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The co-learning in the design, simulation and optimization of a solar concentrating system

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ABSTRACT

Due to the significant environmental and economic impact of the solar energy on our life, many solar concentrator systems (SCSs) exist today, the majority of them being very costly to construct. In this paper, an efficient low-cost SCS based on Reif research was implemented using principles of collaboration and co-learning. This system basically converts the solar-thermal energy to other forms of usable energy such as electrical energy. It mainly consists of three parts: (i) the primary concentrators (PCs), which collect the solar radiations coming from the sun and reflect it upward to the secondary concentrator; (ii) the secondary concentrators (SCs) which are moving concentrators suspended on cables above the solar collecting field; and (iii) the receiving energy collector (REC). The final results showed that the proposed system functions in the expected limits.

1. Introduction

Solar energy is the most viable source for energy in this planet. Solar concentrating system uses mirrors or lenses in order to concentrate sunlight in a small area and convert it into usable energy. Countries in the Middle East and North Africa are ideally suited for solar harvesting. Each square meter of land in Saudi Arabia for instance, receives about 5.78 kW h/m^2 average solar insolation (direct solar energy from the sun) per solar day, while other counties of the Middle East and North Africa receive from 5 to 7 kW h/m^2 of solar insolation each solar day. By most estimates, yearly, these regions receive approx. 2 MW h/m^2 per year (Reif, 2010), and other estimates vary between 1.7–2.2 MW h/m^2 per year.

This research is based in Saudi Arabia; therefore, all the statistics from this area are used. Saudi Arabia is an oil producer country, and it depends mainly on a nonrenewable energy source (oil), the need of an efficient energy source being much needed. Current SCSs are expensive to construct, with costly materials, support structures and tracking systems, requiring 15–24 years for recovery of capital and maintenance costs. The scope of this work is to provide development and demonstration of a novel solar concentrating system that is much less costly to design and construct, and yet provide high efficient conversion of solar power to useable energy.

Dr. John Reif from Computer Science department at Duke University invented a novel cost-efficient solar concentrating system (Reif, 2010). The proposed system serves well in hot-sunny regions as Kingdom of Saudi Arabia, as well as the other nations of the Gulf States and North Africa. Key requirements for use by Saudi Arabia are: (i) energy efficiency, (ii) cost-effective to construct and maintain, (iii) durability. This system has two levels of concentration primary and secondary which makes it more efficient than other existing systems in the market. It is generally designed to be inexpensive, durable and highly reflective.

Inspired by this system and taking into consideration the harsh environmental conditions of the kingdom, in this work, an affordable approach to solar concentrating system is proposed. It will provide Kingdom of Saudi Arabia and other regions with solar energy in a more efficient manner compared with the existing ones. Also, it will help decrease the consumption of non-renewable energy (Pitz-Paal et al., 2012). The major areas of benefit for this system are:

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– Desalination. Solar desalination has critical importance to the kingdom by providing a major reduction in the Kingdom's consumption nonrenewable energy. The proposed system can also be used to provide heat energy to drive steam generation of electrical power.
– Improvement of arid and semi-arid regions. The proposed system provides the cost-effective transformation of dry desert and semi-desert regions to wet regions that can support crops, transforming largely unproductive arid lands into regions for farming and other mixed uses, such as commercial enterprises requiring water, residential, and recreation areas.

The research presented in this paper was carried out using the principles of collaborative and co-learning. According to Panitz (1999), collaboration is a philosophy of interaction and personal lifestyle while co-learning is a personal philosophy. The co-learning strategies employed were the ones proposed in Felder and Brent (2001)). A great amount of knowledge transfer was involved. It included discussion and meetings, mostly using the internet, through online communication software. Initially, just one of the groups (located at Duke University) had base knowledge about the system, the member of this group being co-author and inventor. The second group (located at KAU) worked on the simulation part and was represented by computer scientists. The third group (located at Effat University) worked on the hardware implementation. A strong relation was established between the last two groups, as the hardware implementation was based on the software simulation results.

