Genset Optimization for Biomass Syngas Operation

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Additional information is available at the end of the chapter

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Abstract

Although biomass is underrepresented in current methods for power generation, it has great potential to help meet the growing need for clean energy. This chapter details the modification of a gasoline-powered two-stroke genset for operation on syngas from a woodchip-powered gasifier. Generator and engine modifications along with a flexible air/fuel control system are described. Results from genset operation indicate a sustainable power output of 360 W with a biomass consumption rate of approximately 6 kg/hour. Optimum power production was achieved at an air/fuel ratio close to 1. After several hours of operation the engine was disassembled and inspected, revealing significant deposits on the piston and crank case parts, indicating that the engine would require weekly maintenance under such operating conditions.

Keywords: Biomass, Renewable, Gasifier, Syngas, Genset

1. Introduction

Today biomass is a neglected source of renewable energy, as most current efforts focus instead on sources such as wind, hydro, solar and even wave power. However, before the widespread use of fossil fuels (notably coal during the industrial revolution), biomass was the primary form of non-animal power for centuries. Burning biomass cooked food, heated dwellings in cold climates, and was involved in the transition out of the Stone Age as humans began smelting metals. Since the discovery of easily exploitable, apparently abundant fossil fuels, the relative importance of biomass has steadily fallen. Additionally with the increasing pressure of an exponentially growing human population, otherwise renewable power sources have often became non-renewable through over-exploitation. Consider that the hills around Katmandu Nepal have been completely deforested by the search for firewood. This reminder emphasizes that *biomass* is not necessarily *sustainable,* and therefore can be considered non-renewable, depending on how it is exploited.

Currently, most consumed energy originates from the combustion of fossil fuels, such as petroleum, coal, and natural gas [1]. These fossil fuels formed over a period of millions of years within the Earth, and once the reserves of fossil fuels are depleted, civilization is likely to be literally out in the cold. Scientists estimate that the reserve of fossil fuels will be depleted within the next 50-120 years. Fortunately there are other viable fuel sources that can replace fossil fuels [2].

Accordingly, the use of renewable resources for energy production is becoming a strategic focus of many governmental institutions worldwide. Efforts are being made to increase the portion of renewable energies within many national energy supply structures [3]. A large number of renewable resources, including solar, wind, hydropower, geothermal, and biomass, are being examined for suitability as sources of energy for electrical power generation [4]. These energy sources are called "renewable" because it is assumed that they will be available as long as the planet remains habitable. Renewable energy offers the advantages that, in many cases, it can be produced locally and on a relatively small scale. These aspects provide a feasible solution for countries that do not have sufficient fossil fuel resources.

In most developed countries, the economy depends heavily on fossil fuels. For instance, the majority of road vehicles are powered by gasoline and diesel and most power plants use coal or other fossil fuels to produce electricity. Changing these systems can be expensive and time-consuming. Thus, recent research into renewable power has focused on developing new fuels for transportation and electricity supply [5].

One of the most promising renewable energy sources for electric power production is biomass, which is arguably the most important source of renewable energy today. If used correctly, biomass can supply power while maintaining environmental compatibility [3]. In fact, innumerable biomass waist products that could form the basis of a clean power generation system are currently causing disposal problems.

Biomass is defined as organic material that originates from plants and includes algae, trees and crops. Biomass is produced when green plants convert sunlight into chemical energy through photosynthesis. Thus, biomass can be considered as organic matter that stores the energy of sunlight in chemical bonds. Generally, biomass is categorized into four groups: woody plants, herbaceous plants and grasses, aquatic plants and manures [1].

One main thrust of biomass research is focused on developing liquid fuels or "biofuels" for transportation, including ethanol, biodiesel, and blended gasoline [6]. Ethanol is widely used as a biofuel in many countries, either as ethanol alone or blended with petroleum-based gasoline [7]. Aside from the use of biomass as fuel for transportation, many studies have been conducted on the use of biomass for electricity generation. These studies indicate that biomass gasification and subsequent combustion of the so-called "producer gas" or "synthetic gas" shows great promise for delivering a significant amount of today's electrical power requirements [5, 8, 9].

In remote areas where grid electrical power does not exist, conventional fuels may also be scarce. Without a local source of electrical power, satellite communications, although available even in extremely remote locations, cannot be used. To address this issue, a "hybrid" photovoltaic and biomass genset power system was developed. The genset was powered with the combustible products of anaerobic gasification of biomass, or "syngas". This chapter describes the optimization of a small gasoline-powered genset for the production of electrical power using gasified woodchips. The genset was specified to be a two-stroke gasoline unit for ease of field servicing. This chapter details the conversion of the genset to syngas operation, optimization of the genset, development of a flexible air-fuel control system and performance measurements of the genset in syngas operation.

