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STUDY, MODELLING AND ASSEMBLEY OF A STIRLING ENGINE

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***Abstract**: The Stirling engine is used to remove the electrical load from the internal combustion engine and thereby increasing the fuel efficiency of the engine. The Stirling engine is powered by the temperature difference at the radiator ends. Alternator is used to supply power to all the electrical and electronic appliances in the automobile. At present, the alternator's rotor is rotated by engine's shaft through belt. Now the Stirling engine is used to rotate the rotor of alternator. This paper is to show the increase in efficiency of an engine using Stirling engine. Worldwide attempts are being made to increase the use of our renewable energy sources as well as to use our current fossil fuel energy sources more efficiently. Waste heat recovery forms a substantial part of the latter and is the focus of this project. Stirling technology finds application in both the renewable energy sector and in waste heat recovery. Investigating the applicability of Stirling engines in the above-mentioned fields is relevant to develop\ more efficient external combustion units as well as to utilize our renewable energy sources. Developing a design analysis and synthesis tool capable of optimizing Stirling powered units forms the main objective of this project.*

I. INTRODUCTION

The Stirling motor - a heat engine which converts heat into work - is the second oldest heat engine. It has many positive properties, e.g. it only needs a temperature difference to work, irrespective of whether the difference is achieved by solar heating or conventional fuel. This makes it very flexible and beneficial to the environment. discuss the thermodynamic principles necessary for the understanding of the operating of the Stirling engines. Taking into account that we have built a -Stirling motor in this laboratory, The objective of this report is to provide a assessment of Stirling engine systems covering technical trends, commercialization status, and economic feasibility. The assessment includes free-piston and kinematic Stirling engine designs of commercially available and emerging technologies for distributed resource (DR) applications.

History:

The original Stirling engine was designed and developed by Reverend Dr Robert Stirling, a fantastic engineer and a reverend with the church. At that time it was called a ‘hot air’ engine, no one knows when the term Sterling engine became widely accepted. Stirling received the original patent in 1816, and had his first engine built and working as a water pump in a quarry in 1818, and later powering an iron foundry in 1845. Stirling was trying to come up with an alternative to the current steam engine and later the internal combustion engine.

The downside to the steam engine is the necessity to use boilers, which have the off chance to explode. Stirling sought to build an equivalent engine that would not have such a potentially deadly side effect. Although the Stirling engine eventually lost to the steam engine for popular support, it continues to be useful. The Stirling engine produces a higher efficiency rate than either the steam or internal combustion engines. However, it must run at very high temperatures to achieve maximum power output and efficiency.

This limits its commercial utility and contributed to its decline

Stirling engine Stirling engine is a heat engine operating by cyclic compression and expansion of air or other gas, the *working fluid*, at different temperature levels such that there is a net conversion of heat energy to mechanical work. Or more specifically, a closed-cycle regenerative heat engine with a permanently gaseous working fluid, where *closed-cycle* is defined as a thermodynamic system in which the working fluid is permanently contained within the system, and *regenerative* describes the use of a specific type of internal heat exchanger and thermal store, known as the *regenerator*. It is the inclusion of a re-generator that differentiates the Stirling engine from other closed cycle hot air engines. Originally conceived in 1816 as an industrial prime mover to rival the steam engine, its practical use was largely confined to low-power domestic applications for over a century.

The Stirling engine is noted for its high efficiency compared to steam engines,[4] quiet operation, and the ease with which it can use almost any heat source. This compatibility with alternative and renewable energy sources has become increasingly significant as the price of conventional fuels rises, and also in light of concerns such as peak oil and climate change. This engine is currently exciting interest as the core component of micro combined heat and power (CHP) units, in which it is more efficient and safer than a comparable steam engine

Like the steam engine, the Stirling engine is traditionally classified as an external combustion engine, as all heat transfers to and from the working fluid take place through a solid boundary (heat exchange) thus isolating the combustion process and any contaminants it may produce from the working parts of the engine. This contrasts with an internal combustion engine where heat input is by combustion of a fuel within the body of the working fluid.

