Power Generation Using Low Temperature Differential Stirling Engine Technology

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ABSTRACT

A global paradigm shift in power generation towards sustainability and low environmental impact has driven associated research. Many possible power generation technologies exist, and no single technology will satisfy all (or even most) generation requirements. A Stirling engine based power generation system is being investigated for the potential economic use of low-grade (low enthalpy) heat (sub 100^0 C), especially from remote geothermal sources where the heat can not be used in direct applications.

A 500 W prototype Stirling engine system has been designed to begin determining the potential viability of using low enthalpy heat sources, where temperature differentials may be as low as 30^0 C, for practical power generation. The design methodology has utilised the modified Beale Number, preliminary numerical modelling, and fin-tube heat exchanger approximations. The result is a novel gamma-type engine configuration capable of being pressurized to 1 MPa. Being a research prototype, important engine parameters such as displacer piston velocity profile, piston phasing, and those associated with the regenerator matrix, are able to be varied in order to optimise engine performance.

1. INTRODUCTION

Most of the world's electric power generation is currently realized with fossil-fuel combustion (International Energy Agency, 2008). Unfortunately, this situation is not likely to substantially change for at least the next few decades, particularly when considering the planned construction of many hundreds of coal-fired power plants in China, India, (Chiefio, 2009) and the USA (National Energy Technology Laboratory, 2009). Even so, the growing awareness of fossil-fuel resource limitations, consideration of environmental impact, and observed increases in electric power usage, has led to research, development, and implementation of a wide range of sustainable, low environmental impact power generation technologies. The most common examples are hydro, wind, geothermal, tidal/wave, solar-thermal, and more arguably, photovoltaic, and nuclear.

Owing to its vast, globally-available, sustainable, and low environmental impact nature, geothermal-based power generation is set to become a much larger contributor than it currently is. However, owing to the relatively low temperatures involved (as compared to fired systems), plant efficiencies have been limited (to around 15%). Considering economic practicalities, this has limited the lower-range of geothermal temperatures that can be practically used. As both the cost of power generation rises, and geothermal power generation technology is refined, the lower-range of temperatures will extend downwards.

As the temperature differentials reduce, different technologies must be considered when trying to meet commercial requirements. Lower temperature differential (to around $100 – 200^0$ C) power generation has been primarily achieved with organic Rankine cycle technologies (Madhawa Hettiarachchi, et al., 2007). In commercial examples, economic viability is difficult to achieve as capital costs are high. There is some evidence that Stirling engine-based technology may offer some advantages over turbine-based systems in low temperature differential applications. This includes geothermal low-grade heat sources as suggested by Kolin, et al., (2000). These advantages are based on the ability to use low-cost, materials, fabrication methods, and maintenance regimens. As such, we have developed a research programme, looking at the potential practical viability of Stirling engine based power generation systems utilising low-grade heat sources, where temperature differentials down to around $40 – 100^0$ C may be considered.

One of our initial approaches is detailed here whereby a research engine has been designed to look at defining some of the more important parameters that will affect engine performance, such as the compression ratio, piston phasing, displacer velocity profile, and regenerator configuration. Results from this engine will help in the follow-on design that will attempt to address the critical cost-based factors associated with commercial viability.

2. BACKGROUND

2.1 Stirling Engine Fundamentals

Stirling engines are a practical type of heat engine, where a working gas is cyclically heated and cooled (without any phase-change). The subsequent heat flow through the engine is used to create work, usually via a power-piston system. No mass (gas) is transferred into or out of the engine. As the power piston is normally connected to a crank shaft, rotational motion is obtained and an electric generator can be coupled to this shaft. To function, Stirling engines only need a source and sink of heat, which makes them relatively versatile when considering possible sources of heat for a given application. This feature also means that if the heat source is sustainable and clean, the Stirling engine-based power generating system will be too.

While there are many different possible engine configurations, most (and especially low temperature differential variants) include the following fundamental components; the hot and cold heat exchangers, a regenerator (a heat storage element essential for high-efficiency operation), a power piston, and a working gas displacement piston (called the displacer) (Kongtragool, and Wongwises, 2003).

