion efficiency for biogas was in the range of 79 to 87.4%.

4. ENERGY BALANCE IN THE SYSTEM

In a Stirling cycle engine the total heat input Q_{total} consisted of hest coming from biogas and heat from the regenerator. An energy balance diagram can be constructed where different output and heat inputs can be shown with respect to heat input from fuel ie, $Q_{fuel.}$ An energy balance diagrams were constructed, for maximum efficiency condition of operation. Heat recovered from the regenerator Q_{reg} in the Stirling engine was almost 134% of Q_{fuel}. Literature showed it could be as high as 400%[1,4]. Total heat input Q_{total} was 234% of Q_{fuel}, Mechanical out put was 63% of Q_{fuel}, Heat loss Q_{loss} was 171% of Q_{fuel}, Electrical output was 56% of Q_{fuel} as shown in figure 14. Overall efficiency was calculated from electrical output to total heat input, Q_{total}. The maximum overall efficiency was found to be 24%.

Table-3: Heating Components for Maximum Efficiency

Heat input from fuel Q_{fuel}	0.98 kW
Heat recovered from regenerator Q_{reg}	1.31 kW
Total heat input into the heater head Q_{total}	2.29 kW
Electrical output	0.553 kW
If Generator Efficiency η_{gen} = 0.9 then,	90%
Mechanical output	0.614 kW
Heat loss Q_{loss} = [Assuming all frictional losses converted to heat]	1.676 kW

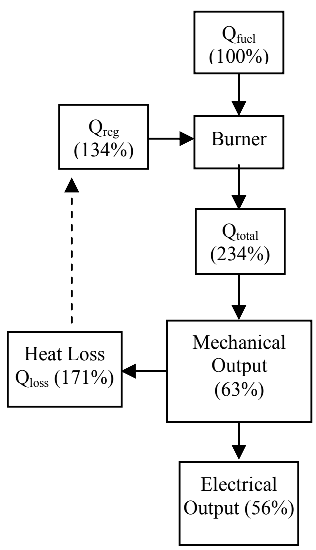

Fig 14. Energy Balance for 553 watt power (Maximum Efficient Operation, 24%).

5. DISCUSSION

The fuel and air flow rate increased almost linearly with the load but with different rate and for this reason the AF ratio was not constant and varied with load for biogas. The AF ratio also increased with load but at the peak load it decreased. The value of AF ratio varied between 30 to 44, which indicated very lean burning. The stoichiometric AF ratio for biogas is 5, so the air flow rate was very high due to the fact that more air flow was necessary to increase the fuel flow rate through the venturi and also to maintain the material temperature in the burner within a reasonable range. Here the instantaneous fuel flow rate was not measured, so an average value of fuel flow rate was taken into consideration. The engine speed and blower speed is 1400 to 2900 rpm and 400 to 18650 rpm respectively.

The specific fuel consumption for biogas was found to be higher at high and low load. It was found to be minimum at 550 to 650 watt range and the value was 488.3g/kW-hr considering 50% CH_4 and 434 g/kW-hr considering 60% CH_4 in biogas. The overall efficiency also achieved the highest point at that range i.e. 550 to 650 watt range and the value was 24.1% considering 50% CH_4 and 22% considering 60% CH_4 in biogas. It was found to be less both in high and low loads than that range. The overall efficiency of the Stirling engine was higher compared to SI engine of that range available in the market, that are 12-18% efficient[6].

The torque of the Stirling engine was almost flat over the variation of power. It varied from 2.71 N-m to 3.54 N-m in the range of power from 400 watt to about 550 watt and 3.54 N-m to 3.88 N-m in the range of power from 550 watt to about 900 watt for Biogas. So, the curve is very flat in the working range, which is typical of Stirling engine characteristics. The Helium pressure initially was 550 psi, after 700 hours of operation that was reduced to 450 psi indicating some slow leakage. Part load characteristics of Stirling engine are better compared to internal combustion engine of similar power range. It was found that the part load efficiency of Stirling engine at 40 to 100% of maximum load varied between 14 to 24% and that of 1.5 kW KUBOTA petrol engine varied between 7 to 12% [6]. The output of the generator was 13.8 DC Volt with varying current with load. To make varying current with load the speed of the engine was changed. It is not a problem for DC output but for AC output the speed of the engine needs to be made fixed with variable load.

The different temperatures such as head temperature, swirler temperature, and coolent temperature are within the limits of materials used and the cooling water circulated across cold end and optionally across the shunt resistance, could maintain the water temperature safely below any boiling situation.

6. CONCLUSION

The prototype DEKA Stirling engine-genset was capable of satisfactory operation using biogas as fuel. During the engine operation the hot end temperature could be maintained within reasonable limits. The decrease of working fluid pressure if kept running at high loads, indicated need of further sealing improvements. The overall efficiency for small scale electrical power generation was found to be better with respect to comparable gasoline run generators.

7. REFERENCES

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