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A LOW TEMPERATURE DIFFERENTIAL STIRLING ENGINE-BASED POWER GENERATION RESEARCH PROGRAMME

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ABSTRACT

Owing in part to the increasing global realisation that sustainable and environmentally responsible power generation is one of the most critical issues facing modern civilization, research into power generation alternatives is also on the increase. Due to its inherently low conversion efficiency, the use of low-grade heat energy for electric power generation has been largely overlooked as a serious option.

new research programme has been created at the University of Canterbury which aims to show that low-grade heat (especially from geothermal sources) can be economically used for electric power generation. The premise of the research is based on the relative advantages offered through the implementation of appropriate low temperature differential Stirling engine-generator designs.

The initial practical phase of the research is the design, construction and testing of small-scale prototypes that will operate with a temperature differential of as low as 30 K and output approximately 1 kW of electric power. Key considerations of the prototype designs are their scalability to larger power systems, and potential for commercial application. These considerations have led to the important inclusion of primarily common low-cost plastic and metal materials, and low engineering precision and technology mechanics.

KEY WORDS

Stirling engine, renewable energy, power generation, geothermal, waste heat.

1. Introduction

Although there have been proponents of sustainable power generation systems for many years, it has not been until recently that a major upturn in research and development of such sustainable systems has occurred. It would be comforting to think that this significant shift towards sustainable power generation development was primarily attributable to an increasingly wide-spread realisation that sustainability and environmental responsibility is a key benefit to civilization. While this is undoubtedly a contributing factor, it appears the trend is motivated more by industrial organisations accepting the limited remaining fossil fuel resource predictions and the need to secure their financial future by investing in alternative technologies.

Although the widely popular option of modern nuclear power plants have an arguably acceptable level of environmental impact, it is still unclear whether it is truly a sustainable, or even obtainable (for a large number of nations) technology, especially if it is expected to supplant a majority of the global fossil-fuel power generation capacity. Recognition of a need to have a diverse range of sustainable power generation systems has led to research and development of a very wide range of technologies. Common examples of these are based on wind [1], hydro [2], solar (-electric and -thermal) [3, 4], and geothermal [5].

Considering sustainable thermal power generation systems in particular, these have existed commercially for a number of decades where the heat source has traditionally been of a high quality (that is, high temperature and high capacity). The primary form of commercially successful sustainable thermal power generation is geothermal [5]. Economic/commercial viability is determined by the cost of building and running these plants compared to the revenue they create within a particular power generation market. With the unavoidable increasing cost of fossil fuel based systems, lower-grade geothermal (and other) heat sources will start to become economically viable for power generation. The lower limit of heat grade is therefore defined by economic factors and the technical ability to convert that low-grade heat into electric power.

Conversion of low-grade heat into mechanical power (and consequently electric power), is generally carried out using either Rankine cycle (organic) technology [6], or Stirling cycle technology [7-9]. Each of these thermodynamic cycle technologies have their own set of advantages and disadvantages, leading to different physical implementations depending on application.

Owing to the perceived technology advantages associated with the Stirling cycle and the skill base of the research team, a new research programme has been initiated at the University of Canterbury to investigate the potential of economically viable Stirling engine power generation systems utilising low-grade heat sources. The decision to research Stirling engine technology in no way discounts the substantial potential of Rankine cycle technology (and related variants), or other technologies (such as thermo-photovoltaics [10]) in this area of thermal power generation.

2. Key Factors

2.1 Economics, and Environmental Impact

To be commercially viable, any power generating technology must offer some kind of added value to a company. Usually, this added value is measured in financial terms, whereby some level of profit is expected over the operating lifetime of the power generation system. Sometimes less tangible or economic value can also be considered, such as the level of sustainability and environmental impact (although these have an increasing bearing on economics due to various taxes/tariffs based on aspects such as carbon emissions and environmental impact).

Owing to the relatively low emissions/environmental impact of geothermal power generation systems, if the Stirling engine technology can satisfy the usual economic constraints, then it should also achieve commercial viability. The power generation market found in New Zealand will form the basis of the economic constraints in this instance. This is a particularly apt market to consider, as the per-kWh unit cost to consumers in New Zealand is very low relative to most other countries (domestic – around \$0.25 NZD per kWh ≈ \$0.20 USD per kWh). As such, for commercial viability, power generation companies must be able to keep generation costs below around \$0.07 USD per kWh.

