Solar Powered Stirling Engine

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Abstract *- The aim of this project is to design, build, and test a Stirling engine capable of generating between 200-500 watts of electricity. Here, we are using parabolic dish reflectors to concentrate the solar rays on the hot end of the engine. They have the highest heat-electricity conversion efficiencies among all designs (up to 30 %). The size of the concentrator is determined by its engine. A Stirling system's concentrator with a nominal maximum direct normal solar insolation of 1000 W/m2 and a 25-kW capacity of several designs were studied before settling on an alpha type configuration of the engine. The heater, cooler, regenerator, flywheel and piping systems have been designed, will be analysed and constructed. Instrumentation was built into the engine to record temperatures throughout the assembly. Several tests were performed on the engine in order to improve its running efficiency, and critical problem areas were isolated and addressed.*

Keywords - Heinrici Stirling engine, Schmidt, adiabatic, simple analysis, five volume approach, renewable energy, waste heat recovery

I. INTRODUCTION

The per capita consumption of the earth's non-renewable energy sources, which includes gas, petroleum and coal, is related in one way or the other to the economical wealth of the society or country involved. Three-quarters of mankind's carbon dioxide production is due to the consumption of non-renewable energy sources .The depletion of these non-renewable energy sources has become a highlighted focus point for scientists throughout the world. Studies to improve the efficiencies of machines (like automobile engines, power generation plants etc.) fuelled by non-renewable energy sources have become a highly specialized field of interest for manufacturers. The consumers' demand for "green products" has increased due to global warming and also lead to an increased effort to stop or decrease pollution.[1]

Renewable energy in the form of solar electricity generators for remote applications is another possible field of application of Stirling engines. Van Heerden (2003) studied a solar-dish Stirling system and found that the technology is not mature enough at this point in time mainly due to lack of investment in product development, but that it is capable of delivering an average solar-to-electricity conversion efficiency of 24%, which is higher than the current photo-voltaic systems.[2] Waste heat recovery systems form a substantial part of the methods developed to increase the efficiency of various systems. For the past five decades, research was focused on large energy system applications and ground breaking work was done in this field. Lotun (2001) designed and evaluated a small scale waste heat recovery system for automotive applications using steam technology. He concluded that there is a need for further investigation into waste heat recovery systems for application on smaller scale automobile internal combustion (IC) engines.[3] BMW Research engineers in Munich, Germany, have utilized steam technology to harness the wasted heat energy in the exhaust systems of their cars (Sapa-dpa, 2006). A combination of modern technology and older steam technology are used to absorb the waste energy, and this is then converted to mechanical energy used to increase vehicle power output. [4]

This paper focuses on the design of a Stirling engine for distributed solar thermal applications. In particular, we design for the low temperature deferential that is attainable with distributed solar collectors and the low cost that is required to be competitive in this space. We will describe how these considerations drive the core design, the methodology for improving the design, and summarize progress made in fabrication of the engine for experimentation. Stirling engines can have broad signicance and technological advantages for distributed renewable energy applications. A key advantage of a solar thermal system is that they can incorporate thermal energy storage in a cost-effective manner. In addition, Stirling engine systems are fuel-flexible with respect to the source of thermal energy and unprocessed waste heat can be harvested for CHP purposes as well. The ability to extract unconverted thermal energy for waste heat applications greatly improves the overall thermal efficiency of the system. [5]

A short introduction to the functioning of Stirling engines follows to contextualise the content presented here. Stirling engines are combusted externally and modern versions of this engine have a closed internal gas cycle. The 'hot-air' engine, first so referred to by the Rev. Robert Stirling, was renamed after its inventor in the early parts of the twentieth century, since it was found that gasses with lighter molecular weight such as helium and hydrogen were superior to air, and the title Stirling engine was therefore considered to be a more appropriate description than ‘hot-air’. [6] One of the well-known advantages of Stirling machines is their capability to operate on any form of thermal energy. This implies that Stirling technology could be applied in either the solar powered or waste heat recovery sectors. Market competitiveness for Stirling engines in the above mentioned fields is a topic being exploited by various research groups, as mentioned by Morrison (1999), and is an indication of the relevance and applicability of the use of this ‘old technology’ to solve modern problems regarding the current rate of fossil fuel depletion.[7]

In a beta configuration similar to the engine used in this study, two pistons are present, namely the displacer and the power piston as shown in Figure 1.Two variable volumes, namely the expansion and compression spaces and three fixes volumes, namely the hot Side heat exchanger (Heater), the cold side heat exchanger (Cooler) and the regenerator constitutes the rest of the engine.

