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Electric Power Generation Using Stirling Engine

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***Abstract*— The performance of Stirling engine meets demands of the efficient use of energy and environmental security and therefore they are the subject of much current interest. The Stirling engine is both practically and theoretically a significant device, its practical virtue is simple, reliable and safe which was invented by Robert Stirling in 1816. The Aim of this paper is to design and build a Stirling Engine Capable of Generating Electricity. Here Concentrated Solar energy is used as a potential Heat source. The main principle is the pressure and temperature difference between the Hot and Cold air, due to this pressure and temperature difference the pistons move to and fro. The pistons here are coupled with the flywheel, thus as the pistons move it rotates the flywheel. The Flywheel being coupled with the generator produces electricity.**

Stirling Engine has the potential to use renewable heat source more easily, quieter and more reliable to low maintenance. Due to the advantage of the renewable source of energy i.e. the solar energy which is a free and eco-friendly source of energy and to minimize the use of other non-friendly and costly sources of this solar energy is being used.

The study was undertaken to discuss the various sources of providing heat to the Stirling engine which included providing heat by burning waste, providing heat by using a gas cylinder and many more sources. In comparison to an internal combustion engine, Stirling engine offers high efficiency and less exhaust emission.

***Index Terms*— Stirling Engine, internal combustion engine .**

I. Introduction

As we know that this is the age of technologies and is expanding in all fields, in every field energy is the major source acting as a catalyst for the developmentof any part of any nation. Nowadays there is a heavy demand for renewable energy sources or equipment which doesn't relyon fossil fuels and research is followed by the same. Stirling engine follows the principles of Stirling cycle and works on heat energy, this heat energy is collected from solar energy and is then converted to electrical energy, with a better efficiency as compared to other convenient generators on a small scale.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.

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A. History of StirlingEngine:

The Stirling engine (or Stirling's air engine as it was known at the time) was invented and patented in 1816. It followed earlier attempts at making an air engine but was probably the first put to practical use when, in 1818, an engine built by Stirling was employed pumping water in a quarry. The main subject of Stirling's original patent was a heat exchanger which he called an "economizer" for its enhancement of fuel economy in a variety of applications. The patent also described in detail the employment of one form of the economizer in his unique closed-cycle air engine design which is now generally known as a "regenerator". Subsequent development by Robert Stirling and his brother James, an engineer, resulted in patients for various improved configurations of the original engine including pressurization, which by 1843, had sufficiently increased power output to drive all the machinery at a Dundee iron foundry (founded in 1790).

By 1820 the foundry was manufacturing steam engines, building engines and boilers for the steam tug William Wallace in 1829, and in the 1830s building locomotives for the Dundee and Newtyle and the Arbroath and Forfar Railways. James Stirling (1800–1876) was the manager of the Dundee Foundry until 1846.In 1846 the Foundry was taken over and renamed Gourlay, Mudie& Co. This company was dissolved in 1853, and then operated as Gourlay Brothers & Co., with four brothers – Alexander, William, Gershom, and Henry Gourlay – as partners.

Considering the reduction of fossil fuels, the pollution of the environment and the climate change, society turned to the renewable energy sources. The mankind explores new opportunities for utilization ofenergy sources which are practically inexhaustible - wind, geothermal energy, solar energy and others. The aim is to improve the characteristics of the construction and operation of the installations, preventing any harmful effects on the environment. These requirements are largely satisfied by Stirling engine driven by the solar energy. Though it has been disputed, it is widely supposed that as well as saving fuel, the inventors were motivated to create a safer alternative to the steam engines of the time, whose boilers frequently exploded, causing many injuries and fatalities.

The need for Stirling engines to run at very high temperatures to maximize power and efficiency exposed limitations in the materials of the day, and the few engines that were built in those early years suffered unacceptably frequent failures (albeit with far less disastrous consequences than a boiler explosion) — for example, the Dundee foundry engine was replaced by a steam engine after three hot cylinder failures in four years.

B. Working of Stirling engine:

Since the Stirling engine is a closed cycle, it contains a fixed mass of gas called the "working fluid", most commonly air, hydrogen or helium. In normal operation, the engine is sealed and no gas enters or leaves the engine. No valves are required, unlike other types of piston engines. The Stirling engine, like most heat engines, cycles through four main processes: cooling, compression, heating, and expansion. This is accomplished by moving the gas back and forth between hot and cold heat exchangers, often with a regenerator between the heater and cooler. The hot heat exchanger is in thermal contact with an external heat source, such as a fuel burner, and the cold heat exchanger being in thermal contact with an external heat sink, such as air fins. A change in gas temperature causes a corresponding change in gas pressure, while the motion of the piston causes the gas to be alternately expanded and compressed.