The paper is organized as follows. Section 2 presents the state of the art related to field of capturing solar energy. In Section 3, the methodology and design applied for the proposed system is described. The results obtained out of the simulations are presented in Section 4. The last section concludes the paper.

2. Solar energy capturing – state of the art

The sun's energy is the starting point for the chemical and biological processes on our planet. In the same time, it is the most environmentally friendly form of energy and can be used in many ways, being suitable for all social systems (Elsayed, Taha, & Sabbagh, 1994; German Solar Energy Society, 2010).

The sun is not the only energy source we use nowadays, a high percentage of power stations being based on fossil fuel. In these stations, the energy from the burning fossil fuels such as coil and oil is converted into electricity. On the other hand solar power plants use energy from the sun to generate electricity. Solar energy plants can be divided into two major parts: solar energy plants that use the sun's light as a source of energy (photovoltaic system) and the plants that convert the sun's heat into energy (solar collector systems).

2.1. Solar collector systems

Solar concentrating systems make use of the sun heat to generate energy. It uses lenses or mirrors as well as tracking system to focus a large area of sunlight into a small beam. The concentrated heat is then converted into usable energy (electricity). There are two types of solar collectors: non-concentrating (stationary) and concentrating (Kalogirou, 2014a, chap. 3). The difference between the two consists in the capability of following the sun's direction.

Solar concentrator systems typically consist of various key optical components: a primary concentrator, possibly a secondary concentrator, a solar receiver containing some form of solar absorber or an energy storage system (Lave & Kleissl, 2011). Primary concentrators of a solar concentrator system are those parts that first receive the solar radiation, and first concentrate it. The majority of the surface area and materials comprising a solar concentrator are generally in its primary concentrator, which needs to be durable and protected from the horizontal winds. Most of the prior designs for solar concentrating systems currently used employ solar troughs, linear Fresnel concentrators, dish systems and solar towers that are very costly to manufacture and maintain.

In order to test the thermal efficiency of the solar collectors, two basic methods can be applied: under steady-state conditions or using a dynamic test procedure (Kalogirou, 2014b, chap. 4). Also, different standards can be used, among which, the most common are: ISO 9806-1:1994 (Standard, 1994) and the ANSI/ASHRAE Standard 93:2010 (ASHRAE, 2010).

The solar concentrating system (SCS) has many advantages over the other solar systems, such as: (i) *Cost-effective*: Vastly decreased capital costs 30–50% of prior SCSs, by use of inexpensive concrete and not requiring large-scale structural support structures; (ii) *Low Energy Loss and High Efficiency*: Estimated total optical loss <59.7% (of incoming solar energy reaching the solar) and 40.3% optical efficiency: typical for many conventional SCSs; (iii) *Highly Durable* due to immobility of primary concentrators and use of concrete; (iv) *Scalable to Very Large Systems*; (v) *Compact Use* of Land; (vi) Uses *Well-Developed* and Commercially Available Components; (vii) provides *Conventional Concentration Performance*: Adjustable design, capable of solar concentration ratios ranging up to 40:1 or more.

A stationary collector has the same intercepting area as its absorbing area (Tian & Zhao, 2013). Three main types of stationary collectors can be encountered: (i) flat plate; (ii) stationary compound parabolic collector and (iii) evacuated tube collector.

A flat plate collector consists of glazing covers, absorber plates, insulation layers, recuperating tubes and other auxiliaries (Tian & Zhao, 2013). Among their advantages one can enumerate: cheap to manufacture, they collect both beam and diffuse radiation and since they are fixed no sun tracking is required (Kalogirou, 2014a, chap. 3).

A compound parabolic collector is a non-imaging concentrator with the capability of reflecting all the incident radiation (Kalogirou, 2014a, chap. 3). There are two types of compound parabolic collectors (symmetric and asymmetric) and they employ two types of absorbers (the fin type with a pipe and tubular absorbers) (Kalogirou, 2014a, chap. 3).