The desired specification was for a 2 kWh/day electrical output, ideally from a system operating less than 8 hours per day, 4 days per week, serving as backup power to a photovoltaic power system during extended periods of heavy clouding. As the largest readily available two-stroke genset is a 65 cc, 650 W unit (Yamaha EF950), it was agreed to use this as the base engine in this study.

2. Syngas

When organic material is heated with a limited air flow, it breaks down into simpler chemicals in the form of a hot gaseous exhaust. In a gasifier, organic material is burned with a restricted air flow to prevent complete combustion of the material, resulting in the production of a combustible mixture of gases known as "producer gas," "synthetic gas" or, in the case of woody biomass, "wood gas." Whereas individual components of the gas may vary based on the gasifier design, operating conditions and biomass, the primary energy carriers in the gas are generally carbon monoxide (CO), hydrogen (H_2) and methane (CH_4) [10]. As some air enters the system, allowing a small amount of combustion, the syngas also contains appreciable amounts of nitrogen (N_2), carbon dioxide (CO_2) and water (H_2O). Because these gases do not contribute to combustion, they act to dilute the fuel, reducing its heating value.

The gasifier used in this work was a small down-draft unit developed by the University Science Malaysia. This gasifier, shown schematically in Figure 1, is designed to burn wood pellets and delivers approximately 5 kW of combustible gas for direct combustion as well as for use in engines. Wood pellets are loaded into the gasifier from the top every 20-25 minutes of operation.

The ash settling tanks perform two tasks: cooling the gas and allowing any solid matter present to settle out. The condenser is responsible for condensing and removing water and the oil bath is used to clean the gas before introduction into an engine. The starting pump is used to establish air flow through the gasifier during starting. Once the gas begins flowing, it is burned at the flare column. When a flame can be sustained, it is then directed into the engine, and the starting pump is switched off.

A typical analysis of the resulting syngas is given in Table 1. The gas from this system generally produces a heating value of 4.5 MJ/kg.

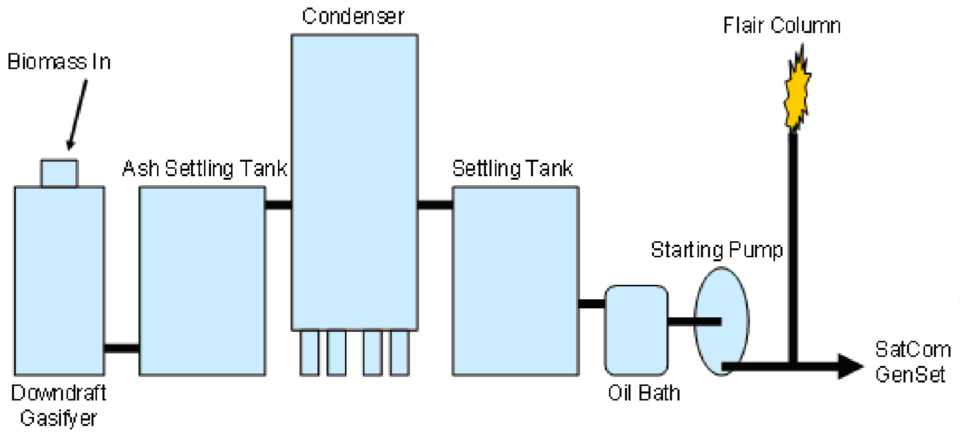


Figure 1. USM's 5 kW down-draft wood pellet gasifier system.

Component	Mole %
N_2	45
CO	20
CO_2	15
H_2	14
CH_4	4.0
O_2	0.2

Table 1. Syngas components [11]

3. Syngas combustion chemistry

The following chemical equation describes the stoichiometric combustion of the syngas in air [11, 12]:

$0.45\ N_2 + 0.20\ CO + 0.15\ CO_2 + 0.14\ H_2 + 0.04\ CH_4 + 0.002\ O_2 + a\ (O_2 + 3.76\ N_2) = x\ CO_2 + y\ H_2O + z\ N_2$

Carbon balance provides us with the following: $0.2 + 0.15 + 0.04 = x$ or $x = 0.39$. Hydrogen balance results in $2(0.14) + 4(0.04) = 2y$ or $y = 0.22$. Oxygen balance then gives $0.20 + 2(0.15) + 2(0.002) + 2a = 2x + y$ or $a = 0.248$. Thus, for stoichiometric combustion we have the fuel mass of

