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# Design and development of an educational solar tracking parabolic trough collector system

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ABSTRACT: Renewable energy sources and systems have become popular topics of study for thermal engineering students. This article presents the design, development, testing and evaluation of an educational single-axis solar tracking parabolic trough collector that represents a standalone system to produce process heat at a moderate temperature for instructional and demonstrative purposes. The parabolic trough solar collector consists of a stainless steel parabolic reflector, a flat solar receiver, a thermal storage tank and a closed loop tracking system. The tracking system comprises electro-mechanical components such as a control box, a DC motor, a photo sensor and a gear box. A small power unit, which consists of a 12 V battery and two photovoltaic panels, is used to power the tracking systems. This apparatus is compact and portable. The system was designed and built *in house* with the help of a senior design team. The unit has been used in applied thermal science courses, such as renewable energy as a demonstration unit. This type of activity serves to enhance the students' understanding of renewable energy sources and energy conversion processes. The feedback from the students was very positive and they feel that such apparatus has enhanced their learning of renewable energy and heat transfer concepts.

Keywords: Solar, experimental, tracking collector

## INTRODUCTION

Acquiring new instructional laboratory apparatus is a challenge because of budgetary limitations. In addition, the apparatus designed by companies specialising in education equipment may not exactly reflect the educational objective intended by the faculty. These obstacles had forced the authors to look for alternative sources from which to acquire *high tech* experimental laboratory apparatus for demonstrating thermodynamics and heat transfer processes. It was decided to develop and build in house a cost effective solar tracking parabolic trough collector that could be employed to demonstrate some fundamental concepts in heat transfer and renewable energy. This was accomplished by a team of senior design students.

Parabolic trough solar water heating is one of several well proven solar energy technologies. It is being used on a commercial scale to produce high pressure steam for power generation, as well as on a small scale for commercial and residential applications [1]. A small scale version of such a system can be used to produce process heat at moderate temperatures (up to 150°C), which is required by most of small factory processes, such as food canning, paper production, air-conditioning, refrigeration, sterilisation, etc.

The performance of this type of solar collector can be improved greatly by using one of the solar tracking techniques to concentrate a direct solar beam onto the focal point. The tracking technique basically depends on the tracking axis of a solar beam reflector. A comparison of different tracking modes has been thoroughly investigated in the literature [2][3]. These studies showed that adopting the two-axis solar tracking technique causes the highest increase in system energy output and improves solar energy contribution. It has been reported in the literature that the two-axis solar tracking system consumes more energy than the single solar tracking techniques due to the extra control power requirement. Therefore, using the two-axis mode cannot be justified unless the amount of energy produced compensates for the additional elements and maintenance cost.

Various studies were conducted to develop a low cost parabolic trough collector for moderate temperature applications. An air conditioning system using a parabolic trough collector was developed and used in educational building [4]. This system incorporates a parabolic trough collector of 52 $m^2$. It generates chilled and heated water, depending on the season, for space cooling and heating. A parabolic trough collector of 10.5 $m^2$ area was used to supply the heat which drives a steam jet ejector chiller at a temperature of 140°C [5]. System performance was investigated experimentally and the results showed that collector efficiency may vary between 30-60%, depending on system load and operation conditions.

