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Experimental and theoretical investigations of a γ-type Stirling engine powered by a parabolic solar concentrator in the city of Karaj: a case study

Hasan Sabahi, Mansoor Keyanpour-Rad[a] and Ali Asghar Tofigh

Department of Energy, Materials and Energy Research Center, Karaj, Iran

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Abstract – This paper provides theoretical and experimental investigations on the performance of a Stirling generator in the city of Karaj which is located about 40 km west of Tehran. A designed and fabricated γ-type Stirling engine was mounted in the focal point of a parabolic solar concentrator to generate electricity at the site of the Materials and Energy Research Center (MERC) which is located in the south east of the city of Karaj. This engine was able to operate with any heat source when the source provides a minimum temperature of 220 °C and therefore, a parabolic concentrator with 1.9 m diameter was used for this purpose throughout the experiments. The maximum of net electrical power obtained in the system was 11.16 W with calculated total efficiency of 0.54% when the solar radiation at the experimental area was measured to be 860 W.m^{-2}. In order to program the generator to operate as a small stationary power plant at the site of MERC, the annual performance of the Stirling generator was evaluated by using the solar data collected at the site for consecutive 12 years. Typical days were extracted from the data for each month of the years to estimate the average hour numbers of the days when the solar radiation was sufficient enough to produce electrical power by the Stirling electrical generator.

Key words: Case study / Karaj city / Stirling engine / solar radiation / electricity generation

1 Introduction

The increase in pollution and leakage of fossil fuel sources has been developing the application of renewable energies which have advantages, such as availability, low pollution and risk. Solar energy is the most promising renewable energy source and being considered as the most powerful one among these clean sources of energy [1]. Various technologies have been developed to convert solar radiation to electricity. Stirling engines are thermomechanical devices for generating rotational energy from absorbed heat of solar radiation and converting it to electricity by means of an electrical generator.

These engines can be powered by any source of thermal energy (combustion energy, solar energy, etc.) and when solar energy is considered for the heat source, they are mounted at the focal points of solar parabolic concentrators which furnish the required thermal energy for their operation [2]. Varieties of Stirling engines exist which are generally classified into three different categories according to their configurations, namely α, β, and γ types [3]. The α-type of configuration features two pistons, each in its own cylinder; β-type has a piston and a displacer in the same cylinder; and γ-type has a piston and a displacer, each in its own cylinder [4].

Although Iran has vast resources of fossil fuels, but because of environmental pollution aspects of using such sources, especially the air pollution in large cities of Iran, therefore some activities have been focused in application of renewable energy sources. The feasibility of application of solar heating systems in houses and industries of Iran was fully studied by Keyanpour et al. [5]. The study showed that this country has significant potential of solar energy and it is completely feasible to use solar heating systems in many regions of Iran. Southern Khorasan and Khuzestan provinces of Iran receive significant amounts of solar radiation such that the application of solar systems in these regions is more economical. Delgan, Mahshahr, Shushtar, Abadeh, and Fadashk stations in Iran have recorded an annual average of horizontal solar radiation of above 500 J.m^{-2} which shows the high potential for photovoltaic applications in these regions of Iran [6,7]. Therefore, some projects pertaining to solar energy applications have been utilized and carried out by the Iran Ministry of Energy [8].

[a] Corresponding author: m.kianpour984@yahoo.com

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MERC energy site is located in the southern part of the city of Karaj which is located about 40 km west of Tehran with the latitude of 35.55° north and the longitude of 50.54° east. It has a moderate climate and receives average solar radiation of 4.36 kW.h.m^{-2}.day with minimum of 1.45 kW.h.m^{-2}.day for cloudy days in January and February and maximum of 7.3 kW.h.m^{-2}.day for sunny days in June and July, while the average wind speed and relative humidity in this city are reported to be about 3.56 m.s and 32.9%, respectively. Therefore, because of excellent solar energy the renewable energy site of MERC receives each day, this study was organized to provide experimental and theoretical evaluations of a γ-type Stirling engine which was mounted at the focal point of a parabolic concentrator to generate electricity. To operate this electrical generating system as a stationary small power plant at the MERC site, the solar data of 12 consecutive years was theoretically evaluated.

2 Theoretical aspect of the experiments

The experimental solar system was mainly composed of γ-type Stirling engine and a solar parabolic concentrator which converted solar energy to electricity by means of an electrical generator.