$Mf = 0.45(28) + 0.20(28) + 0.15(44) + 0.14(2) + 0.04(16) + 0.002(32) = 25.8$ gm

and an air mass of

$Ma = 0.25(32+ 3.76(28)) = 34.32$ gm

Together, these yield an air/fuel mass ratio of 34.32/25.8 = 1.33. In terms of moles (i.e., volume, assuming the two flows are at the same temperature), the air/fuel ratio is 0.248(4.76) / (0.45+0.2+0.15+0.14+0.04+0.002) or about 1.2 times as much as air consumed per unit fuel by volume. This result has two important ramifications for the conversion of the engine to syngas operation. First, the fuel induction system will have to be capable of delivering a large amount of fuel, commensurate with the air flow. For this reason the fueling control system will consist of two identical throttle valves, one for air and the other for fuel. Secondly, as the air intake is reduced to about half the normal flow (compared to gasoline operation), the power will also be reduced to about half of the gasoline rated power.

4. Engine modifications

The Yamaha 950 two-stroke, 240 VAC, 50 Hz, 3000 rpm, 650 W generator is shown in Figure 2. It was operated on gasoline to achieve the baseline fuel consumption of 682 g/hour and power production of 640 W, which is very similar to its rated power. Electric power–specific fuel consumption of the gasoline base model was 1066 gm/kWh, which is a rather high fuel consumption value typical of small crankcase scavenged two-stroke engines.

Figure 2. The Yamaha 950, 650 W genset, assembled by Kaba.

As the generator is an induction machine, a capacitor is placed in parallel with the AC output. This is necessary to cause the generator to self induce. In addition, the nominal value of the capacitor, 15 μF, is well matched to operation at 3000 rpm. As producer gas burns relatively slowly compared to gasoline, it was anticipated that the generator would be used at lower speeds. Lower speeds require a higher capacitance value for optimum output. Tests showed that increasing the generator's parallel capacitor from 15 μF to 35 μF (adding a 20 μF, 400 V capacitor in parallel), as shown in Figure 3, greatly improved the power production at lower speeds.

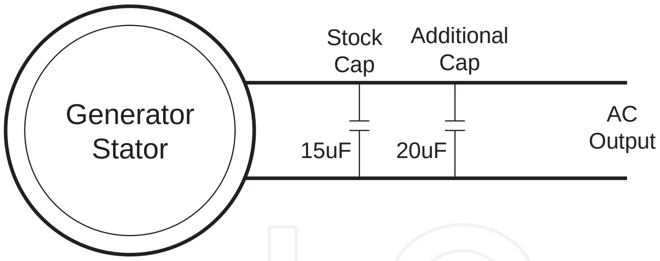
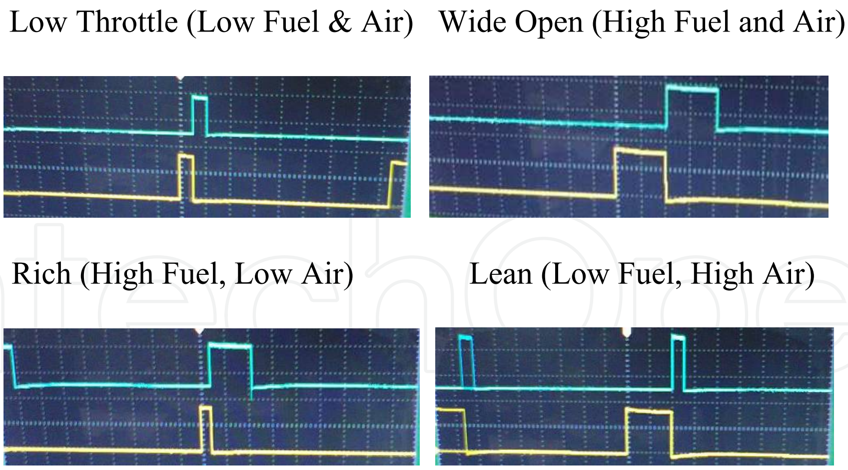


Figure 3. Output capacitance was increased from 15 to 35 μF.

The flame speed of syngas is significantly lower than gasoline. Thus, the spark timing was advanced by approximately 13° to improve power and efficiency when operating on syngas. This was accomplished by moving the flywheel/magneto keyway in such a way that the magneto (responsible for triggering the spark event) was advanced by 13° as shown in Figure 4.

Figure 4. Flywheel with mark indicating new keyway providing spark advance.

