Analysis of a Biomass-fueled Stirling Heat Engine

James Robinson

April 29, 2008
1. Introduction
   - Objectives
   - Justification

2. Characteristics
   - Tradeoffs

3. System

4. Maximization

5. Inputs/Outputs

6. Reducing emissions

James Robinson — Analysis of a Biomass-fueled Stirling Heat Engine
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- Justify reasons for analysis
- Describe Stirling Engine functions and their benefits.
- Present a biomass system that incorporates a Stirling Engine
- Identify methods for improvement
- Define inputs/outputs of the system
- Suggest new applications for a Stirling engine that decreases emissions/environmental impact
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Introduction

Characteristics

System

Maximization

Inputs/Outputs

Reducing emissions

Stirling Engine

Figure: Model Stirling Engine

Justification

- Stirling Engines have an elegant design
- The environmental impact is potentially very low
- The technology needs to be improved

Figure: Inside of a Stirling Engine

Figure: P-V and T-S diagram of a theoretical Stirling engine (Sonntag et.al., 2003)
Figure: Inside of a Stirling Engine Steps 1-2 (Ross, 1977)
**Figure:** Inside of a Stirling Engine steps 3-4 (Ross, 1977)
Figure: Inside of a Stirling Engine

### Advantages

- Heat source external to the engine
- Quiet while operating
- Rejected heat can be cogenerated-no corrosive exhaust

### Disadvantages

- Operates at close to limit of materials properties
  - Temperature affects metallurgical properties
  - Pressure strains gaskets and seals
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The primary goal of the small scale plant sowed in Figure 3 is the grid independent production of electricity from biomass in the capacity range of 5 to 30 kW. The principle arrangement of the components is indicated in Figure 3. The important parts of the small scale power production unit are the biomass combuster, the Stirling engine as showed in Figure 1, the electric generator, the engine cooler circuit with pump, fan and the water/air heat exchanger. Biomass wastes like coffee shells, rice husks, agricultural residues or any kind of wood may be used as a fuel. Adaptations of the biomass combuster to several biofuels for improvements of the combustion process will be necessary. The heater of the Stirling engine is directly heated by the hot flue gas of the combuster. A heat exchanger with smooth surface at the flue gas side for heat recovery is used to preheat the combustion air to some hundred degree centigrade before entering the combuster. The belt driven blower and the cooling water pump (not visible in Figure 3) of the engine cooler are important components for rejecting the heat.

**Figure:** Biomass-Stirling engine prototype (Podesser, 1999)
The higher weight of Stirling engines operating with air (nitrogen) as working gas is of little significance in stationary applications. The coefficient of performance generally does not depend on the working gas.

The crank mechanism used in the Stirling engine was that of a series produced engine for a motor cycle. Figure 1 shows this biomass test Stirling engine. The relatively large dead space of the heat exchangers requires, therefore, that the active working space of the entire Stirling engine be adapted accordingly.

### Technical Performance Data Measured

The tests with the experimental Stirling engine were performed on a testbed configuration with a wood chip furnace. Results were found as shown in Table I:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue gas temp.</td>
<td>1000°C</td>
</tr>
<tr>
<td>Dust content</td>
<td>70 ... 700 mg/m³N</td>
</tr>
<tr>
<td>Engine cooler</td>
<td>30 ... 70°C</td>
</tr>
<tr>
<td>Cylinder cooler</td>
<td>20 ... 30°C</td>
</tr>
<tr>
<td>Rod seals cooler</td>
<td>20 ... 30°C</td>
</tr>
<tr>
<td>Thermal input</td>
<td>12.5 kW</td>
</tr>
<tr>
<td>Engine cooler</td>
<td>8.75 kW</td>
</tr>
<tr>
<td>Cylinder coolers</td>
<td>0.52 kW</td>
</tr>
<tr>
<td>Rod seals cooler</td>
<td>0.03 kW</td>
</tr>
<tr>
<td>Shaft power max.</td>
<td>3.2 kW</td>
</tr>
<tr>
<td>Mean pressure</td>
<td>33 (40) bar</td>
</tr>
<tr>
<td>Bore/stroke</td>
<td>140/51 mm</td>
</tr>
<tr>
<td>Swept piston volume</td>
<td>840 cm³</td>
</tr>
<tr>
<td>Compensator</td>
<td>17 liter</td>
</tr>
<tr>
<td>Working speed</td>
<td>600 RPM</td>
</tr>
<tr>
<td>Idling speed</td>
<td>950 RPM</td>
</tr>
<tr>
<td>Efficiency (COP)</td>
<td>0.25 ... 0.28</td>
</tr>
<tr>
<td>Crank mechanism</td>
<td>DUCATI 500 cm³</td>
</tr>
<tr>
<td>Flywheel/starter</td>
<td>Austrian Truck</td>
</tr>
<tr>
<td>Working gas</td>
<td>air, nitrogen</td>
</tr>
</tbody>
</table>

### Process Configuration in Principle

Figure 2a shows the configuration of the biomass Stirling engine unit in principle which includes a heat exchanger to preheat the combustion air by heat recovery from the flue gas. This measure makes sense if the relationship between electricity produced (ELP) and the biomass fed (BFin) should be enlarged. The Sankey diagram in Figure 2b indicates further that this relationship reaches 0.20. The COP expected for this application will be 0.33. The Sankey diagram shows the relationship between the electricity produced and the thermal capacity of the combustor. It is easy to see that the combustor has to have about 50 kWth if an electric power of 10 kW is generated. The heat rejected by the engine cooler at temperatures of 60/40°C will reach about 25 kWth at full load.

