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Modeling and Analysis of Zenith based Passive Solar Tracking Mechanism

R. Rahul, T. Srinivas, Himanshu Mishra, N.Tamiloli, B.V. Dharmendra

Abstract— A novel gravity-based, power-free solar tracking mechanism is being developed to track the movement of the sun across day length. A compound parabolic collector having 3 parabolic segments is chosen due to its high intercept factor and suitability to the current tracking as compared to a cylindrical parabolic collector. Used to concentrate the incident solar radiation to the focal point, the Compound Parabolic Collector accumulates heat at the central coil, which is in turn used for process heating applications. The working of the tracking mechanism is studied to find the tracking loads in the east and the west sides of collector. We intend to simulate the tracking motion from the sunrise to sunset, in order to validate the empirical findings. The identified design variants are sprocket wheel diameter, suspension, solar collector's weight, counter balance and loading on the shaft. The recommended diameter for the sprocket wheel and shaft is 2500mm and 50mm respectively.

Keywords: Passive tracking, Solar, Collector, Design.

I. INTRODUCTION

A large part of the research community has dedicated its interests towards the research and development of electricity driven solar tracking mechanisms. Living in a country like India, where majority of the population does not get any access to a continuous power supply or sometimes, any supply of electricity at all, developing a power-free mechanism for solar tracking has a multitude of advantages. The system that we are designing in this paper is going to be used for process heating in village based industries.

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* Correspondence Author

R. Rahul*, Mechanical engineering department, Koneru Lakshmaiah Education Foundation, Guntur, India. Email: rajhrahul27@gmail.com

T Srinivas, Mechanical department, of Dr B R Ambedkar National Institute of Technology Jalandhar, Jalandhar (Punjab) ,India Email: srinivast@nitj.ac.in

Himanshu Mishra, Mechanical engineering department, Koneru Lakshmaiah Education Foundation, Guntur, India. Email: himanmishra.nitr@gmail.com

N. Tamiloli , Mechanical engineering department, Koneru Lakshmaiah Education Foundation, Guntur, India. Email: tamiloligg@gmail.com

B.V. Dharmendra , Mechanical engineering department, Koneru Lakshmaiah Education Foundation, Guntur, India. Email: dharmbv@gmail.com

The applications of the system are have a wide spectrum. The water heated by the concentrator to be used in the system can be used for the generation of electricity. The power free or passive solar tracking mechanism is mounted on a shaft and it helps track sunlight on a concentrator designed to maximize the concentration of sunlight to a point by using a CPC (Compound Parabolic Collector).

The CPC has three parabolas incorporated into its design for a maximum concentration of sunlight due to its high intercept factor.

The intercept factor of a system is the fraction of the diffused reflected radiation intercepted by the absorber tube. The intercept factor can be determined by computing the ratio of the solar radiation absorbed by the receiver and the total incident radiation on the aperture of the collector. As a result of the selected design, the CPC provides a relatively higher intercept factor than other collectors in solar tracking experiments. Riffelmann, Neumann and Ulmer [1], through their extensive work on solar parabolic collectors, developed flux maps for the receiver to calculate the intercept factor, thus analyzing the optical properties of the collector. It is through the work of Riffelmann, Neumann and Ulmer that we can notice a small offset in the collector will cause a drop in the intercept factor of the parabolic trough collector. The work of Kim, Han and Seo [2] reinforce the need of an efficient tracking mechanism. Through extensive experimentation and analysis, Kim, Han and Seo reported that there is a 14.9% increase in the thermal efficiency of a compound parabolic collector. He also noted that there is a 50% increase in the thermal efficiency when the compound parabolic collector is used with a single axis tracking mechanism coupled with a motor. Tao, Hongfei, Kaiyan and Mayere [3] proposed a new design for a collector. It was a multiple curve compound parabolic collector, a design still used to obtain a high intercept factor for the incoming solar radiation. The multiple curve compound parabolic collectors were designed to ensure high heat emission circumstance around the receiver.