Usually, this concentrating collector has a concave reflecting surface for intercepting and focusing the heat flux (Tian & Zhao, 2013). Various types of this concentrator can be encountered: (i) parabolic trough collector; (ii) Fresnel collectors; (iii) parabolic dish reflectors and (iv) heliostat field collectors (Kalogirou, 2014a, chap. 3).

2.1.1. Linear concentrating systems

Linear concentrating system collectors capture the sun's energy with large mirrors that reflect and focus the sunlight onto a linear receiver tube. The receiver contains a fluid that is heated by the sunlight and then used to create superheated steam that spins a turbine which drives a generator. The most commonly used linear concentrating systems are: parabolic trough system and linear Fresnel reflector system.

Parabolic solar trough concentrators and linear Fresnel concentrators are similar (Morin, Dersch, Platzer, Eck, & Häberle, 2012) both consisting of a long reflector, which acts as the only concentrator, aligned on a north–south axis with a collector tube running along its length. The reflector is rotated to track the sun's movement and its reflected concentrated solar energy is captured by its collector tube. In a parabolic solar trough concentrator, the cross-section of the reflector is parabolic, whereas in a linear Fresnel concentrator the reflector has Fresnel shape (it is a continuous surface of a parabolic cross-section of the same curvature, with stepwise discontinuities between them).

2.1.2. Dish systems

A dish system uses a mirrored dish similar to a satellite dish. In order to minimize the cost the mirrored dish is usually composed of many smaller flat mirrors formed into dish shape. The parabolic dish gathers solar energy from the sun and concentrates it into beams of light. Then, the concentrated beams are reflected onto a central engine that produces electricity. The dish is mounted on a structure that allows it to rotate to track the movement of the sun to collect the maximum amount of sunlight throughout the day. The receiver in this system is mounted at the focal point of the dish.

2.1.3. Power tower system

A power tower system uses a large field of flat, sun-tracking mirrors to focus and concentrate sunlight onto a receiver on the top of a tower. The receiver in this system contains a liquid that is heated with the concentrated sunlight and then the heat is used to power a turbine that generates electricity.

2.2. Photovoltaic system

We all know that the sun's energy creates heat and light, but it also can be converted to make electricity. One technology is called solar photovoltaic, or PV for short. A PV system consists of many solar panels used to convert solar radiation into usable electrical energy. PV panels are made from semi-conductor material such as silicon that is able to gather high concentrations of electrons. Through the phenomenon of photovoltaic effect, when a photovoltaic cell is exposed to sunlight, the impact of solar radiation onto the solar cell generates electricity.

The first generation of PV technologies was developed using crystalline structures with Silicon (mono-crystalline, poly-crystalline and emitter wrap through) and over the years researchers are trying to improve it (Chow, 2010; El Chaar, Lamont, & El Zein, 2011; Ibrahim, Othman, Ruslan, Mat, & Sopian, 2011; Kumar & Rosen, 2011). Another technology used for PV cell production is thin film, which in comparison with crystalline silicon cells is more promising and has the potential of reducing the material and manufacturing costs without affecting performance and cell's lifetime (El Chaar et al., 2011). There are different approaches related to thin film, among which we can enumerate: thin film c-Si and pc-Si solar cells, thin-film amorphous and nano-Si solar cells (in different configurations such as amorphous Si double or triple junctions; tandem amorphous Si and multi-crystalline Si), and thin film chalcogenide solar cells (El Chaar et al., 2011; Hasan & Sumathy, 2010; Parida, Iniyan, & Goic, 2011; Razykov et al., 2011).

Photovoltaic panels can be considered as an efficient way to convert solar energy to usable electrical energy especially in hot regions. Installation of PV's can be performed on the rooftops or on the ground, which allows a good use of the available space. On the other hand photovoltaic system requires additional equipment and high performance PV panels are very costly per square meter. For example, the direct current (DC) must be converted to alternating current (AC) and batteries for storing the converted energy for later use must be available. Another drawback of PV systems is that they can be easily damaged, which require additional insurance cost. Also, the output of solar photovoltaic system depends on the availability of solar radiation.