Figure 2: Biomass Stirling engine (a) for grid independent electricity production and Sankey diagram (b).
Biomass Heated Stirling Engine

System

1. Rated output: 3 kW
2. Combustion of biomass: 12.5 kW
3. Rejected heat, via coolant: 8.75 kW
4. Average pressure ≈ 33 kPa
5. Efficiency 25%
Biomass Heated Stirling Engine

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5. Efficiency 25%
\[ \eta_{HE} = \frac{W_{HE}}{Q_H} \]

\[ = \frac{3.2\, kW}{12.5\, kW} \]

\[ = 25.6\% \]
Maximization Methods

Possible Methods for Improvement

- Increase temperature of hot side, decrease temperature of cold side
- Maximization requires no addition of heat
- Best achieved by effective heat exchange
- Coolant can be used but requires pumping work
- Regenerator: No heat, no work
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Maximization Methods

Regenerator

Figure: Diagram showing the regenerative matrix to increase efficiency (West, 1986)
Figure: Work output increased (1-2′-3-4-1), heat input remains the same (a-2′-3-4-d-a)
Maximization Methods

Efficiency Increase

New Efficiency Calculation

\[
\eta = \frac{W}{Q} = 1 - \frac{\frac{5}{2}(T_H - T_C) + T_C \ln \left(\frac{V_f}{V_i}\right)}{\frac{5}{2}(T_H - T_C) + T_H \ln \left(\frac{V_f}{V_i}\right)}
\]

\[
= 1 - \frac{\frac{5}{2}(1473 - 333) + 333 \ln(840)}{\frac{5}{2}(1473 - 333) + 1473 \ln(840)}
\]

\[
\eta = 59.7\%
\]

*Temperatures in Kelvin

Derived with Wes Bliven
Combustion of Biomass

Assumptions

- Biomass consists of 3 main molecules in woody plants: Cellulose, hemicellulose and lignin
- Complete combustion
- All carbon emitted as $CO_2$

Example

$$C_6H_{10}O_5 + \frac{1}{2}C_5H_8O_4 + \frac{1}{2}C_{10}H_{12}O_3 + 14.25O_2 + 49.31N_2$$

$$\rightarrow 13.5CO_2 + 10H_2O + 49.31N_2$$

- For every unit of biomass (774 g), 594 g of $CO_2$ are produced
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Using a typical Heat of Combustion for biomass $20 \frac{kJ}{g}$ (Levine, 1991):

$$CO_2 \text{ emissions} = \eta \times \frac{m_{CO_2}}{m_R} \times \frac{1 \text{ g}}{20 \text{ kJ}} \times \frac{3600 \text{ kJ}}{1 \text{ kWh}}$$

$$= (0.256)(\frac{594 \text{ g}}{774 \text{ g}})(\frac{1 \text{ g}}{20 \text{ kJ}})_R(\frac{3600 \text{ kJ}}{1 \text{ kWh}})$$

$$CO_2 \text{ emissions} = 33.15 \frac{g}{kWh}$$
Combustion of Biomass
Avoided $CO_2$ Emissions

**Figure:** CO2 equivalent offset by use of bio-fuels (CA DOE, 2007)

- Converting $3400 \frac{lb_m CO_2}{MWh}$ to $1.54 \times 10^{-3} \frac{g}{kWh}$
- Avoided $CO_2$ during combustion is negligible.
- Must be higher accounting for life-cycle of live plant
Modifications to Biomass Flume

Possibilities

- Long, heat resistant pipes allow particulates to settle.
- Cloth fiber filters enhance catchment of particulates
- Electrostatic precipitators

**Figure:** Electrostatic precipitator

http://www.bbc.co.uk/schools/gcsebitesize/physics/images/ph-elect28.gif
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Figure: 10 kW Stirling-Dish assembly (Reinalter et. al., 2008)

- Only outputs are 18.53 kW waste heat and 10.85 kW net work.
- Overall efficiency is 39.4%. Stirling engine efficiency is 34.3%.
Figure: Southern California Edison 150 kW model of a potential 825 MW system

http://www.edison.com/pressroom/pr.asp?id=5885
Conclusions

- The biomass fired Stirling engine can run constantly given fuels supply
- Efficiency can be increased from 25% to a maximum of 59% if a regenerator is used
- Major downfall of biomass-fired Stirling engine is the dust and emissions
- Improvements to the heat source can make the use of Stirling Engines more viable
References


5 Ross, Andy (1977) Stirling Cycle Engines, Imperial Litho/Graphics


Questions?

**Figure:** Large 25 kW Stirling engine built by Stirling Energy