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# Review of Stirling Engines for Pumping Water using Solar Energy as a source of Power

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## ABSTRACT

**In order to satisfy the rising energy demands of global consumption a new eco-friendly renewable power source needs to be explored, conceptualized and developed. Solar energy is a free and clean energy resource which is available to humans or the local culture in abundant. An attempt is made to study Stirling cycle, its application and its suitability to use this source as pumping water in rural sector. Review of study is done for the development of Solar Stirling engine which will help in development of the engine which can be used for pumping water at rural areas using solar energy as a source. The engine developed will have its wide application not only in rural sector but also for generating electricity by attaching a generator of required capacity to the shaft of an engine.**
*Keywords* - **Stirling engine, Solar energy, Pump**

## I. INTRODUCTION

Limited availability of petroleum product and electricity in rural areas and high demandable human need for water; make demand for searching another alternative for pumping water. Also limitation of fissile fossil fuels has captured our attention on searching renewable and sustainable energy such as solar, wind etc. One optional and potential engine solving this problem is the solar Stirling engine. This is simple type of external heat engine which use solar energy as source and make more suitable for rural areas. Water is basic need for humankind from beginning and there are several sources available for it. But water from source to consumer level required pumping facilities using different techniques. Many rural areas in India are still suffering from a lack of access to energy services for water pumping, especially electricity supply. Solar applications could play that role and supply electrical energy needed in rural, remote, and deserted areas for rural electrification. Similarly solar energy can also be used for water pumping in rural areas where electricity is not available.

## II. ENERGY AND POWER CAPACITY

The evaluation of solar Stirling engine water pumping is related to several factors such as: (1) areas where underground water is available and needed, (2) daily volume of water to be pumped, (3) the pumping depth, (4) site features and climatic conditions, (5) infrastructure and local technical skills, and (6) technical alternatives available for water pumping. The daily electrical energy needed and the nominal power required for different values of the pumping depth H multiplied by the daily volume of water needed V (m3/s) calculated based on the relation:

$$W = \frac{\rho g V H}{3600} = 0.002725VH \ (Wh/day) \quad (1.1)$$

The technical alternative options which could be available to provide electric power for water pumping in the site are: 1.Extension of national electric grid (extension to 5 and 10 Km), 2. Diesel generation set, 3.Photovoltaic systems, 4.Solar Stirling engine. The total costs of a water pumping system include: investment costs (capital costs), and recurrent costs (running and maintenance costs). The cost analysis has been done for determining the cost of different daily pumped water (in $m^3$) for different pumping depth (in m) given in ($m^3 \times m$) produced from the four technical alternatives options during the life of the system which assumed to be 20 years [1]

## III. STIRLING ENGINE

Stirling engine is a simple type of external combustion heat engine. It was first proposed by Robert Stirling in 1816 (UK, Patent no.4081) [2]. Since then, several Stirling engines based upon his invention were built in many forms and sizes. The Stirling cycle engine is environmental harmless and high theoretical efficiency and almost silent operation. Stirling engine can be supplied with several gases as working fluid, such as air, helium, hydrogen, nitrogen etc. Plenty heat sources can be employed on Stirling engine including combustible materials, agricultural waste, biomass, biogas, solar energy and so on. Heat is then converted to mechanical or useful work using Stirling engine. In

1920, the Stirling engine was terminated by the rapid development of the internal combustion engine and the electric motor. In most models, the engines operate with a heater and cooler temperature about 6500°C and 650°C, respectively [2].The thermal limit for the operation high temperature Stirling engine depends on the material used for its construction. Engine efficiency ranges 30-40% resulting in a typical temperature range of 6500°C - 8000°C, and normal speed range is from 2000 to 4000 rpm [3]. The ideal Stirling cycle has three theoretical advantages [4]. First, the thermal efficiency of the cycle with ideal regeneration is equal to the Carnot cycle. Therefore, the quantity of heat taken from the external heat source is reduced; these results in improving the thermal efficiency as shown in Fig. 1.

