ISSN No:-2456-2165

An Experimental Study on Performance Investigation of Solar Dish Sterling Engine in Pakistan

Sameeullah Khan Pathan [1,2], Muhammad Ali Abro [1]
Mujeeb Iqbal Soomro [1*], and Abdul Shakoor Shaikh [2]
[1]Department of Mechanical Engineering, Mehran University of Engineering and Technology, Shaheed Zulfiqar Ali Bhutto Campus, Khairpur Mir's 66020, Sindh, Pakistan
[2]Department of Mechanical Engineering Technology, Benazir Bhutto Shaheed University of Technology & Skill Development, Khairpur Mir's 66020, Sindh, Pakistan

Abstract:- Pakistan is among the developing countries of the world which suffers from worst energy crises. The energy crises of the country could be overcome by utilization of renewable energy sources such as solar energy. This research presents an experimental study on the performance investigation of solar dish sterling engine. The designing of the dish and sterling engine was performed on AutoCAD software. The system was fabricated locally, and experimental study was performed for the weather conditions of Sukkur, Sindh, Pakistan. The system consisted of a parabolic dish, solar reflectors, gamma Sterling Engine (double acting type), fan blades, flywheel and dynamo (alternator) having capacity to generate almost 100 watts of electricity. The horizontal radiations falling on dish were directly focused on the receiver (displacer) end of the sterling engine. The heat produced due to solar radiations was used to run the gamma type sterling engine. The experimental study that the total efficiency of the sterling engine was about 70.96% by neglecting the losses.

Keywords:- *Energy Crises; Solar Energy; Sterling Engine; Pakistan.*

I. INTRODUCTION

Energy consumption is globally proliferated due to rapid development in technology, growth in population, and changes in living standards. However, the impact of higher energy consumption on the environment has created an alarming situation throughout the globe. Therefore, the area of energy conservation has grasped a high share in the recent research. During last two decades energy consumption has increased by 49% in various sectors, which has proportionally raised the CO_2 emission by 43% in developed countries. The demand for energy in most of the underdeveloped as well as in the developing countries such as South East Asia, Gulf Countries located in the Middle Eastern region, the South America and Africa is growing at a rate of 3.21% per annum. It is expected that such a growth rate is bound to outdo average consumption and energy requirement of the developed countries by around year 2020. The energy consumption in rest of the world, is not going to be that high as estimates suggest as in the countries just mentioned [1, 2]. Back in 2015-16, the consumption of electricity in Pakistan was 78.2 MTOE, of which 77.71% was produced domestically and 0.49% was imported and its significant share is produced by utilizing non-renewable energy resources. In Pakistan, new plans are aimed to raise country's dependence on imported oil for power generation to 50% and 50% on renewable energy resources by 2030.

Amongst all the technologies of power generation on a macro levels available today, the concept of the concentrated solar power (CSP) is enticing. This is because it helps conserve fossil fuels which reduces the environmental impacts. In CSP plant, the solar radiations are directed to a point or line. The heat received from the solar energy is employed to raise the temperature of a working fluid [3, 4]. In addition, CSP plant can produce electricity even when sun set due to its inherent capability to store heat energy. It enables CSP to produce power with later conversion of stored energy. They also require some backup systems based on other energy resources in order to ensure continuous supply of electricity. Being commercially viable for electric power generation, it has diverted attention of both private and government sector to use CSP technologies and it will significantly contribute in world's energy mix [5, 6]. Parabolic dish is a type of CSP, and it generally use an engine such as Sterling engine which utilized heat from solar energy to produce power.

Sterling engine was invented by Robert Sterling in 1816 [7]. It has the capability of being powered by any sort of energy provided externally, including waste [8, 9]. Sterling engine is focused because of its high efficiency. It can meet the efficiency of a Carnot's engine, theoretically [10]. It needs low maintenance as compared to other engines. Sterling engine is externally heated engine consisting of two Isochoric (constant volume) and two Isothermal (constant temperature) processes. Due to resistance in transfer of heat, the losses in energy such as heat losses, occurring due to gas leakage, can be seen in actual Sterling engine. This results in low thermal efficiency. However, vis-à-vis theory, the thermal efficiency of Sterling cycle is high as compared to the Carnot's cycle. Sterling engines are generally categorized as (a) Free Piston, and (b) Kinematic Engines. In free piston engines, the synchronization between piston and displacer is offered by springs and pressure exerted by the gas. On

ISSN No:-2456-2165

the other hand, Kinematic engines include a mechanism comprising of components such as Crank, Lever, Rhombic and Ross Yoke. By piston configuration, Sterling engines are grouped into three classifications, namely, alpha (α), beta (β) and gamma (γ). The Beta type Sterling engines have one piston. The placement of both its power piston and displacer is coaxial. Gamma type & Alpha type engines have two cylinders. In alpha type engine, both cylinders employ a piston while in gamma type engine there is one piston in the cylinder while the other contains a displacer at the other end [11, 12].