The chief aim of this design manual is to teach people how to design Stirling engines, particularly those aspects that are unique to Stirling engines. To this end in Section 3, two engines have performance data and all pertinent dimensions given (fully described). In Section 4 automotive scale engines, for which only some information is available, are presented. Section 5 is the heart of the report. All design methods are reviewed. A full list of references on Stirling engines to April 1980 is given in Section 7. Sections 8 and 9 are personal and corporate author indices to the references which are arranged according to year of publication. Section 10 is a directory of people and companies active in Stirling engines. Appendix a gives all the property values for the materials most commonly used in Stirling engine design. The units employed are international units because of the worldwide character of Stirling engine development. It gives the nomenclature for the body of the report. The nomenclature was changed from the first edition to fit almost all computers.[4]

The selected engine design for this application is at an operating point of 20Hz with 30 bar pressurized air as the working fluid. Operating at 20Hz provides good balance between output power and losses, and also allows the engine to interface with a 6-pole alternator to achieve an electrical frequency of 60Hz, allowing direct grid connection if desired. A gamma configuration is chosen as a natural geometrics with the heat exchangers and to reduce sealing challenges. The rated power output of the engine was designed at 2.5 kW, a level appropriate for satisfying the majority of demands in small buildings, residential or commercial. A kinematic piston design was chosen to simplify the design with respect to the dynamics of the system and the fabrication process.

Table1. Design Parameters

Design Quantity	Value
Nominal Power Output	65 W
Thermal Electric Efficiency	21%
Fraction of Carnot Efficiency	65%
Hot side Temperature	180˚c
Cold side Temperature	30˚c
Working Gas (Air) Pressure	25 Bar
Engine Frequency	20 Hz
Electrical Output	60 Hz, 3ϕ
Regenerator Effectiveness	0.9967
Piston Swept Volume	2.2 L

The heat exchangers were optimized for the trade_ between heat transfer electiveness and own frictional losses. The objective is to provide a high conductivity, high cross-sectional area thermal path for input heat to own. The large total open area presented to the gas own is designed to lower own resistance while providing for low temperature drops in the thermal path.

Due to the relatively low hot-side temperatures as compared to traditional Stirling engine applications, high overall efficiency is harder to achieve and requires careful design in maximizing heat transfer capabilities of the heat exchangers in order to reduce temperature drops. Careful optimization of various loss components versus metrics such as output power is an important part of the design process. The Stirling engine system as described was designed with these considerations in mind. Furthermore, the engine must be designed at low cost to be competitive for energy applications. This requires component geometries and materials to be designed to simplify fabrication and utilize low-cost mate-rails and mass-produced components. The overall engine geometry and components such as the regenerator, heat exchanger, and mechanical components were designed to meet these constraints. The Stirling engine as designed is expected to achieve relatively high performance as a fraction of the Carnot efficiency and have low-cost in fabrication in mass production. We will be conducting experimentation to verify the design performance in the near future.[8]