As mentioned above, the air and fuel flows are similar in terms of volume. Thus, to control air and fuel flows, an air/fuel control system was created using two identical servo throttles: one each for air and fuel. To simplify operation, an electronic controller was developed to provide two main control functions: the overall throttle as well as a separate air-fuel ratio (AFR) control. When the throttle control is opened, both the air and fuel throttle are opened proportionally. As the AFR control is adjusted, the air and fuel throttles are actuated in opposition; i.e., as the AFR is increased, the air valve is opened slightly and the fuel valve is closed by a similar amount. Reducing the AFR control opens the fuel valve and closes the air valve by a similar amount. This mechanism provides independent control over the throttle and AFR. The servo motors are pulse width modulated units, where position (and thus throttle opening) is proportional to the width of the pulse provided to the motor. Various throttle and AFR signals are shown in Figure 5.



Low Throttle (Low Fuel & Air) Wide Open (High Fuel and Air)

Rich (High Fuel, Low Air) Lean (Low Fuel, High Air)

Figure 5. Fuel servo signal (blue, top) and air signal (yellow, bottom) at various throttle and AFR settings.

The digital display of the controller shows various operational parameters, including engine speed, temperature, throttle and AFR settings. The servomotor and digital display are shown in Figure 6. The servo motor is located below the throttle valve, and the pipe exiting to the right connects to the fuel throttle and fuel supply. Air and fuel are poorly mixed in the "T" junction, however, complete mixing occurs as the gases pass through the crank case of the engine before being transferred into the combustion chamber of the two-stroke engine. This provides good mixing of the air–fuel mixture.

Figure 6. Digital display (left) and air servo valve (right).

5. Bottled syngas operation

Initial measurements were made using a bottled syngas, shown in Figure 7, consisting of 80% N_2 and 20% H_2. This allowed tuning and testing of the engine and instrumentation before the final runs using biomass-produced syngas. Fuel flow was measured via an instrumentation-grade "rotameter". Finally, as the engine is a two-stroke operating on gaseous fuel, provision for two-stroke oil had to be provided. This was accomplished via the addition of a two-stroke oil reservoir and electrical solenoid pump operated by the AFR controller. This allowed convenient adjustment of the two-stroke oil flow rate.

Figure 7. Bottled syngas (left) and fuel flow rotameter (right).

It was necessary to establish a starting procedure when using the bottled syngas for consistent starting. Fuel pressure was regulated down to near atmospheric pressure. However, in this configuration fuel flows even without engine operation, flooding the intake manifold. The throttle was set to approximately 10%, and the air fuel ratio was adjusted slightly lean to encourage air flow. Once the engine was started, the throttle could be opened and the air/fuel ratio adjusted for best operation. The genset running on bottled syngas with 13° spark advance and modified generator was able to exceed 3000 rpm and 300 V without an electrical load. Power production was evaluated with various loads and air/fuel ratios. The genset achieved a maximum electrical power output of 160 W (130 V at 1.15 A) with a fuel conversion efficiency of about 12.4%.

The power is significantly lower than the original gasoline configuration (which achieved 640 W), but the fuel conversion efficiency is better, as the gasoline engine achieved only 8%. The improvement in efficiency is likely a result of the "lean" combustion, as we have approximately 40% more dilution with additional N_2 when running the bottled syngas [13].

Low power production is common on syngas engines as approximately half of the incoming charge is fuel, reducing the available oxygen intake by about 50% [14]. Additionally, syngas tends to burn very slowly, as it is predominantly CO with abundant N_2 dilution. This results in a power de-rating of approximately 75% when run on syngas converted gasoline engines. Thus, the low power produced when running on the bottled syngas (160 W) was expected with the original gasoline production of 650 W.

6. Biomass syngas testing

Having verified the genset's functionality on bottled syngas, the engine was tested using syngas at the University Science Malaysia's Bio-Energy Laboratory. The gasifier is rated at approximately 5 kW (gas out) when burning wood pellets. Typically 4 kg is loaded at a time, and reloading occurs at 20 to 25 minute intervals (Figure 8). The main gasifier, measuring approximately 50 cm in diameter with a 125 cm height, feeds an ash-settling chamber approximately the size of a 200 liter barrel, a condensation unit measuring 50 cm × 50 cm × 150 cm tall, another settling barrel, an oil bath filter and a startup blower before being fed to the flare, sampling stack and the engine.

Down-draft gasifier

Reloading wood pellets

Gas production

Biomass near end of burn

Figure 8. USM's 5 kW down-draft wood pellet gasifier.

