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Off-feed Axis Solar Concentrating Collector with a β-configuration Stirling Engine

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***Abstract*—India is endowed with abundant natural and renewable resources of energy. There is a growing census that renewable energy sources will be a viable alternative in solution of energy needs. In an attempt to tread the line between the demand and supply energy, selected contemporary project will address how the applicability of the low temperature differential designed Stirling engine with solar collector is relevant to develop more efficient to utilize our renewable energy sources and low cost i.e. required to be competitive in this space. The system, primarily uses Stirling engine placed at the focal plane of a parabolic collector. The preliminary prototype design and methodology follows the process, i.e., Heat to mechanical & latter to electric. The conversion of the solar energy per thermal way into electricity is a major stake. The simulation presented provides satisfactory prediction of Solar Energy Extraction System performance as compared to the experimental data by scaling i.e. Three times the power obtained, in comparison to photo-voltaic cells. Experimental verification of simulation being carried out and presented here. Shortcomings of the methodology for simulation are highlighted and an alternative approach to solving particulars suggested.**

Keywords—Stirling engine, solar collector, thermal energy, electrical energy

I. INTRODUCTION

Any physical activity in this world, whether by human beings or by nature is caused due to the flow of energy in one form or the other. Energy is most basic infrastructure input required for economic growth and development of a country. Thus, with an increase in the living standard of human beings, energy consumption also accelerated by leaps and bounds.

The flummoxed country has been in a state of suspended animation for too long. Unravels, Oil prices shot up four folds causing a dreaded energy crisis the world over. This result in the fulminating spiral price rise of various commercial energy sources leading to global inflation similarly sword crossed with each other. Also, the emissions from non-renewable resources are responsible for a large mortality and morbidity burden on human health. Energy technology will need to address important challenges in order to be adopted at high penetrations in a modern electric grid.

The sun is a sphere of intensely hot gaseous matter with a diameter of about 1.39×10^9m and is about 1.5×10^{11}m away from the earth, continuously generating heat by thermonuclear fusion reactions converting hydrogen atoms into helium atoms [6]. India receives solar energy equivalent to more than 5000 trillion kW/year, which is far more than its total annual consumption. The daily global radiation is around 5 kWh/m^2. Per day with the sunshine ranging between 2300 and 3200 hr. per year in most parts of India [7]. It is thus apparent that if irradiation on only 1% of the earth's surface could be converted into useful energy with 10% efficiency, solar energy could fulfill the energy needs of the entire world population. Total energy on earth is less than solar energy incident upon the earth in one year [10].

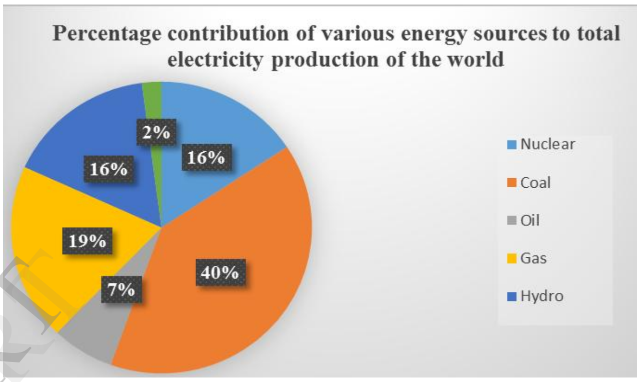

Fig. 1. Different sources of commercial energy can be compared on the extent of their contribution to world scene quantified [8]

This led to the idea of revisiting the old Stirling engine technology along with a parabolic collector for the relatively modern thermal energy utilizing the application.

A. Stirling Engine Background

Stirling engines can have broad significance and technological advantages for distributed energy application. In addition, Stirling engine systems are fuel flexible with respect to source of thermal energy and unprocessed heat can be harvested. A Stirling engine is a heat engine operating by cycle compression and expansion of air or other gas [3]. The working fluid at different temperature levels, such that there is a net conversion of heat energy to mechanical work.