The gas follows the behavior described by the gas laws that describe how a gas' pressure, temperature and volume are related. When the gas is heated, because it is in a sealed chamber, the pressure rises and this then acts on the power piston to produce a power stroke. When the gas is cooled the pressure drops and this means that less work needs to be done by the piston to compress the gas on the return stroke, thus yielding a net power output.

The ideal Stirling cycle is unattainable in the real world, as with any heat engine; efficiencies of 50% have been reached, similar to the maximum figure for Diesel cycle engines. The efficiency of Stirling machines is also linked to the environmental temperature; a higher efficiency is obtained when the weather is cooler, thus making this type of engine less interesting in places with warmer climates. As with other external combustion engines, Stirling engines can use heat sources other than from combustion of fuels.

When one side of the piston is open to the atmosphere, the operation is slightly different. As the sealed volume of working gas comes in contact with the hot side, it expands, doing work on both the piston and on the atmosphere. When the working gas contacts the cold side, its pressure drops below atmospheric pressure and the atmosphere pushes on the piston and does work on the gas.

To summarize, the Stirling engine uses the temperature difference between its hot end and cold end to establish a cycle of a fixed mass of gas, heated and expanded and cooled and compressed, thus converting thermal energy into mechanical energy. The greater the temperature differences between the hot and cold sources, the greater the thermal efficiency. The maximum theoretical efficiency is equivalent to the Carnotcyclehowever the efficiency of real engines is less than this value because of friction and other losses.The Carnot cycle is a theoretical thermodynamic cycle proposed by French physicist Sadi Carnot in 1824 and expanded upon by others in the 1830s and 1840s. It provides an upper limit on the efficiency that any classical thermodynamic engine can achieve during the conversion of heat into work, or conversely, the efficiency of a refrigeration system in creating a temperature difference (e.g. refrigeration) by the application of work to the system. It is not an actual thermodynamic cycle but is a theoretical construct.

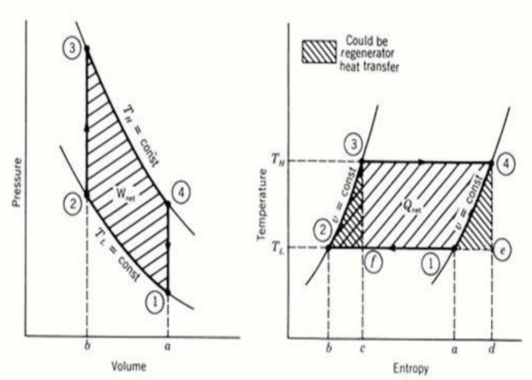
Very low-power engines have been built that run on a temperature difference of as little as 0.5 K. In a displacer type Stirling engine you have one piston and one displacer. A temperature difference is required between the top and bottom of the large cylinder to run the engine. In the case of the low-temperature difference (LTD) Stirling engine, the temperature difference between your hand and the surrounding air can be enough to run the engine. The power piston in the displacer type Stirling engine is tightly sealed and is controlled to move up and down as the gas inside expands. The displacer on the other hand is very loosely fitted so that air can move freely between the hot and cold sections of the engine as the piston moves up and down. The displacer moves up and down to control the heating and cooling of the gas in the engine.

There are two positions:

1. When the displacer is near the top of the large cylinder; inside the engine most of the gas has been heated by the heat source and it expands. This increases the pressure, which forces the piston up.
2. When the displacer is near the bottom of the large cylinder; most of the gas in the engine has now cooled and contracts causing the pressure to decrease, which in turn allows the piston to move down and compress the gas.

C. The StirlingCycle:

Stirling engines exhibit the same processes as any heat engine: compression, heating,expansion, and cooling. Stirling engines operate on a closed regenerative thermodynamic cycle.Gas is used as the working fluid, and undergoes cyclic compression and expansion in separatechambers with changing volume. In a typical Stirling engine, a fixed amount of gas is sealedwithin the engine, and a temperature difference is applied between two piston cylinders. As heatis applied to the gas in one cylinder, the gas expands and pressure builds. This forces the pistondownwards, performing work. The two pistons are linked so as the hot piston moves down, thecold piston moves up by an equal distance. This forces the cooler gas to exchange with the hotgas. The flow passes through the regenerator, where heat is absorbed.



Ideal Pressure-Volume and Temperature-entropy charts of the Stirling cycle.

