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A Stirling engine for use with lower quality fuels

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A R T I C L E I N F O

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A B S T R A C T

A Stirling engine for use with lower quality fuels was designed. The design is a derivative of the GPU-3 (ground power unit-3), modified to be used with a lower combustion gas temperature (900 °C). It is to be used in a generator set producing 5 kWe. The engine model used is based off of the ideal adiabatic model with decoupled loss mechanisms. Single-cylinder and two-cylinder engines were analyzed using a preheater and CGR (combustion gas recirculation). The analysis shows that the external surface area of the heater plays a very important role in determining the system performance. Maximum system efficiency was found by significantly increasing the surface area at the expense of increased dead volume. A single-cylinder configuration was found to offer the best combination of system efficiency (23.6%) and manufacturing cost.

1. Introduction

Currently there is a lot of interest in increasing the use of renewable fuels from biomass and unconventional fuels such as municipal waste as alternatives to fossil fuels. Gas or steam turbines are usually employed in large scale generation of electricity, while at smaller scales, internal combustion engines, whether compression or spark ignition, are employed. They all operate acceptably well at higher temperatures that fossil fuels can reach. At lower temperatures and smaller scales (less than 100 kW), the advantages of these modes of generation are significantly diminished. Additionally, they are more susceptible to problems caused by the particulates generated by the use of unconventional fuels. An external combustion engine such as the Stirling engine offers the ability to use unconventional fuels without these drawbacks.

Fuels that have higher levels of impurities and lower heating values are considered to be lower quality fuels. Table 1 shows heating values and impurity content for some representative fuels. Pure methane and eastern USA bituminous coal are considered high quality fuels.

In the sections that follow, a brief description of the research project is presented. Next the methodology for modeling the Stirling engine and the complete electrical generation system is provided. Finally, the results of the design analysis for a system producing a net of 5 kWe are offered.

2. Background

The goal of this research is to develop a Stirling engine based electricity generation system that uses existing, mature technologies, does not rely on high quality petroleum based fuels, and is intended for use in military applications. One such application is part of the self-sustaining wastewater treatment system for forward operating bases [9]. Various fuels may be used, including biogas, wood, pellets made from other biomass, coal, and garbage. It may also be used with solar heating. The specific fuel would necessitate a unique combustor and possibly a particulate filter. The complete system needs to be truck transportable.

The specific engine to be used is a derivative of the General Motors GPU-3 (Ground Power Unit-3). The GPU-3 was developed for the U.S. Army as a silent generator for use in Vietnam. It is a single cylinder β-type, using a tube bundle heater, a water–air radiator, and rhombic drive. Using hydrogen as the working fluid, it produced up to 9 kW shaft power. A handful of prototypes were built and trialed but it was not accepted into service. Its dimensions and performance have been extensively documented in the literature, for example [16,17,5,10].

The complete system needs to produce a net 5 kWe. The temperature of the products of combustion exiting the combustor is to be 900 °C. The adiabatic flame temperature needs to be below the point at which ash begins to melt (1250 °C) if such fuels as wood and garbage are used [13]. The dimensions of the GPU-3 engine are changed to better suit the lower heater temperatures. Two-cylinder versions are investigated as well, being either in parallel or staged

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Table 1
Properties of lower quality fuels.

Fuel	Higher heating value (MJ/kg)	Lower heating value (MJ/kg)	Moisture content (% by weight)	Ash content (% by weight)
Methane[a]	56	50	–	–
Eastern USA bituminous coal[b]	30	–	6.0	9.7
Western USA subbituminous coal[b]	19	–	30.4	9.2
Hardwoods[b]	20	10	50	2.1
Agricultural[b]	19	13	30	5.9
Municipal waste[c]	10	–	30	36

[a] Ref. [19].
[b] Ref. [2].
[c] Ref. [24].

in a simplified Fauvel–Stirling arrangement [21]. To increase the thermal efficiency and reduce NOx emission, a CGR (combustion gas recirculation) system is added. CGR is a variant of EGR (exhaust gas recirculation) [22].