Solar energy changes to electrical power according to the following equation [9]:

$$P_f = E_s A \eta_t = E_s A \eta_{conc} \eta_{rec} \eta_s \eta_{Gen} \quad (1)$$

where P_f is the final power of the system, A is the effective normal area of the concentrator to solar beam, E_s is solar radiation emitted to the concentrator and η_t is the total efficiency of the system. The cylindrical cavity receiver efficiency (η_{rec}) as a function of solar insolate and mirror parameters is reported by Costea [10]. Bejan and Petrescu [11,12] for Stirling engine thermal efficiency (η_s) expressed a relation between the Carnot cycle efficiency and the second law efficiency for Stirling engines. The concentrator efficiency (η_{conc}) could be calculated similar to the Rafeeu [13] method, and the efficiency of the generator (η_{Gen}) is extracted from the company documentation (Kormos), which is reported to be 40 W.

3 Experiments

Figure 1 shows the complete experimental set up. A parabolic concentrator with diameter of 1.9 m was used to focus the solar beam radiation in its focal point, where the hot end of the engine was mounted to absorb the high thermal energy of the solar radiation. The inside surface of the concentrator was covered with a mirror, as shown in this figure. The tracking was done via 2 degrees of freedom, one movement was spinning on the vertical axis normal to the earth surface and the other was created by up and down movement via a hydraulic arm which caused rotation about the parallel axis to the earth surface. Energy demand of the motors was supported by solar PV panel which was installed beside the concentrator. The solar beam radiation was normal to the PV panel surface by tracker system in all the times.

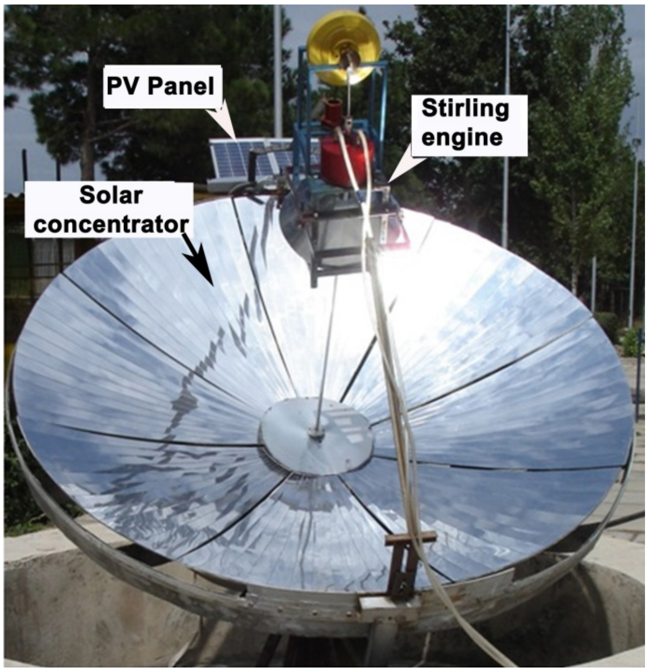

Fig. 1. The complete electrical generator system.

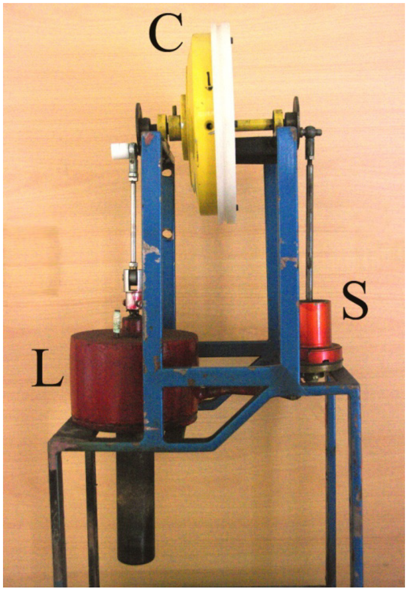

Fig. 2. The fabricated Stirling engine (L: large cylinder, S: small cylinder, C: coupling).

The single acting-acting Stirling engine with gamma configuration, as shown in Figure 2, was designed and fabricated according to the method reported in reference [14]. The engine consisted of a power piston and one displacer sited in the two separate cylinders, as shown in this figure. The hot point of the engine which receives the heat energy of solar radiation, was installed at one of the ends of the large cylinder (L) which was mounted exactly at the focal

Table 1. Main design parameters and characteristic of the Stirling generator.

