OVERVIEW OF VARIOUS STUDIES ON TECHNICAL ASPECTS AND SIGNIFICANCE OF A STIRLING ENGINE INCORPORATED CSP SYSTEM

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Abstract

Solar energy has been playing a crucial role as a clean energy source for power generation without any carbon emissions and many countries have been diversified and adopted the technologies such as solar PV and solar thermal technology, while these methods are still having limitations such as lower efficiencies, challenges in the thermal energy storage, requirement of larger areas. Stirling engine is a type of heat engine that uses an external combustion mechanism for the operation, while the thermal energy from the external heat source is converted into mechanical work and then to electricity, whereas the working fluid is used in this type of heat engine will be chemically inert. This paper overviewed various beneficial aspects of a Stirling engine such as this heat engine is eco-friendly, quiet, efficient and the most noticeable advantage of Stirling engine is the heat absorbed by the working fluid can also be stored by various phase changing materials using regenerators. This paper describes the studies on off-grid power generation for micro-scale applications, design aspects of the CSPP-Stirling engine system, and also various studies on the working parameters of the system.

Key Words: Carbon Emissions, Power generation, Regenerators, Solar Thermal Energy, Stirling Engine, and Thermal Energy Storage.

1. Introduction

Power generation in recent times has become an important per capita energy efficiency development factor globally as all the countries are diversifying to utilize renewable energy which has been playing a crucial role in the sustainable development of the power sector as the sources of this energy kind are abundant, while some renewable sources like solar, wind, hydro and biomass can be harnessed with reduced emissions of greenhouse gases which could be caused due to the utilization of fossil fuels for energy generation [1]. The hybridization of renewable sources can improve the energy efficiency by overcoming the limitations of power generation from standalone systems and also provides a wide scope in installing off-grid hybrid renewable energy systems based on the resources available especially in rural areas because of various factors such as area, climatic conditions, population, hard terrains and revenues [2]. Thus, the integration of various power generation systems with renewable energy can reduce the gap between energy demand and supply in rural areas. Moreover, solar energy is one of the effective alternatives that has been replacing the traditional and conventional power generation using fossil fuels such as coal, oil, diesel, and other gases like LPG, CNG, etc., for power generation. This replacement also protects the environment and ecological conditions [3]. Many advancements have been made in solar power plants for concentrating and capturing solar energy to achieve an appropriate output efficiency, while various equipment such as concentrators (LFRs) and collectors (HFCs, CPCs, PDCs, and PTCs) is used to fulfill the objective of concentrating solar radiation [4-9]. Adoption of a cost-effective technology is a barrier as cost per square meter accounts for the total cost of installation, while the concentration ratio should be appreciable to attain a good range of temperatures to ensure optimum efficiency of the respective system. The Concentration of solar energy can be done at much lower costs when compared to the electricity-generating using solar PV systems [10]. Usually, LFRs and PTCs are used for medium-temperature applications ($<\approx 500$°C), while PDCs and HFCs are used for higher temperature applications (>500°C) [11]. Another barrier that has been affecting the efficiency of a CSPP is energy storage. These concentrators are arranged in a manner by which the sun rays are converged and focused by mirrors onto a certain point at which various power generation systems such as water boilers, Stirling motors, and gas turbines are installed. The power generated should be consistent and regulated because renewable energy sources are uncontrollable and unpredictable as they completely depend on climatic conditions such as humidity, solar radiation, wind speed, temperature, etc. There are many methods to utilize and also store the solar thermal energy and one of the most effective methods is the integration of solar thermal energy with a Stirling engine as this external combustion system has an appreciable range of efficiencies and also this heat engine could be more eco-friendly as any heat medium can be used to drive this Stirling engine, while this also reduces the dependency on the fossil fuels and the power generation from this system can be done without any carbon emissions. The basic representation of power generation using a Solar-dish Stirling engine is shown in figure 1.