Solar tracking mechanisms can be broadly divided into two categories, namely- active and passive. Active solar tracking mechanisms use electricity for the purpose of solar tracking. Passive solar systems, on the other hand, do not use electricity and thus, increase the efficiency of the overall system without using energy developed by the system. A few of the methods employed for passive solar tracking include- controlling the motion of the collector with energy stored in the form of potential energy, gravitational energy or spring energy. Prapas, Norton and Probert [4] designed and experimented with an azimuth axis based tracking mechanism for a parabolic collector to exploit the large amounts of diffuse radiation lost by the system.

Natarajan and Srinivas [5] proved the merit of the North-South orientation for a single axis collector for year round benefit.

The passive solar tracking mechanism thus developed by them was slightly expensive, but its accuracy in operation improved the thermal collection efficiency by a significant amount. There were a large number of systems designed to increase the efficiency of tracking mechanisms coupled with solar panels. A particular piece of work that drew a lot of attention in this regard was the work of Rana [6], who designed a single polar axis tracking mechanism for tracking the sun and increasing the radiation incident on the surface of solar photovoltaic panels. The system developed by Rana had two axes of controls.

The vertical axis was fixed and it had a horizontal pivot which allowed this system to rotate at different speeds. The special feature of the tracker was that it had a provision for the misalignment of the system by every 2 to 3 degrees instead of using the motor thus increasing the effective output yield.

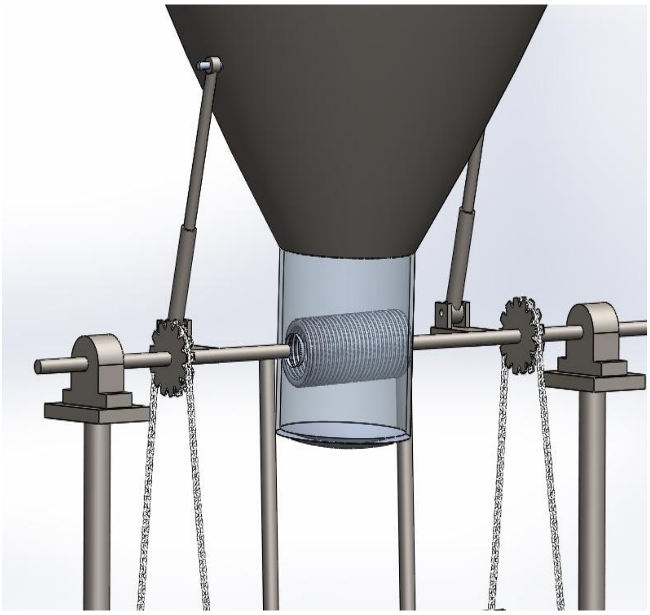
The sparse work in the field of passive solar tracking was one of the reasons for our piqued interest to conduct research in this domain. As explained earlier, a passive tracking mechanism does not need electricity, a battery, or motors to drive the collector; the collector is moved by stored energy. The best example of natural or power free tracking is that of a sun flower. Vandenbrink, Brown, Harmer and Blackman [7] described the mechanism of the rotation of a sunflower towards the sunlight during the day and it's rotation back to its original position in the night. Trihey and Bayswater [8] made use of two extensible members to track solar radiation. The working of the system was based on the imbalance of the solar energy falling on the extensible surfaces. This imbalance caused the rotation of the collector, thus resulting in an effective tracking mechanism. Poulek [9] made a low cost single axis tracking mechanism by using shape memory alloy actuators instead of bimetallic strips which were used till then. These actuators could be rotated when cool and would rotate back to their original position when they were heated. They offered a 2% energy efficiency increase over the conventional bimetallic strips. Farooqui [10] constructed a box shaped solar cooker that employed an azimuth axis based solar tracking mechanism. This box shaped cooker coupled with a tracking mechanism was used for solar tracking for a period of six hours, three hours before noon and three hours post noon.