The Stirling engine, formerly known as a hot air engine, based on an idea first proposed by a Scottish minister Robert

Stirling in 1816. This was long before the invention of petrol and diesel engine, at a time when the steam engine was coming on the scene. After development the superior power to weight (& volume) characteristics of steam engine led to the abandonment of a Stirling engine. However, Stirling engine remained a matter of academic interest during the whole of the 19th century because of its unique feature that, if the ideal Stirling thermodynamic cycle were practically realizable the efficiency of a frictionless Stirling engine would be the same as that of a Carnot cycle engine [1], i.e., The maximum theoretically attainable in any heat engine.

II. Design and Fabrication

A. *Design and Fabrication of Stirling Engine*[16]

A prototype, *beta configuration Stirling engine* had been assembled which constitutes a single power piston arranged within the same cylinder on the same shaft [5]. The *Displacer* piston is a loose fit and does not extract any power from the expanding gas, but only serves to *shuttle the working gas from the hot region to the cold region*. When the working gas is pushed to the hot end of the cylinder it expands and pushes the power piston. When it is pushed to the cold end of the cylinder it contracts and the momentum of the machine, usually enhanced by a flywheel, pushes the power piston the other way to compress the gas.

*1) Displacer:*The Displacer is made from steel wire wool wrapped around a piece of steel wire. Displacer needs to fall freely under its own weight inside of the pressure vessel. The diameter of the pressure vessel is 65 mm with a height of 90 mm, Taking radial clearance of 2 mm, so the diameter of the Displacer is approximately calculated as 60mm and height is 65mm.

$$Stroke = (height\ of\ cylinder - thickness\ of\ Displacer) - (2 \times clearance) \qquad (1)$$

Stroke =15 mm, calculated from Eq 1.

$$Crank\ radius = \frac{stroke}{2} \qquad (2)$$

Crank radius, calculated 7.5mm, calculated from Eq 2.

Fig. 2.1. Steel wool displacer inside a can serving as a pressure vessel

*2) Power piston and cylinder:*Power piston is the most important part of the engine. It produces a power stroke from the expansion of air in power piston. Power piston and cylinder must have very low friction. From empirical relation power *piston expansion volume should be around 1/25 times swept volume of the Displacer cylinder* [1]

Swept volume of Displacer cylinder

$$= \frac{\pi}{4} \times 65 \times 65 \times 15 = 49774.6\ mm^3$$

$$\text{Power piston expansion volume} = \frac{49774.6}{25} = 1990.984 mm^3$$

$$\text{Diameter of power piston cylinder} = \sqrt{\frac{1990.984 \times 4}{\pi \times 15}} = 13\ mm$$

*3) Crankshaft:*It converts reciprocating motion into rotary motion and also supports flywheel. With 2 mm diameter of wire, 90 mm length and 90° phase angle.

Fig. 2.2. Crank Shaft

4) Flywheel:Made up of plastic with 120 mm diameter, 1 mm thickness.

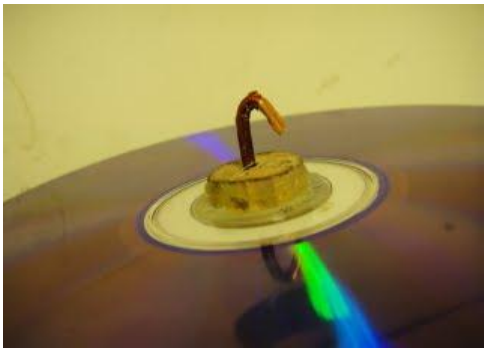

Fig. 2.3. Flywheel

Fig. 2.4. Final assembly of prototype Stirling engine model

B. Design and Fabrication of Parabolic Collector

A sheet molding compound, mixture that includes reflective metallic material and ultraviolet scattering compositions is mixed with resin, calcium carbonate, and a catalyst cure poured onto a sheet of polyethylene film that has fiberglass added in chopped form [10].