Gasifier startup requires approximately 15 minutes before the gas can flare (Figure 9). Starting of the genset was performed on syngas, without gasoline assist. For each configuration tested, a specific startup procedure was required, and when followed, the genset started quite easily, generally with a single pull of the starter. To the surprise of the USM laboratory personnel, the engine would start and run on the biomass syngas even when the flare could not be sustained (typically a prerequisite for engine operation). This was attributed to a robust ignition system and careful air-fuel ratio control. Additionally, the genset was able to run and continuously produce power during re-fueling of the producer gas system.

Figure 9. Flare (left) and gas sampling for analysis (right).

Many different configurations of gasifier operation, engine settings and electrical load were evaluated. Initially, fuel flow was measured with the rotameter; however, this device quickly tarred up and became obscured with the deposits. Thus, flow measurements were made quickly, and the flow meter was subsequently bypassed. The final genset is shown in Figure 10. The electrical load (off camera to the left) consisted of various 1 kW, 62-ohm resistors configured as required.

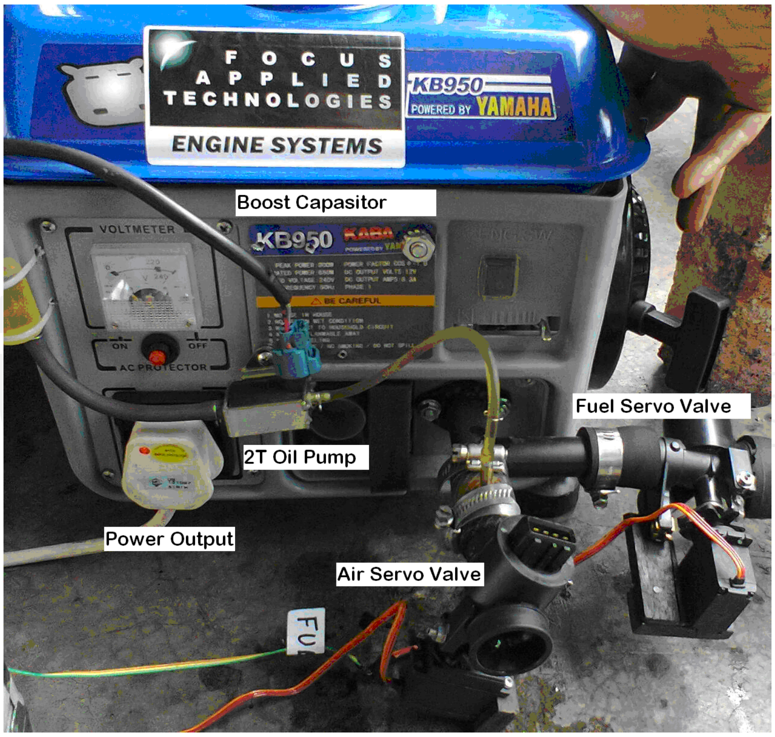


Figure 10. Modified syngas genset. Two-stroke oil reservoir is at upper left. Controller, fuel meter and electrical loads are not shown.

During operation, the output voltage, current and frequency were measured using an Agilent true RMS digital multimeter. A typical run consisted of selecting an operating configuration, varying the load and varying or optimizing the engine controls. The engine was operated at the optimum operating point for extended periods, and the system was shut down briefly during configuration changes. The ancillary equipment and test environment can be seen in Figure 11.

Figure 11. AFR and throttle controller are to the left of the engine, as is the digital display. Note that the gas supply system has relatively large pipes to supply the unpressurized syngas.

7. Biomass syngas operation results and analysis

The first observation made was that the genset started on syngas surprisingly well. Starting and operational servo valve settings are strongly influenced by the configuration under test in expected ways: with greater restrictions in the fuel flow path (such as the fuel flow meter), the fuel valve had to be opened relative to the air valve to admit more fuel. When the startup blower was in operation, the fuel valve could be closed somewhat with respect to the air valve due to the higher pressure of the fuel.

During a single biomass load, the quality of the fuel varied from the beginning of the burn to the end, requiring slight adjustments to the AFR control to maintain optimum power [15]. It was also noticed that the fuel flow meter caused significant restriction to the fuel flow, which in turn resulted in a much lower optimized AFR controller setting. Once the fuel flow meter was removed the best AFR was near 1, as expected based on the chemistry presented earlier. Similarly, the optimum throttle depended on the specifics of the configuration under test. In all cases, the power output varied smoothly with changes in throttle and AFR, and the engine was very easy to control.