The literature survey which was performed before embarking on this project revealed that the thermal efficiency of a solar concentrating collector lied in the range of 50-60%. This efficiency is increased by improving the collector geometry, bettering the receiver design and increasing the effective power yield of the system by using a power free/ passive solar tracking mechanism. The design that we have developed has incorporated each of these changes into the system. A Compound Parabolic Collector (CPC) is used in the system in order to increase the intercept factor of the solar radiation. A twisted tape insertion is used in the absorber tube in order to increase the efficiency of the receiver. The system needs the operators' attention at sunrise and noon and it will work continuously for the period of an entire day without the use of external power. The mechanism developed is novel and it works independent of the collector weight because of the attachment of a counter weight. It employs a variable suspension system to counter the tracking load.

The main objective of the current work is the modeling of this tracking mechanism and demonstrating the analysis of the shaft that houses the collector, the counter balance, the sprockets for the tracking load, the pivots of the suspension rods and the bearings on which the entire system is made to rest. The system which is modeled over the course of this paper has a low value of the tracking error. It is a simple design, needs low cost materials, is easy to fabricate and cost effective.

II. METHODOLOGY

The system functional requirements are based on the experiment objectives and the capability of the power-free tracking concept, constrained by the certain design parameters which are discussed later. The system shown in Fig 2.a and Fig 2.b comprises of chiefly 3 parts: collector, receiver, tracking mechanism. The collector is a 9m sq. Compound Parabolic Collector (CPC) that has been constructed for this experiment. The CPC is a structural configuration of three parabolas incorporated into one design to achieve a maximum concentration of sunlight leading to a higher intercept factor and in turn, a greater efficiency as compared to parabolic and parabolic trough collector.



Fig(1): Receiver (Copper) Coil

The receiver coil is a copper tube (Dia. 0.5 inch) that is wound in a helical shape (enclosing a sphere) with its axis parallel to that of the shaft on which the entire system is housed. This arrangement can be seen in the pictorial representation as depicted above in Fig (1). The shape of a helix is such that its radius progressively increases, reaches a maximum (30 cm) and then decreases. The aforementioned shape is adopted as the radiation received by the collector is concentrated on to an imaginary sphere at the focal region of the collector. Water that passes through this coil and will undergo heating which can be used in various applications such as power generation and process heating.

Fig.(2.a): Complete modeling (isometric view)

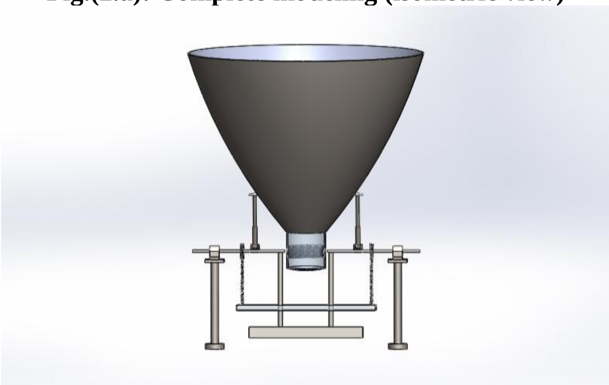


Fig (2.b): Complete modeling (front view)

In this paper, emphasis has been laid on the design, modelling and analysis of the tracking mechanism. As can be seen in Fig 3, the tracking configuration developed consists of several components. The Fig. shows the assembly of shaft, sprocket wheel-chain mechanisms, tracking loads, collector and counter weight. Central to the tracking mechanism is a 50mm diameter shaft, made of High Grade Mild Steel (Grade Quality). The diameter of the shaft is chosen as per the calculations shown below

