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Design and development of Solar Stirling Engine for power generation

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Abstract: Solar energy reaching earth's surface has small intensity of about 5-7.5KW-h/m^2. Hence for any worthwhile application, sufficient solar energy should be collected with a help of solar collectors. This paper provides a study on the configuration of solar Stirling engine and analyzes the performance of using a parabolic reflector as a heat source. The parabolic reflector functions due to the geometric properties of the paraboloidal shape, any incoming ray that is parallel to the axis of the dish will be focused at a point. The key principle of a Stirling engine is that a fixed amount of a gas is sealed inside the engine. The Stirling cycle involves a series of events that change the pressure of the gas inside the engine, causing it to do work. The engine design should be that of a gamma-configuration, double acting, vertical Stirling engine. The assembly consists of a gamma sterling engine and a parabolic reflector placed on a vertical stand along with a convex lens and a tacho generator. The study is exposed further with considerations of designing parameters involved in fabrication of the components of the system. The drafting and modeling of different parts or components of the assembly is done with the help of Solid edge.

Keywords: Sterling engine, parabolic reflector, tacho generator, solar energy.

1 Introduction:

Solar energy is considered as the main renewable energy source we can use because it is available in abundance and also in the form that can be harnessed easily. The Earth obtains 184 peta watts (PW) of solar radiation at the outer atmosphere. On an average 35% is returned to the outer space while the rest is utilized by clouds, ocean and earth surface. The solar energy from the sun has been utilized by people since old times using various unique technologies. These technologies include solar heating, solar photovoltaics, solar thermal electricity, solar architecture and artificial photosynthesis, which can make considerable contributions to solving some of the most crucial energy problems the world currently faces.

A parabolic reflector is a reflective device used to accumulate or projection of energy such as light, sound, or radio waves. Its shape is part of a circular paraboloid, that is, the surface caused by a parabola gyrating around its axis. The parabolic reflector convertsarriving waves moving along the axis intospherical waves uniting towards the focus. On the other hand, a spherical wave created by a point source located in the focus is reflected into a plane wave transmitted as a collimated beam along the axis. Parabolic reflectors are used to accumulate energy from a farawaysource (for instance sound waves or arriving light energy) and concentrate it to a common focal point, thus rectifying spherical oddness found in common spherical reflectors.

The parabolic reflector operates due to the geometric characteristics of the paraboloidal shape: any arriving rays that are parallel to the axis of the dish will be reflected to a central point, or focus. Because various kinds of energy can be reflected in the above said way, parabolic reflectors can be used to gather and accumulate energy entering the reflector at a specific angle. Similarly, energy emitted from the focus to the dish can be transferred outwards in a beam that is parallel to the axis of the dish.

Aluminum foil is made in thin metal layers, with a thickness less than 0.2 millimeters (8 mils), thinner gauges down to 6 µm (0.2 mils) are also widely used. In our country, foils are usually measured in mils

Aluminum has reflectivity index value more than silver and gold. For lower wavelength radiations Aluminum shows very good reflectance % than gold and silver.

The Stirling engine is a heat engine that is vastly different from the internal-combustion engine in your car. Invented by Robert Stirling in 1815, the Stirling engine has the potential to be much more efficient than a gasoline or diesel engine. But today, Stirling engines are used only in some very specialized applications, like in submarines or auxiliary power generators for yachts, where quiet operation is important.

A Stirling engine uses the Stirling cycle, which is unlike the cycles used in internal-combustion engines.

[1]The gasses used inside a Stirling engine never leave the engine. There are no exhaust valves that vent high-pressure gasses, as in an IC engine, and there are no explosions taking place. Because of this, Stirling engines are very quiet.

[2]The Stirling cycle uses an external heat source. No combustion takes place inside the cylinders of the engine.

[3]The key principle of a Stirling engine is that a fixed amount of a gas is sealed insidethe engine. The Stirling cycle involves a series of events that change the pressure of the gas inside the engine, causing it to do work.

A tachogenerator is an electric generator that generates a voltage that is accurately proportional to the speed of the shaft. Tachogenerator is specifically designed to provide an accurate signal over a specified range of load currents and operating temperatures.

Tachogeneratoris a small AC or DC generators that output a voltage in proportion to the rotational speed of a shaft. They are capable of measuring speed and direction of rotation, but not position. They convert a rotational speed into an isolated analog voltage signal that is suitable for remote indication and control applications. Tachogenerators are also used in servo systems to supply velocity or damping signals and may be mounted on or in the same housing as a servo motor.