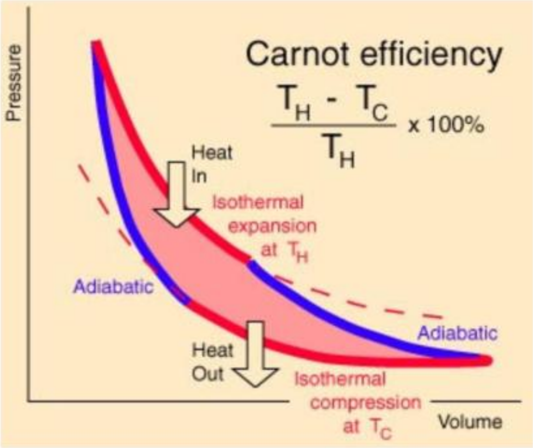
There are many possible implementations of the Stirling engine most of which fall into the category of reciprocating piston engine

Functional description

The engine is designed so that the working gas is generally compressed in the colder portion of the engine and expanded in the hotter portion resulting in a net conversion of heat into work.[2] An internal Regenerative heat exchanger increases the Stirling engine's thermal efficiency compared to simpler hot air engines lacking this feature

Operation:

In general, engines and heat engines work very similarly. They have involved the expansion of gas to power a piston to do work on the engine drive shaft. Both heat engines and internal combustion engines use this system. When the gas inside the piston is heated, it expands till its temperature drops to the lowers temperature used by the engine. This pushes the piston and does work on the system. Then the cool gas contracts and the piston retracts.



The Carnot Cycle is a graph of pressure and volume inside a piston of a theoretical heat engine that is the most efficient that is physically possible between the desired temperatures.

It involves four stages:
heating of the gas, adiabatic expansion of the gas, cooling of the gas, and adiabatic compression of the gas.
The Stirling engine is one of the few real world heat engines that come close to the theoretical efficiency of a Carnot engine.
A Stirling engine system has at least one heat source, one heat sink and up to five[heat exchanges. Some types may combine or dispense with some of these

Applications and Advantages

Because of its nature to exclude the heating as an external part, the whole system is closed and contains no valves and is therefore low-maintenance, silent and non-vibrating. It does not need oil and as a result no refilling. The temperature difference can also be achieved by environmental friendly fuels or even by solar energy, which is used in solar power plants and block heat power plants. And the only theoretical limit to its efficiency is the thermodynamic limit. It has been designed for the use in submarines and ships, e.g. by the Swedish company Kockums. By putting work into the machine, it can be and is used as a cooling device without the need for a cooling agent in cryogenics. One disadvantage is that the engine runs best continuously, thus making fast power changes impossible. Besides, the bad power to weight ratio of most types is a burden for mobile applications.

Heat source

Point focus parabolic mirror with Stirling engine at its center and its solar tracker at Plataforma Solar de Almería (PSA) in Spain

The heat source may be provided by the combustion of a fuel and, since the combustion products do not mix with the working fluid and hence do not come into contact with the internal parts of the engine, a Stirling engine can run on fuels that would damage other types of engines' internals, such as landfill gas which contains siloxane. Other suitable heat sources include concentrated solar energy, geothermal energy, nuclear energy, waste heat and bioenergy. If solar power is used as a heat source, regular solar mirrors and solar dishes may be utilized. The use of Fresnel lenses and mirrors has also been advocated, for example in planetary surface exploration.[9] Solar powered Stirling engines are increasingly popular as they offer an environmentally sound option for producing power while some designs are economically attractive in development projects.

II The function of the Stirling motor

In order to be able to discuss all features of the Stirling engine, I would like to give a short repetition about the Carnot process. The following sub-chapter The Ideal Stirling Process should give an overview about the mechanism in the Stirling engine, which results then in the real Stirling process.

A little bit of thermodynamics

In this sub-chapter I want to present some terms and equation that will be needed.
Work is defined as an amount of energy obtained or needed to change a system relative to a force, e.g. the gravitational force where as heat is the amount of energy in a system resulting from its thermodynamic nature.

The ideal gas equation $pV = nRT$

is valid for an ideal gas, where the atoms do not occupy any volume and they interact only through elastic collisions. p stands for the pressure, V for the volume the gas occupies, n stands for the number of moles, R is the molar gas constant and T is the temperature. From now on, we will arbitrarily discuss a gas with one mol, which allows us to set n equal to one.
The 1st law of thermodynamics describes the conservation of energy:

$$dQ = dU - dW$$

where dQ represents the amount of heat transferred to the system, dU describes the change of the internal energy of the system resulting in a change of temperature and dW stands for the work that is done by the system. There are several processes with different behaviour, if you keep one parameter of the system fixed. In an isotherm process, the temperature T of the gas remains constant, such that dQ = dW and pV = const.

For the chorister process, the volume V is constant and dQ = dU, while dU = dW and TV −1 = const. has to be used for the adiabatic process (no heat transfer dQ = 0).