Such a competitive generation market has forced the conventional high-grade geothermal power generation plants in New Zealand to have power conversion efficiencies of around 15% [11]. The major financial limitation facing these plants is the capital cost of the plants themselves at around \$3 million USD per MW generation capacity. As such, utilization of low-grade geothermal heat with conversion efficiencies possibly as low as 1% must be accompanied by correspondingly lower plant costs in order to remain commercially viable.

2.2 Stirling Engine Basics

Stirling engines are closed system machines that cycle a working gas through a regenerator, back and forth between hot and cold heat exchanger surfaces (heat reservoirs) [7]. While there is a vast array of potential engine configurations, mechanical work is usually extracted through a piston-crank arrangement.

The theoretical Stirling *P-V* thermodynamic cycle curve is shown in Figure 1 [7], where *P* is the gas pressure (Pa), and *V* is the gas volume (m^3). The arrow direction indicates the progress of the engine cycle. Since the gas expansion (①→②) is carried out at a higher pressure than the gas compression (③→④), there is net work output.

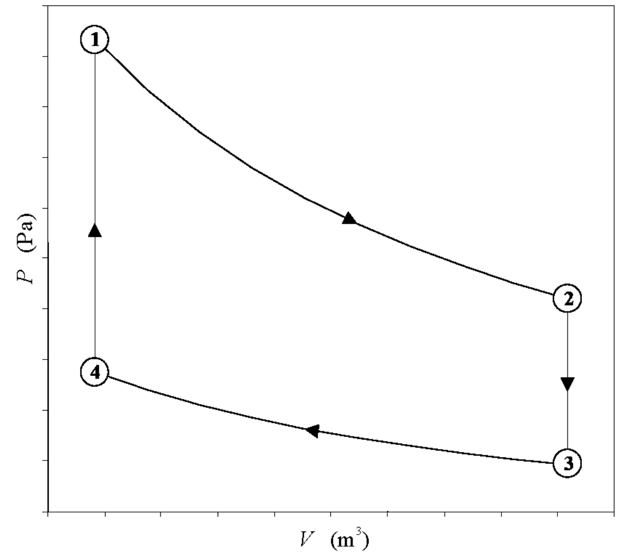

Figure 1. The ideal Stirling thermodynamic cycle (*P* vs *V*)

Based on the theoretical cycle dynamics, output work, *W* (J), is estimated by equation 1.

$$W = mR\ln\left(\frac{V_2}{V_1}\right)(T_H - T_C) \quad \text{(J)} \qquad (1)$$

where *m* is the gass mass (kg), *R* is the specific gas constant (J/kgK), V_1 is the gas volume at point 1 in Figure 1, V_2 is the gas volume at point 2 in Figure 1, T_H is the hot reservoir temperature (K), and T_C is the cold reservoir temperature (K). Equation 1 essentially calculates the area enclosed by the cycle shown in Figure 1.

The thermodynamic efficiency, η, of the Stirling cycle is approximated by equation 2.

$$\eta \approx \frac{(T_H - T_C)}{T_H} \qquad (2)$$

For temperature differentials as low as 30 K (where T_C = 300 K), the theoretical efficiency is around 9%. Given heat exchanger, regenerator, mechanical and electric generator losses, and sub-optimal gas flow dynamics, it is reasonable to consider that the practical system efficiency could be as low as 1% for such a temperature differential.

More comprehensive details of Stirling engine theory can be found in the literature review [7].

3. The Research Programme

If a Stirling engine-based power generation system with a temperature differential of around 30 K is to be potentially commercially viable, it should aim to achieve a power generation cost of around $0.07 UD per kWh, with an expected practical power conversion efficiency of no more than 1%. For this to be achieved a research programme is required that minimises system capital and running costs, yet maximises power conversion efficiency.

3.1 Intended Pathway

The intended research pathway is as follows;

1. Analyse power generation market constraints, and obtain research funding.
2. Design and fabricate small-scale prototypes to investigate key engine-generator parameters
3. Upscale final prototype to commercially acceptable power (greater than 50 kW per unit)
4. Set up a research pilot power plant that uses waste heat from an existing commercial geothermal power plant
5. Investigate local and global market viability.