The original GPU-3 was designed to run on number 1 diesel fuel. The temperature of the products of combustion was about 2100 °C [5]. The proposed derivative of the GPU-3 is to operate using a combustion gas temperature of only 900 °C. Both engines produce approximately the same level of power, but supplying the necessary rate heat ($\dot{Q}$) input to the derivative engine is significantly more difficult due to the lower gas temperature. Additionally, the lower gas temperature results in a lower heater tube temperature, reducing the engine's efficiency. Therefore the rate of heat input needs to increase as temperature drops to achieve the necessary power output. Equation (1) is Newton's law of heating:

$$\dot{Q} = U \cdot A \cdot \mathrm{LMTD} \tag{1}$$

From Equation (1), the convection coefficient (U) is a function of the fluid velocity. It is limited by the need to keep fan power consumption reasonable. The LMTD (Log-mean-temperature-difference) is determined by the gas temperature and tube temperature, which in turn is a function of the fluid velocity. Only the surface area (A) can be increased significantly.

The other effect of the reduced combustion temperature and heater tube temperature is the need for a larger swept volume to produce the necessary amount of power. Using the ideal Stirling thermodynamic cycle (isothermal compression/expansion and isochoric heat addition/rejection) as a guide, the amount of work produced per cycle can be shown to be [10]:

$$W = m \cdot R \cdot \ln(r) \cdot (T_e - T_c) \tag{2}$$

where W is work per cycle; m is the mass of gas; R is the gas constant; r is the compression ratio; T_e is the expansion space temperature; T_c is the compression space temperature.

As the temperature of the expansion space is reduced, the amount of work done per pass is reduced. The expected increase of the heater size will result in a lower compression ratio, further reducing the net work. As a result, the swept volume of the engine needs to increase considerably to produce the required power.

Hoegel et al. [4] performed a theoretical analysis of the operating and geometric parameters of low-temperature difference Stirling engines. The engine was an alpha type using helium at a mean pressure of 5 MPa. The engine speed and piston phase angle were varied to find optimum heater, cooler and regenerator configurations for a two heat source temperatures: 150 °C and 750 °C. The software Sage was employed, which uses a quasi 1-D CFD model. Mechanical losses including friction were not included. The number of heater and cooler tubes was found to be between 2.5 and 3 times more at the low temperature, while the heater and cooler tube lengths at the low temperature were about 2/3 of the length of the high temperature tubes. The regenerator length was found to be nearly the same, while its porosity was higher for the low temperature. The proposed derivative of the GPU-3 should have heater tube temperatures in the middle of the range of the two temperatures used in this study.

Aksoy and Cinar [1] investigated the effect of increasing heater surface area on a moderate-temperature difference Stirling engine. The Stirling engine was a beta type with rhombic drive and a smooth cylindrical heater. The hot end temperature was kept at 673 K and the engine operated using air at atmospheric pressure. The internal surface area of the heater was increased 2.5 times by the addition of longitudinal slots. The work per cycle increased by a factor of 1.5.

Podesser [15] reports on the design and use of a Stirling engine for use with biomass. The engine is a twin-cylinder alpha type. The crank mechanism is from a motorcycle engine. The engine runs on air or nitrogen at a mean pressure of 33 bar and 600 rpm. The temperature of the products of combustion is 1000 °C. The engine produces 3.2 kW of shaft power while receiving 12.5 kW of heat. The piston swept volume is 840 cm^3. The heater tube bundle is estimated to have 150 tubes at a length of 70 cm. The proposed derivative of the GPU-3 should be of similar, albeit smaller, size due to the higher efficiency of the rhombic drive and hydrogen.

3. Methodology

The complete engine plus auxiliaries is shown in Fig. 1. The components include the Stirling engine, a fan, a heat exchanger used as a preheater, a combustor, a CGR (combustion gas recirculation) system, and a fuel pump. Included within the Stirling engine are the alternator, heater, cooler, and water-to-air radiator (heat exchanger). The fan supplies the mass flow rate of atmospheric air to the system with a minimal pressure increase. The air is then heated in the preheater using the hot exhaust gases coming from the engine. The combustor burns the fuel increasing the air and CGR gas mixture temperature to its operating point. The resulting

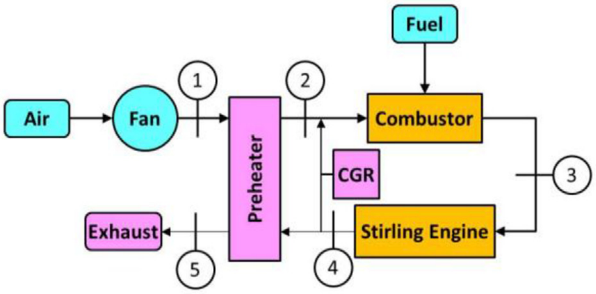

Fig. 1. Complete system.