An asymmetrical segment of a paraboloid is utilized as a reflector, here the focus and the feed section are located to one side of the dish or positioned as an offset to the axis. This design increases the area for radiation reception, so more energy can be accumulated at the focus after reflection. This setup of parabolic dish is widely used ashousehold satellite television dishes. An offset-feed dish has higher efficiency than a conventional dish of the same aperture [10].

The height, width and the maximum depth of the paraboloid are measured taking reference fromthe edge across the dish from top to bottom.

These three dimensions; height, width and maximum depth, can beused to calculate the focal length of the dish. Following is the Legon's equation to calculate the focal length of an offset dish antenna.

$$Focal\ length = \frac{(width)^3}{(16 \times depth \times height)} \qquad (3)$$

Parabolic antennas are based on the geometrical property of the paraboloid that all the paths are of the same length. So a spherical wavefront emitted by a feed antenna at the dish's focus will be reflected into an outgoing plane wave travelling parallel to the dish's axis. The length of material is 600 mm and height of the aluminum material is 555 mm. The focal point is made at the distance of 400 mm.

Metallic Parabolic Dish was tried to make shiny and reflective by using sandpaper and file, but it need perfect hands on it.

Applying Solar reflective film (78% heat reflective) as shown in Fig. 2.5, parted into various strips and stuck to the collector surface at a time to make the most reflective surface possible, to avoid any air entrapping and distortion of the film. The irregular surface is more depressive and less shiny, so care is to be taken.

Fig. 2.5. Final dish after application of solar reflective film

III. EXPERIMENTAL SETUP

The system, comprises of a parabolic dish collector (which is made up a dish concentrator and a thermal reflector) and a Stirling heat engine located at the focus of the dish, tracks the sun and focuses solar energy into a cavity absorber where solar energy is absorbed and transferred to the Stirling engine,where

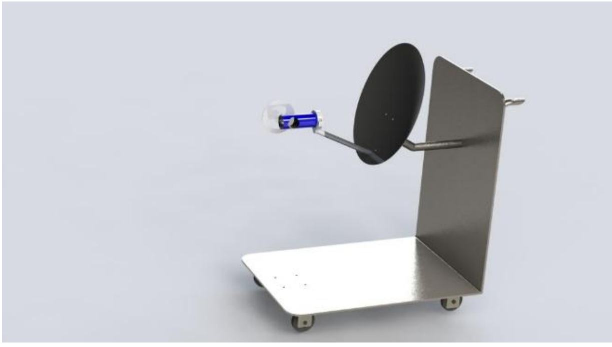

Fig. 3.1.SolidWorks® 2014 rendering of proposed model

the displacer's hot-end gets heated, thereby creating a solar powered Stirling heat engine, as shown in Fig. 3.1. & Fig. 3.2.

The expansion side of the Stirling engine model is thermally coupled to heat source and compression side of Stirling device is placed in an environment. Typically, thermal insulation between two sides, so there will be a temperature rise inside an insulated space.

In Stirling-parabolic collector, the solar radiation is converted to electricity in three stages. In the first stage, radiation is converted to heat by focusing the solarradiation onto a light absorbing heating base of the Stirling engine, by means of a parabolic reflector. In the second stage, the heat is

Fig. 3.2. Experimental Setup of prototype Stirling engine model

converted to mechanical power by a Stirling engine. In the final stage, the mechanical power is converted to electricity by an alternator**.**

IV. SIMULATION

A. Motion Analysis of Crank

The following motion study analysis is done on SolidWorks® 2014 to understand and the motion of theDisplacer and the crank employed in the Stirling engine model. The model is simulated at an angular speed of 60 rad/s.