II. IDENTIFY, RESEARCH AND COLLECT IDEA

Stirling engines have found various applications as energy converters for highly-concentrated solar thermal plants, coolers and heat pumps, and other specialized applications such as space light. This design differs from typical applications in that we design for lower temperature differentials and that low cost of materials and fabrication is a priority. In contrast, size and mass are of lower importance. This application area has been the focus of less research in the literature and warrants additional investigation. In particular, as renewable energy and energy efficiency have become more critical areas of research in recent years, the design and development of a Stirling engine system that can be commercialized for thermal energy generation applications and as a combined heat and power system would add significant value. Other sections in this design manual describe what is going on in Stirling engines today. This section outlines the mathematics behind the Stirling engine process itself. Stirling engine cycle analysis will first be discussed. This subsection discusses what really goes on inside a Stirling engine starting out with the simplest assumptions and then progressing to more and more real Fistic assumptions. This subsection is the basis for the subsequent three subsections that discuss first-order design methods, second order design methods and third-order design methods. First-order design methods start with limited information and calculate power output and efficiency for a particular size engine. Use of the first-order method assumes that others have or will actually design the Stirling engine. First-order analysis is for systems engineers who want to quickly get a feeling for the capability of a Stirling engine. Second-order design methods take all aspects of the Stirling engine into account and are for those who intend to design a new Stirling engine. A wide spectrum of methods falls under the heading of second-order analysis. In second-order analysis it is assumed that a relatively simple Stirling engine cycle analysis can be used to calculate the basic power output and heat input. It further assumes that various power losses can be deducted from the power output. These power losses are assumed to be calculable by simple formulas and do not interact with other processes. It is further assumed that the separate heat losses can be calculated by simple formula and are addable to the basic heat input. It is further assumed that each one of these heat losses is independent of the others and there is no interaction. The engine is simulated by dividing it up into a number of sections, called nodes. Equations are written which express the conservation of heat, mass, momentum for each node. These equations are programmed into a digital computer and the engine is simulated starting with an arbitrary initial condition and going until the cycle repeats with a desired degree of accuracy. For those designers who are embarking on the original design of a Stirling engine, the choice must be made between second- and third-order design methods. Generally, as the complexity and therefore the cost of computation increases, the accuracy and general applicability of the result should also increase One cannot draw a graph of computation costs versus accuracy of result and place the different computation methods upon it.

III. LOSSES IN A STIRLING ENGINE

The energy losses in a Stirling engine are due to the thermodynamic and the mechanical processes. Compression and expansion are not adiabatic. The exchangers are not ideal since the pressure drops in the engine and the losses of heat in the exchangers exist. To accurately predict power and efficiency requires an understanding of the principle parasitic loss mechanisms.

A. energy dissipation by pressure drops in heat exchangers

Pressure drops due to friction and to area changes in heat exchangers is given by, G is working gas mass flow, d is the hydraulic diameter, r is gas density, V is volume and fr is the Reynolds friction factor. The internal heat generation which occurs when the gas is forced to flow against the frictional drag force, m is the mass flow rate.

B. energy lost by the internal conduction

Energy lost due to the internal thermal conductivity between the hot parts and the cold parts of the engine through the exchangers are taken into account. These losses are directly proportional to the temperature difference at the ends of the exchanger.

C. energy lost by external conduction

Energy lost by external conduction is considered in the regenerator which is not adiabatic. These losses are specified by the regenerator adiabatic coefficient, definite as the report between the heat given up in the regenerator by the working gas at its passage towards the compression space and the heat received in the regenerator by the working gas at its passage towards the expansion space. So the energy stored by the regenerator at the time of the passage of gas from the expansion space to the compression space is not completely restored with this gas at the time of its return.

D. energy lost by shuttle effect

Shuttling the displacer between hot and cold spaces within a machine introduces another mechanism for transferring heat from a hot to a cold space. Thus an important thermal effect appears in Stirling engines called ‘Shuttle heat transfer’ having the effect of increasing the apparent thermal conductance loss. The displacer absorbs a quantity of heat from the hot source and restores it to the cold source.[9]

IV. STUDIES AND FINDINGS

A. Bits and Pieces together

The development of the framework helped to support complex system level recommendations in Stirling engines design for the two intended WHR and CHP applications. Alpha-type Stirling engine designs are advantageous over beta and gamma to minimize capital cost while generating more electricity at the same time. Nevertheless, the framework shows how alpha-type engines are not advantageous in all ranges of engine output powers. Each engine type appears to be power-cost Pareto optimal for a specific output power range. It is therefore important to know early in the design the power output range of interest to the customers to be targeted. Another important conclusion of the engine design. This conclusion is valid in almost the entirety of the range of calculated efficiencies, with the exception for low efficiency – low cost engine design, where gamma engines hold an advantage. Wide commercialization of low power – low cost gamma engines study conducted the beta-type engines feature advantages in terms of maximizing efficiency while minimizing capital cost of already in place in industry is an empirical proof for advantageous architectures of gamma type engines for low power applications (such as model toys and tool kits). Reference of already accomplished work as a starting building block of its paper.