1. Process 1-2: Isothermal compression. Here One piston

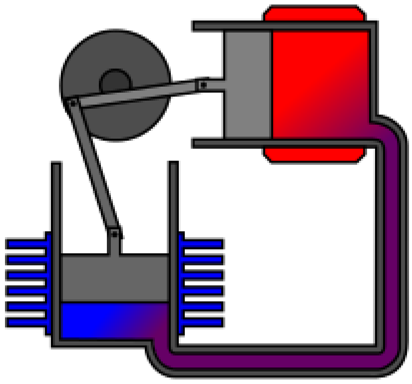
compresses the working fluid withinthe compression volume, while the other is stationary. This increases the pressure of thesystem at a constant temperature.
Q (1-2) =area 1-2-b-a on T-s diagram
Work is done on the working fluid
W (1-2) =area 1-2-b-a on P-v diagram.

2. Process 2-3: Isochoric transfer I. Here both pistons move in opposition (90° out of phase) totransfer the working fluid from compression to expansion volume. The regenerator, in anideal situation, raises the fluid temperature to 3' using heat stored from process 4-1.External heat supplies the remainder.
Q (2-3) = area *2-3-c-b* on T-s diagram
Work done [W (2-3)] is zero.
3. Process 3-4: Isothermal expansion. The expansion piston is moved by the expandingfluid, which is maintained at a constant temperature by the external heat source. Work isdone in this stage on the piston by the working fluid.
Q (3-4) = area *3-4-d-c* on T-s diagram
Hot air expands
Work is done by the working fluid
W (3-4) = area *3-4-a-b* on P-v diagram.
4. Process 4-1 Isochoric transfer II. The reverse process of 2-3, both pistons work to transferthe fluid from the expansion to the compression space. The regenerator absorbs heatfrom the fluid, reducing the fluid temperature to that at 1'
Q (4-1) = area *1-4-d-a* on T-s diagram
Work done [W (4-1)] is zero

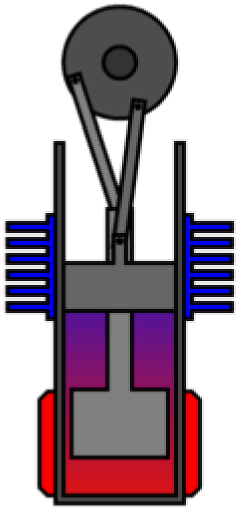
D. Configurations

There are three major types of Stirling engines that are distinguished by the way they move the air between the hot and cold areas:

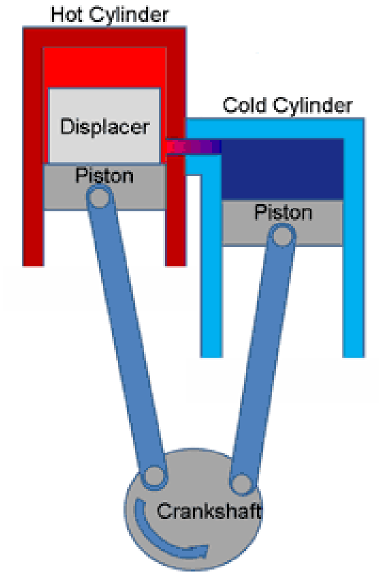
1. The **alpha** configuration has two power pistons, one in a hot cylinder, one in a cold cylinder, and the gas is driven between the two by the pistons; it is typically in a V-formation with the pistons joined at the same point on a crankshaft.



2. The **beta** configuration has a single cylinder with a hot end and a cold end, containing a power piston and a 'displacer' that drives the gas between the hot and cold ends. It is typically used with a rhombic drive to achieve the phase difference between the displacer and power pistons, but they can be joined 90 degrees out of phase on a crankshaft.



3.The **gamma** configuration has two cylinders: one containing a displacer, with a hot and a cold end, and one for the power piston; they are joined to form a single space with the same pressure in both cylinders; the pistons are typically in parallel and joined 90 degrees out of phase on a crankshaft.



E. Material selection

Among the materials listed copper has highest oxidation resistance thermal conductivity and melting point which is essential for engine and as the thermal expansion of copper is less the engine can be operated at high temperature for a longer duration. But the material cost is too high and hardness is low compared to othermaterials inaluminum the thermal conductivity is high, weight is less but material strength is less compared to copper.Thermal expansion is high so it cannot be operated for a long time at high temperatures. In stainless steel oxidationresistance is high compared to other materials also it has better strength compared to aluminum but the cost of thematerial is very high.