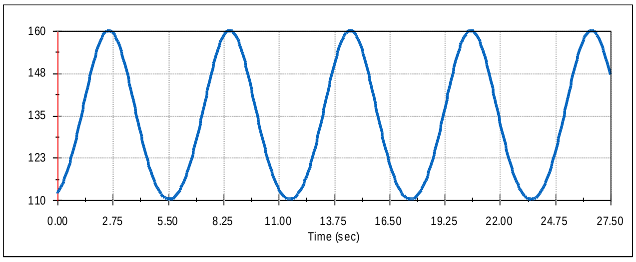

Fig. 4.1.Linear displacement vs. Timeplot

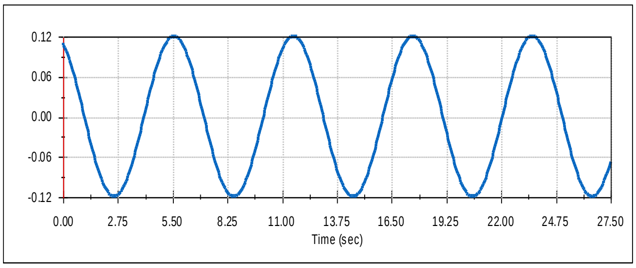

Fig. 4.2. Linear velocity vs. Timeplot

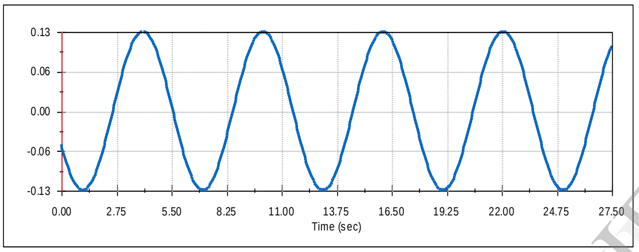

Fig. 4.3.Linear acceleration vs. Timeplot

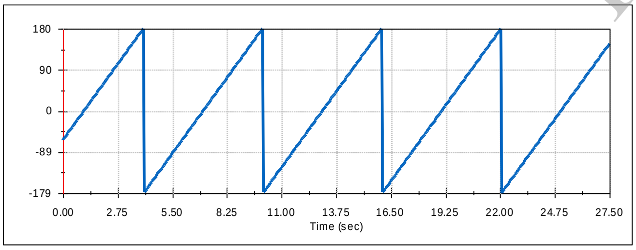

Fig.4.4.Angular displacement vs. Timeplot

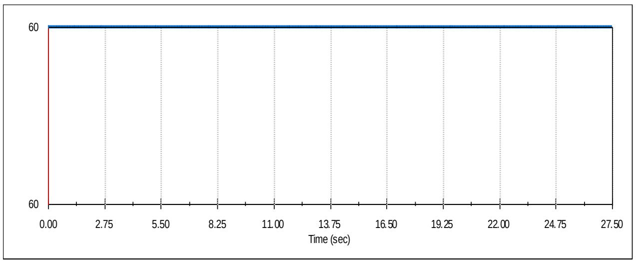

Fig.4.5.Angular velocity vs. Timeplot

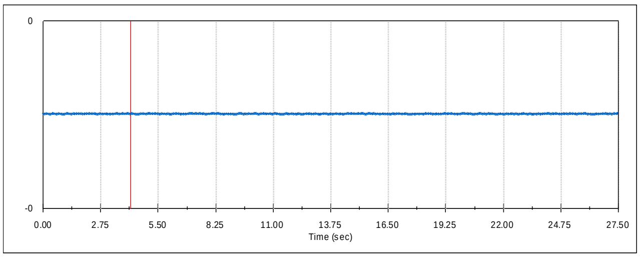

Fig. 4.6.Angular acceleration vs. Timeplot

B. Static Analysis of Crank

The following analysis is done on SolidWorks® 2014 to understand and study the working and performance the crank employed in the Stirling engine model. Here the crank is constrained using bearings and sliding fixtures, a force of 0.4233 N is applied to the crank where the string and crank comes in contact. The material used is Galvanized Iron (because it is cost effective & easily available than any other alternative), in the form of a 2 mm gauge wire, with properties as follows:

- Yield strength: 5.51485×10^{8} N/m^2
- Tensile strength: 8.61695×10^{8} N/m^2
- Elastic modulus: 1.2×10^{11} N/m^2
- Poisson's ratio: 0.31
- Mass density: 7100 kg/m^3

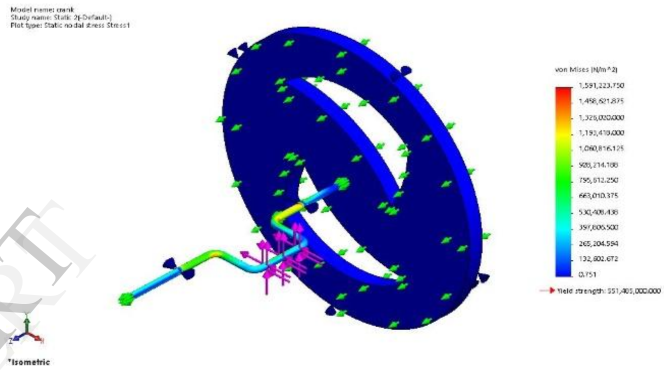

Fig. 4.7. Image of crank showing Von Mises Stress

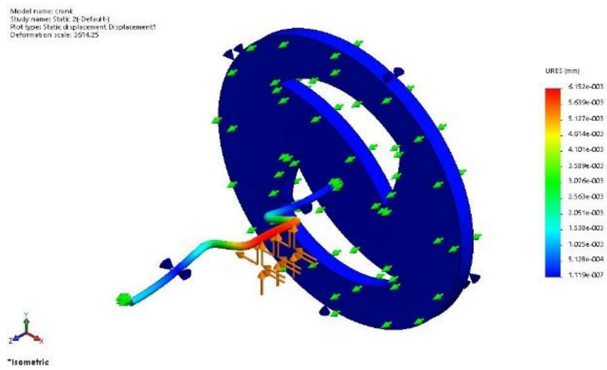

Fig. 4.8. Image of crank showing after scenario Deformations

- Shear modulus: 7.7×10^{10} N/m^2

C. Fatigue Analysis of Crank

The following analysis is done on SolidWorks® 2014 to understand the failure time and criterion of the crank employed in the Stirling engine model. Here the previous static analysis data are further processed to get the fatigue curve of the crank. Similarly, as from the previous analysis the crank is constrained using bearings and sliding fixtures, a force of 0.4233 N is applied to the crank where the string and crank comes in contact. The material used is Galvanized Iron, in the form of a 2 mm gauge wire, with properties as follows:

- Yield strength: 5.51485×10^8 N/m^2
- Tensile strength: 8.61695×10^8 N/m^2
- Elastic modulus: 1.2×10^{11} N/m^2
- Poisson's ratio: 0.31
- Mass density: 7100 kg/m^3
- Shear modulus: 7.7×10^{10} N/m^2

The criterion of failure is assumed to be Von Mises stress, i.e. loading will be done according to the static study, and where the stress is found to be maximizing the component will be found to fail at that section.

The Fig. 4.9.depicts the SN curve (semi-logformat) or the stress vs. cycles plot of the crank after a series of deforming cycles. The study shows that the scaledfatigue curve of crank with stresses ranging from 1.3×10^7 to 2×10^7 N/m^2, and cycles ranging from 10^4 to 10^8 cycles.