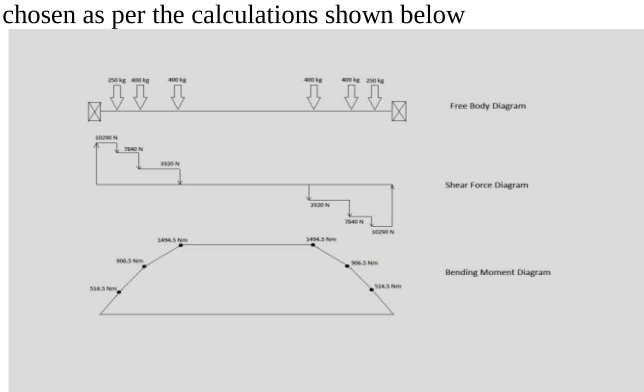


Fig (3.a): Configuration of components on shaft – Arrangement1

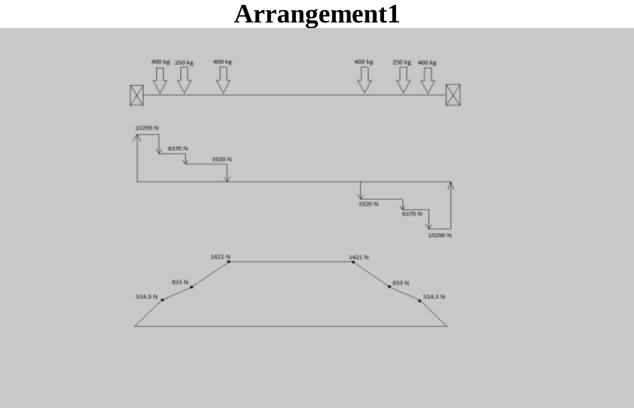


Fig.(3.b): Configuration of components on shaft – Arrangement 2

The Fig.s, (3.a) and (3.b) drawn above, depict the shear force and bending moment diagrams for two different arrangements of components on the shaft. The diameter of the shaft is a function of the maximum bending moment experienced along its entire length. The minimum diameter of the shaft for a given value of maximum bending moment can be determined by the use of the following formula-

$$\frac{\tau}{r} = \frac{M}{J} \qquad (1)$$

Where,

τ = Shear strength of the selected material (MPa)
r = Radius of the shaft (mm)
M = Maximum bending moment (Nmm)
J = Polar moment of inertia = $\pi * r^4/4$ (mm^4)

For the two configurations depicted in the above Fig.s, (2.a and (2.b), calculations have been performed to determine which configuration allows for a better factor of safety. These calculations proceed as follows:

Result 1:

$$r^3 = \frac{M \; x \; 4}{\pi \; x \; \tau} \qquad (2)$$

$$r^3 = \frac{1494.5 \; x \; 4}{\pi \; x \; 200}$$

r = 21.18mm

Result 2:

$$r^3 = \frac{M \; x \; 4}{\pi \; x \; \tau}$$

$$r^3 = \frac{1421 \; x \; 4}{\pi \; x \; 200}$$

r = 20.83mm

From the results computed above, we can observe that Result 2, which corresponds to arrangement 2, gives us a lesser minimum radius. Thereby, arrangement 2 allows a higher factor of safety. Consequently, we choose this arrangement as for our shaft design.

Configuration of solar collectors, counter weight and sprocket wheels on the shaft is illustrated in the Fig. (3.a) and Fig. (3.b). In the first arrangement, sprocket wheels are fixed at outermost ends of the shaft and the counter weight is fixed inside these sprocket wheels. The diameter in this case is determined to be 21.18 mm. In the second arrangement, counter weight is fixed near outermost ends of the shaft and sprocket wheels are fixed inside it. Here, the diameter is found to be 20.83 mm. Thus, the second arrangement is determined to be a better choice among the two configurations. However, owing to ease of fabrication and negligible difference in both cases, the first arrangement can also be put to use while implementing the system.

For ease of explanation, we have divided the apparatus into various subsystems viz. (a) Collector Subsystem; (b) Tracking Load Subsystem; (c) Counterweight Subsystem. The combination of these subsystems represents the simplest approach for satisfying the system functional requirements.

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The design and performance of the actual experiment hardware will be based on how well the subsystem functional requirements are satisfied. The key design drivers, the types of analysis used, the functional developmental testing, and pictures of the final designs will be discussed in the appropriate subsystem sections of this paper.

A. Collector Subsystem

The gross weight of the Compound Parabolic Collector (CPC) is 800 Kg. It is attached to the shaft at two points. Two slip-on flanges are arranged on a common axis with a distance of 1 meter in between them. The Mild Steel shaft is passed through the central bore of the flanges and linked to them using butt welding method (check). The periphery of the flanges is welded to a framework, which is attached to the collector. This arrangement of the mechanism can be seen in Fig (3). Intuitively, we can observe that a clockwise rotation in the shaft will lead to transmission of rotary motion to the flange, framework and eventually, the collector. The velocity of rotation of the collector is controlled by varying the angular velocity of the shaft. The approach employed for rotating the shaft is discussed in the subsequent subsystem.