Several research works have been carried out on manufacturing, testing and development of Sterling engine by analysing the different parameters, viz, fluid, temperature, and pressure [13-16]. There are some numerical studies, as well, to forecast the performance of the engine for the sake achieving optimization [17-19]. V.S. Reddy et al. [20] carried out the study for the objective of exergy and thermo-economic analysis of a parabolic dish Sterling engine solar power plant at Jodhpur, India. The parabolic dish was designed in so as to have a capacity of 50 Megawatts, comprising of 2000 units, each having a design capacity of 25 Megawatts. The Energetic efficiency varied from 15.568% to 27.086% whereas the exergy efficiency varied from 16.824% to 29.176%. The unit cost of electric energy generated per kWh was found to be about 8.785 INR, with the plant's operating life being 30 years. Mohammad H. Ahmadi et al. [21] carried out research for deriving a value for heating efficiency of Sterling engine along with thermal efficiency, thermal power output and thermo-economic factor. In addition to this, the research also found out the exact engineering values of the three variables mentioned [22-23]. It was concluded that heating efficiency, power yield and economics of a Sterling engine highly relied upon temperature of source and of working fluid, temperature ratio, and property of irreversibility. The numerical values for the three mentioned variables were obtained using three different approaches namely, (i) fuzzy decision making approach, (ii) linear Mapping (LINMAP), and (iii) Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The thermal efficiency ranged between 40% and 45% while the thermal efficiency of dish Sterling system ranged between 35% and 40%. In case of dimensionless thermo-economic expression, it was found using Non-dominated Sorting Genetic (NSGA-II) algorithm. Gholamalizadeh, E. et al. [24] constructed a parabolic dish Sterling engine to carry out the energy and exergy investigation of a parabolic dish Sterling engine at Kerman, Iran. Exergy and energy efficiency were computed regularly. It was observed that the maximum collector energy and collector exergy efficiency were 54% and 41.5%, respectively. Moreover, total energetic efficiency and exergetic efficiency were 12.2% and 13.2%, respectively. The energy losses were found to be the highest in the receiver, viz, 56.1%. Considerable energy losses were also found in the Sterling engine and concentrator, with percentages of 34.12 and 9.68, respectively. Percentages for the losses in exergy were also determined for receiver, Sterling engine, and concentrator with numeral values of 43.4, 23.3, and 33.3, respectively. Li, H.Y. et al. [25] analyzed the energetic and exergetic efficiency of a power plant working on concentrating solar radiations using thermal energy storage system. The concentrating solar power plant employed a parabolic dish concentrator, receiver, thermal energy storage reservoir and Sterling engine. The observations were recorded during both day and night. The conclusions were that thermal storage system does not decrease the efficiency of the Sterling engine and rather improves its energetic and exergetic efficiency as well as the design and selection of parabolic dish. Çınar, C. et al. [26] carried out a case study related to the alpha type Sterling engine with helium gas as the working fluid. The charge pressure was kept within 1 to 4 bars, while the heating temperature ranged within 800 ºC to 1000 ºC. The maximum output power recorded during the analysis was 30.7 watts at an engine speed of 436 revolutions per minute. The highest power yield was gained at a heating temperature of 1000 ˚C and 3 bars of charge pressure.

This research presents an experimental study on the performance investigation of solar dish sterling engine. The system has been fabricated locally, and experimental study has been performed for the weather conditions of Sukkur, Sindh, Pakistan to evaluate the performance of the system.

II. STERLING ENGINE

Sterling engine is based is based on closed cycle external combustion engine. /many working fluids are used in Sterling engine i.e., air, helium, and hydrogen. Usually air used which is sealed in a container. This means that fixed amount of air is used which is heated externally and produced useful work. Sterling engine works on two constant thermal processes and two constant volume processes. Sterling sterling engine can work on any heat source given externally including fossil fuels, hot air, chemical, nuclear, and solar energy. It can run on low temperature as low as 7 ^{0}C between the source and sink. Fig. 1 shows the different fuels used to run sterling engines. If sterling engine seen as mechanical arrangement it is designed in many simple arrangements consisting about at least 20 parts [27, 28].