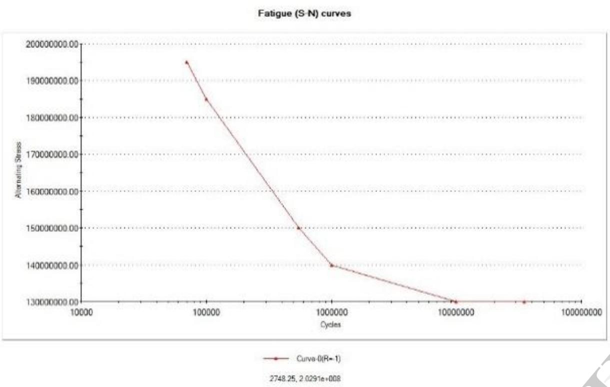

Fig.4.9. Image of crank showing SN curve (Stress vs. Cycles plot)

V. CALCULATION

The World Radiation Centre (WRC) has adopted a value of the solar constant as, I_{sc} = 1367 W/m^2 (1.940 Cal/cm^{2}min., 432 Btu/ft^2 or 4.921 MJ/m^{2}hr.) [2]. This has been accepted universally as a standard value ofthe solar constant.

According to the location and time, following parameters are observed:
Location: RAIPUR
Longitude: 21°15'19" N
Latitude: 81°37'47" S
IST: 05:53 to 18:35 hr. (from sunrise to sunset)
Ambient temperature: 36°C (daily basis temperature for the date)

No. of days (n) =106 days: 16th of April, 2014, (from 1st of January, 2014)

Humidity: 34%
Wind speed: 5 m/s

The extra-terrestrial radiation deviates from the solar constant value, hence given by [2]:

$$I_{ext}=I_{sc}[1.0+0.33\cos\left(\frac{360\times n}{365}\right)] \quad (4)$$

I_{ext}= 1355.688 W/m^2

Beam radiation received on earth per sq. m on a plane surface normal to the direction of radiation, may be estimated as [2]:

$$I_N = I_{ext}e^{[-T_R/(0.9+9.4\sin(\alpha))]} \quad (5)$$

Where, T_R (turbidity factor)=3.9, [2]
α (inclination angle) =45^0,

I_N =808.757 W/m^2

Normal beam radiation I_b, and diffuse radiation I_d, on horizontal surface are recorded from following expressions[2]:

$$I_b = I_N \cos\theta_z \quad (6)$$

Where, θ_z (zenith angle) =45^0,

I_b= 571.75 W/m^2

$$I_d=(1/3)(I_{ext}-I_N)\cos\theta_z \quad (7)$$

I_d= 128.91 W/m^2

Total radiation (global radiation) [2],

$$I_T=I_bR_b+I_dR_d+R_r(I_b+I_d) \quad (8)$$

R_b, ratio of flux beam radiation on an inclined surface to a horizontal surface,

$$R_b=\frac{\cos\theta_i}{\cos\theta_z}=1 \quad (9)$$

R_d, ratio of flux of the diffused radiation falling on inclined surface to a horizontal surface,

$$R_d=\frac{1+\cos\beta}{2}=0.854 \quad (10)$$

R_r, the reflected component comes mainly from the ground and surrounding objects,

$$R_r=\rho\left(\frac{1-\cos\beta}{2}\right)=0.114 \quad (11)$$

I_T = 571.75 × 1+ 128.91 × 0.854 + 0.114 × (571.75+128.91)

= 761.71 W/m^2

Since, reflectivity (ρ) = 0.78,

$$\rho=\frac{I_u}{I_T}, [6]$$

I_u = 0.78 I_T= 0.78 × 761.71

= 594.137 W/m^2

I_u is useful radiation on the parabolic collector,
$I_{loss}$is loss due to transmissivity and absorptivity,

$$I_{loss}=I_T-I_u=167.57 \quad (12)$$

Now the concentration ratio can be given as [8]:

$$C\ (Conc.\ Ratio)=\frac{aperture\ \ area\ of\ concentrator}{area\ of\ absorber} \quad (13)$$