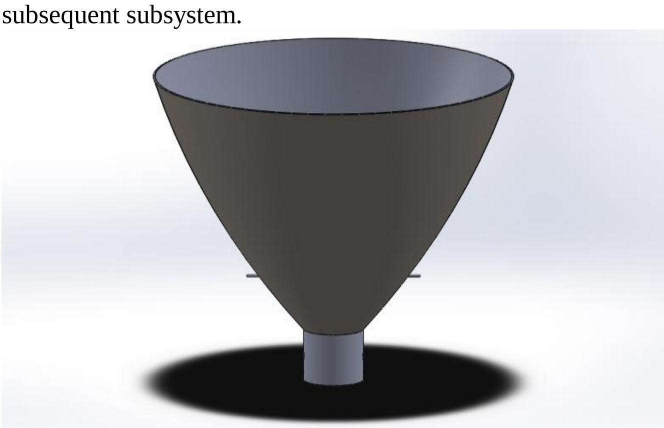

Fig.(3): Compound Parabolic Collector

B. Tracking Load Subsystem

The major challenge is to design and fabricate a tracking mechanism which operates in congruence with the motion of the Sun. As we already know, the Sun's alignment and rate of movement varies on a daily, weekly and seasonal basis. Factoring in these parameters, a mathematical model has been developed by Srinivas and Natarajan [5] for the Sun's motion at Vellore (12.9165°N, 79.1325°E). Our proposed tracking load mechanism is intended to be consonant with the values obtained from this model.

The design of the tracking mechanism is propelled by the range of the collector rotation velocity required during summer and winter. Fig. 5 depicts the structure of the tracking load mechanism. A chain and sprocket wheel arrangement is used to facilitate the movement of the tracking load. In the nature of the previous subsystem, two sprockets are arranged on a common axis and the shaft is passed through it and welded. A chain is wound around each of the sprocket gears. The ends of one chain are attached to a tracking load on either side (East and West) of the shaft. Likewise, the second chain is connected to the other end of the tracking loads as shown in Fig (4.a) and (4.b).

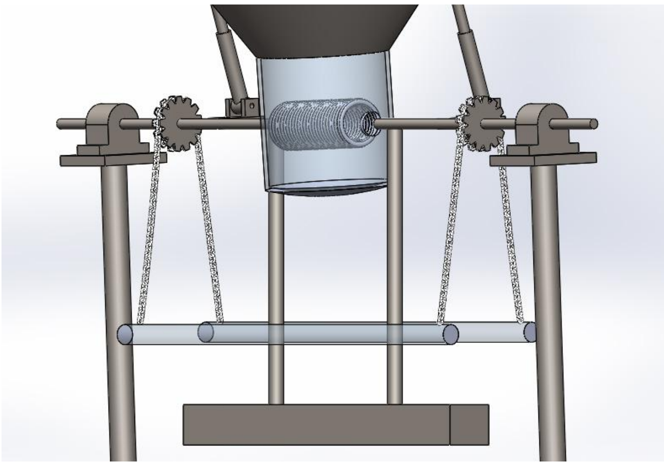

Fig (4.a): Tracking load subsystem (view I)

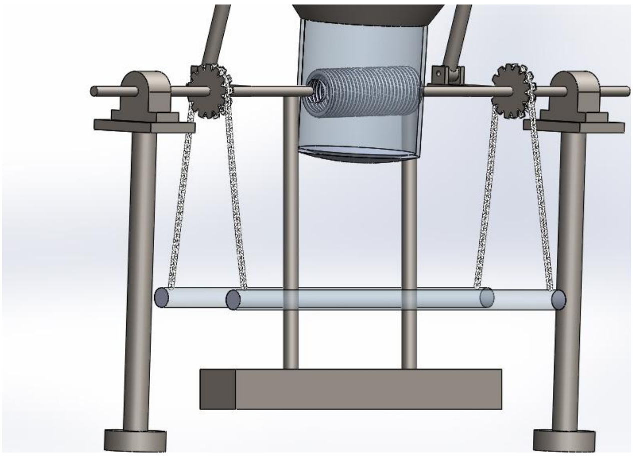

Fig.(4.b): Tracking load subsystem (view II)