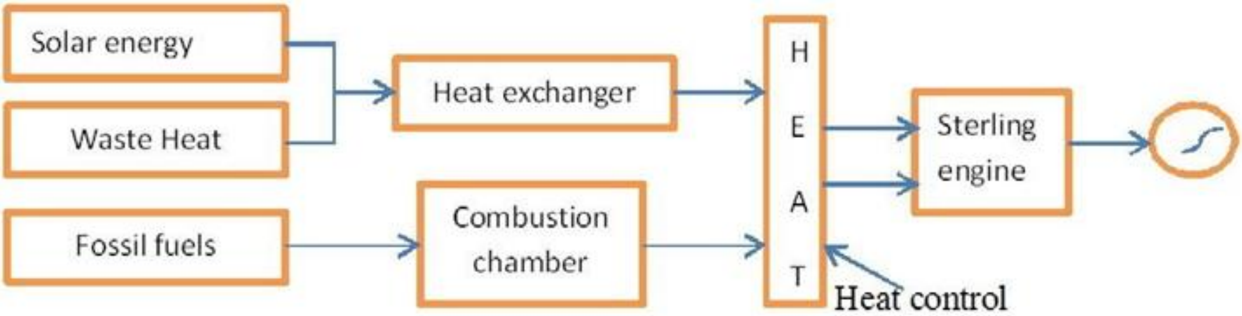

Fig 1:- Different Fuels Used to Run Sterling Engines.

There are three main types of sterling engine which are alpha, beta, and gamma. Fig. 2 shows the types of sterling engines (a) Alpha (b) beta (c) Gamma. In this study, gamma type Sterling engine was selected because of its simple construction.

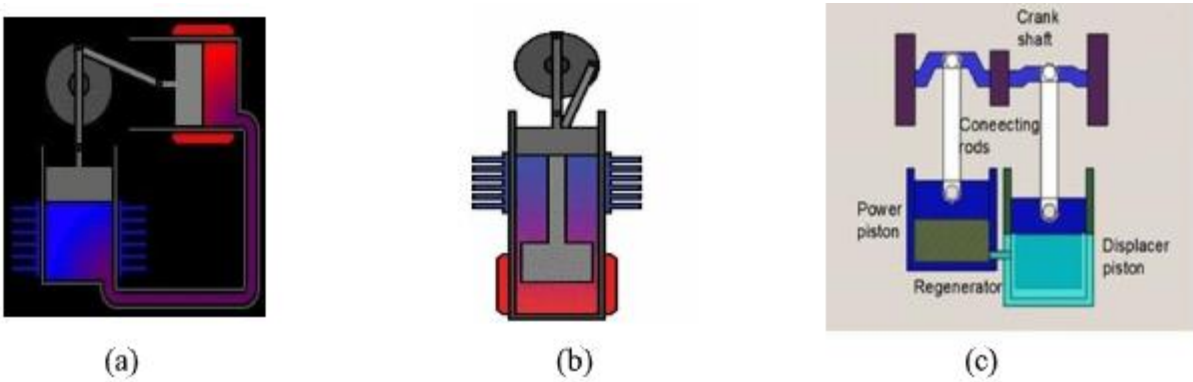

Fig 2:- Types of Sterling Engine (a) Alpha (b) Beta (c) Gamma.

Sterling engine can work on many sources i.e., thermal, bio gas, solar and nuclear etc., but we are focusing on the solar energy as the energy from the sun is abundant in nature and available completely free of cost. It can be utilised by concentrate solar energy by solar collector through a parabolic dish which is an efficient way to concentrate solar energy. With the help of solar dish concentrator, a huge amount of solar energy can be concentrated to the focal point where sterling engine is installed. To energize sterling engine, the solar radiations are transformed into heat energy and that energy thus obtained is utilized to run sterling engine. Electricity thereby is produced by employing an alternator. Solar radiations directly strike on parabolic dish, due to parabolic shape of dish these radiations concentrated and directed to the displacer piston. As the temperature increases air which is used as fluid expands and pushes the displacer piston upward means constant thermal expansion takes place, than hot air enters into the regenerator where heat is dissipated and air become to cool thus constant volume heat rejection process takes place than that air is compressed by the power piston so constant thermal compression process at its start so the cool air enters into the displacer piston through regenerator thus constant volume heat addition process starts through concentrated solar heat energy.