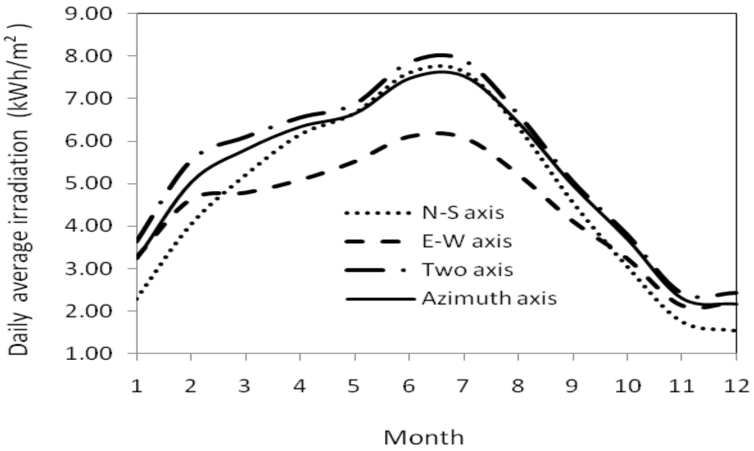
Odeh et al reported a design of a single solar tracking axis parabolic trough collector suitable for moderate temperature applications in remote area [6]. The proposed design was based on selecting locally available materials that can achieve the required level of collector performance. In this article, the authors extend the work of Odeh et al by developing, testing and evaluating the design of single solar tracking axis parabolic trough collector that was reported by Odeh et al [6]. The system is designed to be self-powered and operate for moderate heat load applications with minimal supervision in a remote area.

## PARABOLIC TROUGH COLLECTOR AND SOLAR TRACKING METHODOLOGY

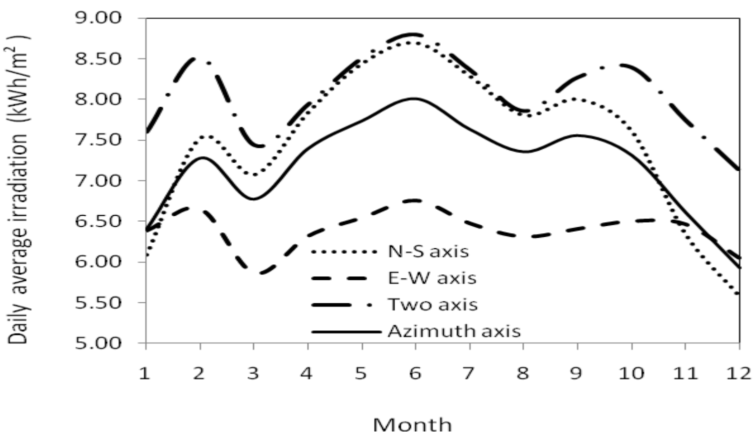
The selection of tracking axis configuration is based on load profile, site latitude and solar irradiation. To show the effect of tracking technique on the amount of incident solar irradiation, four major tracking configurations were examined: North-South (N-S) tracking axis, East-West (E-W) tracking axis, two-axis tracking, and azimuth tracking axis. Daily average solar irradiation was generated using the RETScreen International irradiation data bank [7] and used to plot the incident irradiation on these tracking configurations for two extreme irradiation sites (cold/wet and hot/arid climate) as shown in Figure 1.

The figure clearly shows that for the given latitudes the two-axis tracking mode provides the maximum solar irradiation. However, in the cold/wet climate at latitude 45° the difference between the three solar tracking configurations (N-S axis, two-axis and azimuth axis) is not significant, specially, between the fourth and eighth months. The small increase in collector annual input solar energy in the two-axis tracking mode may not justify the increase in the capital and running costs due to the use of an extra tracking motor system. Contrary to this, in the case of hot/arid climate (latitude 25°) significant differences in solar irradiation between the solar tracking configurations can be reported in most of the year.

Parabolic trough collectors usually track the sun with one degree of freedom using the E-W axis or the N-S axis. Solar tracking by these modes maintains the plane of a solar beam so that it is always normal to the collector aperture. Thus, the solar beam from different points of the parabolic trough-reflecting surface is collected on the focal line receiver.




a)




b)

Figure 1: Daily average incident irradiation on a surface of different tracking axis configurations; a) cold/wet climate, latitude 45°; b) hot/arid climate, latitude 25°.

PARABOLIC COLLECTOR SYSTEM DESIGN

An inclined single axis tracking parabolic trough collector was designed to generate hot water or steam at a pressure close to ambient. The parabolic collector system consists of four main parts: a parabolic trough reflector, a solar receiver, a power supply, and a tracking control and mechanism.