2 Literature survey:

[1] Review of Stirling Engines for Pumping Water using Solar Energy as a source of Power,Rakesh K. Bumataria*, Nikul K. Patel** *(Department of Mechanical Engineering, Faculty of Technology & Engineering, The M S University of Baroda, Gujarat-390001)

From their study they concluded that there is a hope for rural area to develop gamma type Stirling engine. In this engine solar energy can be used for heating hot end of engine up to maximum of 4500C to 8000C and air cooled fin can be used for cooling the cold end of engine up to 350C to 700C. Theoretically designed such type of engine will give efficiency of about 52% to 72%. As there was limitation of availability of other working fluid; air will be the best working fluid for it. Based on Standardization of available centrifugal pumps in market the speed of the engine should be design as per the speed of pump i.e. 1000, 1500, 2500, 3000 RPM. Hence new renewable source solar Stirling engine will give good hope.

[2] BanchaKongtragool and SomchaiWongwises, a The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology.Thonburi, Bangmod, Bangkok 10140, Thailand.

The aim of this study is to find a feasible solution which may lead to a preliminary conceptual design of a workable solar-powered LTD Stirling engine. Since this Engine is designed for use in rural areas; the engine design should be as simple as possible. The most appropriate type of solar-powered Stirling engine would be the LTD Stirling engine. The engine design should be that of a gamma-configuration, double-acting, vertical, LTD Stirling engine.
Since, during two-thirds of the day, solar energy is not available, solar/fuel hybrids are needed. This engine should be powered both by solar energy and heat from any combustible material.

3 Working and operation:

When a gas is heated it expands. If the same gas is sealed inside the cylinder of an engine when heated, the expansion results in pressure increase. Also, if the same air when cooled it would cause the air to contract, this contraction would cause the pressure in the engine cylinder to drop. This pressure increase and decrease, due to heating and cooling, can be used to move a piston back and forth, as shown in figure. It is noted that the pressure and temperature are proportional to each other.

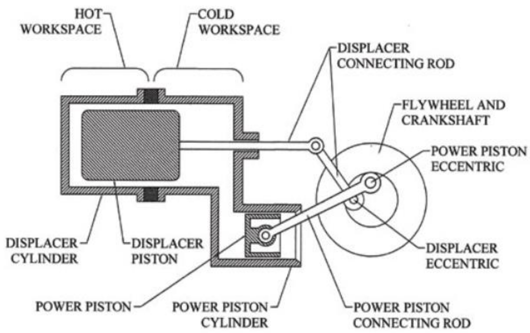

Figure 3.1 Stirling engine

The piston is linked to a circular disc, known as a flywheel. Heating and cooling of the gas in the engine will result in movement of the piston that in turn rotates the flywheel. The rotating flywheel is mechanical energy, which the engine has converted from the temperature difference of the gas. This process of heating air to raise pressure in order to turn a flywheel is the characteristics of a heat

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engine, hence Stirling engine is a type of heat engine. The Stirling engine operates continuously on a cycle by heating and cooling of gases, within the engine over and over again to produce useful power. The air is sealed inside the engine cylinder, so it is known as a closed cycle heat engine. As it does not require inlet and outlet valves, it is simpler in construction. The Stirling engine produces power for a portion of the cycle when the gas is expanding; it requires an input energy during the compression of the gas. The fly wheel's momentum is gained from expansion of the gas is used to compress gas. The Stirling engine is an external combustion engine means that engine obtains heat from outside rather than inside the working cylinder. The Stirling engine has the advantage of being able to generate power from any source of heat.

Gamma Stirling:
Gamma type Stirling engine in has a total of four operating stages. The stages of operation are as follows:

Cycle 1– Expansion (Heating):
Displacer is at the cold end. Power piston is at mid position. Gas in the displacer cylinder is at the hot end, so it heats up and expands due to pressure increase. Pressure increase pushes the power piston forward to the end of its stroke, this rotates the flywheel. This is known as the power producing phase in the cycle.

Cycle 2– Transfer of hot air:
Displacer is at mid position. Power piston is at the bottom of stroke. Most of the expanded gas is still in the hot end of the cylinder. The flywheel's momentum will push the crankshaft the next quarter turn. The gas is moved around the displacer to the cold end of the cylinder.