III. EXPERIMENTAL SETUP

Table 1 lists the characteristics of solar reflective material. Fig. 3 shows fabricated solar dish concentrator. The dimensions of parabolic dish are as diameter of parabolic is 1.584m, area of concentrator is 1.9708 m^2. Table 2 shows the dimension of the parts designed and assembled into Sterling engine.

Material	Reflective (%)	Emissive (%)
Polymeric Film, mon-metal	98	2
Aluminium, acrylic	98	2
Silver, Aluminium acrylic	97	3
Silver, acrylic	95	5
Aluminium	86	14

Table 1:- Characteristic of Solar Reflective Material

Fig 3:- Fabricated Solar Concentrator Parabolic Dish

S.No.	Part name	Specification
1	Bore of power piston	5.36 cm
2	Stroke	3.5 cm
3	Swept volume	$79.23cm^3$
4	Bore of displacer piston	5.37 cm
5	Stroke	4.27 cm
6	Swept volume	$97.01\ cm^3$
7	swept volume ratio	1.22
8	Compression ratio	3.128
9	Phase angle	90^0

Table 2:- Specification of Sterling Engine

The model of gamma type Sterling engine was fabricated using different parts. The fabricated sterling engine is shown in Fig. 4.

(a) (b) (c)

Fig. 4 (a) Parts (b) Fabricated Model (c) Installed Model

ISSN No:-2456-2165

IV. RESULTS AND DISCUSSION

The solar reflectors are used to concentrate solar energy through a parabolic dish, the solar radiation falling on earth in Sukkur region is 5.35 $kWh/m^2/day$ and 181 W/m^2 plane of array irradiance. Average day length hours in Sukkur are 8 hours [29]. Concentrated energy in the form of heat we get varying amount of heat in different timings. Table 3 shows the ambient temperature, temperature of displacer, and temperature after solar heat energy concentrated and strikes at the displacer end on Day 1. It is observed that the temperature at the morning from 10 to 11 am is not much effective that's why the engine is not running during these hours after 12 pm to 1 pm temperature tends to raise and causes the running of engine. Day 2 experiment readings are presented in Table 2 in which same pattern is followed.

Time Interval	Average ambient temperature	Temperature at displacer end	Engine Status
10 am to 11 am	23.6 ^0C	56 ^0C	Not running
11 am to 12 pm	26.3 ^0C	152 ^0C	Running
1 pm to 2 pm	29.8 ^0C	246 ^0C	Running
2 pm to 3 pm	30.5 ^0C	300 ^0C	Running
3 pm to 4 pm	30 ^0C	298 ^0C	Running

Table 3:- Readings of Day 1 Experiment

Time Interval	Average ambient temperature	Temperature at displacer end	Engine Status
10 am to 11 am	24.6 ^0C	58 ^0C	Not running
11 am to 12 pm	27.3 ^0C	157 ^0C	Running
1 pm to 2 pm	28.8 ^0C	249 ^0C	Running
2 pm to 3 pm	30 ^0C	310 ^0C	Running
3 pm to 4 pm	30 ^0C	298 ^0C	Running

Table 4:- Readings of Day 2 Experiment

➢ ***Calculations***

Solar radiation generated power input:

Consider that a fixed or unchanged quantity of heat strikes the parabolic dish reflectors. The total amount of heat received per second is given by;

J=Solar constant (w/m^2) ×Area (m^2) ×Time (sec) (1)
$J=1050\times(1.524)^2\times1$
J=1915.6 Joules

Ideal ratio of the volume:
Considering a rise in temperature up to 75%

Volume ratio, $V_R= (1+DeltaT/1100)$ (2)
$V_R = (1+75/1100)$
$V_R = 1.06$

Expansion Space Volume:
The Expansion in the space volume is obtained by output power and Beale number [30]

$P_0=B_n\times p\times f\times V_e$ (3)

B_n= Beale Number usually ranges between 0.0031-0.0071
P= pressure measured in bar
f= frequency of operation in Hz

$V_e= P_0/B_n\times p\times f$ (4)

$V_e= 390/(0.005\times101.325\times6.08)$

$V_e =126.61\ cm^3$

Ideal Volume Ratio:
Ideal volume ratio= V_{max}/V_{min}

$V_R= V_c + V_e/ V_c$ (5)

$V_c= V_e/ V_R-1$

$V_c= 126.61/(1.06-1)$

$V_c= 2110\ cm^3$ Flywheel Inertia:
The moment of inertia of the flywheel I will be

approximated as:

$$I=0.5 \times m \times (r_i^2 + r^{\ 2}) \qquad (6)$$

Where

m= Mass of flywheel r_i = Inner radius
r_o= Outer radius $I=0.5\times0.980\times((125\times10^{-3})+(105\times10^{-3}))$
$I=523.7\times10^{-3}$ kg m^2

It is expected to design a flywheel whose center of gravity lies at center from all directions.

