A Biomass-Fired 1 kWe Stirling Engine Generator and Its Applications in South Africa

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Abstract

This paper describes a biomass fired Stirling engine generator — Biowatt™. The system, which includes free-piston Stirling engine, two-stage biomass pellet burner, cooling and starting sub-systems, is described. The engine is designed for a life of over 40,000 hours and life tests are ongoing. Burners for other biomass fuels such as chunk wood are also being developed. This generator consumes between 1.2 and 1.4 kg/hr of biomass, depending upon the quality of the biomass, and produces over 1 kW of electric output and 4 kW of heat. Distributed environmentally acceptable generators such as this can help to meet South Africa's need for rural electrification. These systems add value to the scarce fuel wood resources and are an economically attractive alternative to central power stations.

Introduction

Concerns with global warming and the need to reduce CO_2 emissions are growing internationally. At Kyoto in 1997, numerous countries made a commitment to reduce their carbon emissions. Biomass electric generation is carbon neutral as long as renewable biomass is used, and is an appropriate option for both developed and developing nations. This paper describes a prototype biomass-fired electric generator for small-scale distributed power production. A free-piston Stirling engine with linear alternator uses heat produced from burning biomass pellets to generate mechanical energy, and converts that energy into alternating current electrical output. With other burner configurations, this system can use chunk wood or other biomass fuels. Where there is market interest, such burners will provide a cooking surface. Each is a stand-alone system, with integral cooling systems, heat rejectors, and engine power controls. These systems are being developed as part of a range of biomass-fired electric generation products that will be marketed under the name Biowatt™.

System

The generator consists of a burner, an engine with linear alternator, cooling system, and, in the case of the pellet fired system, a battery and starting system. The system produces more than 1 kW_e of 240 V, 50 Hz AC electricity. A prototype system is shown in Figure 1. These generators can be used in a stand-alone mode or connected to the utility grid. They can also be used as electric generators only, or as cogeneration units where the user requires both the electrical output and the heat produced. The system produces about 4 kW of heat for each 1 kW of electricity. The engine/alternator design can be modified for 120 V, 60 Hz AC electrical output.

Presented at the 9th International Stirling Engine Conference, South Africa, June 2-4,1999

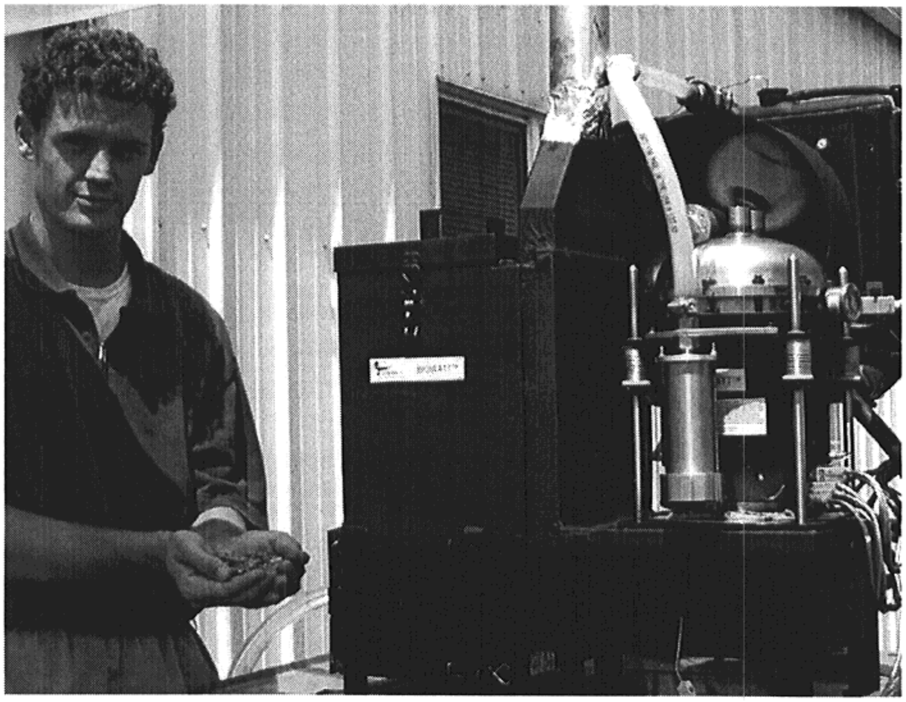

Figure 1. Prototype pellet burning 1 kW_e system

BURNER

Biowatt™ biomass pellet burners take advantage of two-stage combustion to insure high temperature combustion with minimal emissions. The burner is comprised of a fuel hopper, a gasifier, a fuel-air mixing and burn tube, a secondary burn-heat transfer section, an exhaust gas recuperator, and the final stack. Burners optimized for chunk wood differ in a number of ways, including the fuel hopper and gasifier details. Figure 2 shows a schematic of the pellet burner.