Low-power operation was not strongly dependent on the actual electrical load, but was restricted by the throttle and governor. The governor of the gasoline version controls operation to the rated speed of 3000 rpm. This was bypassed for most of the tests to investigate a wide range of operating speeds and outputs. Electric power output of 120 W was achieved on loads from 61 to 183 ohms with the fuel flow restricted by the flow meter. Fuel flow rates of 1.5 scfm (standard cubic foot per minute) were measured for the first 30 minutes before the flow meter became obscured by internal tarring. As the system was allowed more air and fuel, the power level rose to approximately 270 W for loads of 120–180 ohms. Further improvements in fuel flow and bypassing of the genset governor allowed full power operation with a power output of approximately 430 W on both the 122 and 183 ohm loads.

At these higher powers, the genset was running near the rated speed. Fuel consumption was estimated at approximately 2 scfm of gas (about 3.2 m^3/hour) or about one third of the gasifier's rated capacity.

Output V	Load Ohms	Current A	Power We	Hz	Throttle %	AFR	Fuel Flow SCFM	Comment
122	122	1.0	**122**	30	44	0.54	1.1	Choked
86	61	1.4	**121**	26	62	0.50	1	Choked
150	183	0.8	**123**	33	72	0.50	1.1	Choked
220	183	1.2	**264**	41	44	0.50	1.5	With Flow Meter
184	122	1.5	**278**	38	18	0.50	1.4	With Flow Meter
245	183	1.3	**328**	45	52	2.08	~2	No Flow Meter
280	183	1.5	**428**	48	106	1.92	~2	Bypass Govenor
220	122	1.8	**397**	50	72	1.92	~2	Bypass Govenor
210	122	1.7	**361**	50	80	1.25	~2	Average over 1 Hour w/ Reloads
229	122	1.9	**430**	50	100	1.04	~2	Fully Optamized

Table 2. Summary of various loads, powers, and settings

From the above data, it can be observed that at very low power settings (choked operation), the power output is independent of applied load. Opening up the overall flow allows greater power production, with similar power recorded for the 122 and 183 ohm loads. The initial runs indicated that the system was not receiving sufficient fuel flow (as evidenced by the low AFR values). This led to the improvement of the fuel flow path, eventually necessitating the elimination of the fuel flow rotameter, which was becoming clogged with tar. As the engine operation approached the rated speed (50 Hz), the governor became the limiting factor. Once bypassed, the power rose further and approximately 430 W was produced with both the 122 and 183 ohm loads. During testing, steady runs of over 60 minutes were achieved in this configuration at powers of 360–400 W, even while refueling was taking place.

The gasifier requires a blower to start the gas flow. The gasifier's capacity is more than twice the genset's capacity, so the blower was kept on most of the time to insure good gas flow through the gasifier, and the extra gas was flared. In one test, the blower was shut down, and the full gas supply delivered to the genset. It was capable of sustained operation in this condition. However, over the course of 15 minutes, the gas quality began to degrade due to the lower flow rate of air entering the gasifier. The blower was placed back in operation and the whole system returned to steady state within several minutes. This underscores the need to carefully size the gasifier for the genset and power demand.

Power output was measured to be a smooth function of throttle, generally achieving maximum power at 50–100% throttle range. The data in Figure 12 indicates an optimum throttle position of about 60% with the flow meter in-line at a load of 183 ohms.

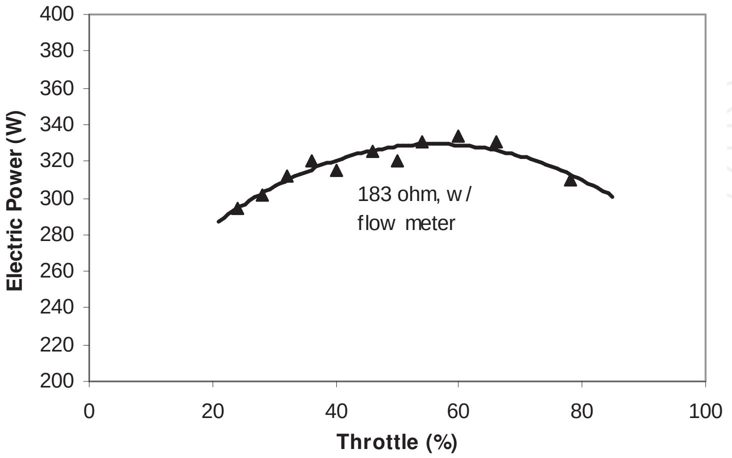


Figure 12. Variation in electrical power output as a function of throttle setting with flow meter in line.

For most runs, the AFR was optimum near stoichiometric with an AFR about 1.1–1.2 (Figure 13), in agreement with the estimated stoichiometric volumetric AFR of 1.2 as determined earlier. Again the power varied smoothly with AFR. Optimum AFR varied over the biomass burn cycle. Significantly, more power was produced when the flow meter was eliminated, as this was restricting the fuel delivery to the engine.