Parabolic Trough Reflector

A parabolic steel frame with an aperture width of 1.8 m, rim angle (*Ø*) of 74°, focal line of 2 m and focal point length (*f*) of 0.6 m was used. The type of reflecting surface used in this study was 0.0005m×2m×1m stainless steel sheet type (430 BA). The sheet has enough flexibility to adopt the shape of the parabolic steel frame. This frame was constructed from steel trusses, as shown in Figure 2, to withstand the effect of wind force and any deformation in the shape of the parabola that might occur. The two stainless steel sheets were connected to the frame from its edges by sliding them inside 3 cm grooves at the edge of the frame. Total frame mass including the reflecting surface was approximately 70 kg. This frame configuration allows the testing of different reflecting surfaces. This design can be implemented and produced in a university workshop and does not require special high technical equipment in producing the reflecting surface parabola.

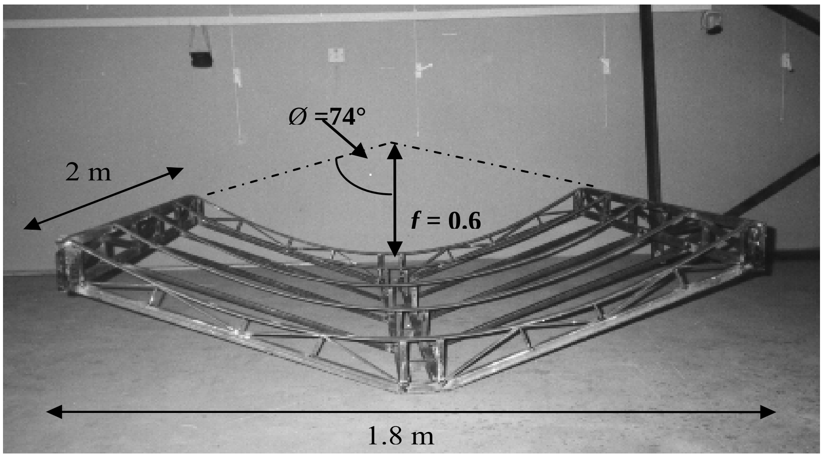



Figure 2: Parabolic steel frame.

Solar Receiver

The width of the receiver is estimated from the width of the solar flux pattern in the focal line. This can be estimated by evaluating the width of the image reflected by each segment on the parabola. Total flux (W/m$^2$) on the focal line can be evaluated by segmenting the parabolic reflector and evaluating the reflected solar energy of each segment:

$$Total\ flux = flux\ (1) + flux\ (2) + \cdots + flux\ (n) = \sum_{i=1}^{n} flux\ (i) \quad (1)$$

$$flux\ (i) = \left[\frac{\left(I_b/n\right)}{W_{img}L_r}\right] \quad (2)$$

where $n$ is the number of reflector segments, $i$ is the segment number, $I_b$ is the solar energy collected from each segment (Wh) and $L_r$ is the receiver length (m). The image width, $W_{img}$, depends on the segment number or local rim angle, $Ø_{ri}$, of the parabola and was evaluated by the method reported by Duffie and Beckman [8]. To evaluate the flux pattern (W/m$^2$) in the focal point of the parabola, the accumulation of flux from all parabola segments has to be considered. Therefore, at any distance from the focal point:

$$flux\ pattern = L_r.(flux\ (i)W(i) + flux\ (i+1)W(i) + \cdots + flux\ (n)W(i)) = \sum_{i=1}^{n} flux\ (i) \quad (3)$$

In general, solar flux pattern at different distances from the focal point can be evaluated by:

$$pattern(i) = \left[\sum_{i}^{n} flux(i)\right] \cdot \left[W(i) - W(i-1)\right] \cdot L_r \quad (4)$$

Solar flux pattern is generated at different beam incident angles using Equation (4). Odeh et al reported that solar flux decreases as one moves away from the receiver centre [6]. The deviation of the beam incident angle from the normal produces a significant reduction in solar flux and an increase in the maximum width of the solar image. Based on that, Odeh et al concluded that the receiver width must be around 6 cm to intercept all solar images during low solar elevation angle hours [6]. The receiver unit consists of a copper tube 2 m long, with a diameter of 2 cm that is fixed on a 6 cm wide and 2 m long copper sheet. Both the copper tube and copper sheet are sprayed with a black coating. The receiver tube is inserted inside a rectangular casing insulated from the back and covered from the front with a single glazed opening, as shown in Figure 3. The receiver unit is mounted at the focal line using the adjustable supports on the two sides.