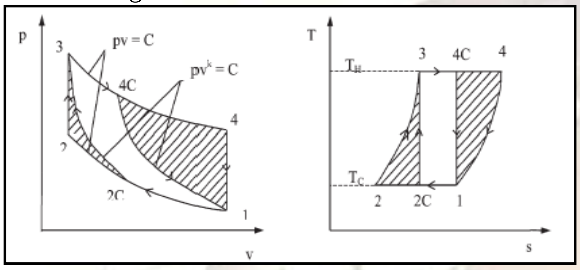


**Figure 1 Comparison of Stirling and Carnot Cycle**

The second advantage, over the Carnot cycle, is obtained by substitution of two isentropic processes with two constant-volume processes. This results in increasing the p–v diagram area. Therefore, a reasonable amount of work from the Stirling cycle is obtained without the necessity to use very high pressures and large swept volumes, as in the Carnot cycle. The third advantage has recently been discovered. Compared with all reciprocal piston heat engines working at the same temperature limits, the same volume ratios, the same mass of ideal working fluid, the same external pressure, and mechanism of the same overall effectiveness, the ideal Stirling engine has the maximum possible mechanical efficiency. These three advantages reveal that the Stirling engine is a theoretical equivalent of all heat engines. A Stirling engine is a closed-cycle regenerative heat engine with a gaseous working fluid. The most common applications of Stirling engines [5] are automobiles, marine engines, aircraft engines, combined heat and power applications, solar power generation, Stirling cryo coolers, heat pump nuclear power.

There are several reason to use Stirling engine for different application [4], (i) Almost impossible to explode (ii) Inside pistons can be used air, helium, nitrogen or hydrogen used as working gas (iii) Oil, gas, nuclear power, and renewable energies like solar, biomass or geothermal (iv) Emission reduced due to external combustion (v) Run very silent and no need of air supply for combustion (vi) Construction having very less vibration (vii) Bearing and seal can be cooler side so run for long time (viii) Extremely flexible. The Stirling engine could be used in many applications and is suitable where [6], 1. Multi-fueled characteristic is required. 2. A very good cooling source is available. 3. Quite operation is required. 4. Relatively low speed operation is permitted. 5. Constant power output operation is permitted. 6. Slow changing of engine power output is permitted. 7. A long warm-up period is permitted. Most of such suitability will be full-fill by using solar energy as heat source, air fin cooling, in gamma type Stirling engine.

## IV. SOLAR ENERGY

Using sunlight as a viable heat source for Stirling engine yields a method of producing power without harmful emissions and without using manufacturing methods which deplete the Earths of its precise natural resources. Stirling engines provide a methodology for generating power for use in a small system to drive any equipment like electric generator, centrifugal pump. Throughout the history, there have been many methods explored on gathering sunlight for power generator. Some of the most successful methods of using solar energy [7], in order to produce power are Photovoltaic, Brayton Cycle Steam Engines, and Stirling Engines. Photovoltaic are an array of cells which contain a special material that can convert solar radiation into electrical current. Photovoltaic have continuous ability to generate power, because photovoltaic have no moving parts, it makes the system extremely reliable and operates with minimal maintenance. It is also worthy to note that many current solar panels use silicon as main material in the cells, which makes high cost. Brayton Cycle is a type of thermodynamic cycle used in heat engine that uses steam as the working fluid in order to produce power. It cost-benefit analysis is mostly good for very large scale applications but would not make sense for smaller engines and also its maintenance may cause a problem with long-term applications. Stirling engine is a type of heat engine that generates power through the compression and expansion of the working gas in its cylinder via a hot end and cold end. Low cost due to relative inexpensiveness. The materials used for the engines are neither exotic nor rare therefore making the parts list more cost effective than other means. It has also high ability because it will continue to compress and expand a gas as long as the temperature difference exists therefore making it a very viable option for power generation with respect to other heat engines. The conclusion of the studies is that we will use a Stirling engine for the conversion of solar energy into useful energy.