The research programme is only in its initial stages whereby market and environmental constraints have been considered and initial engine-generator prototype designs are being created (elements of Step 1, and Step 2 in the research pathway). Another element of Step 1 that has been initiated are applications for funding of Step 2.

Steps 3 through 5 require an industry partner to deal with the large-scale aspects of the research. There are a number of companies in New Zealand that own geothermal power plants, and some of these have already expressed a substantial interest in the potential offered by this research programme.

Step 4 will answer a key component of the system's viability, in that the full heat exchanger requirements will be included in the implementation. It has been suggested in the literature that it is the cost of the heat exchanger components of such geothermal low temperature differential systems that constitute most of the capital cost of the system [6], which in turn directly relates to overall commercial viability. However, the publication specifically addresses organic Rankine cycle technology whereby the heat exchanger material is titanium, so it is unclear if the cost assumption is completely valid for the intended Stirling engine technology implementation which may not require the use of such expensive material.

3.2 Small-scale Prototyping

Initially, a range of small-scale system prototypes (around 1 kW output power) will be designed and built. This will allow the research team to have the greatest combined input into the system development, maximising utilization of the available skill base. This is expected to yield the best possible system given available resources.

3.2.1 Engine Configuration

Owing to its flexibility in physical layout, good heat exchanger properties for low temperature differentials, and low mechanical losses, the fundamental Stirling engine configuration that has been considered most appropriate for the intended application is the Gamma-type engine. These engines have a single power piston (used to extract mechanical power), and a large displacer piston (used to cycle the working gas through the regenerator between the heat exchangers).

In order to keep the overall volume of the engine to acceptable levels for a given output power, it is expected that the working gas of the engine will be pressurized (see equation 1, whereby the ideal gas law suggests that m increases if P increases, given the average volume and temperature remain the same). A pressure of up to 1 MPa has been assumed. This high pressure aspect has resulted in a novel engine-generator configuration that is conducive to pressurization and future optimisation of operating lifetime. A simple illustration of this configuration is given in Figure 2.

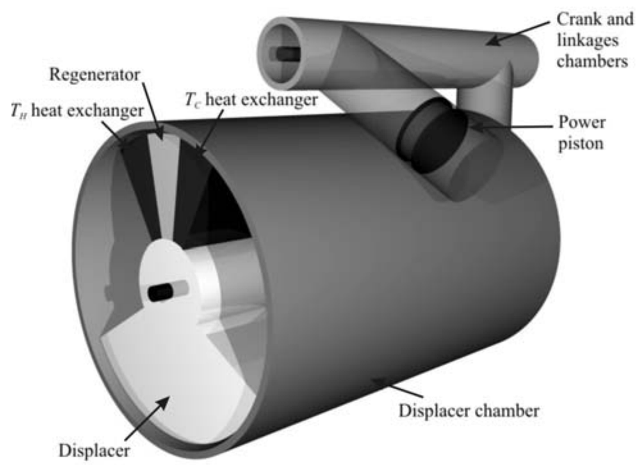

Figure 2. Novel Gamma-type Stirling engine/generator configuration where the displacer reciprocates on a central axis

3.2.2 Design and Modelling

The prototype designs are being carried out via two approaches. One approach uses a simple general design equation (which includes a figure known as the *Modified Beale Number*) that provides rough base-line parameters to create an engine design. The other approach uses software tools to generate computer models of engine designs.

The first approach uses the modified Beale number, B_M, as identified by equation 3 [7].

$$P_O = \frac{B_M V_S P_{av} f\left(T_H - T_C\right)}{\left(T_H + T_C\right)} \qquad \text{(W)} \qquad (3)$$

where P_O is the output power (W), V_S is the swept volume of the engine (m^3), P_{av} is the average engine pressure (Pa), and f is the engine rotational frequency (Hz). Assuming a 1 kW engine with a low temperature differential of 30 K (T_C = 300 K), a low B_M of just 0.1 [7], and a conservative f of 1 Hz (60 rpm), the engine requires a swept volume of around 200 litres at a pressure of approximately 1 MPa.

The second, software tool/simulation approach, has the potential to yield more accurate designs, with the ability to trial many different variations before fabrication is attempted. The primary software tool being used at this stage is the commercially available software called Sage™. This software is used by NASA for its Stirling machine development in aerospace applications [12, 13]. Initial Sage modelling carried out by our group, of a conventional alpha-type engine, has identified that the optimum phase angle between the gas movement through the heat-exchangers/regenerator and the power piston is not necessarily the conventional 90°. The implication here is that the prototype engine designs should include the ability to alter the phasing.