The Carnot process

It is fundamental to understand the Carnot process when discussing heat engines. Introduced 1824 by Nicolas L´Leonard Sadi Carnot in his work R´reflexion surly puissance mo-trice du feu et surliness machines pro-pres ´developer puissance, it is a process which does not change the total entropy S and is therefore reversible. That is the reason, why in reality, one can only achieve approximations to the Carnot process. The (periodically working) Carnot machine is attached to a heat-bath and a cold-sink and contains of a piston in a cylinder. The heat-bath and the cold-sink have an infinite capacity, meaning that they can absorb or emit any amount of heat without ever changing their temperature. The Carnot

process contains four steps:

1. an isotherm expansion at high temperature Th
2. an adiabatic expansion from Th to a lower temperature Tc
3. an isotherm compression at low temperature Tc and
4.an adiabatic compression form Tc to high temperature Th

During the first step, a heat amount Qh is taken from the heat-bath and the corresponding work W1 = RTh ln(Vb/Va) is done by the engine.

In the adiabatic, second step, the work W2 = cv(Th − Tc) is done by the engine.

Then in the third step, the heat Qc is transferred from the engine to the cold-sink and the work

W3 = RTc ln(Vc/Vd) is done on the engine.

During the fourth step, the work W4 = cv(Tc −Th) is done on the engine.

From the adiabatic process, we see that Vb/Va= Vc/Vd, resulting in W1 = W3.

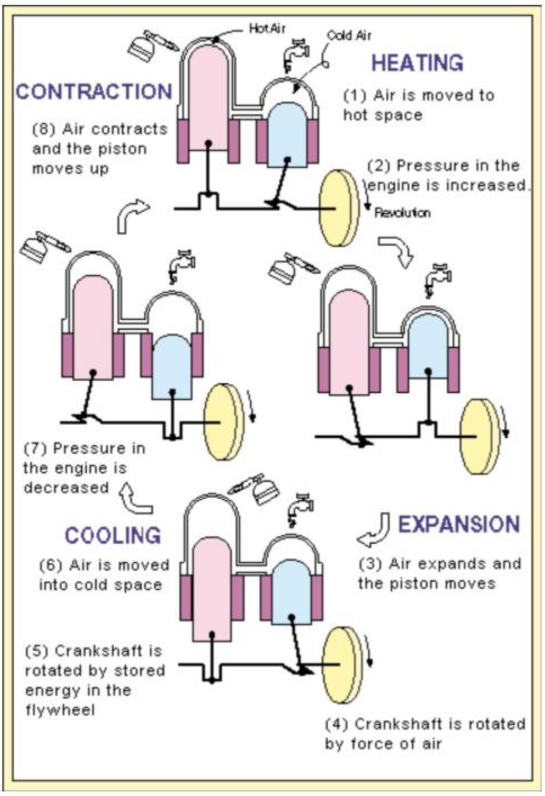
It follows that Qh − Qc = W, where

W = R(Th − Tc) ln(Vb/Va)

is the total work that is done by the engine during the four steps.

The degree of efficiency n = W/Q1 can be written as

$$\eta = \frac{T_h - T_c}{T_h}$$



Various Free-Piston Stirling Configurations... F."free cylinder", G. Fluidyne, H. "double-acting" Stirling (typically 4 cylinders)

"Free piston" Stirling engines include those with liquid pistons and those with diaphragms as pistons. In a "free piston" device, energy may be added or removed by an electrical linear alternator, pump or other coaxial device. This avoids the need for a linkage, and reduces the number of moving parts. In some designs, friction and wear are nearly eliminated by the use of non-contact gas bearings or very precise suspension through planar springs.

Four basic steps in the cycle of a “Free piston” Stirling engine,

1. The power piston is pushed outwards by the expanding gas thus doing work. Gravity plays no role in the cycle.
2. The gas volume in the engine increases and therefore the pressure reduces, which will cause a pressure difference across the displace rod to force the displace towards the hot end. When the displace moves the piston is almost stationary and therefore the gas volume is almost constant. This step results in the constant volume cooling process which reduces the pressure of the gas.
3. The reduced pressure now arrests the outward motion of the piston and it begins to accelerate towards the hot end again and by its own inertia, compresses the now cold

gas which is mainly in the cold space.