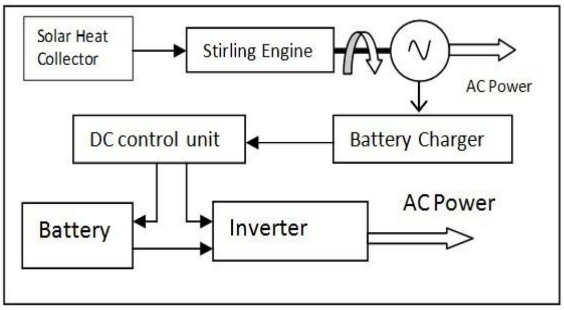


**Figure 2 Small Scale Electric Power from Solar Thermal Energy**

The schematic as shown in Fig. 2 illustrates a small scale electric power from solar thermal energy system which utilizes solar Stirling engine. In this system, the solar heat collector provides heat for the solar Stirling engine which in turn provides AC power. The electrical power can be transferred to a battery charger, then to DC control unit which can either go into a battery or into an inverter. Efficiencies for this type of small scale system can range from 18% to 23%.

## V. REVIEW OF LITERATURE

Mahendru [8], make case study on solar powered water pumping project in Samastipur, Bihar, India. In this technology solar panel operating voltage-220V×8 panels, maximum power per panel-230 W, maximum power of solar array-1840 W, submersible pump-2HP, water discharge-12000 lit/hour on sunny day, size of each pond-1 Acre, total ponds-44. Khandker et. al. [9], suggested that the provision of high quality energy services to rural areas has lagged behind urban areas. It is both financially and physically more difficult to service remote and poor populations compared to those living in urban areas. There are still significant challenges in improving the reliability of power supply in rural area in the country. The challenges are basically two-fold: How to improve the access of rural households to electricity beyond the current rate of 56 percent and how to ensure reliable and adequate supply of electricity. Although rural energy activities receive significant support from the Government of India, our findings would tend to confirm that there is still a long way to go to ensure that the rural poor can take advantage of the many benefits of modern energy and the services that they provide to consumers.