Volume of cylinder:

$$V= (\pi \times r^2) \times \text{height} \qquad (7)$$

$$V= (3.142 \times 2.15 \times 2.15) \times 8$$

$$V= 116.19\ cm^3$$

$$V= 116190.0\ mm^3$$

Engine Efficiency:

$$\eta = T_{hot} - T_{cold} / T_{hot} \qquad (8)$$

$$\eta = 310 - 90 / 310 \times 100$$

$$\eta = 70.96\%$$

V. CONCLUSION

Pakistan is among the developing countries of the world which suffers from worst energy crises. The energy crises of the country could be overcome by utilization of renewable energy sources such as solar energy. This research presents an experimental study on the performance investigation of solar dish sterling engine. The designing of the dish and sterling engine was performed on AutoCAD software. The system was fabricated locally, and experimental study was performed for the weather conditions of Sukkur, Sindh, Pakistan. The system consisted of a parabolic dish, solar reflectors, gamma Sterling Engine (double acting type), fan blades, flywheel and dynamo (alternator) having capacity to generate almost 100 watts of electricity. The horizontal radiations falling on dish were directly focused on the receiver (displacer) end of the sterling engine. The heat produced due to solar radiations was used to run the gamma type sterling engine. The experimental study that the total efficiency of the sterling engine was about 70.96% by neglecting the losses.

REFERENCES

[1]. L. Pe´rez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," Energy and Buildings vol. 40 pp. 394–398, 2008

[2]. D. Kumar, R. A. Memon, A. G. Memon, I. A. Tunio, and A. Junejo, "Impact of Auxiliary Equipments' Consumption on Electricity Generation Cost in Selected Power Plants of Pakistan," Mehran University Research Journal of Engineering & Technology, vol. 36, pp. 419-434, 2017.

[3]. S. A. Kalogirou, S. Karellas, K. Braimakis, C. Stanciu, and V. Badescu, "Exergy analysis of solar thermal collectors and processes," Progress in Energy and Combustion Science, vol. 56, pp. 106-137, 2016.

[4]. Y. Cao, "HEAT PIPE SOLAR RECEIVERS FOR CONCENTRATING SOLAR POWER (CSP) PLANTS," in Proceedings of the ASME 2013 7th International Conference on Energy Sustainability ES2013, July 14-19, 2013, , Minneapolis, MN, USA, 2013, pp. ES2013-18299.

[5]. M. RIAZ and T. GURR, "SOLAR FLUX DENSITY DISTRIBUTIONS ON CENTRAL TOWER RECEIVERS," Solar Energy, vol. 19, pp. 185-194, 1977.

[6]. S. Kuravi, J. Trahan, D. Y. Goswami, M. M. Rahman, and E. K. Stefanakos, "Thermal energy storage technologies and systems for concentrating solar power plants," Progress in Energy and Combustion Science, vol. 39, pp. 285-319, 2013

[7]. Rizzo JG. The Sterling engine manual. Somerset: Camden miniature steam services. 1997 p. 1,43, 153, 155.

[8]. H. Karabulut, H. Solmaz, M. Okur, F. Sahin, Dynamic and thermodynamic analysis of gamma type free-piston sterling engine, J. Facult. Eng. Architect. Gazi University 28 (2) (2013) 265–273.

[9]. [9] G. Xiao, U. Sultan, M. Ni, H. Peng, X. Zhou, S. Wang, Z. Luo, Design optimization with computational fluid dynamic analysis of b-type Sterling engine, Appl. Therm. Eng. 113 (2017) 87–102.

[10]. V. Punnathanam, P. Kotecha, Effective multi-objective optimization of Sterling engine systems, Appl. Therm. Eng. 108 (2016) 261–276

[11]. C.H. Cheng, H.S. Yang, Theoretical model for predicting thermodynamic behavior of thermal-lag Sterling engine, Energy 49 (2013) 218–228.