The National Renewable Energy Laboratory of the US Department of Energy (DOE) has made a number of cost analysis that concluded that the currently operating PV systems produce electricity (per kW h) at a cost (including finance costs for construction and repair) of more than two to three times of the current commercial market price of electricity (per kW h). These studies also concluded that with current PV technology, it was not currently feasible to ever get a payback period for construction and repair cost within the PV unit's expected functional lifetime. PV never produces enough electrical energy to pay for both their initial construction and subsequent repair.

Since cooling by either natural or forced circulation can reduce the PV temperature, an alternative is to use Photovoltaic thermal systems (PV/T) (Hasan & Sumathy, 2010). The advantages of this system are: (i) dual purpose; (ii) efficiency and flexibility; (iii) wide application; (iv) cheap and practical (Hasan & Sumathy, 2010).

2.3. Reif's solar concentrating system

Reif invented a novel system for collecting and concentrating solar energy. This novel system uses two stages of concentration – primary and secondary – as shown in Fig. 1 and it is very low in cost due to the material used, which are not only cheap but also widely available.

The system is composed of 3 main components: (i) primary concentrators (PCs); (ii) secondary concentrator (SC); and (iii) receiving energy collector (REC).

3. Methodology and design

In 2010, Reif developed a novel, low cost system for collecting and concentrating heat energy from the sun (Reif, 2010). Inspired from this system, in this work, a new SCS is proposed (which will be called nSCS), its main components including parts for collection of solar radiation, concentration, and the absorbance of the concentrated solar energy as shown in Fig. 2.

The primary concentrators (PCs) are located on the ground. They are reflective optical parts (parabolic trough reflectors or linear Fresnel reflectors) which collect and reflect upward to the secondary concentrators (SCs) the solar energy incoming from the sun. The SCs are suspended on wires above the solar collecting field, and they further concentrate solar radiation by directing it to the ends of the solar collecting field. This solar energy is directed sidewise to the receiver. Our prototype includes immobile primary concentrator and a secondary concentrator that (i) tracks the solar energy reflected and partially concentrated from the PC and (ii) directs that solar energy to a metal sheet for temperature measurements. The required accuracy of horizontal positioning of the SC (to track the solar energy reflected and partially concentrated from the primary concentrators) is approx. 1–2 cm, which is very easily achieved by a conventional linear stepper motor.

The receiving energy collector (REC) is the part that absorbs the concentrated solar energy of the concentrated solar energy and is used for collecting and transporting the solar thermal energy concentrated by the system. RECs are very well developed devices with a high performance, available on the commercial market. The REC consists of a long glass tube (similar to a Dewar flask or vacuum flask) that is filled with heat transport fluid, which is pumped through the REC which absorbs the incoming concentrated solar thermal energy and transmits it to the heat transport fluid.

Based on these provided principles {14}, the actual system was implemented into two prototypes (simple foil and stainless steel). In order to digitally control the system, a parallel port was used to interface with the stepper motor using MATLAB. The main advantage MATLAB has over other programming languages like C, C++, and Visual Basic is that it does not require any special device driver to run in Windows XP. Stepper motor is used to control the number of rotations, direction and rotational speed, and it is easy to control it using MATLAB. In the proposed system we are allowing the stepper motor to be controlled from an IBM-compatible PC parallel port. Stepper motor is widely used in various automation system applications. In the proposed system a unipolar stepper motor is being interfaced with a personal computer parallel port in order to control the SC. A simplified schema of the steps performed to implement the proposed prototypes is presented in Fig. 3.