The ideal Stirling cycle *P-V* diagram is shown in Figure 1 (Kongtragool, and Wongwises, 2003), where *P* is the gas pressure (Pa), and *V* is the gas volume (m^3). The cycle direction shown is for motor operation (the reverse

direction would indicate heat-pump operation). Since the gas expansion (①→②) occurs at a higher pressure than the gas compression (③→④), there is net output work.

Net work output, W (J), is approximated by (1).

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

where m (kg) is the mass of the gas enclosed by the engine, R (J/kgK) is the specific gas constant, V_1 (m^3) is the enclosed gas volume at point 1 in Figure 1 (power piston at lowest position in its cylinder), V_2 (m^3) is the gas volume at point 2 in Figure 1 (power piston at highest point in its cylinder), T_H (K) is the temperature of the engine hot-side, and T_C (K) is the temperature of the engine cold-side.
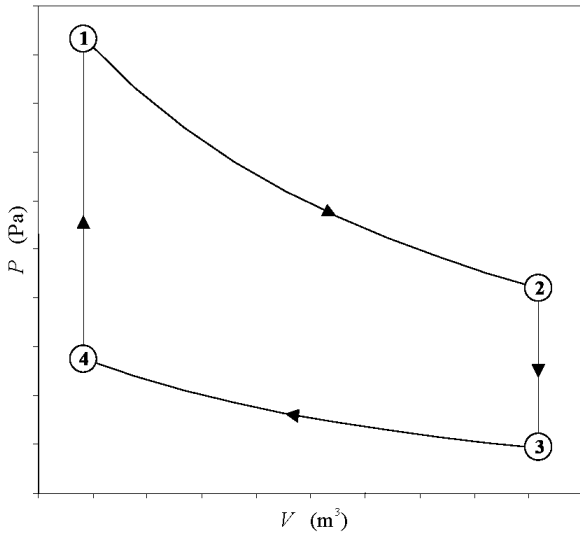

Figure 1: The ideal stirling cycle (P vs V).

The theoretical efficiency, η, of the Stirling cycle is estimated by (2).

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

Using (2), if the temperature differential is 40 K, where T_C = 293 K (20^0 C), the theoretical efficiency is only around 12%. Non-ideal operation associated with heat transfer, real gas behaviour, non-ideal piston and displacer motion, and both mechanical and electrical losses could reduce this efficiency by an order of magnitude.

More details of low temperature differential Stirling engines can be found in the literature review by Kongtragool, and Wongwises (2003).

2.2 Commercial Viability

The introduction of any technology into a given commercial market requires that technology to offer some value to the technology owners. While usually based on direct economic factors, in the power generation market value can also be added through consideration of increased sustainability and/or improved environmental impact. Increasingly, there are tariffs/taxes associated with sustainability factors such as carbon emissions and

environmental impact. It is also possible to extract value through the ability to promote the use of the sustainable technology, potentially leading to an increased market share.

In the case of implementing Stirling engine technology in the conversion of low-grade heat into electrical power, the inherent low thermodynamic efficiency associated with a low temperature differential will make it a difficult task to achieve a net positive commercial value. This is especially true if a given power generation market is reasonably competitive, as it is in most developed countries. However, owing to the low temperatures and specifically low engineering tolerances involved with Stirling engine technology, it will be possible to utilize low-cost materials (for example, plastics) and low-cost manufacturing methods which will help achieve the desired commercial viability. Also, optimising engine performance will be a very important goal for commercial viability. Initial engine operation research is concentrating on the effect of core parameters such as, the phasing between the power piston position and displacer, the displacer velocity profile, and the compression ratio.