Properties ------------- - Material	**Melting Point (K)**	**Thermal Conductivity (W·m−1·K−1**	**Thermal Expansion (µm·m−1 ·K−1)**	**Brinnel Hardness**	**Oxidation resistance**
Aluminium	933	237	23.1	67	Medium
Stainless Steel	2400	19	17	110	High
Cast Iron	1260	60	10.8	415	Poor
Copper	1357	401	16.5	85	High
Mild Steel	2600	147	14	130	Moderate

The material which we have selected is mild steel even though thermal conductivity is lesser it is slightly near to the copper and the thermal expansion is lesser when compared to aluminum, it also has a high melting point, cost of the mild steel also less compared to others. The main disadvantage of using mild steel is that it reacts with atmospheric air so it readily undergoes oxidation reaction.

I. Solar Powered Stirling Engine

A solar-powered Stirling engine is a heat engine powered by a temperature gradient generated by the sun. It was patented by Roelf J. Meijer in 1987. His invention relates a heat engine, such as a Stirling cycle engine, with a solar dish collector in order to produce electricity. This apparatus consists of a large dish aimed at the sun to reflect the rays into the focus point, which is located at the center of the dish. Solar energy is then collected in the form of heat to fuel a Stirling cycle engine, which operates by letting heat flow from a hot source to a cold sink in order to do work. The work output of the Stirling cycle is then used to drive a generator and create electric power. Moreover, in Meijer's solar-powered engine, it is important that the dish always is pointed directly at the sun so that no shadows would be present in the solar dish collector, hence optimizing heat collection. This is where he ran into some issues because, in order for the apparatus to have a complete range of motion, lubrication and rotational systems would be necessary and may compromise structural stability.

The second type of solar-powered Stirling engine was patented by NASA on August 3, 1976, which employed the use of solar energy in order to freely pump water from a river, lake, or stream. The purpose of this apparatus is to "provide a low-cost, low-technology pump having particular utility in irrigation systems employed in underdeveloped arid regions of the earth… [using] the basic principles of the Stirling heat engine.

Recently, a company called "Sunvention" Solar Energy created a device very similar to what NASA came up with in 1976 that can pump 100,000 gallons per day purely off of solar energy and usage of the Stirling cycle costing only US$1,250 This apparatus, much like the others, uses a large solar dish to collect heat from the sun creating a high-temperature source and also employs the low-temperature water it collects from a nearby stream as its low-temperature source allowing for a great range in temperature which in turn allows for more work to be done. The work done in Sunvention's apparatus is used to pump the water into nearby crop fields allowing for a "low-cost, low-technology pump having particular utility in irrigation systems employed in underdeveloped arid regions of the earth".

A. *Solar Radiation*

The sun can be considered a spherical radiation source that is 1.39 x m in diameter and at a distance of about 1.50 x m from the Earth (Frank P. Incropera, 2002). Due to Earth‟s Ozone Layer, the radiation felt by body outside our atmosphere would be different than the radiation felt on Earth surfaces. In fact, the solar radiation reaching Earth can be treated as a series of parallel rays that would form an angle θ, the *zenith angle*, with respect to the normal surface of any horizontal surface outside our atmosphere. Therefore, the extraterrestrial solar irradiation $G_{s,o}$ is dependent on the global position of the object as well as the time of day and year.

$$G_{s,o} = S_c * f * cos\theta \qquad c$$

The solar constant, S_c, can be defined as the flux of solar energy incident on a surface which is oriented normal to the sun's rays at the point in which the Earth is at its mean distance away. The solar constant is given as

$$S_c = 1353 \; W/m^2$$

and the correction value for the eccentricity of Earth's orbit about the sun is given by 0.97 ≤ ≥ 1.03.

B. *Energy from Sunlight*

The amount of energy received from the sun for a period of 12 hours (43200 seconds) is given as

J = Sc x A x T

Where: Sc = Solar Constant = 1353 W/m^2

A = Area in m^2

T = Time in seconds

$$\left(1353\ {}^{W}/_{m^2}\right) x\ (1\ m^2) x\ (43.2 * 10^3\ sec) = 58.45 * 10^6\ J$$

II. Generator:

A Stirling engine requires a generator to convert the mechanical output of the engine into electrical output. Various generators are available ranging from low power output to high power output, alternating current or direct current.

III. Objectives

- To develop the experimental setup for Electricity generation using solar-powered Stirling engine.
- To build an engine which will use the temperature difference between its hot end and cold end to establish a cycle of a fixed mass of gas, heated and expanded, and cooled and compresses.
- To convert thermal energy into mechanical energy.
- To convert mechanical energy into electrical energy.
- To utilize the renewable source of energy i.e. the solar energy as a heat source.
- To concentrate a large number of solar radiations on a single point source.
- To study the efficiency of Stirling engine.

IV. 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 is more important than the capital cost per unit power. 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 microCHP, 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. Stirlings 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 the high cost per unit power, low power density, and high material costs

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