Moreover, an energy storage system in a power generation plant is recommended as it stores the excess energy available from the renewable resources in the form of thermal energy and electricity, such that the stored energy will be utilized whenever it is required to fulfill the energy demand. Various energy storage methods such as organic Rankine cycles, Stirling cycles, Brayton cycle, etc., are implemented to recover the excess energy in many combined heat and power applications, while Stirling engines can be significantly used for energy storage and medium temperature applications, these type of heat engines can be integrated with CSPPs for energy storage and power generation which would be a viable alternative to the other thermodynamic cycles as any heat source can operate this kind of heat engine. The Stirling engine incorporation with a CSPP as it can overcome the environmental challenges such as carbon emissions, global warming, habitat loss, and can also protect the eco-system [12].

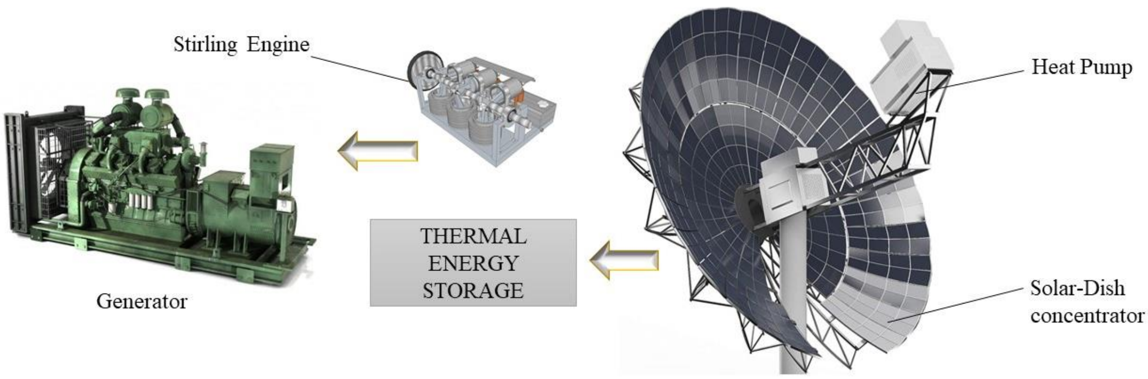


Figure 1: A Solar-dish Stirling engine incorporated with a Thermal Energy Storage

2. Working of a Stirling Engine

Stirling engine is an external combustion engine that was invented by Dr. Robert Stirling in 1816. These Stirling engines have a unique operating cycle that exhibits a closed regenerative thermodynamic process known as "Stirling Cycle" which includes the combination of various cyclic expansion and compression processes such as isothermal compression in stage 1, isochoric heating in stage 2, isothermal expansion in stage 3 and isochoric cooling in stage 4 as shown in figure 1 and the working of the displacer is shown in table 1 [13, 14]. PV and TS representation of the Stirling cycle along with the process flow sheet describing the principle have been shown in figure 2. This regenerative thermodynamic cycle has an appreciable efficient of about 40% which is greater than both otto and diesel engines which have their respective efficiencies of about 25% and 35 % [15]. The Stirling engine works on the temperature difference of the working fluid which can be achieved by any thermal energy source such as concentrated solar energy, biomass combustion energy, etc., that can heat the working fluid which operates the engine, whereas various gases such as hydrogen, helium, air, and nitrogen can be used as working fluids and thus the system will be safer to utilize as the flow by the continuous volume changes in the working fluid and temperature raise at the cold sie is regulated by the installation of various extended surface systems for cooling the engine.