Thermal Storage Tank

Energy collected in the receiver unit is transferred to a thermal storage tank by circulating heat transfer fluid in a closed loop. To select the right size of thermal storage tank, a method developed by Odeh and Morrison for parabolic trough solar collector was adapted [9]. Solar energy contribution (or solar fraction) increases with the ratio of storage tank/collector area to its optimum value at 15 ($l/m^2$). Considering the collector aperture area (3.6 $m^2$ in this study), the optimum size of the thermal storage tank is around 54 litre. The thermal storage tank, shown in Figure 4, is a coil heat exchanger tank with outer surface insulation covered by metal drum. The tank, which is mounted on a stand next to the collector consists of a copper tube coil immersed in a water tank, a pressure gauge, a temperature measurement probe and a 40 W DC water pump is used to circulate the working fluid (distilled water) between the receiver and thermal storage tank heat exchanger coil.

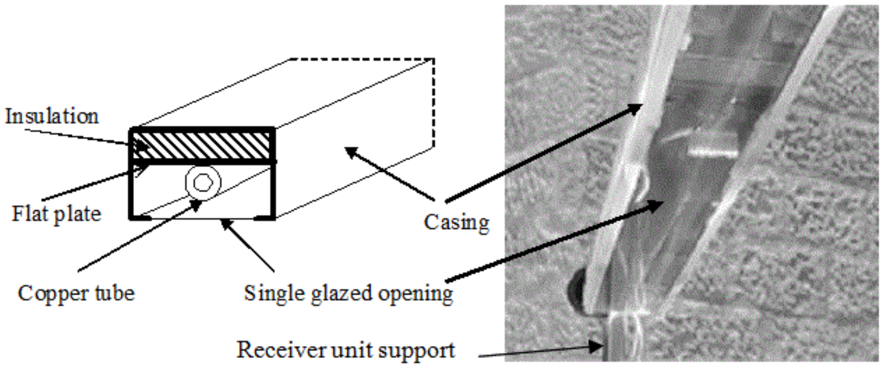



Figure 3: Flat receiver configuration.

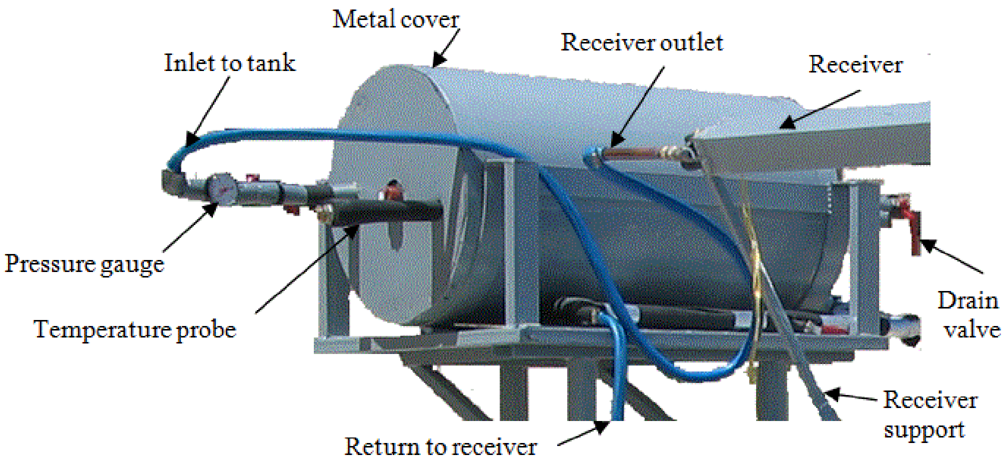
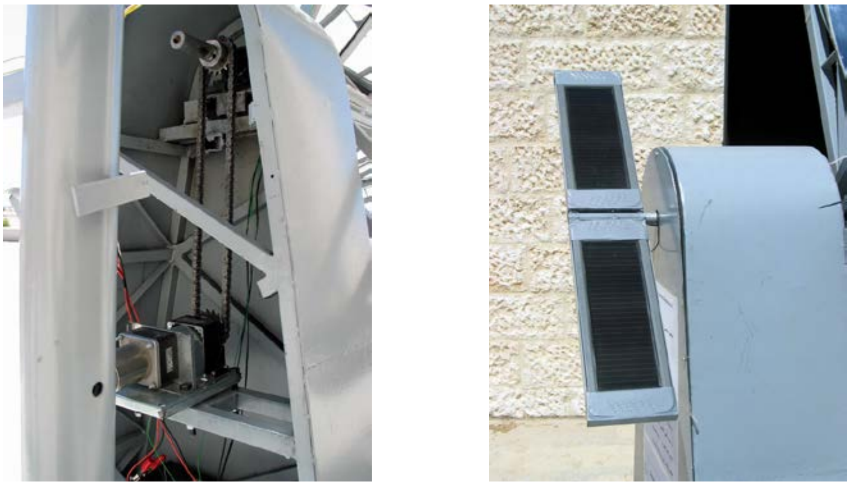