The tracking load is a cylindrical, hollow container (diameter- 500 mm, length- 1000 mm). To achieve gravity controlled (power-free) tracking mechanism, the tracking load is required to have a controllable weight. In order for the system to be automatic, the weight should also be time variant. Owing to these reasons, the cylinders are to be filled with a fluid. As the fluid is flows into or out of the container, the weight of the tracking load will increase or decrease respectively. The fluid chosen is water because it is (a) non-corrosive (b) cheap and easily available.

The system is designed to perform operation from 8 a.m. to 4 p.m. As explained earlier, the two water containers are connected to the shaft with the help of the chain and sprocket mechanism. The two containers are on either side of the shaft and the fulcrum of the system coincides with the axis of the shaft. Essentially, one container is on the East side (Container 1) and the other one is on the West side (Container 2) since the shaft is aligned in the North-South direction. Throughout this process, Container 2 holds 200 liters of water. At 8 a.m. (initialization), Container 1 holds 400 liters of water. Due to the difference in weight, Container 1 remains at a lower vertical level than Container 2. Container 1 is fitted with a control valve.

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This valve is used to administer the rate of the water outflow (dripping). This outflowing water is collected in a separate tank and can be reused for refilling Container 1 on the following day. As the water flows out of container 1, its weight decreases. This change of weight on the right side of the fulcrum causes an anti-clockwise moment (as observed from the South-North direction). Container 1, getting lighter, translates upwards and Container 2, downwards.

The translational motion of the water containers is converted to rotary motion of the shaft in the same (anti-clockwise) direction. As a result, the collector also moves in an anti-clockwise direction since it is welded to the shaft with the help of slip-on flanges. Thus, we can imagine the collector moving from East (morning) to West (evening) conforming to the direction of movement of the Sun.

The above mechanism only delineates the direction of movement of the shaft. The other parameter that needs to be addressed is the angular velocity of the shaft. This can be done by varying the dripping rate of water from Container 1. At higher dripping rate, Container 1 will move upwards with a higher velocity leading the shaft to rotate with a higher velocity. At lower dripping rate, a lower shaft velocity can be achieved. Since the shaft welded to the collector is one entity, both have the same angular velocity. Ergo, we have successfully engineered a tracking mechanism which is power-free in nature.

C. Counterweight subsystem

The design drivers for the counterweight subsystem include the weight of the collector and the distance between the center of gravity of the collector, and the fulcrum (central axis of the shaft). Essentially, a counterweight is a weight or a force that offsets another, providing balance and stability to a mechanical system.

In this case, it is designed to be a row of concrete blocks arranged in a hollow, rectangular steel (check) frame. The overall weight of this element is 800 Kg, which is equal to the collector weight. It is tethered to the shaft in a manner similar to that of the collector i.e. the two ends of the counterweight are connected to the shaft with the help flanges which are welded onto the shaft.

III. RESULTS AND DISCUSSIONS

Configuration and working of the proposed tracking system are solved using principles of engineering mechanics and strength of materials. The system is configured in such a way that it facilitates continuous tracking operation from sunrise to sunset. The mechanism is so designed that it achieves a neutral position during noon time. Position of the solar collector when MRCPC axis is perpendicular to the ground is called neutral position. At this condition, the tracking load consists of equal weights of water in both headers, that is, 200 kg in each header. Upon application of a small external force, due to hydraulic suspension, the collector tries to come back to its neutral position. Tracking movement of the solar collector can be achieved by either discharging or refilling the headers or by a combination of both discharging and refilling. For refilling technique, constant flow rate of water has to be maintained and the piping adds to tracking load. Hence, for reasons of robust design and simplicity of operation, the discharging technique was chosen for the proposed system. At sunrise, east header is fully loaded with 400 kg water while west header remains loaded at 200 kg. At the time passes, water is discharged from east header with a constant flow rate such that 200 kg of water is drained from it till noon. Thus, the collector attains neutral position at noon as both the headers have equal amount of water. In the afternoon, water is continually discharged from the same east header until it goes empty. Thus, the collector rotates from noon to west till it attains sunset position. The equal and opposite counter weight nullifies the effect of collector weight on tracking load. Therefore, its role is not deemed necessary to be studied.

