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# Performance testing of a Fresnel/Stirling micro solar energy conversion system

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ABSTRACT

In this study, a beta-type Stirling engine was tested with concentrated solar radiation. The displacer cylinder of the engine was modified by integrating a concentrated solar radiation receiver. Basically, the receiver is a cavity drilled in a separate part mounted on top of the displacer cylinder by screws. Tests were conducted with three cavities made of aluminium, copper and stainless steel. The solar radiation was concentrated by a Fresnel lens with 1.4 $m^2$ capture area. Among the cavities, the highest performance was provided by aluminium cavity and followed by the stainless steel and copper cavities respectively. The maximum shaft power was observed as 64.4 W at systematic tests conducted with the aluminium cavity. The maximum shaft power corresponded to 218 rpm engine speed and 2.82 Nm torque. For this shaft power, the overall conversion efficiency of the system was estimated to be 5.64%. The maximum torque measured with aluminium cavity was 2.93 Nm corresponding to 177 rpm below which the engine stopped. The Fresnel-lens/Stirling-engine micro power plant established in this investigation was more efficient than the micro power plants presented in the literature.



## 1. Introduction

Researches related to the conversion of solar energy into power were initiated in 1870 by John Ericsson, who established a micro solar energy conversion plant generating steam and producing power via a steam engine. The power of the prototype was reported as 373 W where the steam was produced directly in a collector [1]. It is also known that Ericsson built a solar engine working with air. The development of the petroleum industry and internal combustion engines decreased the interest in solar power after the end of nineteenth century. Until the petrol crisis in 1973, the interest in solar power was very low. After 1973, the petrol crisis stimulated investigation of solar energy, and a large number of research projects were initiated to develop solar energy technologies for electricity generation [2]. Investigations progressed in two different branches: photovoltaic and thermal power technologies [3]. Photovoltaic technology facilitates a direct conversion of sunlight into electricity via photovoltaic materials, which were discovered in 1839 by Edmund Becquerel [4,5]. In 1958, a second photovoltaic cell made of gallium arsenide was discovered with 11% conversion efficiency. In the 1960s, amorphous silicon cells were developed, which are more practical to use but less efficient than crystal photovoltaic cells. Photovoltaic cells providing conversion efficiencies of about 30% were developed but have not been commercialized yet [6].

In solar thermal power technology, the conversion of the solar radiation into electricity is performed via a thermodynamic system and an electricity generator. So far, four different thermal power technologies have been developed and they are the parabolic trough, the power tower, the chimney, and the dish/engine [7].

In parabolic trough technology, the sunlight is concentrated onto a pipe receiver to heat up a heat transfer fluid. The heat transfer fluid conveys the heat to a heat exchanger where a high pressure vapour is generated. The generated vapour is fed to a steam turbine to generate power and electricity. The tracking mechanism of parabolic trough technology is one-dimensional and the concentration ratio is about 75 [3,8]. The parabolic trough technology is able to generate vapour at about 400 °C [1,9]. The first solar power plant with parabolic trough technology was established in California Mojave Desert in 1984, and it has been still generating electricity since then [10,11]. The total annual solar-to-electricity conversion efficiency of the parabolic trough system was reported as 15% [12].

The power tower technology is a point focusing system where a group of mirrors reflect the incident solar radiation onto a receiver placed on top of a tower. The mirrors aligned around the tower mostly have a spherical surface profile and they are called as a heliostat. In tower power technology, the concentration ratio of the solar radiation is between 500 and 1000. The receiver may have

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a temperature in excess of 1200 °C, and it is produced from ceramics capable of resisting high temperatures. The heat appearing in the receiver is used for generating high pressure steam. The steam obtained is expanded by a steam turbine coupled with an electricity generator. The power tower technology is also used for drinking water production, hydrogen production, and chemical reactions [13].

The solar chimney is a technology which converts solar radiation into electricity without concentrating the solar radiation. The chimney consists of a circular tower, a transparent roof, and an air stream turbine [14–17]. The air flow is induced by the buoyancy of warm air. The air is heated as a result of the greenhouse effect under the transparent roof, becoming lower in density, and thus a continuous air flow is induced. The air enters the system through the peripheral aperture around the roof and exits from the top of the tower. The turbine installed in the circular tower is run by the air stream, and the power obtained is converted into electricity by an electricity generator coupled to the turbine. The chimney built in Spain demonstrated the viability and reliability of the chimney concept, but the thermal conversion efficiency of the chimney was too low. To improve the thermal efficiency of the chimney technology, it was estimated that a tower having heights of hundreds of metres would be required [14].

The dish/engine system comprises a parabolic dish concentrator, a receiver, a heat engine such as a Stirling engine, and an electricity generator coupled to the engine. In these systems the dish concentrates and reflects the solar radiation into the receiver which is a cavity absorbing the radiation and transferring to the working fluid as heat. The engine converts the heat into the mechanical power and transmits to the electric generator [18].