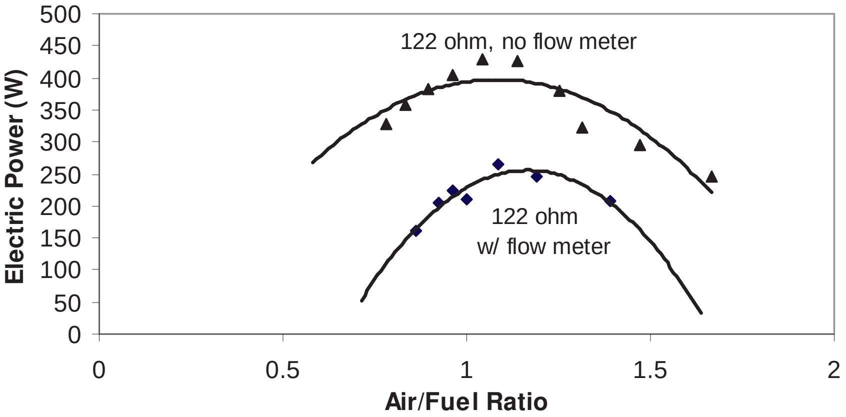


Figure 13. Variation in electric power output as a function of AFR. Peak power occurs near 1.1 AFR.

The genset was operated almost continuously for over 3.5 hours, with short shutdowns between configuration changes. Power output was approximately 360 W most of this time, resulting in a total energy production of 1.26 kWh (4.5 MJ). The total biomass fuel consumption during this time was 20 kg, producing a syngas with a heating value of approximately 4.5 MJ/

kg. As the genset is undersized for this gasifier, it was only capable of consuming about one third to one half of the syngas produced (the balance being flared). Thus, the overall energy consumption was determined to be approximately 7–10 kg or approximately 0.55 MJ of electric power per kg of biomass. The biomass is assumed to have a heating value of approximately 20 MJ/kg, resulting in an overall system efficiency of approximately 0.55/20 (2.75%). While this number appears quite low, it must be understood that this includes the efficiency of the gasification system, combustion, engine, and generator together. Looking at just the genset, it can be estimated that the fuel consumption was approximately 1.7 m^3/hour, which, assuming a heating value of 1.5 kWh/m^3, would give a power consumption of 2.55 kW (syngas), for a power production of 360 W, resulting in a genset efficiency of about 14%. This is a reasonable efficiency for a two-stroke induction generator and is in general agreement with the efficiency achieved using bottled syngas.

Higher powers require higher generator operating speeds. At higher speeds, however, the engine efficiency will drop. This is primarily a function of the speed of combustion of the fuel. As the engine speed is increased, there is insufficient time to completely burn the fuel before expansion of the mixture, resulting in burning occurring well into the expansion stroke or even into the blow-down phase and flame release into the exhaust system. This gives hot exhaust gases, as was observed at higher speeds, representing inefficient combustion. Thus, operation at lower speeds will improve the overall system efficiency, but will degrade the rated power production.

Finally, it was noticed that in contrast to gasoline engine operation, the exhaust emissions were perfectly clear. This is likely from better control of the two-stroke oil, as well as improved combustion of the oil, which is not mixed with a liquid fuel.

After 2 hours of operation, the spark plug was removed and inspected. Its light brown appearance indicated good operation, with no evidence of tarring or oil buildup that could cause fouling as shown in Figure 14. At the end of the run, the fuel valve was inspected and found to contain heavy deposits of tar. It was estimated that the fuel intake valve would require cleaning after approximately 10 hours of operation.

Figure 14. Spark plug at 2 hours of operation (left) and fuel valve after 3.5 hours (right).

8. Engine tare down inspection

As mentioned, the fuel flow meter became obscured by tar after about 30 minutes of operation. This occurred despite the presence of particulate filtering, condensation chamber, and oil bath filter. Tar buildup was expected, as tar tends to condense on cooler surfaces, and the flow meter was the coldest element prior to the engine.

The head showed (Figure 15) a thick buildup of soot, uniform except for a lighter color on the lower (hotter) side of the head. The piston crown similarly had a thick buildup of soot. The inside of the bore had a dark film of tar and oil, but still had decent tribological properties. The use of two-stroke oil was measured to be 15 ml for the 3.5-hour run, significantly less than the typical flow rate on gasoline, however, quite sufficient for syngas operation because the gas does not remove the oil from the target surfaces as gasoline does. Oil "wetting" marks can be seen on the edges of the piston in the photo below.