4. As the pressure increases, a point is reached where the pressure differential across the displace rod becomes large enough to begin to push the displace rod (and therefore also the displace) towards the piston and thereby collapsing the cold space and transferring the cold, compressed gas towards the hot side in an almost constant volume process. As the gas arrives in the hot side the pressure increases and begins to move the piston outwards to initiate the expansion step as explained in (1).

In the early 1960s, W.T. Beale invented a free piston version of the Stirling engine in order to overcome the difficulty of lubricating the crank mechanism.[19] While the invention of the basic free piston Stirling engine is generally attributed to Beale, independent inventions of similar types of engines were made by E.H. Cooke-Scarborough and C. West at the Harwell Laboratories of the UKAERE.[20] G.M. Benson also made important early contributions and patented many novel free-piston configurations.[21]

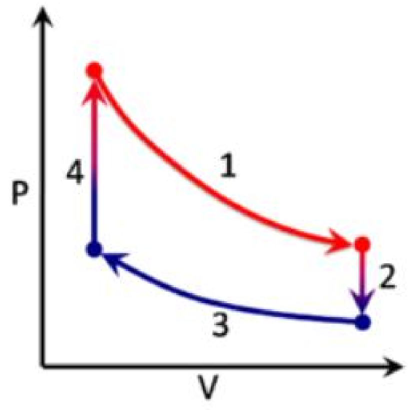
What appears to be the first mention of a Stirling cycle machine using freely moving components is a British patent disclosure in 1876.[22] This machine was envisaged as a refrigerator (i.e., the *reversed* Stirling cycle). The first consumer product to utilize a free piston Stirling device was a portable refrigerator manufactured by Twinbird Corporation of Japan and offered in the US by Coleman in 2004.

Thermoplastic cycle

Thermoplastic devices are very different from Stirling devices, although the individual path travelled by each working gas molecule does follow a real Stirling cycle. These devices include the thermoacoustic engine and thermoacoustic refrigerator. High-amplitude acoustic standing waves cause compression and expansion analogous to a Stirling power piston, while out-of-phase acoustic travelling waves cause displacement along a temperature gradient, analogous to a Stirling displace piston. Thus a thermoplastic device typically does not have a displace, as found in a beta or gamma Stirling.

Theory

Main article: Stirling cycle



A pressure/volume graph of the idealized Stirling cycle

The idealized Stirling cycle consists of four thermodynamic processes acting on the working fluid:

1. Isothermal Expansion. The expansion-space and associated heat exchange are maintained at a constant high temperature, and the gas undergoes near-isotherm expansion absorbing heat from the hot source.
2. Constant-Volume (known as isovolumetric or isochoric) heat-removal. The gas is passed through the regenerator, where it cools transferring heat to the re-generator for use in the next cycle.
3. Isothermal Compression. The compression space and associated heat exchange are maintained at a constant low temperature so the gas undergoes near-isotherm compression rejecting heat to the cold sink
4. Constant-Volume (known as isovolumetric or isochoric) heat-addition. The gas passes back through the re-generator where it recovers much of the heat transferred in 2, heating up on its way to the expansion space.

Theoretical thermal efficiency equals that of the hypothetical Carnot cycle - i.e. the highest efficiency attainable by any heat engine. However, though it is useful for illustrating general principles, the text book cycle is a long way from representing what is actually going on inside a practical Stirling engine and should only be regarded as a starting point for analysis. In fact it has been argued that its indiscriminate use in many standard books on engineering thermodynamics has done a disservice to the study of Stirling engines in general.

III Analysis

Comparison with internal combustion engines

In contrast to internal combustion engines, Stirling engines have the potential to use renewable heat sources more easily, to be quieter, and to be more reliable with lower maintenance. They are preferred for applications that value these unique advantages, particularly if the cost per unit energy generated ($/kWh) is more important than the capital cost per unit power ($/kW). On this basis, Stirling engines are cost competitive up to about 100 kW.

Compared to an internal combustion engine of the same power rating, Stirling engines currently have a higher capital cost and are usually larger and heavier. However, they are more efficient than most internal combustion engines. Their lower maintenance requirements make the overall *energy* cost comparable. The thermal efficiency is also comparable (for small engines), ranging from 15% to 30%. For applications such as micro-CHP, a Stirling engine is often preferable to an internal combustion engine. Other applications include water pumping, astronautics, and electrical generation from plentiful energy sources that are incompatible with the internal combustion engine, such as solar energy, and biomass such as agricultural waste and other waste such as domestic refuse. Stirling are also used as a marine engine in Swedish *Gotland*-class submarines. However, Stirling engines are generally not price-competitive as an automobile engine, due to high cost per unit power, low power density and high material costs.