In large dish/Stirling systems, having more than 100 $m^2$ collector area, constructed before 1990, kinematic and free piston Stirling engines were used. In most cases the engine and electric generator are constructed hermetically and charged with helium or hydrogen. The charging pressure of the working fluid to the engine was more than 100 bar. The expected performance appeared above 700 °C [18]. Because of very big installation expenditure and operating difficulties, these systems were abandoned [3]. After 1990, investigation of low cost and structurally simple solar energy systems became fashionable. In this content, the engines named as 'Low Temperature Difference' (LTD) attracted very much attention [19].

A parabolic concentrator used in a dish/Stirling solar system may provide a concentration ratio of more than 3000 [18]. For parabolic dishes made of back-silvered low-iron glasses, 70–80% reflection efficiencies were reported under 1000 W/$m^2$ solar radiation [20]. In dish/engine systems, the performance of the receiver is one of the most important factors determining the total efficiency of the system. Receivers used in solar energy application are designed at different shapes such as hemispherical, cylindrical, conical and so on [21]. A receiver may cause heat losses by radiation, convection and reflection [22]. For ordinary cavity receivers with no perfect isolation and absorptive surface, the efficiency is reported as lower than 40% [23]. In sophisticated receivers designed for dish/Stirling systems, the efficiency is reported as between 65% and 90% where the solar radiation is absorbed by the surface of the tubes, in which the working gas of the engine circulates, or by the surface of a sodium heat pipe [24]. Total conversion efficiencies exceeding 30% were reported for this system [18]. The total annual solar-to-electricity conversion efficiency of the dish/engine technology was reported as 18% [2].

In the current situation, the share of renewable energy technologies such as wind, solar, geothermal, and biomass in worldwide energy consumption is 2.1% [25]. For the current situation, the production of solar electricity is not attractive to private investors because it is not competitive with fossil fuel based electricity. However, it is known that the combustion gases generated by internal combustion engines and thermal power plants have harmful effects on the health of living things and environment. Solar electricity is one of the plausible technologies to reduce the generation of combustion gases. In the near future, the electrical vehicles are expected to take place of the vehicles with petrol engines. These developments may increase the competitiveness of solar power via increasing the demand for electricity.

In this study a beta-type Stirling engine was tested with solar energy. The solar radiation was focused into a cavity situated on top of the displacer cylinder. To concentrate the solar radiation into the cavity, a Fresnel lens with 1.4 $m^2$ capture area was used. The influence of cavity materials on the performance of engine was studied by manufacturing and testing three cavities made of aluminium, copper and stainless steel. The highest performance was obtained with aluminium cavity.

## 2. Experimental facilities

In the experimental system, a non-regenerative, beta-type, Stirling engine was used by modifying its displacer cylinder. In this engine, heating and cooling of the working fluid is performed via the flow channel between the displacer and its cylinder. The channel also performs as a regenerator. Before modification of the displacer cylinder, the maximum power of the engine was measured as 253 W at 545 rpm engine speed, 4.5 bar helium charge pressure and 360 °C heater temperature [26]. The other technical specifications of the test engine are given in Table 1.

The modified displacer cylinder consists of two sections as seen in Fig. 1. The upper section works as a cavity and heater while the lower section works as a regenerator and cooler. The coupling of the sections was made with delicate flanges. The upper section (cavity and heater) was manufactured as a unique part and involves no resistance limiting the flow of heat from the cavity to the heater. Fig. 2 illustrates the dimensions of cavities made of copper and aluminium or stainless steel. The lower section of the displacer cylinder was manufactured from stainless steel. Fig. 3 illustrates the photographs of cavities made of aluminium, stainless steel and copper.

In order to prevent heat loss, the outer surface of the displacer cylinder was insulated from the surrounding air. A ceramic fibre blanket with thermal conductivity of $k = 0.08$ W/mK was used for isolation. The thickness of the ceramic blanket was 40 mm, and the free surface of the blanket was coated with aluminium foil. The heat transfer area at the working fluid side of the displacer cylinder was enlarged by growing span-wise slots 3 mm in depth and 2 mm in width [26–28].

The hot-end temperature of the displacer cylinder was measured via a thermocouple embedded into the cavity wall. The torque of the engine was measured by a Prony-type hand dyna-

**Table 1**
Technical specification of the test engine.

| Parameters | | Specification |
|---|---|---|
| Engine type | | β |
| Power piston | Bore × stroke (mm) | 70 × 60 |
| | Swept volume (cc) | 230 |
| | Material | Aluminium |
| Displacer | Bore × stroke (mm) | 65 × 79 |
| | Swept volume (cc) | 262 |
| | Material | Stainless steel |
| Displacer cylinder | Material | Stainless steel |
| Lubricant filled in crankcase | | SAE 20/50 |
| Working fluid | | Helium |
| Cooling system | | Water cooled |
| Compression ratio | | 1.63 |