Christoph et. al. [10], analyze the Stirling engine from economic point. They pointed that (i) Only a very small power operation can carry out a Stirling engine, which contributes a lot to energy conservation. (ii) If solar is used to produce energy for the Stirling engine, the cost would be cut down for quite a lot, it costs much to manufacturing. (iii) Stirling engine exhausts cleanly and avoid lot of pollution, which reduce so much cost for pollution control and government. (iv) At the end of 18th century and the early 19th century the heat engine efficiency is very low, only 3% to 5% but now the efficiency of Stirling engine can come up to 80% or even more. So another part of cost is saved. Risberg [11], built a Stirling engine with specification as follow: Crankshaft – 7 inches long with a ½ inch depth, Crankshaft supports – 4.5 inches high, 1.25 inches wide, Pressure Vessel and displacer – 3 9/16 inch diameter, Displacer Bottom - 1.3 inches high, Displacer Top pin - 2.2 inches high, Stand - 3.5 inches high. Efficiency, Torque, Power, Angular speed, and acceleration are all unknown since the engine did not successfully run. Kwankaomeng and Burapattanon [12], develop a gamma type Stirling engine with double power piston working temperature range of 512-54°C at the hot head engine and air cooler section respectively. The prototype has displacer diameter and stroke of 218.5 mm and 80 mm respectively. And power piston diameter and stroke of 98.5 mm and 110 mm respectively. The engine was improved and tested over wide range of operating conditions for comparison. The results indicate that power of the improved prototype is better than unpressurized engine and using air as working gas. The maximum engine power was 5.05 W at 68.7 rpm and maximum torque was 0.978 N-m at 45 rpm. Maximum engine speed was 130 rpm at temperature of 560° C. The test results showed that the engine started operation in 5 minute at temperature about 490° C on the hot engine head and temperature of 47°C at air cooler section. Hirata et. al.[13], evaluate performance for a 100 W Stirling engine on the basis of pressure, pressure loss, leakage of working gas, buffer space loss, indicated work and power, mechanical loss etc. analytical and compare with model. From this they conclude that 1. The pressure loss at the regenerator, the gas leakage and the heat transfer in the buffer space was presented. It can simulate the engine performance adequately. 2. The buffer space loss of the prototype engine is estimated adequately, when it is considered the heat transfer with the number of heat transfer unit, NTU=0.1.3. Working gas flowed without an enough extending in the regenerator in the prototype engine. Koichi [14], develop compact and low cost a gamma type Stirling with simple moving-tu4be-type heat exchangers and a rhombic mechani4sm. Its target shaft power is 50 W at speed of 4000 rpm and mean pressure of 0.8 MPa. The test was done in without load, using air in atmospheric condition. Also, a mechanical loss measurement was done in highly pressurized condition in which the engine was driven by motor. Thombare and Verma [15], published review paper on isothermal analysis, heat transfer in isothermal and adiabatic model, maximum obtainable efficiency, Schmidt's theory, heat transfer phenomenon in different parts of sterling engine such as heater , cooler, regenerator analysis, engine configuration and classification, working fluid, power and speed control, performance governing factor and different characteristics of Stirling engine. Stirling Energy Systems (SES) [16] Company in partnership with Sandia National Lab managed to break the world record for solar-to-grid conversion efficiency at an amazing 31.25 % on January 31, 2008. SES Serial 3 was erected in May 2005 as part of the Solar Thermal Test Facility which produced up to150kW of grid ready electrical power during the hours of sunlight. Each dish consisted of 82 mirrors that can focus the light into an intense beam (Systems, 2008). SES solar Stirling engine, named Sun Catcher, was awarded the 2008 Breakthrough Award winner by Popular Mechanics for its role as one of the top 10 world-changing innovations. The Sun Catcher is a 25 kWe solar dish Stirling system which uses a solar concentrator structure which supports an array of curved glass mirror which are designed to follow the sun and collect the focused solar energy onto a power conversion unit. The diagram below illustrates the workings of SES's Sun Catcher. Minassians and Sanders [17], make feasibility study of a low-cost solar-thermal electricity generation technology, suitable for distributed deployment, based on nominating solar concentrators, integrated with free-piston Stirling engine devices incorporating integrated electric generation. Concentrator collector operates at moderate temperatures, in the range of 120°C to 150°C. This temperature range is consistent with the use of optical concentrators with low-concentration ratios, wide angles of radiation acceptance which are compatible with no diurnal tracking and no or only a few seasonal adjustments. Therefore, costs and reliability hazards associated with tracking hardware systems are avoided. They further outline the design, fabrication, and test results of a single-phase free-piston Stirling engine prototype. A very low loss resonant displacer piston is designed for the system using a very linear magnetic spring. The power piston, which is not mechanically linked to the displacer piston, forms a mass-spring resonating subsystem with the gas spring, and has a resonant frequency matched to that of the displacer. The design of heat exchangers is discussed, with an emphasis on their low fluid friction loss; an appropriately dimensioned Stirling engine candidate is discussed. Wood et. al. [18], preliminary design a linear motion free-piston Stirling engine / blower coupled to a rotary turbine / generator. The design combines several features of prototype free-piston machines that are nearing commercial production. The Stirling driver is comprised of two conventional, displacer types, free-piston engines configured as a dynamically balanced opposed pair. Using the outer face of its power piston, each engine drives a single-acting blower. The single turbine / generator use commercial units and are separate from the engines and connected by ductwork. The engines and turbines utilize the same helium working fluid. Moon and Miller [19], complete a rigorous computational model of the engine using Fluent fluid dynamics software. After that attempt they made to model the engine in Solidworks' Floworks application, that software proved inadequate for analyzing the transient states present in Stirling engine operation. Then they conduct another experiment in order to determine the actual heat flux concentrator capable of producing, in order to closely match the performance of engine with that of our dish. Finally, they finalize all design elements and. They also wrote all CNC code using Solidworks and Mastercam, in order to do the required machining using SDSU's facilities. Kangtrageal and Wongwises [6], published a review of solar power Stirling engine. They give some idea about low temperature differential Stirling engine, its characteristics. Also state that engine operation of the Stirling engine depends on the material used for construction. Engine efficiency ranges from about 30% to 40% resulting from a typical temperature range of 923-1073 K and a normal operating speed from 2000 to 4000 RPM, motion diagram , engine indicated work, Stirling engine feasibilities for rural and remote areas, engine optimization techniques, utilization of solar energy using concentrating collector, solar disc technology.