Fig. (5) plots the angle of MRCPC axis to the horizontal from sunrise to sunset. It changes from 0° to 90° in the east (forenoon) from sunrise to noon. Then it changes from 90° to 0° in the west (afternoon) from noon to sunset. The angular velocity of solar collector can be computed from day length. At equinox, which means at 12 hour day length, the angular velocity is 15° per hour. Angular velocity of collector is the ratio of 180° and day length, since 180° collector rotation has to be carried out from sunrise to sunset. During winter season, as the day length is lower, the angular velocity is higher. Similarly, as the day length is higher in summer season, the resultant angular velocity is lower. Also, loading on hydraulic suspension is maximum at sunrise and sunset positions and it is minimum at noon position

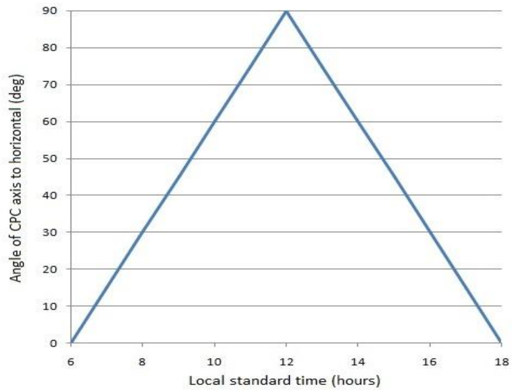

Fig.(5): Variation of MRCPC axis angle over day length

Fig. (6) shows the plots of total load to the time from sunrise to sunset. At sunrise, as the east header will be fully loaded with water to 400 kg, the load will be the maximum. As time progresses, water are slowly discharged from the header and the resultant load goes on decreases. As afternoon passes by, the load goes on reducing gradually and reaches minimum at sunset.There is a gradual reduction in the flow rate of discharged water as the head decreases over time. However, this change acts in the support of non-linear motion of sun across the sky, thus resulting into uniform decrease in total load from sunrise to sunset.

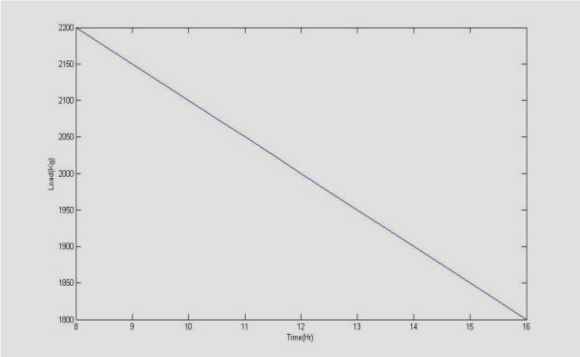

Fig.(6): Load vs. time

Fig. (7.a) depicts the stress distribution on the shaft, it can be observed that the maximum value of stress appears to be near the ends of the shaft. As we move from the ends towards the center, stress is found to be almost equally distributed. Fig. (7.b) illustrates the distribution of strain on the shaft. Shaft is determined to be strained the highest at both its ends. However, towards the center of the shaft, strain is observed to be evenly distributed. Deflection of the shaft upon full loading is demonstrated in Fig. (7.c). It is observed that the maximum deflection occurs at the center of this shaft. Since the shaft rests on bearings at both ends, it acts like a fixed beam. Thus, the ends of the shaft remain fixed at their original positions while deformation occurs mostly towards the center.