3. RESEARCH ENGINE DESIGN

3.1 Initial Base Configuration

A substantial amount of available literature suggests that a gamma-type configuration is most appropriate for low temperature differential engines (reviewed by Kongtragool, and Wongwises, 2003). These engines have a power piston and a displacer. To increase power density in Stirling engines, the working gas can be pressurized (this has the effect of increasing heat transfer owing to the higher gas density). Keeping these criteria in mind, a novel gamma-type engine configuration that supports significant pressurization was conceived. This engine concept is shown in Figure 2.
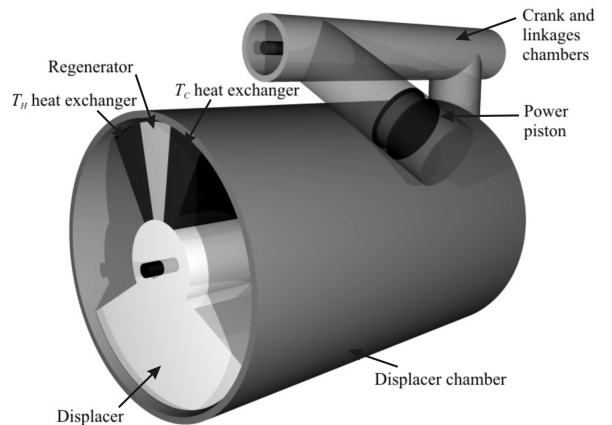

Figure 2: Novel gamma-type stirling engine/generator concept.

The set of connected cylinders offers a good geometry for pressure vessel design. The added consideration of minimizing the number of high pressure sliding seals resulted in the rotationally-reciprocating displacer concept.

To physically realise this concept, along with making provision for variation of the core parameters mentioned, and internalization of the electric generator, the initial practical configuration was developed as shown in Figure 3.

3.2 Design and Modelling

Owing to the expected amount of variation the research engine was to be subjected to, the initial design has extensively utilised approximations. The first approximation makes use of a simple first-order design equation based on a figure known as the Modified Beale Number. The modified Beale number, B_M, is identified by (3) (Kongtragool, and Wongwises, 2003).

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

where P_O is the output power (W), V_S is the swept volume of the power piston (cm^3), P_{av} is the average engine pressure (bar), and f is the engine rotational frequency (Hz). This equation was used to roughly determine a power piston size requirement, given our intended power output and pressure specifications.
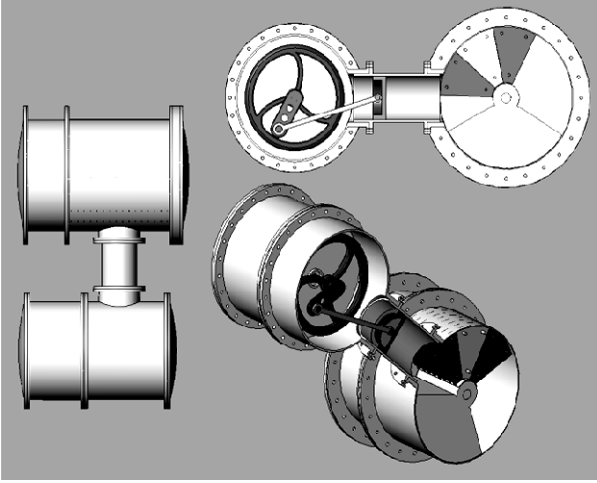

Figure 3: The initial practical research stirling engine/electric generator configuration.

The compression ratio of low temperature differential engines is usually very small. A method for approximating the ideal compression ratio which depends on the temperature difference (ΔT) of the engine in question was developed by Kolin (1991). The formula states:

$$V_R = \left(1 + \frac{\Delta T}{1100}\right) \quad (4)$$

where V_R is the engine compression ratio (defined as the ratio of V_2/V_1 as detailed in Section 2).

Heat exchanger design is a very involved process. Owing to the base configuration chosen, a fin-tube heat exchanger type was utilised. Using approximations provided by Hewitt (1998), it was possible to estimate the required surface area needed for the heat exchangers.

A software tool used to create computer models of engines (Sage^{TM}), and evidence provided by analysis of Phillips Stirling engine operation (Martini, 1983) were used to indicate what range of phase variation might be required to achieve optimum performance. Sage^{TM} is a parametric-based software tool, and is used by NASA for its Stirling machine development (Lewandowski. and Regan, 2004; Regan and Lewandowski, 2005).