Mechanical configuration	Gamma
Power piston	
Bore × stroke (cm)	4 × 9
Swept volume (cc)	113
displacer piston	
Bore × stroke (cm)	3.4 × 4.5
Swept volume (cc)	41
Flywheel diameter (cm)	20
Phase angle	90°
Concentrator characteristics	
Surface area	0.91π
Tracker	2 axis
Generator detail	
AC/DC mode	DC
Power (watt)	40
Voltage (volt)	24

point of the solar concentrator. Other side of the cylinder was the cold end of the engine where the absorbed heat was given off to the surrounding through convection. A shell and tube heat exchanger, which contained water as the cooling fluid, was used in the system. The other cylinder (S), as a displacer, was smaller than the large one (L) which did not connect to the heat source and could transfer thermal energy to the environment. Two pistons were connected to the coupling (C) with 90° differential phases and the engine working fluid was chosen to be the air.

For increasing the speed of the engine by 20 times and transmitting mechanical energy from the engine to the generator, a pulley and belt was carefully connected to the engine and the generator. The generator produced electrical energy from the rotational energy of the coupling, and so, a 40-watt DC generator was installed to the system, as shown in Figure 1. In order to measure the solar radiation received at the site of MERC, a pyrometer (Kipp&Zonen CMP21) was used throughout the experiments. The characteristics of the complete electrical generating system are listed in Table 1.

4 Results and discussions

By inserting the data listed in Table 1 into equation (1), the total efficiency of system was calculated to be 1.2%. Ultimately by taking account the efficiency obtained for the system and also the solar radiation received at the MERC site, which was 860 J.m^{-2}, and the surface area of the concentrator, the final electrical power of the Stirling generator was predicted to be 25 W.

Experimental results showed that when input energy of 860 J.m^{-2} was supplied by the parabolic concentrator, the final electrical power of the Stirling system was 11.16 W and the total efficiency of the system calculated to be 0.54% when the speed of the rotating couple of the engine was reached to 280 rpm. The difference of 11.16 W (experimental) and 25 W (theoretical), as founded and calculated respectively for the final power

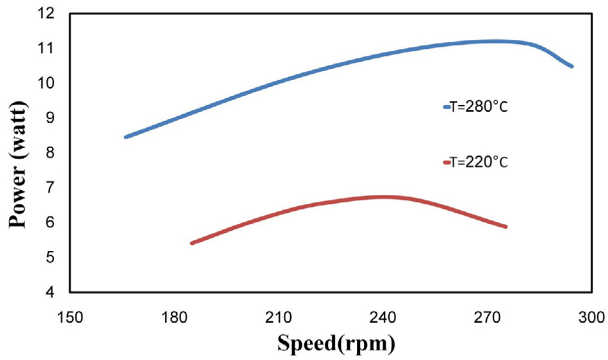

Fig. 3. Variation of power with the speed of the engine for 2 different input energies for the Stirling engine.

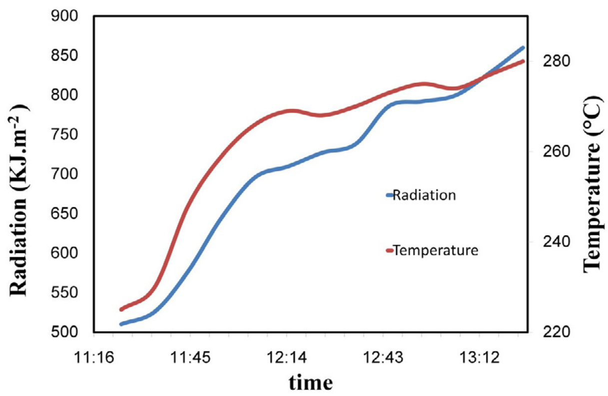

Fig. 4. Variation of temperature and radiation absorbed by the hot end of the Stirling engine during the experiments.

of the electrical generating system, was assumed to be related to the errors in fabrication of the complete electrical generating system.

As shown in Figure 3, it was noticed that in the higher speed above 280 rpm, the power of the engine started to decrease at the temperature of 280 °C. For obtaining a more efficient electrical generating system, it was noticed that the temperature difference between the hot and the cold ends of the engine should be 190 °C when the cold end temperature of the engine was 30 °C (close to the ambient temperature). It was also noticed that the minimum solar radiation should be 510 J.m^{-2} for the engine to start operation (the temperature of the hot end of the engine was 220 °C).

Figures 4 and 5 show the variation of the hot end temperature of the engine versus the solar energy during the experiments. Although increasing the surface area of the concentrator could provide more solar energy for the system and hence furnishes more heat for the hot end of the engine, but because of limitation of the metallic material used for fabricating the hot end of the engine, the increase in temperature at noon time could damage this component of the engine.