Cycle 3– Contraction (Cooling):
Displacer is at the hot end. Power piston is at mid position. The majority of the expanded gas is moved to the cold end. The gas cools and contracts, allowing the piston inward towards the hot work space of the displacer cylinder.

Cycle 4– Transfer of cold air:
Displacer is at mid position. Power piston at top of its stroke, is ready to start the power output stroke. The contracted gas is near the cool end of the cylinder. Flywheel momentum pushes the crank another quarter turn, moving the displacer and transferring the gas back to the hot end of the cylinder.

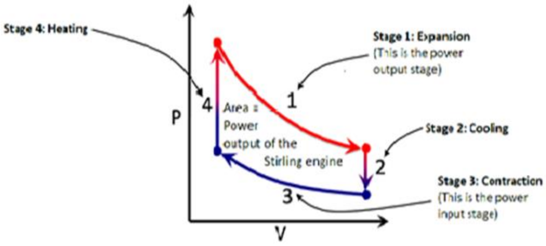

Figure 3.2 P-V plot of stirling engine

The volume of gas in the power piston can be calculated based on the diameter of the piston and the position of the piston.
Volume of the cylinder* = ( )* *height
The change in volume during the expansion process can be calculated as.
Change in volume* = ( )**distance moved by the power piston

4 Construction:

Given below is proposed solid edge model of solar sterling engine with a parabolic reflector.

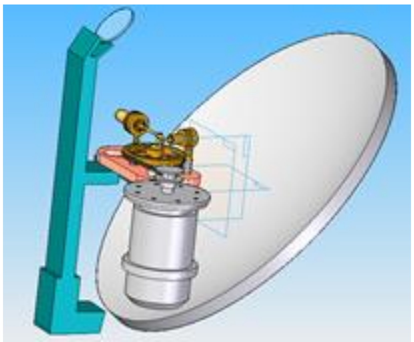

Figure 4.1 Assembled Solid edge model of solar stirling engine

A more intricate calculation is required to obtain the diameter of the dish measured all along its surface. This is occasionally called the "linear diameter", and matches the diameter of the flat, circular sheet of material,typically metal, which is the ideal size to be cut and bent to prepare the dish. Two intermediate results are useful in the calculation: $P = 2F$ (or the equivalent: $P= R^2/2D$) and$Q = \sqrt{P^2 + R^2}$.

The diameter of the dish, calculated along the surface, is then given by:$(\frac{RQ}{P} + P \ln \frac{R+Q}{P})$ where $\ln x$ means the natural logarithm of x, i.e. its logarithm to base "e".$P = 2F$

The volume of the dish, the quantity of fluid it could accommodate if the rim were horizontal and the vertex at the bottom (e.g. the capacity of a paraboloidal wok), is representedby$(\frac{\pi}{2} R^2 D)$ where the symbols are described as above. This can be related with the formulae for the volumes of a cylinder ($\pi R^2 D$) a hemisphere$(\frac{2\pi}{3} R^2 D$

where $D = R$) and a cone$(\frac{\pi}{3} R^2 D$) Of course,(πR^2) is the aperture area of the dish, the area bounded by the rim, which is proportionate to the quantity of sunlight the reflector dish can intercept.

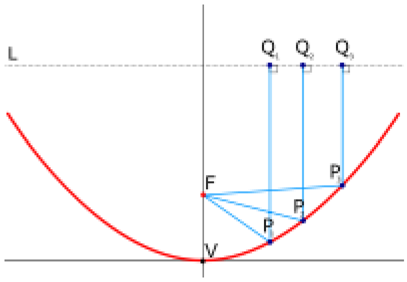

Figure 4.2 Parallel rays arriving to a parabolic reflector are concentrated at a point F. The vertexes V, and the axis of symmetry passes through V and F.

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Table 4.1 Specifications of proposed reflector

Parameters	Specifications
Reflective surface	Aluminium
Thickness	0.03mm
Width	100mm
Reflectivity	>75%

5 Experimentation:

Reflectivity and reflectance usually refer to the portion of incident electromagnetic power that is redirected at an interface. Aluminium has reflectivity index value more than silver and gold. As we can see in the fig. 4.1, for different incident radiations having different wavelengths the reflectance % varies for different materials. For lower wavelength radiations Aluminium shows very good reflectance % than gold and silver. But for higher wavelength radiations all the three metals show similar reflectance %.