Figure 4: Thermal storage tank configuration.

Control and Power Supply System

A closed loop control system was designed to track the sun around the N-S axis. This system consists of a DC motor, a speed reduction unit, a photo resistance sensor unit and a controller. Two photo resistances ($R_R$ and $R_L$) are located on either side of the parabolic reflector. When the solar beam plane is normal to the aperture of the collector, the two resistances must have almost equal resistance. A slight change in the sun's position will cause different beam intensity on the photo resistance and, thus, different resistance. The photo resistances are used as part of a Wheatstone bridge circuit to give zero voltage when the radiation plane is normal to the aperture area of the reflector (sun in centre of the parabola). If the incident angle changes, the sensors give a voltage proportional to that change. The controller amplifies this voltage and sends a signal to the motor to track the sun by keeping Wheatstone bridge output voltage equal to zero.

Two 10 W silicon photovoltaic modules (Sinopuren) were used to charge 12V/70 Ah battery needed to drive the DC motor, control components and a DC closed loop HT water pump. The PV modules shown in Figure 5 were fixed on the tracking frame to improve PV cell efficiency by minimising solar incident angle. Having this type of power supply, the system can operate independently and off the grid. The selection of the PV and the battery sizes were based on the power required by the control system and DC water pump. The required motor torque was estimated experimentally to be 100 Nm. Based on this torque, a 12 V motor unit of 0.75 RPM was found suitable for the tracking mechanism. A sprocket and chain system was used to connect the motor unit with the main tracking shaft as shown in Figure 5. The motor power consumed during system operation was measured to be 2.2 W.



a) Motor, sprocket and chain system. b) Two 1.8 W silicon PV modules.

Figure 5: Tracking motor mechanism with a PV power unit mounted on a tracking shaft.

The control system is capable of achieving tracking shaft radial displacement between 0.1 to 0.3 degree/minute. This solar tracking resolution covers the maximum change in solar elevation angle (0.20 degree/minute) during a typical day, as shown in Figure 6.