Sage is a very difficult software tool to use effectively as the parametric input values needed for the modelling require the user to have an extensive high-level knowledge of thermodynamics, mechanics, and materials. As such, a less complicated parametric simulation tool is also being developed as part of the research programme which is hoped to offer ease of use, real-time simulation/visualization and qualitative assessment, with accuracy somewhere between the rough B_M number approach, and the full Sage simulation tool. It is intended that this software will also be freely available as an educational tool.

3.2.3 Fabrication

As the first approach identified in Section 3.2.2 quickly yielded core design parameters, an initial research prototype has been chosen for fabrication based on those parameters. This design is shown in Figure 3. In this design, an important feature is that the displacer will be actuated by a stepper motor so that various displacer angular velocity profiles and phasing with respect to the power piston can be tested for their effects on output power (indicated by [7] and preliminary Sage modelling respectively to be of importance).

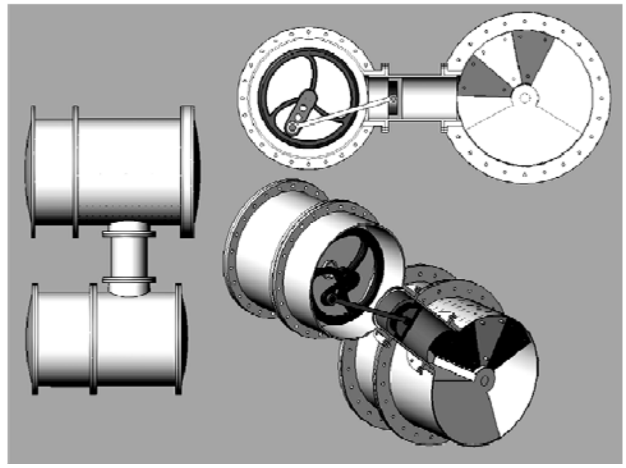

Figure 3. The initial research prototype small-scale Stirling engine/electric generator design currently being fabricated (note, the internal diameter of the displacer chamber is 800 mm)

Another important feature of the research prototype is that the regenerator element will be modular such that various materials and matrices can be trialled. Additionally, it will be possible to adjust the power piston stroke length in order to study the effects of varying compression ratio. Once these aspects of displacer velocity, phase angle, regenerator configuration, and compression ratio have been investigated, a second prototype will be built that has much less potential parameter variability, and focuses on using more cost effective construction materials and methods. Funding for the construction and testing of the research prototype has been secured (see Acknowledgements). To date, the pressure vessel materials, stepper motor, electric generator, sensors and control system electronics have all been purchased, and fabrication is underway.

As the upper temperature of the engine is only around 380 K, the displacer, crank and generator chambers, and even linkages can be entirely constructed from an appropriate plastic (such as polycarbonate). Being able to use such materials substantially lowers costs and overall engine weight, and improves the thermal insulation characteristics of the engine. In order to extend the engine operational lifetime, the power piston cylinder is to be lined with a honed steel tube. Side-loading on the power piston is a concern, and future prototype designs will look at implementing methods of reducing side-loading (such as a rhombic-drive arrangement). Another feature of this general configuration is the requirement of only three low-pressure seals (one for the bearing separating the displacer chamber from the stepper motor chamber, one for the power piston, and one for the seal around the displacer required to force the working gas through the heat exchangers and regenerator). Owing to the relatively low pressure differentials encountered within the closed Stirling engine system, engineering precision required for the displacer and power piston are very low compared to turbine-based or combustion-based mechanical systems, again resulting in lower fabrication and capital costs.

4. Conclusion

A new research programme aimed at developing a commercially viable electric power generation system utilizing low-grade (or waste) heat via Stirling engine technology has been described.

While Stirling engine technology may not be the only technology that can potentially address the defined application, it does appear to be well suited to the underlying requirements of cost versus power generation capacity.

Through progress from small scale prototype designs, modelling, and testing, to pilot plant implementation, the research pathway allows for the best utilization of available resources (including team skill-base), maximising the probability of a successful outcome.

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