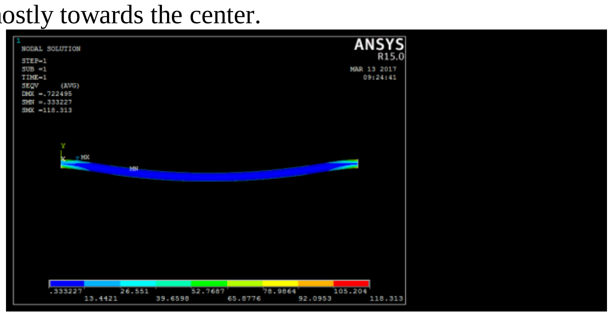

Fig. (7a): Stress distribution on the shaft at full loading

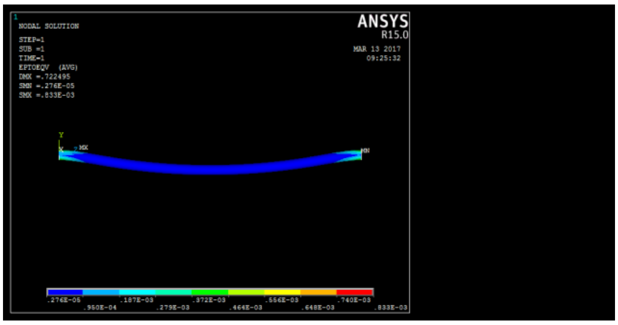

Fig. (7.b): Strain distribution on the shaft at full loading

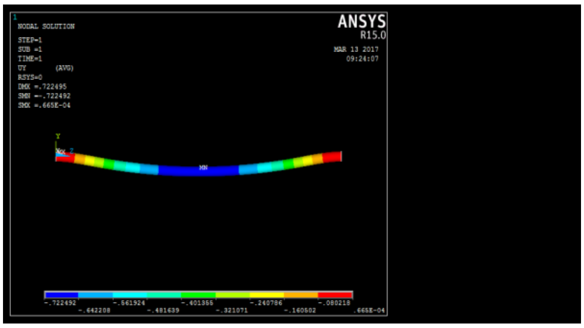

Fig (7.c): Deflection of the shaft at full loading

IV. CONCLUSION

Significant accomplishments at this time include
(a) The design and 3D modeling of a power-free solar tracking mechanism.
(b) Validation of manually calculated results of minimum shaft diameter by computer simulation.
(c) Manufacture of a $9m^2$ compound parabolic collector has 40-50 % higher efficiency then other parabolic collector
(d) Manufacture of every component of the tracking mechanism mentioned in the paper. The experiment is currently in the final stage of hardware assembly and qualification testing. We expect it to be manifested in working condition by the end of April, 2020.

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AUTHORS PROFILE

R Rahul, is working as an Assistant Professor in the Mechanical Engineering Department of Koneru Lakshmaiah Education Foundation, Vaddesawaram, Andhra Pradesh, India. He is expertized in machine design. He did his post-graduation from VIT, Vellore, India. His area of interest in Design, modelling, simulation, artificial intelligence with python and machine learning

T Srinivas , is working as an Associate professor in the mechanical engineering department of Dr B R Ambedkar National Institute of Technology Jalandhar, Jalandhar (Punjab). He did his Ph.D and M-Tech from JNT University College of Engineering, Hyderabad. His area of interest is solar energy.

Himanshu Mishra, is working as an Associate Professor in the Mechanical Engineering Department of Koneru Lakshmaiah Education Foundation, Vaddesawaram, Andhra Pradesh, India. He did his Ph.D. and M.Tech. from National Institute of Technology Rourkela, Orrisa, India. His area of interest is micromachining and optimization. He is an associate

N Tamiloli , is working as an Associate professor in the mechanical Engineering Department of Koneru Lakshmaiah Education Foundation, Vaddesawaram, Andhra Pradesh, India..He did his Ph.D and M-tech from Anna university, Chennai India. His area of interest is machining and optimization.

B V Dharmendra, is working as an Professor in the mechanical Engineering Department of Koneru Lakshmaiah Education Foundation, Vaddesawaram, Andhra Pradesh, India..He did his M.E from PSG Technolgy Coimbatore and PhD from IIT Kanpur, His area of interest is advanced machining process.