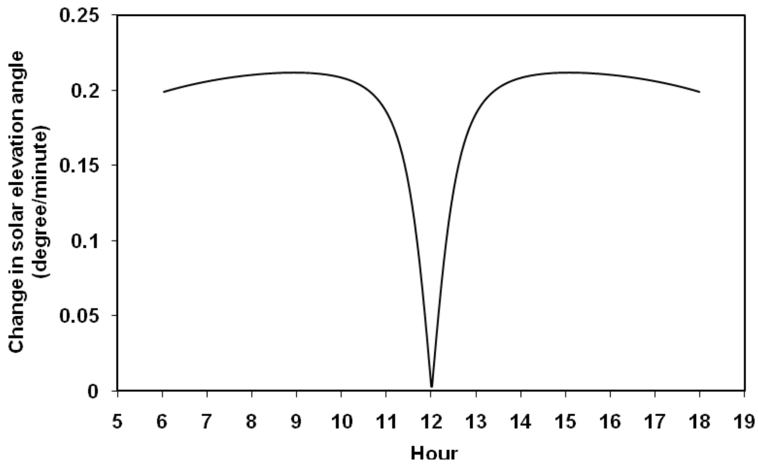



Figure 6: Change of solar elevation angle during a typical day.

SYSTEM TESTING

Figure 7 presents the testing platform of the parabolic solar collector that was developed and constructed in house. The platform allows the flexibility of different outdoor tests, as well as different tracking axes (N-S or E-W axis). The system working fluid (oil or distilled water) inside a closed loop pipe transfers the heat to the storage tank via a tube coil heat exchanger. The storage tank height is adjustable to allow the study of natural circulation effect of the working fluid (i.e. thermosiphon). A DC pump arrangement is adopted to allow for forced circulation of the working fluid.

To validate the experimental setup, a thermal performance test of the trough solar collector was carried out during a clear day. The test was conducted with open loop water flow (the exit water does not return to the thermal storage tank) to achieve constant water inlet condition. Figure 8 shows the variation of both the solar collector efficiency and the solar irradiation with time. The water flow rate is 0.0233 kg/s. The solar collector efficiency is at noon, which does not consider the loss in solar radiation in morning and evening hours due to the increase in incident angle. It can be concluded that the average efficiency of the collector is about 60%. This value is considered acceptable if one compares it with advanced collector efficiency (60-67%) currently used in solar thermal applications [2].

Another test was also carried out in order to investigate the tracking sensitivity test during a cloudy day. The result of this test is presented in Figure 9. It is clearly shown by motor steps that the tracking system can follow the sun although there is reduction in irradiation due to cloud patches. This type of tracking allows the operation of the set up during a day of unsteady weather conditions as well.

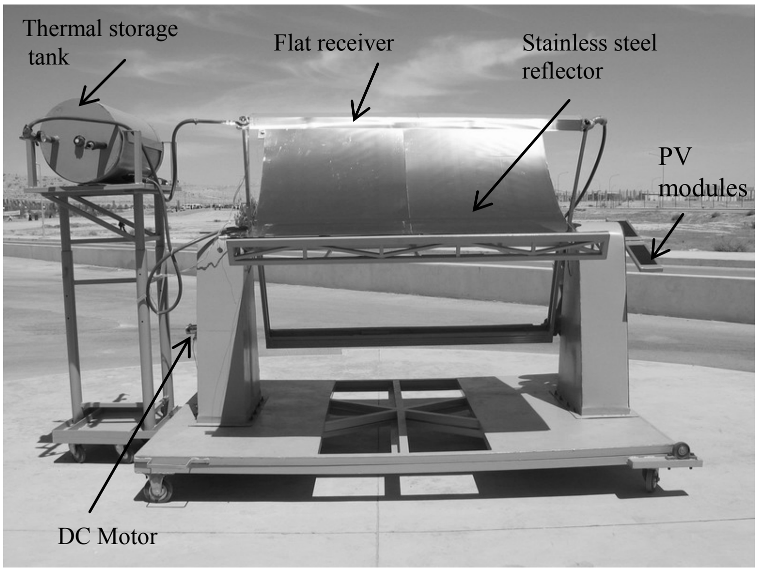



Figure 7: Test platform operating in a sunny day.