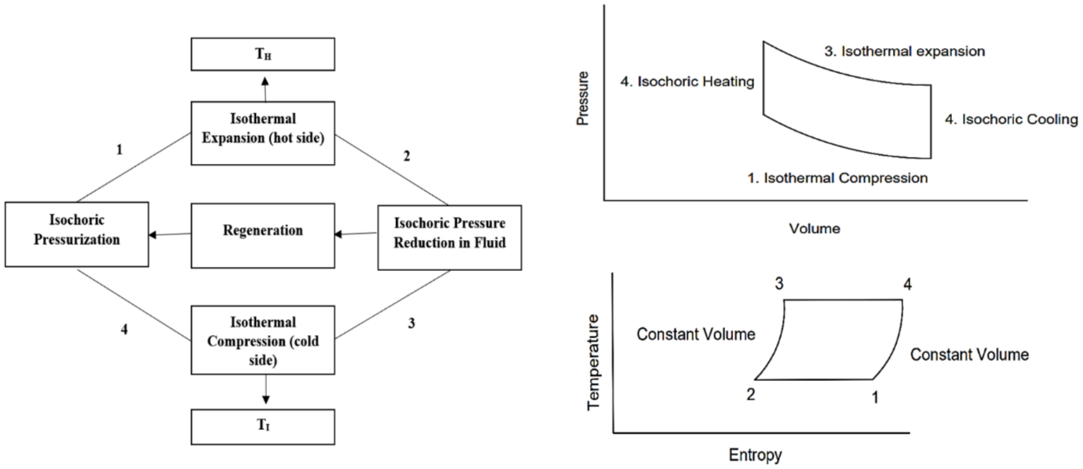
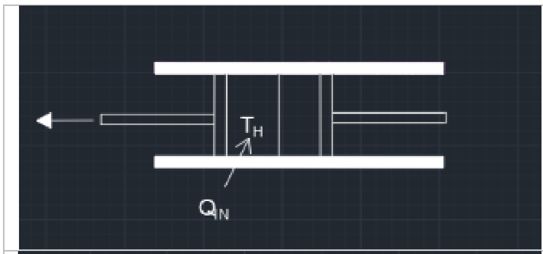
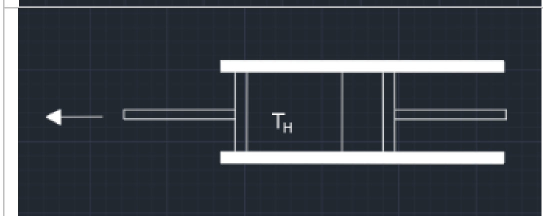
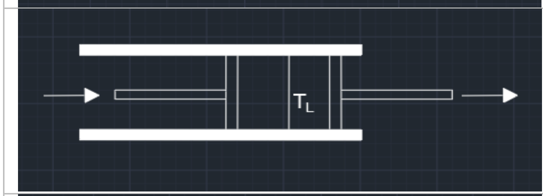
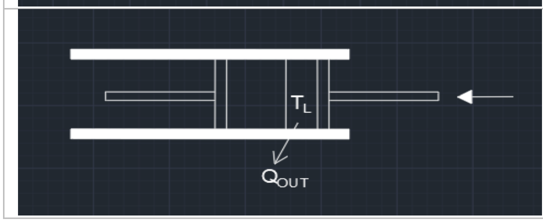


Figure 2: Flowsheet of a Stirling Cycle

Table 1: Summary on the operation of a Stirling engine

	**Step I:** 1. Isochoric or Isometric. 2. Increase in enthalpy of the working fluid. 3. Follows the ideal gas law. 4. Pressure of the working fluid increases.
	**Step II:** 1. Isothermal expansion step 2. Work is done due to the expansion of fluid. 3. Heat transfer takes place between the working fluid and external heat source at a constant temperature.
	**Step III:** 1. Isometric process 2. Enthalpy of the working fluid decreases. 3. Displacement of the working fluid to the cold side from the hot side.
	**Step IV:** **1.** Isothermal contraction of the working fluid. **2.** Work is done due to the compression of fluid.

Considering the environmental aspects and energy utilization to meet the demand, the Stirling engine can be able to deliver an appropriate output with high heat efficiencies, and silent operation with a wide selectivity of operational methods which make it more advantageous in giving an effective low range power outputs by converting solar thermal energy into electricity [12]. However, the power generation from a Stirling engine incorporated CSPP can be a consistent, reliable, and efficient as this combined heat and power system can be suitable for the off-grid power generation in a range of 1-50 kW in residential scale along with building energy demand achieving heat loads [16, 17].