$$= \frac{0.256}{\pi(0.01)^2} = 814.87$$

From Stefan-Boltzmann law,to predict the performance of a solar collector it is necessary to evaluate the radiation exchange between the collector surface and Stirling engine surface, can be evaluated from,

$$q = \sigma\ (T_1^{\,4} - T_a^{\,4}) \quad (14)$$

Fig. 5.1. Image depicting temperature T_1, 380° C

Where, σ(Stefan- Boltzmann constant) = 5.67×10^{-8}

T_1, observed temperature on the Stirling engine surface = 380°C (measured from commercial alcohol thermometer)
T_a, collector surface temperature (ambient temperature)

$$q = 5.67 \times 10^{-8} \times [(380+273)^4 - (36+273)^4] = 9793.24\ W/m^2$$

Heat input to the Stirling engine,

$$Q_{in}=q\times Area \quad (15)$$

$$= 9793.24 \times 0.265$$

$$Work = 2595.21\ W\ or\ 2.595\ kW$$

The prototype Stirling engine model attached to the solar parabolic collector is being linked with the alternator, i.e. with the DC gear motor and further to multi-meter and observed the output parameter needed, as shown in Figure 5.2. & 5.3.

The readings of the following parameters are obtained from multi-meter, given as

Volt, V = 156 mV,
Resistance, R = 2.4Ω,
Power is given by,

$$P = \frac{V^2}{R} \quad (16)$$

Fig. 5.2. Image depicting resistance reading 2.4Ω

Fig. 5.3. Image depicting voltage reading 156 mV

$$P = \frac{(156.1 \times 10^{-3})^2}{2.4} = 0.01\ W$$

VI. RESULT AND DISCUSSIONS

The above generated data for model for collector area = $0.265m^2$ following parameter are under as follows:

TABLEI. RESULT PARAMETER OF SOLAR ENERGY EXTRACTION SYSTEM

S.No.	Parameters	Values
1	Output power	0.01 W
2	Concentration ratio of collector	814.87
3	Heat input	2.595 kW
4	Swept volume of engine	49774.6 mm^3
5	Diameter of engine	65 mm
6	Height of engine	90 mm
7	Energy, time= 8 hr.	0.288 unit

Therefore, by Similitude process, evaluating for area = 1 m^2, working fluid as air and implementing Froude's Model law [5],

$$Area, \frac{A_P}{A_m} = L_r^{\,2} \quad (17)$$

Scale ratio, $L_r = \sqrt{\frac{1}{0.265}} = 1.95$

$$Volume, \frac{vol_P}{vol_m} = L_r^{\,3} \quad (18)$$

$vol_p = 369072.44\ mm^3$

$$Diameter, \frac{D_P}{D_m} = L_r \quad (19)$$

$D_p = 126.75$ mm

$$Height, \frac{H_P}{H_m} = L_r \quad (20)$$

$H_p = 175.5$ mm

$$Power, \frac{power_P}{power_m} = L_r^{\,3.5} \quad (21)$$

$power_p = 0.1035$ W

Energy on daily basis = 2.982 unit

VII. Conclusion

The motion and static fatigue analysis show that no fatigue takes in the crank of the Stirling engine model takes place over the period of cycles, 3.5×10^7 cycles.

The obtained data of Similitude, scaled 1.95, by Froude's Model law is capable of generating prototype power of 2.982 unit (for area = $1m^2$) electrical energy in full day (approx. 8 hr.) with an ordinary sunshine (around 32°C).

Commercial photo-voltaic cells have efficiencies 10% - 20%, can produce electrical energy of maximum 1 unit (for area = 1 m^2) in full day (approx. 8hr.) of sunshine [2].

The simulated results provide a satisfactory prediction of solar energy extraction system performance as compared to theexperimental data by scaling i.e. three times the power obtained from the solar energy extraction system in comparison to photo-voltaic cells.

Depending on the difference between simulated and user defined engine pressure more improvement can be observed from the original simulation.