The fuel hopper stores sufficient fuel for the generator to run without attention for up to 6 hours. For longer periods of operation, a separate fuel store and auger feed can be used. The hopper includes a gasifier (gasification zone) in which the volatiles are driven off by heat from the combustion of the residual carbon in the fuel. The rate of burn and combustible gas generation can be varied over a wide range determined by the rate of admission of primary burn air to the gasifier. The ash formed in this primary combustion zone drops through the grate to an easily removable ash catcher.

The fuel rich gas from the gasifier and a secondary air jet are mixed in a burn tube. The high velocity secondary jet assures turbulent mixing of secondary air with the fuel gas from the gasifier to achieve complete combustion in this tube. The secondary jet also maintains the primary combustion zone at sub-atmospheric pressure, allowing fuel loading without loss of combustion gases. The completely burned gas emerges from the combustion tube at a high temperature, typically about 1300°C, and at high velocity.

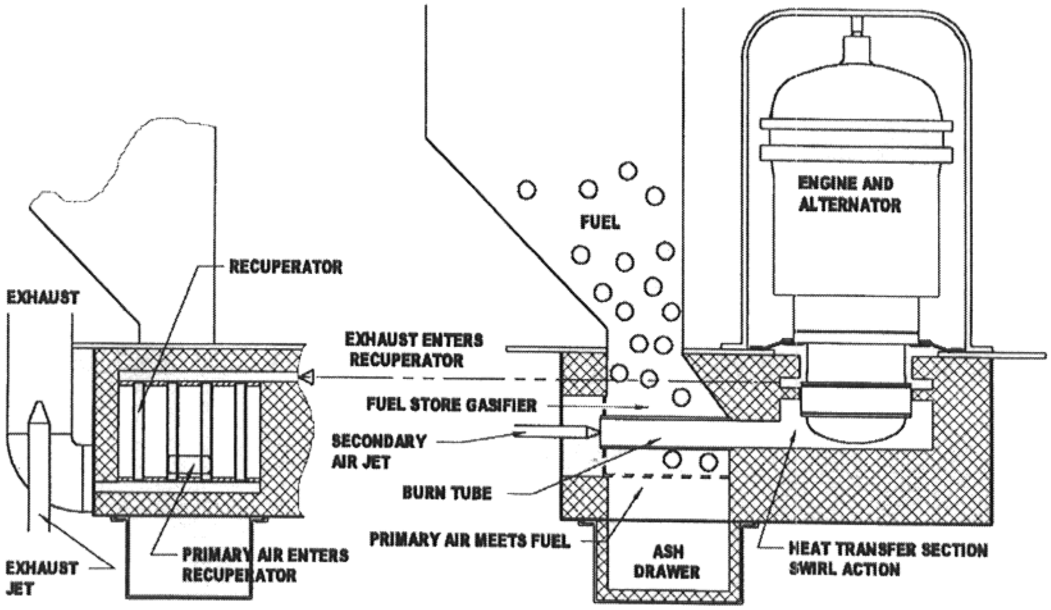

Figure 2. Schematic of Biowatt™ generator with pellet burner

The hot gas from the burn tube swirls around the heater head of the engine, ensuring a uniform temperature distribution around the head. The gas exits through axial fins on the heater head to a collection ring. From the collection ring the exhaust gas enters the recuperator. The remaining energy in the exhaust is partially recovered and used to heat the incoming combustion air in this counter flow heat exchanger. The cooled exhaust gas then goes to the exhaust gas jet ejector.

In the stack, a high-pressure jet of fresh air from the blower transfers momentum to the exhaust gas in the exhaust jet ejector, driving the exhaust out to the atmosphere and keeping the burner at sub-atmospheric pressure. This arrangement prevents leakage of combustion gas to occupied spaces.

The above combination of burner elements assures complete combustion of a variety of solid fuels, chiefly as a result of the highly turbulent mixing of the fuel gas with the secondary air in the flame tube. This innovation eliminates the burden of unburned gases so common in conventional wood burners, caused by laminar flow burning and hence incomplete mixing of fuel and air. The Biowatt™ pellet burner is also capable of burning liquid or gaseous fuels without modification, provided that these fluids are introduced into the burn tube along with the secondary air.