B. Use of Simulation software

This analysis was folded into an optimization routine that scanned over the parameter space and refined design parameters to improve design performance. This step was key in guiding the final design process. Key parameters that were explored include regenerator geometry, heat exchanger meshes, and displacer and Power piston strokes. Example graphs used during the optimization process are displayed in Figure 1 and 2. An important conclusion drawn through this process is that the most significant design tradeoff_ is between increasing regenerator effectiveness by increasing the length of the regenerator stack, and the increased gas

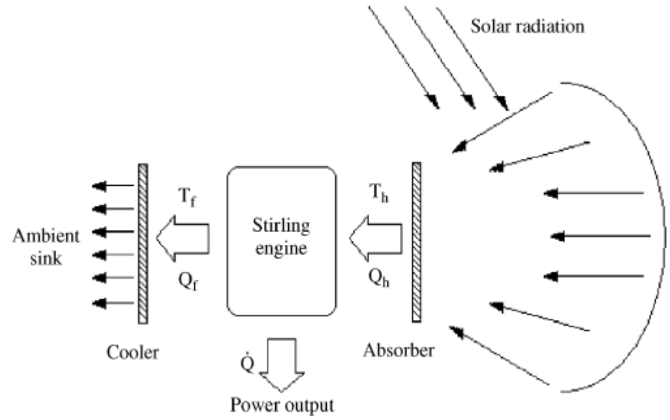

Fig. 1. Schematic diagram of solar-powered Stirling engine.

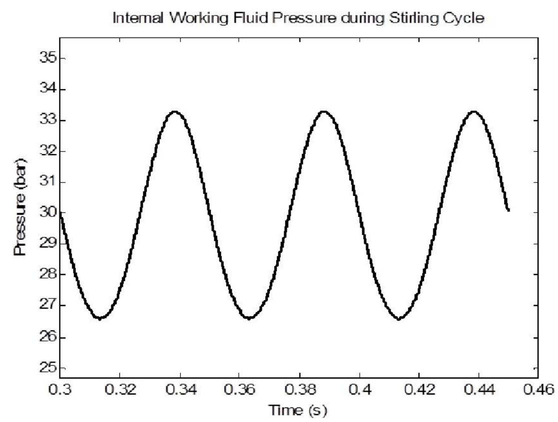

Fig. 2. Internal pressure waveform from adiabatic model.

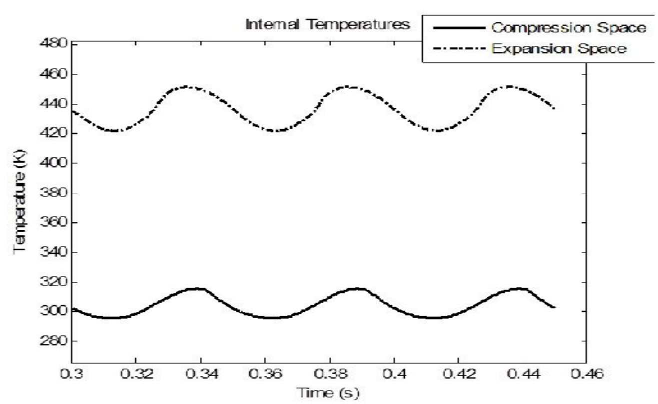

Fig. 3. Temperature waveforms from adiabatic model

V. CONCLUSION

Throughout the process of designing, manufacturing, and testing our Stirling engine, we have uncovered many new insights, problems and solutions concerning the different portions of the engine. We applied our knowledge of thermodynamics to the design of the engine, and developed formulas to predict its power output at different temperature differentials. Overcoming many engineering and design challenges, we were able to build the engine and include the tools necessary to record data inside the engine. From the numerical analysis, we found that our engine is achieving a power output of only 65.2 Watts. This was not large enough to keep the engine in motion after applying an initial pull start. Changes necessary to increase the work output of the engine would include pressurizing the system, as the value for the pressure inside the system has a linear correlation to the work output. Increasing the pressure inside the system would allow the gasses inside to exhibit incompressible flow, and improve mass transfer between the hot and cold sides of the engine. If the machine is pressurized however, there is a risk of explosive decompression, and a pressure gauge becomes necessary to monitor the system. Another route to pursue in order to improve the engine is to reduce the dead volume. The calculated dead volume inside the system of 176.32 cm3 can be decreased by changing the size and shapes of the pipes, heater and cooler. The shape of the heater currently works but is not ideal for the flow of the gasses from inside the hot piston to the piping connecting to the cool side of the engine.

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