VIII. Related Work

Van Heerden (2003) studied a solar-dish Stirling system and found that the technology is not mature enough at this point in time, mainly due to lack of investment in product development, but that it is capable of delivering an average solar efficiency of 24%, which is higher than the current photo-voltaic systems. Also, occupying a smaller area and longer life than traditional PV cell [8]. Having said that even fewer units of solar Stirling plants may be a lesser eyesore than the whole roof carpeted with solar module panels.

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References

[1] Mathur, M.L., Sharma, R.P., *Internal combustion engine*, 8th ed., p.p.486-821; New Delhi; Dhanpatrai, 2011.

[2] Khan, B.H.; *Non-Conventional Energy Resources*,4th ed.; p.p. 1-115; New Delhi; Tata McGraw Hill, 2008.

[3] Snyman, H; Harms, T; Strauss, J; *Design Analysis Methods for Stirling Engines*; Journal of Energy in Southern Africa;vol.19, no.3, august, 2008.

[4] Minassians, Artin; Sanders, Seth; *Multiphase Stirling Engines*; Journal of Solar Energy Engineering, vol.131, may, 2009.

[5] Bansal, R.K., *A textbook of Fluid Mechanics & Hydraulic Machines*; 9th ed., p.p.573-592; New Delhi; Laxmi Publication, 2009.

[6] Garg, H.P. & Prakash, J., *Solar Energy – fundamentals and applications*; 1st revised ed., p.p. 2, p.p. 116-140 & p.p. 418-424; New Delhi; Tata McGraw Hill, 2012.

[7] Singhal, Dr. R.K., *Non-Conventional Energy Resources*; 3rd ed., p.p. 1-36 & p.p. 108-145; New Delhi; S.K. Kataria& Sons, 2012.

[8] Sukhatme, S.P. &Nayak, J.K., *Solar Energy - Principles of Thermal Collection & Storage*, 3rd ed.; p.p. 9-69 & p.p. 200-254; New Delhi; Tata McGraw Hill, 2010.

[9] Raguram, A. &Lingeswaran; *Design Of Stirling Engine & Solar Collectors to Run an Automobile Alternator*; Middle- East Journal of Scientific Research, 20(7), p.p. 815-818, july, 2014.

[10] Wade, Paul; *Offset –Fed Parabolic Dish Antennas*, NIBWT, 1998.

[11] Senthikumar, S., Yasodha, N., *Design and Development of a three dimensional compound parabolic concentrator and study of optical and thermal performance*; International Journal of Energy Science; vol.2, no.2, p.p., 64-68, 2012.

[12] Abbas, M, Said, N &Boumeddane, B., *Thermal Analysis of Stirling Engine Solar Driven*; Revue Des Energies Renouvelables, vol.11, no.4, p.p. 503-514, December, 2008.

[13] He, Mike & Sanders, Seth; *Design of a 2.5 KW Low Temperature Stirling Engine for Distributed Solar Thermal Generation*; American Institute of Aeronautics & Astronautics.

[14] Ahmadi, Mohammad Hossien&Hosseinzade, Hadi, *Investigation of Solar Collector Design Parameters Effect onto Solar Stirling Engine Efficiency*, J Applied Mechanic Engineering, vol.1, issue-1, 2012.

[15] Jadhao, J; Thombare, D; *Review on Exhaust Gas Heat Recovery for I.C.Engines*; International Journal of engineering and Innovative technology; vol.2,no.12; june (2013).

[16] Neha Tiwari, Appu Kumar Singh, Tejas Vishwakarma, Harshal Sharma & Mohammed Suhail, *Exhaust Manifold Waste Heat Recovery System of a Single Cylinder Engine*;Applied Mechanics and Materials (Volumes 592 - 594),(10.4028/www.scientific.net/AMM.592-594.1534), Chapter 5: Thermodynamics and Thermal Engineering, Fuel and Diesel, p.p., 1534-1538, 2014.