With the use of this blower mixing technique, it is possible to use appropriate sensors and computer-chip controlled airflows to achieve essentially clean combustion under a wide range of conditions of firing rate and type of fuel. The air blower power requirement is typically about 2% of system rated power. Biowatt™ requires no grid connection, and the system easily supports the blower from initial engine start-up until shut down. Clean combustion reduces stack emissions, maximizes system efficiency, and therefore minimizes fuel use. The same fuel can be used to generate electricity and to provide for cooking, hot water, or space heating, as required.

ENGINE AND LINEAR ALTERNATOR

The features of the engine and linear alternator have previously been described[1]. This engine is also being developed for natural gas fired cogeneration applications. It includes state-of-the-art non-contact gas bearings[2], effective low-cost finned internal heat exchangers, and a fast-acting internal power control[3,4]. Life tests on this engine are ongoing. The design life is greater than 40,000 hours, and to date over 2000 full thermal start-stop cycles have been completed.

Stirling engine type	single cylinder free-piston
Linear alternator type	1 window permanent magnet
Engine/Alternator mass	20 kg
Gross mechanical power	1250 Watts
Gross electrical power	1100 Watts
Output	240 VAC at 50 Hz
Overall efficiency (electric out/heat in)	23.0%
Operating frequency	50 Hz
Operating pressure	30 bar
Working fluid	helium
Expansion space temperature	470° C
Compression space temperature	120° C
External heater wall temperature	550° C
External cooler wall temperature	85° C
Piston bearing	non-contact hydrostatic
Displacer bearing	non-contact hydrostatic
Piston springing	planar mechanical springs
Displacer springing	planar mechanical springs
Piston seals	non-contact clearance
Displacer seals	non-contact clearance
External hot-end heat-exchanger	stainless steel fins
Internal hot-end heat-exchanger	brazed folded copper fins
External cold-end heat-exchanger	brazed copper fins
Internal cold-end heat-exchanger	soldered folded copper fins
Regenerator	foil annular gap

Table 1. Engine and Linear Alternator Features

The engine and linear alternator were designed to minimize the need for expensive materials. The heater head is 316 stainless steel and the permanent magnets of the alternator are iron-neodymium. The remainder of the engine is aluminum, cast iron and steel. Particular attention has been made to reducing tight tolerances and tolerance stack-ups. Independent manufacturing cost estimates are less than $350/unit in quantities of 10,000's/year.

The engine and linear alternator features are summarized in Table 1.

Balance of System

Waste heat is rejected from the engine by a closed loop liquid cooling system comprising a water pump and a small automotive radiator type heat exchanger with electric fan. The water pump is not electrically driven but is rather an inertia pump. The inertia pump receives its drive from the casing of the engine which vibrates with an amplitude of ~1mm during operation. This pump consumes none of the electric output of the linear alternator and the heat exchanger fan uses less than 20 W of electric power.

Two different starting systems have been tested. In one, a battery and inverter combination provides an electric pulse to the alternator. In the other, the engine casing is manually disturbed with a mass guide combination, which acts as a hammer. The electric start is appropriate in fully automated systems, while the "hammer start" is intended for manually controlled systems.

Performance

To date, ten 1 kW_e Stirling engine/alternators have been fabricated and tested, either at Sunpower or at independent sites. These represent both the 240 VAC, 50 Hz and the 120 VAC, 60 Hz output designs. These engine/alternators were tested using both propane and natural gas, and integrated into Biowatt™ systems with a pellet burner, a chunk wood burner, and a commercial pellet stove with auger feed for fuel. The pellet-burning version was demonstrated publicly at the 1998 Midwest Renewable Energy Fair, Amherst, Wisconsin (continuous operation for three days). After additional modifications, the pellet-burning Biowatt™ was also demonstrated at the BioEnergy '98 conference in Madison, Wisconsin.

The pellet-fueled system has achieved over 1.1 kW net electric output consuming of 1.5 kg/hour of pellets (8-10% moisture). The chunk wood system has achieved over 1 kW net electric output.

We anticipate that a commercial product will be able to achieve the efficiencies and energy flows indicated in Figure 4. With an input of 5.6 kW fuel energy, the electrical output will be 1.1 kWe, with 3.8 kW heat at 75°C available for hot water and space heating. With these improved efficiencies, consumption of pellets would be reduced to about 1.2 kg/hr of pellets and about 1.4 kg/hr of wood depending upon wood quality and moisture content. Nearly 20% of the fuel energy will be converted to electricity. If all of the cogenerated heat is used, system efficiency rises to over 85%.