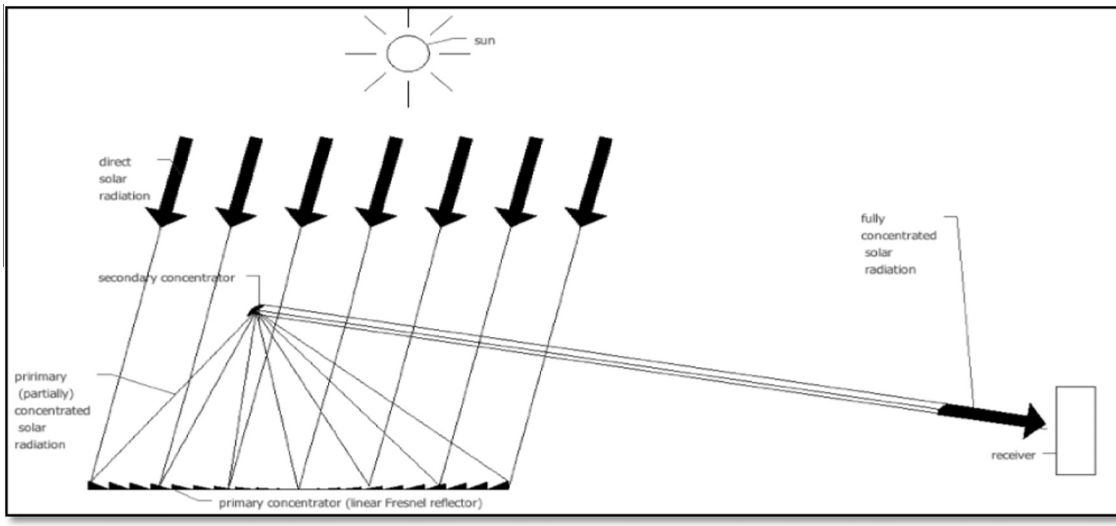

Fig. 1. Reif's solar concentrating system.

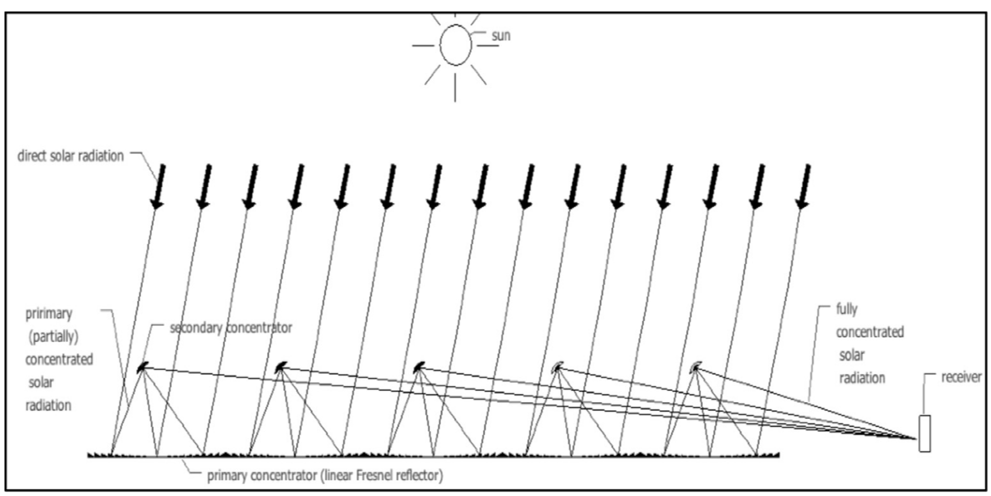

Fig. 2. 2D illustration of overall design of proposed solar concentrating system.

3.1. Design and construction of primary concentrator

The purpose of our PCs is to concentrate and reflect the solar radiation upward to the SCs. In the nSCS, the PCs are positioned flat on the ground and are not mobile. Each PC has a square shape when viewed vertically and its upper surface is a reflective optical surface which provides an initial concentration of direct solar radiation denoted "the primary concentrated solar radiation" (PCSR). Since the PCs are stationary, as the sun moves daily from east to west, the PCSR will move west to east above the PC. The prototype of the primary concentrator was implemented in two different methods, (i) using the foil; and (ii) using the stainless steel mirror.