Figure 15. Cylinder head (left) bore (center) and piston crown (right) indicating significant tar or soot buildup, especially at the colder locations.

The crank case contained a smoky smelling oil and tar mixture. The buildup quantity was not enough to cause alarm, but the color was much darker than typically occurs with gasoline operation. The piston top land had significant carbon buildup, which extended down to the top of the skirt region (Figure 16). No abnormal wear was observed.

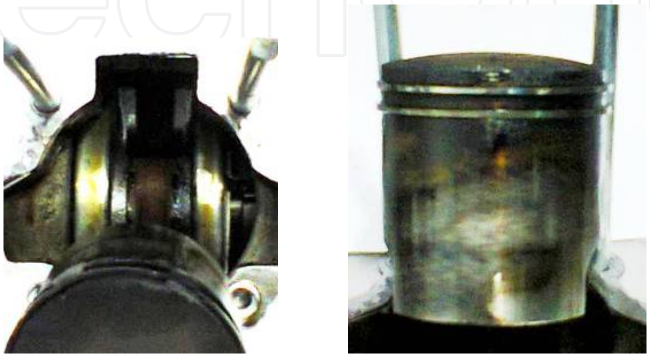


Figure 16. Crank case (left), and piston (right).

It is estimated that the engine should be capable of operating one shift per day, allowing approximately 7 hours of operation without any special attention. After 1 week of operation, however, it is believed that the carbon and tar buildup will be sufficient to warrant maintenance of the piston, bore and head. This maintenance consists of opening the head, cleaning the parts, reassembling and torquing the head bolts to specification. Properly done, this operation should take no more than 30 minutes. It should be noted that this rate of maintenance may adversely affect the life of the engine.

9. Conclusions

Several important conclusions resulting from this study, outlined below, will have ramifications on the commercial exploitation of this or similar biomass power generation systems.

First, the syngas genset was capable of sustained operation at over 360 W of electrical output on syngas, with a peak power of 430 W. This implies a de-rating of 45% from the original gasoline operation (expected from the fuel displacement of incoming air) with the described modifications. Power production efficiency is estimated at 0.55 MJ/kg of biomass, with an overall system efficiency of 2.75% and a genset efficiency of approximately 14%. Although the overall efficiency is rather low, it includes the efficiency of the gasifier, engine, and generator. In addition, a higher efficiency can be expected by better matching the size of the genset to the gasifier. It was observed that the engine was operating significantly faster than optimum for the combustion of the gas, as evidenced by the elevated exhaust gas temperatures. A larger displacement genset designed for lower speed operations would greatly improve thermal efficiency, with a commensurate improvement in the overall efficiency of the system. The air–fuel control system was capable of controlling the engine operation for easy starting and smooth operation over a wide range of circumstances. Two-stroke oil was delivered through an electronically controlled pump, at a consumption of 5 ml per hour of operation, which provided good lubrication. Assuming one shift of operation per day (7 hours of genset operation), it is estimated that the engine will require tear-down for cleaning every 30 hours of operation, or approximately weekly. The sparkplug remained clean during 2 hours of operation; however, the fuel flow meter became unusable after 30 minutes from tarring. The fuel valve showed significant tar deposits after 3.5 hours of operation, indicating that the fuel filtering should be improved or the fueling system would also require frequent cleaning.

10. Recommendation for future work

Based on the above data, a larger generator system is proposed to provide greater power and improved efficiency when compared to the two-stroke syngas genset described above. Such a system should have the following specifications:

Power production:	2k W (electrical)
	240 V, 8.3 A, 50 Hz
Displacement:	400 cc
Engine speed:	2000 rpm
Spark timing:	30° before TDC
De-carbonizing:	Monthly (or every 120 hours of operation)
Biomass consumption:	30 kg/hour(assuming clean, dry wood biomass)

Table 3. Optimized Genset Specifications

These specifications would likely require a non-standard engine and genset. For maximum efficiency, a permanent magnet generator could be used, allowing a somewhat smaller engine of perhaps 300 cc and proportionally reduced biomass consumption. Finally, the engine efficiency can be improved by increasing the compression ratio, as syngas has a much lower tendency to knock than gasoline. Four-stroke engines are somewhat mechanically more complex than the simple two-stroke engine investigated here; however, they are more common for genset operations and may require less servicing as the tar-laden syngas is not circulated through the crank case.

As we move forward in a world of increasing population, environmental concerns, and fuel prices, it is inevitable that the importance of biomass as a power source will also increase. The burden of developing clean, sustainable energy supplies depends on today's engineers and technicians. It is sincerely hoped that the information contained herein will be of benefit in this effort.

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