Application in South Africa

South Africa is in a period of transition. Lack of electricity for rural populations is both a problem and an opportunity. The Government of South Africa and Eskom, the major utility, recognize the need. They also recognize the difficulty in meeting the need through additional large, coal-burning power plants and extensions of the present grid system. Such changes require long lead times and very large investment prior to any delivery of power to remote areas. South Africa's Reconstruction and Development program has an aggressive electrification program to increase electrification to 75% of the population by 2000, from 44% at the end of 1995[5]. The remaining population will inevitably be those furthest from major facilities.

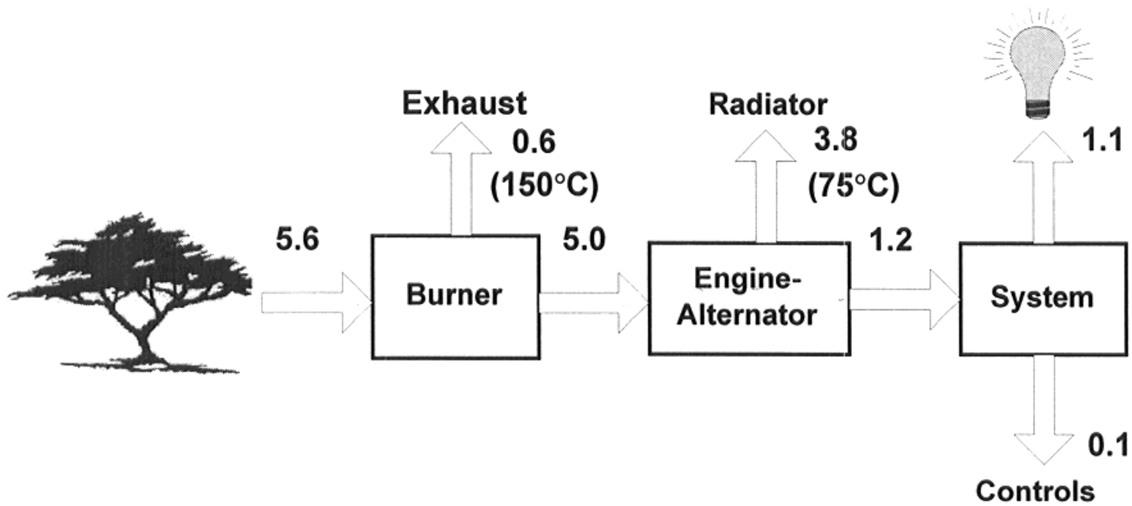

Figure 4. Projected energy flows in kW of a commercial 1 kWe Biowatt™ system with pellet burner

There is wide recognition that renewable energy can and must play a major role in development of further supplies[6]. Eskom has summarized the contribution of renewable energy, defined as nuclear and hydro, to the South African electric supply in the years 1984-97[7]. Renewable energy provides only 3.5 to 10% of total power (all other power is provided by coal-fired plants). Of the small percentage provided by renewables, nuclear power provides more than 80%. These renewable sources of power require large investments and long lead times. The South African Government believes that "renewables can in many cases provide the least cost energy service, particularly where social and environmental costs are included…."[8]

Renewable sources of energy not exploited by Eskom include solar and biomass. At present, solar electrification can most readily be achieved through the use of photovoltaic panels, but at high cost per installed kW. At the same time, biomass use by rural populations is widespread, and provides the only source of energy for some one-third of South Africa's population.[9] As in other developing countries, biomass is often used inefficiently, and increasing use contributes to spreading desertification.[10]

Introduction of technology such as Biowatt™ would increase the efficiency of biomass use while providing modular, distributed electricity. This modular distributed generating capacity would require significantly less capital than central power plants. Further, the initial capital requirements might be largely borne by the end user and there would be opportunities for financing arrangements such as leasing. With the development of large markets for systems such as Biowatt™ in North America, Europe, and Japan[11], the initial higher costs of a new technology will be borne elsewhere. The technology would then become widely available at accessible prices.

A commitment of some portion of the water now required by coal burning power plants could support the development of renewable energy crops and protection of fragile soil.

Conclusion

A free-piston Stirling engine can be used to convert the heat produced in a two-stage pellet burner into alternating current electric output. Burners for other fuel types are also being developed. Life testing is underway with the engine alternator having completed over 2000 full thermal cycle stop-start tests. The engine alternator design minimizes the use of expensive materials and processes. The availability of new technology such as Biowatt™ can contribute to the electrification of developing countries such as South Africa, while supporting the development of renewable energy sources. These generators are much less capital intensive than central power plants and meet the growing worldwide needs for green power and distributed power.

Acknowledgements

The authors would like to thank Dave Shade, Gary Wood, Matt Young, Hans Zwahlen, Todd Cale and Chuck Howenstine for the significant contributions they have made to this technology. The authors thank Meg Hummon for her assistance in writing this paper.

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