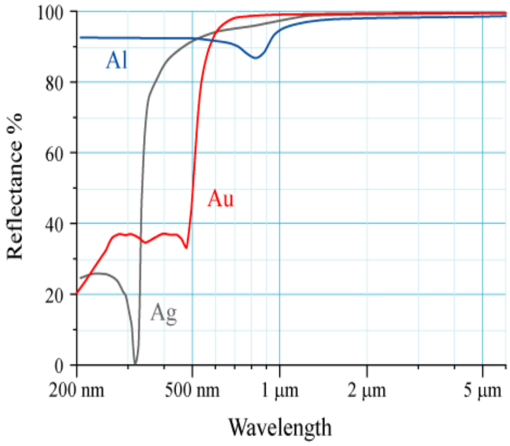

Figure 5.1 Reflectance vs. Wavelength of incident light for different metal

Feasibility testing:

The testing of our assembly was done in two days considering the fact that the solar radiation varies day to day. As we all know the intensity of radiation will be high during the time period 11.00 am to 3.00 pm. Therefore the testing was done during these hours for two days. Following are the results.

DAY 1

Table 5.1 Test results of day 1

Time duration	Average room temperature	Displacer cap temperature	State of the engine
10.00 am – 11.00 am	23°C	35°C	Not running
11.00 am – 12.00 pm	28°C	44°C	Not running
12.00 pm – 1.00 pm	33°C	59°C	Running but not continues
1.00 pm – 2.00 pm	31°C	73°C	Running but not continues

DAY 2

From the results of first day we came to know that intensity of light will be very high during 12.00 to 3.00 pm. Hence we thought of testing in the next day during these hours. Also we thought that for initial heating of the engine we will use an external heat source. This will increase the efficiency of the engine. We used a burner and introduced it near the engine for twice in a minute. Using this burner changed the expected results tremendously.

Table 5.2 Test results of day 2

Time duration	Average room temperature	Displacer cap temperature	State of the engine
12.00 pm – 1.00 pm	35°C	89°C	Continuously running
1.00 pm – 2.00 pm	34°C	103°C	Continuously running
2.00 pm – 3.00 pm	31°C	110°C	Continuously running

4.6.2 Calculations and results

1. Solar power input

Assuming there will be constant amount of heat received by the parabolic reflector.

Amount of energy received per sec is given by

J= solar constant (W/m^2) * Area (m^2)* Time (sec)

J= 1353 * π/4*(0.7^2)*1

J= 520.69 Joules

2. Ideal Volume Ratio

Considering a temperature increase of

70%,

Volume ratio, V_R= (1+ΔT/1100)

V_R= (1+70/1100)

V_R= 1.06

3. Expansion Space Volume

Expansion space volume is calculated using Power output and Beale Number.

P_0=B_n* p * f * V_e

B_n= Beale number usually between 0.003-0.007

p= pressure in bar

f= operating frequency in Hz

V_e= P_0/B_n*p*f

V_e= 1/0.005*10*2

V_e=10cm^3

V_e=0.01 l

4. Ideal volume ratio

Ideal volume ratio= $\frac{Vmax}{Vmin}$m

V_R= $\frac{Vc+Ve}{Vc}$

V_c= $\frac{Ve}{Vr-1}$ = $\frac{10}{1.06-1}$=$\frac{10}{0.06}$= 166.67cm^3

Compression volume V_c=166.67cm^3

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5. Inertia of Flywheel

The moment of inertia I of the flywheel is approximated as:

$I= 0.5*m*(r_i^2+r_o^2)$

Where m= mass of the flywheel.

r_i= inner radius

r_o= outer radius

Ignoring spokes of the rim

$I= 0.5*0.25((65*10^{-3})^2+(90*10^{-3})^2)$

Consider approximate r_i= 65mm & r_0=90mm

$I= 1.54*10^{-3}$ Kg m^2

We are expecting to design the flywheel such that it will be symmetric in all the directions from the centre.

Hence its centre of gravity lies exactly at its centre.

6. Volume of power cylinder

$V= (\pi * r^2)*height$

$$V = 3.14 * 5 * 5 * 35$$

$V = 2747.5\ mm^3$

7. Engine efficiency

$$\eta = \frac{T^{HOT} - T^{COLD}}{T^{HOT}} * 100$$

$$\eta = \frac{110-31}{110} * 100$$

$$\eta = 71.8\ \%$$

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