To study and evaluate the performance of the Stirling generator as a stationary small electrical power plant at the MERC site, the solar radiation of 12 consecutive years

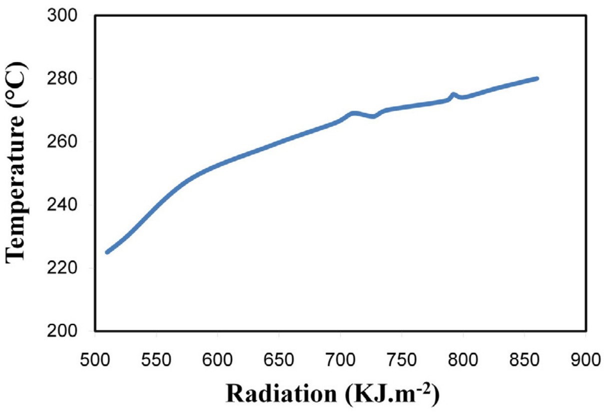

Fig. 5. Temperature changes of the Stirling hot end versus radiation received at the site.

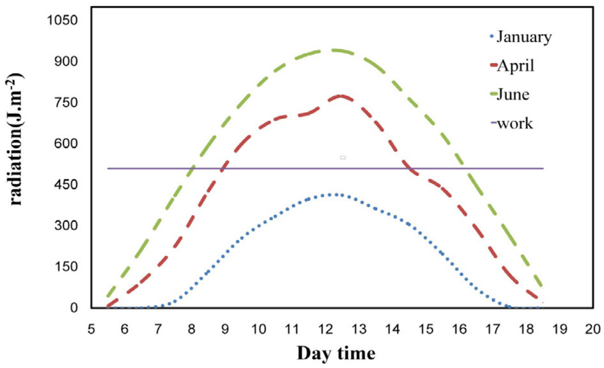

Fig. 6. Average of solar radiation for January, April and June extracted from the 12 years data bank.

(1998–2010) was used in this study. The data were statistically analyzed to calculate roughly the duration of the working hours for the electrical generator system to be used as a small stationary power plant at this site. The sunrise to sunset average solar radiation which received at this site in each month of the 12 years, was calculated. For example the average solar radiation for January, April and June of the 12 years is shown in Figure 6. The so-called "work" line in this figure shows the radiation of 510 J.m^{-2} which is considered as the minimum amount of solar radiation required for the generator system to start operation.

It was discussed that Stirling generators work upon the temperature difference that supplied by the solar heat and showed that a minimum solar radiation of 510 J.m^{-2} was needed to keep the engine continuously running at the site of MERC. Experimental solar data were used to determine the time when the system was able to generate electricity. Figure 7 illustrates those hours which the radiation was more than 510 J.m^{-2} and the Stirling generator could generate electrical energy from the absorbed solar radiation. As it could be noticed from this figure, there was a significant difference between the winter and the summer times, when solar radiation drastically changed from one season to another during the experiment.

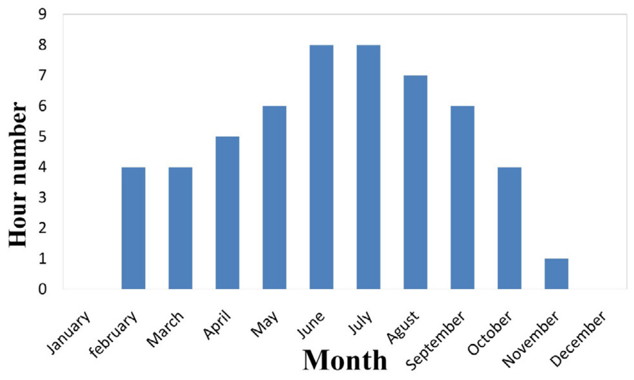

Fig. 7. The time of working hours in every day for each month.

5 Conclusions

The aim of this study was to conduct an investigation for using solar energy to generate electrical energy of a γ-Stirling generator at the site of MERC, which is located in the city of Karaj. For this purpose a γ-Stirling engine was designed, fabricated and mounted at the focal point of a parabolic solar concentrator. The collected solar data for 12 consecutive years in this city helped to predict the performance of the system at the site of MERC as a stationary small electrical power plant.

According to the theoretical investigations, it was predicted that the Stirling generator could have final power of 25 W with the efficiency of 1.2%, but the results obtained from the experimental study showed that the electrical generating system only operated with the final power of 11.16 W and the efficiency of 0.54%.

The solar data of these years were used to find out the efficient working hours in each day of the months at the site and also to evaluate the performances of the generator. The findings of this study are as follows:

(1) The average hour radiation received for each month could be used to identify and predict the number of hours that the Stirling generator can operate.
(2) The system works with the most efficiency in June and July and the least in January and December of each year.

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