Basic analysis is based on the closed-form Schmidt analysis.

Advantages

- Stirling engines can run directly on any available heat source, not just one produced by combustion, so they can run on heat from solar, geothermal, biological, nuclear sources or waste heat from industrial processes.
- A continuous combustion process can be used to supply heat, so those emissions associated with the intermittent combustion processes of a reciprocating internal combustion engine can be reduced.
- Some types of Stirling engines have the bearings and seals on the cool side of the engine, where they require less lubricant and last longer than equivalents on other reciprocating engine types.

- The engine mechanisms are in some ways simpler than other reciprocating engine types. No valves are needed, and the burner system can be relatively simple. Crude Stirling engines can be made using common household materials.[58]
- A Stirling engine uses a single-phase working fluid which maintains an internal pressure close to the design pressure, and thus for a properly designed system the risk of explosion is low. In comparison, a steam engine uses a two-phase gas/liquid working fluid, so a faulty over pressure relief valve can cause an explosion.
- In some cases, low operating pressure allows the use of lightweight cylinders.
- They can be built to run quietly and without an air supply, for air-independent propulsion use in submarines.
- They start easily (albeit slowly, after warm up) and run more efficiently in cold weather, in contrast to the internal combustion which starts quickly in warm weather, but not in cold weather.
- A Stirling engine used for pumping water can be configured so that the water cools the compression space. This is most effective when pumping cold water.
- They are extremely flexible. They can be used as CHP (combined heat and power) in the winter and as coolers in summer.
- Waste heat is easily harvested (compared to waste heat from an internal combustion engine) making Stirling engines useful for dual-output heat and power systems.

Disadvantages

Size and cost issues

- Stirling engine designs require heat exchangers for heat input and for heat output, and these must contain the pressure of the working fluid, where the pressure is proportional to the engine power output. In addition, the expansion-side heat exchange is often at very high temperature, so the materials must resist the corrosive effects of the heat source, and have low creep. Typically these material requirements substantially increase the cost of the engine. The materials and assembly costs for a high temperature heat exchange typically accounts for 40% of the total engine cost.[52]

- All thermodynamic cycles require large temperature differentials for efficient operation. In an external combustion engine, the heater temperature always equals or exceeds the expansion temperature. This means that the metallurgical requirements for the heater material are very demanding. This is similar to a Gas turbine, but is in contrast to an Otto engine or Diesel engine, where the expansion temperature can far exceed the metallurgical limit of the engine materials, because the input heat source is not conducted through the engine, so engine materials operate closer to the average temperature of the working gas. The Stirling cycle is not actually achievable, the real cycle in Stirling machines is less efficient than the theoretical Stirling cycle, also the efficiency of the Stirling cycle is lower where the ambient temperatures are mild, while it would give its best results in a cool environment, such as northern countries' winters.
- Dissipation of waste heat is especially complicated because the coolant temperature is kept as low as possible to maximize thermal efficiency. This increases the size of the radiators, which can make packaging difficult. Along with materials cost, this has been one of the factors limiting the adoption of Stirling engines as automotive prime movers. For other applications such as ship propulsion and stationary microgeneration systems using combined heat and power (CHP) high power density is not required.[59]

Power and torque issues

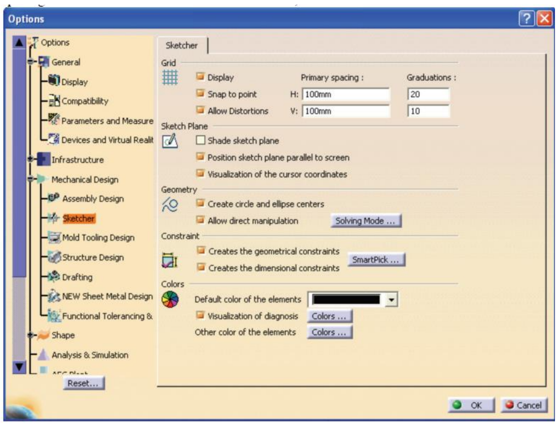
- Stirling engines, especially those that run on small temperature differentials, are quite large for the amount of power that they produce (i.e., they have low specific power). This is primarily due to the heat transfer coefficient of gaseous convection which limits the heat flux that can be attained in a typical cold heat exchange to about 500 W/(m^2·K), and in a hot heat exchange to about 500–5000 W/(m^2·K).[51] Compared with internal combustion engines, this makes it more challenging for the engine designer to transfer heat into and out of the working gas. Because of the Thermal efficiency the required heat transfer grows with lower temperature difference, and the heat exchange surface (and cost) for 1 kW output grows with second power of 1/delta T. Therefore the specific cost of very low temperature difference engines is very high. Increasing the temperature differential and/or pressure allows Stirling engines to produce more power, assuming the heat exchanges are designed for the increased heat load, and can deliver the convicted heat flux necessary.