## VI. CONCLUSIONS

From the above study it can be 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 $450^0$C to $800^0$C and air cooled fin can be used for cooling the cold end of engine up to $35^0$C to $70^0$C. 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 and way for pumping water in rural areas.

## REFERENCES

[1] M. Kordab, Priority option of photovoltaic systems for pumping in rural areas in ESCWA member countries, *Science Direct, desalination, 209*, 2007, 73-77.

[2] G. Walker, *Stirling engine* (Oxford Clarendon Press, Calgary).

[3] W. B. Stine, *Stirling Engines*, (CRC Press, Boca Raton, 1998).

[4] M. J. Dadi, I. M. Molvi, A. V. Mehta, The most efficient waste heat recovery device: a gamma type Stirling engine, *International journal of advanced engineering technology*, January – March, 2012, 189 – 195.
[5] G. Cronenberg, *the Stirling Engine*, Uppasala University, 2005.
[6] B. Kongtragool, S. Wongwises, A review of solar powered Stirling engines and low temperature differential Stirling engine, *Science Direct renewable and sustainable energy*, *7* ,2003, 131 – 154.
[7] D. Aranda, K. LaMott, S. Wood, *Solar Stirling Engine for Remote power and Disaster Relief*, Florida International University, 2010.
[8] V. Mahendru, *Case study on solar powered water pumping project in Samastipur, Bihar, India*, Claro energy private limited, 2012.
[9] S. R. Khandker, D. F. Barnes, H. A. Samad, Energy poverty in rural and urban india, *Policy research working paper, The world bank development research group, agriculture and rural development*, 2011, 5463.
[10] M. Christoph, G. Arnaud, A. Rafael, S. Li, Y. Xue, *Stirling engine*, university of Gavle, 2007.
[11] R. Brandon, *Stirling engine*, Applied Science research, 12th Grade, 2007.
[12] S. Kwankaomeng, K. Burapathananon, Development of a Gamma Type Stirling Engine with Double Power Piston, *The international conference of the thai society of agricultural engineering, Chiangmai, Thailand*, 2012.
[13] K. Hiratai, S. Iwanmoto, F. Toda, H. Kazuhiro, Performance evaluation for 100 W Stirling engine, *8th International Stirling engine conference*, 1997, 19 – 28.
[14] K. Hirata, *Development of a small 50 W class striling engine*, Ship research institute, Shinkawa, Mitaka, Tokyo, Japan, 6-38-1.
[15] D. G. Thombare, S. K. Verma, Technological Development in the Stirling Cycle Engines, *Science Direct, Renewable and Sustainable Energy Reviews*, *12*, 2008), 1 – 38.
[16] S. Sets, *World Record for Solar – to – Grid Conversion Efficiency*, S. E. Systems, 2008.
[17] A. D. Minassians, S. R. Sanders, Stirling engines for distributed low cost solar thermal electric power generation, *Journal of solar energy engineering*, 133, 2011.
[18] J. Wood, N. Lanel, W. Beale, Preliminary design of a 7 kWe free piston Stirling engine with rotary generator output, proc. 10th ISEC, Osnabruck, Germany, 2001.
[19] K. S. Moon, F. J. Miller, *Stirling solar engine design*, San diego state university, 2009.