[12]. D.G. Thombare, S.K. Verma, Technological development in the Sterling cycle engines, Renew. Sustain. Energy Rev. 12 (1) (2008) 1–38.

[13]. T. Li, D. Tang, Z. Li, J. Du, T. Zhou, Y. Jia, Development and test of a Sterling engine driven by waste gases for the micro-CHP system, Applied thermal engineering 33 (2012) 119–123.

[14]. C. Cinar, S. Yucesu, T. Topgul, M. Okur, Beta-type Sterling engine operating at atmospheric pressure, Appl. Energy 81 (4) (2005) 351–357.

[15]. C. Cinar, H. Karabulut, Manufacturing and testing of a gamma type Sterling engine, Renew. Energy 30 (1) (2005) 57–66.

[16]. V. Kuhn, J. Klemeš, I. Bulatov, MicroCHP: overview of selected technologies, products and field test results, Appl. Therm. Eng. 28 (16) (2008) 2039–2048
[17]. N. Martaj, L. Grosu, P. Rochelle, Exergetical analysis and design optimisation of the Sterling engine, Int. J. Exergy 3 (1) (2005) 45–67.
[18]. M. Costea, S. Petrescu, C. Harman, The effect of irreversibilities on solar Sterling engine cycle performance, Energy convers. Managem. 40 (15) (1999) 1723–1731.
[19]. C.H. Cheng, Y.J. Yu, Numerical model for predicting thermodynamic cycle and thermal efficiency of a beta-type Sterling engine with rhombic-drive mechanism, Renew. Energy 35 (11) (2010) 2590–2601.
[20]. ' V. Siva Reddy, S. C. Kaushik and S. K. Tyagi, Exergetic analysis and performance evaluation of a parabolic dish Sterling engine solar powered plant, Int. J. Energy Res. (2012) Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/er.2926 Copyright © International Journal of Energy Research.
[21]. Mohammad H. Ahmadi, Hoseyn Sayyaadi, Amir H. Mohammadi and Marco A. Barranco-Jimenez, Thermo-economic multi-objective optimization of solar dish- Sterling engine by implementing evolutionary algorithm Energy Conversion and Management 73 (2013) 370–380, Energy Conversion and Management journal homepage: www.elsevier.com/locate/enconman
[22]. Petrescu S, Harman C. The connection between the first and second law of thermodynamics for processes with finite speed. A direct method for approaching and optimization of irreversible processes. J Heat Transfer Soc Jpn 1994;33(128).
[23]. Costea M, Petrescu S, Harman C. The effect of irreversibilities on solar sterling engine cycle performance. Energy Convers Manage 1999;40:1723–31.
[24]. Ehsan Gholamalizadeh, Jae Dong Chung. Exergy Analysis of a Pilot Parabolic Solar Dish-Sterling System, © 2017 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/)., Multidisciplinary Digital Publishing Institute
[25]. Heng-Yi Li, Tsair-Fuh Huang, Meng-Chang Tsai, Yung-Woou Lee, Shing-Lei Yuan, Ming-Jui Tsai and Chi-Fong Ai, Energy and Exergy Analysis of a New Small Concentrating Solar Power Plant, *Energy and Power Engineering*, 2013, 5, 300-305 doi:10.4236/epe.2013.54B059 Published Online July 2013 (http://www.scirp.org/journal/epe)
[26]. Çınar, Fatih Aksoy, Hamit Solmaz, Emre Yılmaz, and Ahmet Uyumaz, Manufacturing and testing of an α-type Sterling engine, Applied Thermal Engineering 130 (2018) 1373–1379, Applied Thermal Engineering journal homepage: www.elsevier.com/locate/apthermeng.
[27]. Kongtragool B, Wongwises S. A review ofsolar-powered Sterling engines and low temperature differential Sterling engines. Renewable and Sustainable Energy Reviews 2003;7(2):131–54.
[28]. Tsoutsos T, Gekas V, Marketaki K. Technical and economical evaluation ofsolar thermal power generation. Renewable Energy 2003;28(6):873–86
[29]. http://kryptonenergy.com.pk/sukkur/
[30]. Shung-Wen Kang, Meng-Yuan Kuo, Jian-You Chen, & Wen-An Lu. (2010) 'Fabrication and testing of gamma-type Sterling engine'. Proceedings of the International Conference on Energy and Sustainable Development: Issues and Strategies (ESD 2010). doi:10.1109/esd.2010.5598787