- A Stirling engine cannot start instantly; it literally needs to "warm up". This is true of all external combustion engines, but the warm up time may be longer for Stirling than for others of this type such as steam engines. Stirling engines are best used as constant speed engines.
- Power output of a Stirling tends to be constant and to adjust it can sometimes require careful design and additional mechanisms. Typically, changes in output are achieved by varying the displacement of the engine (often through use of a swashplate crankshaft arrangement), or by changing the quantity of working fluid, or by altering the piston/displace phase angle, or in some cases simply by altering the engine load. This property is less of a drawback in hybrid electric propulsion or "base load" utility generation where constant power output is actually desirable.

Applications

Main article: Applications of the Stirling engine

Applications of the Stirling engine range from heating and cooling to underwater power systems. A Stirling engine can function in reverse as a heat pump for heating or cooling. Other uses include: combined heat and power, solar power generation, Stirling cryocoolers, heat pump, marine engines, and low temperature difference engines.



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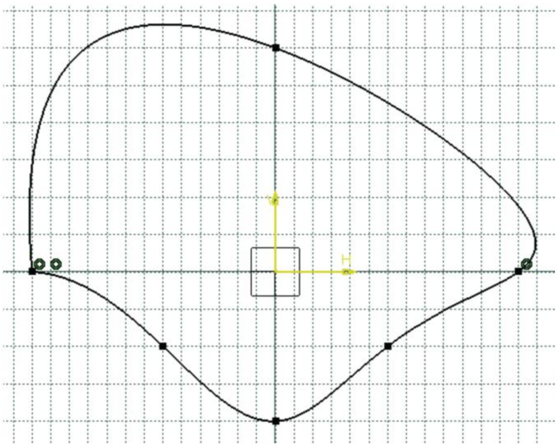

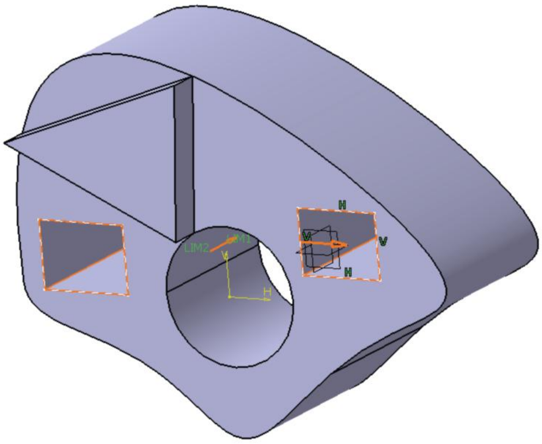

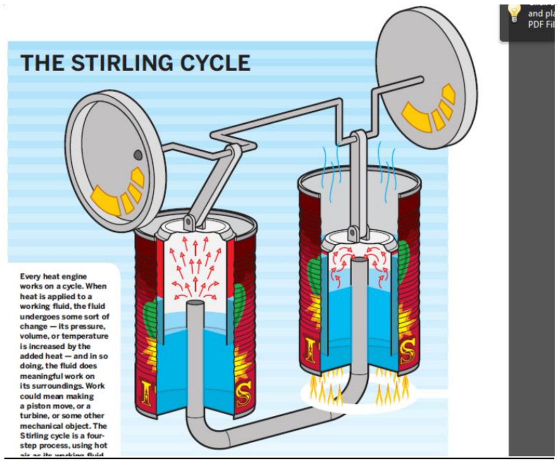

Every heat engine works on a cycle. When heat is applied to a working fluid, the fluid undergoes some sort of change — its pressure, volume, or temperature is increased by the added heat — and in so doing, the fluid does meaningful work on its surroundings. Work could mean making a piston move, or a turbine, or some other mechanical object. The Stirling cycle is a four-step process, using hot

IV CONCLUSION

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 exchanges 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- rials and mass-produced components. The overall engine geometry and components such as the re-generator, heat exchange, 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 leniency and have low-cost in fabrication in mass production. We will be conducting experimentation to verify the design performance in the near future.

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