4. RESULTS

In order to construct a research engine with available mechanical workshop and funding resources, initial research engine specifications were that it should have output power in the region of 500 W, and have the ability to be pressurized to 1 MPa (10 bar). Assuming an engine frequency of 2 Hz (slow owing to the low temperature differentials involved), a very modest B_M of just 0.1 (assuming non-ideal design parameters), and a temperature differential of 40 K (where T_C is 293 K), the swept volume of the power piston needs to be around 4 – 5 litres. Power piston volume was allowed to be varied up to 6 l. Following this, using equation 4, the main displacer chamber volume was calculated to be around 120 l.

Numerous approximations made about the heat exchanger performance (based on equations and methods detailed in Hewitt, 1998), suggest that with the volume of air being displaced at the specified frequency, pressure, and temperature differential, the required surface area for each of the two heat exchangers is conservatively 8 m^2.

Numerical modelling and evidence provided by actual Stirling engine operation (Martini, 1983) suggest that the optimal phasing between the power piston and displacer may vary by more than 20^0 away from the nominal 90^0 often used. Additionally, it is well recognised that the displacer motion (velocity profile) is not ideally sinusoidal (Kongtragool, and Wongwises, 2003).

With these design figures obtained, materials were then sourced to physically realise the engine construction based on the design shown in Figure 3. Honed steel tube to be used for the power piston chamber could only be sourced with a maximum diameter of 228 mm. The stroke length required to achieve 6 l is 150 mm, so the crank and piston connecting rod are variable to achieve a stroke length between 100 – 150mm. The nearest available displacer chamber to meet the pressurization and compression ratio requirements was 800 mm diameter, 7.5mm thick, steel steam pipe. This gives a 130 l gas displacement volume (assuming one third of the total chamber volume is occupied by the displacer – see Figure 3).

With 130 l available for both heat exchangers and the regenerator (one third of the total available chamber volume), each of the heat exchangers were made to occupy one third of that volume, leaving one third for the regenerator. Aluminium plate, 1mm thick was used for the heat exchanger fins, and the 8 m^2 was satisfied by using 150 fins separated by 3mm each.

The displacer chamber has been lined on all surfaces with 3 mm thick high density polypropylene sheet to act as a smooth sealing surface, and to restrict some thermal losses through the chamber wall. The displacer has been constructed primarily from polyurethane foam to reduce its mass, and is to be actuated by two stepper motors so that various displacer angular velocity profiles and phasing with respect to the power piston can be tested for their effects on output power. Two motors are required to develop the torque needed for high displacer acceleration. Displacer gas-sealing is low pressure (in the order of just 50 kPa) and achieved with engineering felt (100% wool).

The power piston has been fabricated out of aluminium to keep its mass as small as possible which acts to minimize flywheel mass and counter-weighting. This will help reduce mechanical wear of moving components. The

length of the piston connecting rod and crankshaft offset is adjustable so that the desired compression ratio can be achieved with minimum unswept gas volume (known as dead-space). Power piston sealing is again achieved with engineering felt which requires no added lubrication (lubricants can be problematic with their tendency to coat heat exchanger surfaces).

A permanent magnet, 3-phase, 1kW low-speed generator has been acquired. This generator has been designed for wind turbine applications, and has a peak efficiency at around 600 rpm. A 10:1 gearing between the engine crank and generator has been added to match expected engine speed with generator peak efficiency speed.

Another important feature of the research prototype is that the regenerator element will be modular such that various materials and matrices can be trialled. The current state of engine fabrication is shown in Figure 4.

Figure 4: Photographs of the initial research engine/electric generator design currently being fabricated. The main pressure chambers are shown on the left, and the power piston is shown on the right.

CONCLUSIONS

A research low temperature differential Stirling engine based power generation system has been designed and is currently under construction. The aim is to identify the effect of certain engine parameters on engine performance and use the results to help design a potentially commercially viable power generation system that is capable of using low-grade heat from a number of sources.

ACKNOWLEDGEMENT

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