3. Technical Approach to the Solar-Stirling Engine

Though the Stirling engines are the most effective devices in converting solar thermal energy into low range power outputs, still they have some disadvantages as their performance depends on their geometrical and physical characteristics which require large volume, while the other disadvantages such as the probability of working fluid leakage, low compression ratios, slow process and thermal limitations in operating conditions of the heater and cooler temperatures became the barriers of engine's performance [18, 19]. Thus, several methods have been adopted for enhancing the performance of a Stirling engine as it has more advantages when compared to ICEs.

Houda H et al. [20], elaborated the technological challenges and various factors affecting the performance of a Stirling engine which included geometric parameters like compression ratio, phase angle between power piston and displacer, dead volume, swept volume, engine speed, oscillations, and the characteristics of regenerators such as the material of construction, porosity, design, lubrication, and temperature distribution. However, for micro/small-scale power generation purposes, tubular heat exchangers are preferred as heaters and coolers, while for low-temperature applications extended surface heat exchangers or fins are sufficient. A. Asnaghi et al. [21] performed thermodynamic analysis on the performance of solar Stirling engines under ideal conditions which included the regenerator effectiveness for hot and cold sides by determining the effective temperature of the regenerator using various approaches such as arithmetic mean approach, logarithmic mean approach, and half hot space-half cold space approach, while considering piston's motion to be simple harmonic, volumes of the of pistons are determined and by assuming the working fluid to be an ideal gas, the pressure equations and mass of the working fluid is determined. Whereas the thermal efficiency of the entire system is determined from the work diagram of the Stirling cycle.

Du Marchie [22] summarized the calculation of various parameters and characteristics of a solar concentrator system such as the area required for the mirrors for utility-scale solar energy, the efficiency of the solar thermal power plant, and determined the other parameters such as path length of solar radiation through atmosphere, zenith angle, average horizontal irradiance on the mirror field affecting the absorbing factor for four different days. This system was economically integrated with the desalination of water and the cost analysis was done by comparing the results of output power with utility-scale solar PV plants. Ana Cristina Ferreira et al. [23], assessed the performance of the Stirling engine by comparing solar energy and biomass by modelling the CSPP and biomass plant, while the solar dish diameter was taken as 8m, and 45° rim angle was assumed at which the heat flux has been increased as the solar radiation will be focused to a smaller receiving area because at 45° angle the focal distance and aperture ratio are lower [24-25]. A two-step numerical model has been developed for an alpha Stirling engine small scale power generation where solar energy and biomass as external sources.

Analysis of the economy of Stirling engine, pollution generation, and efficiency is very important as the Stirling engines are quiet and pollution less with good efficiency of a minimum of 80% and the cost of energy generation will be cut off for sure as long as there is sunshine. The materials and manufacturing costs of the Stirling engine as its efficiency increases with the increase in temperature and so the materials should withstand the higher temperatures. The exploitation of the technology like Stirling engine will reduce the environmental impacts and dependency on the fossil fuels.

4. Conclusion:

This paper reviewed various technical, environmental and economic aspects of a Stirling engine which can be employed for various applications in power generation and co-generation technologies. The versatility of this heat engine makes it a unique model for both commercial and micro-scale purposes, as it is highly efficient, quiet, safe and simple in the operation perspective. The design must be done by considering the leakage probabilities of the working fluid, and effect of lubrication on the working fluid. Even though, there are some limitations such as high costs, low reliability, and low production rates which became the major barriers for Stirling engines to succeed commercially in market. The PCMs used for thermal energy storage also makes the entire system expensive. But still, globally there are many research studies are being done to improve the characteristics of this heat engine as it has a large scope in the energy sector, because besides its limitations Stirling engine when integrated with CSPP can reduce the CO_2 emissions of nearly 60% and the performance can be improved in co-generative operation of this system especially in winters. The Solar-Stirling engine systems can be the better option for off-grid power generation. Lastly, the Stirling engine has a potential to be competitive enough with the other renewable technologies with some necessary technical modifications to make this heat engine a feasible and effective option for power generation in the commercial space such that the penetration of this technology into market would improve the energy efficiency and also quality of the environment by decarbonization. However, still further research is needed to overcome the challenges and making the Stirling engine commercially viable and cost effective.

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