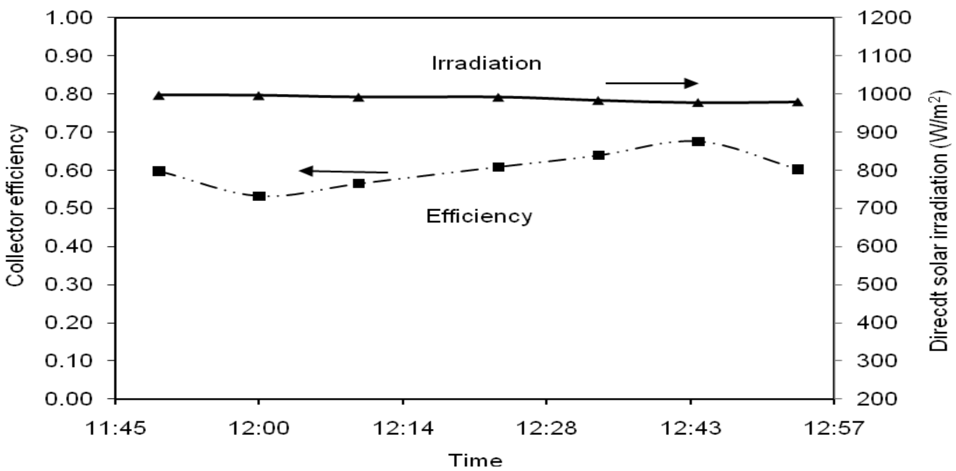



Figure 8: Collector performance during noon hour, working fluid is water, $\dot{m}_w$ = 0.0233 kg/s, N-S tracking axis.

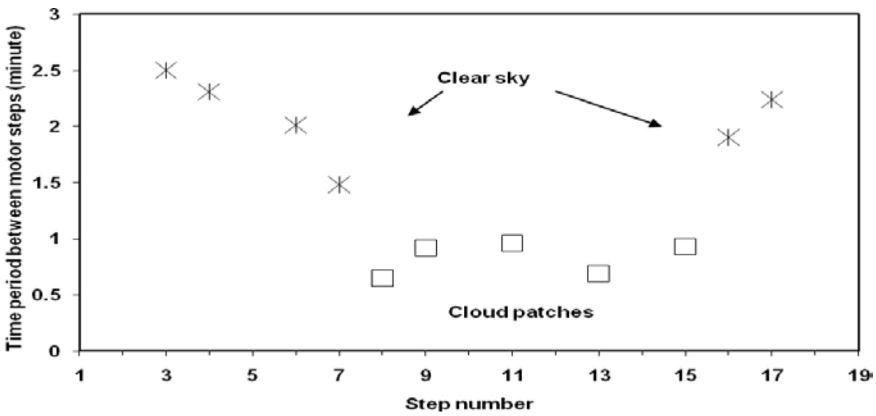



Figure 9: Solar tracking sensitivity during a cloudy day.

EDUCATIONAL BENEFITS

This project provided the opportunity to senior mechanical engineering students to work on a *real world* engineering problem. A team of senior design students was assigned to this project. They applied the science and engineering knowledge learned in previous classes. The project spanned two semesters. In the first semester, they defined the problem, generated several solutions, evaluated the different solutions and performed the detailed design. In the second semester, they built, tested and evaluated the unit. Moreover, the unit has been used in applied thermal science courses, such as renewable energy as a demonstration unit. The set-up and the activity can be used to initiate discussions involving renewable energy and other contemporary issues. While no formal survey was conducted among the students to assess specific learning from this activity, established assessment tools indicate that students are pleased with the experience. The feedback from the students was positive and they felt that such apparatus has enhanced their learning of renewable energy and heat transfer concepts.

## CONCLUSIONS

In this study, an educational single tracking axis parabolic trough collector was designed and constructed for moderate heat load processes for instructional and demonstrative purposes. The solar tracking collector was designed to be a self powered system so it can operate remotely and independently under moderate radiation levels. Once the system is oriented to a certain axis (N-S or E-W), it can operate continuously with minimal technical supervision. Simplicity in manufacturing and operation was considered in the design of this collector, such as using stainless steel as a reflecting surface and a closed loop control system for the single solar tracking axis. The average efficiency of the collector when operated at noon was found to be about 60%.

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