3.1.1. Simple foil implementation

The first prototype was implemented on paper using a box made of cardboard, the method that was followed to obtain the parabolic shape was to simply use a ruler, paper, marker pin and a carpentry square. The ruler was placed on a paper and represented the PC base, the focal line from the parabola being designed to be 25 cm and pointed vertically from the surface of the ruler. The carpentry square was placed on the paper having its corner in contact with the ruler and the upper edge in contact with the focal point. A line was drawn with the lower edge, that process was repeated several times across the ruler as shown in Fig. 4.

The resultant parabola was cut and used to construct the PC (Fig. 5). The disadvantages of following this method are, that the focal point cannot be measured theoretically before or after the curve has been drawn.

The problem of the foil system is that it needs very precise implementation, which we could not achieve due to the lack of some special tools. That's why we moved to the stainless steel model. When we tried the foil system, we could not achieve readable, and enough concentrated radiation.

Using the same method developed for implementing the small version, a model was constructed using wood, and covered with a Reflective Mylar foil roll as a reflector (Fig. 6).

The main problem with this design is that it is impossible to obtain or calculate the original ellipse that the curve is part of. Also, it's hard to calculate the distance of the focal point distance from the curve after the curve is cut. In addition, the Reflective Mylar foil

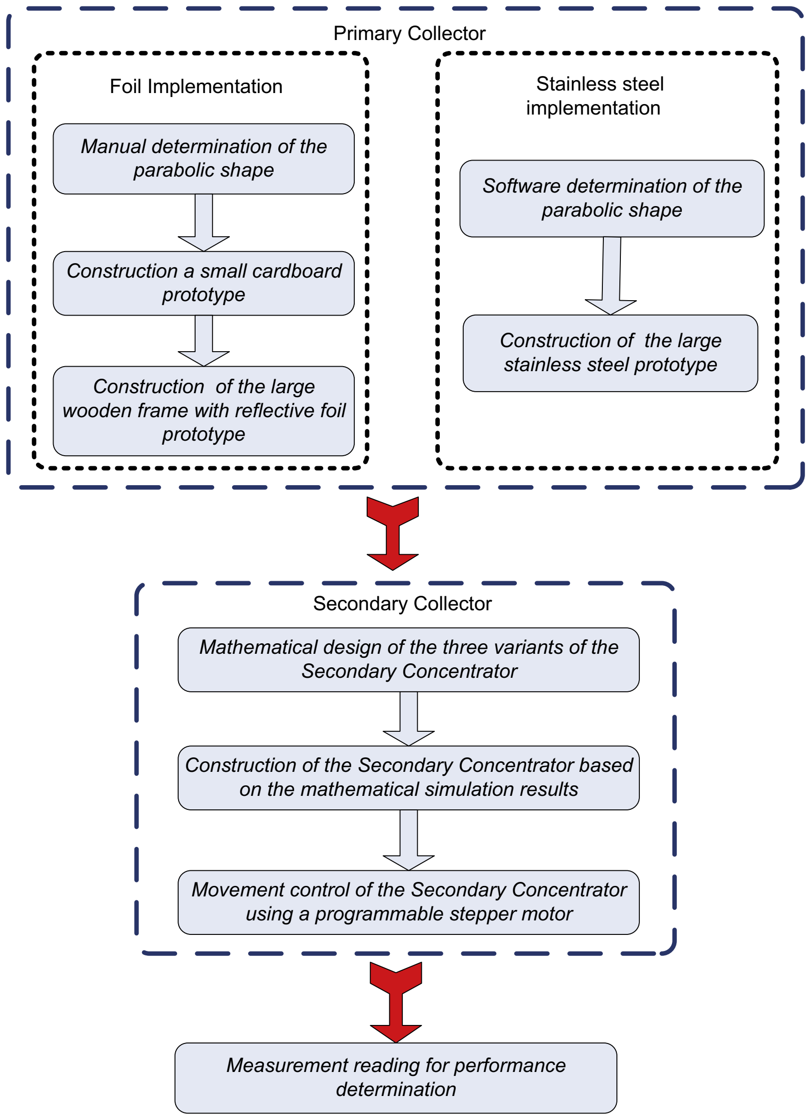

Fig. 3. Steps performed in the design and implementation of the solar collector prototypes.

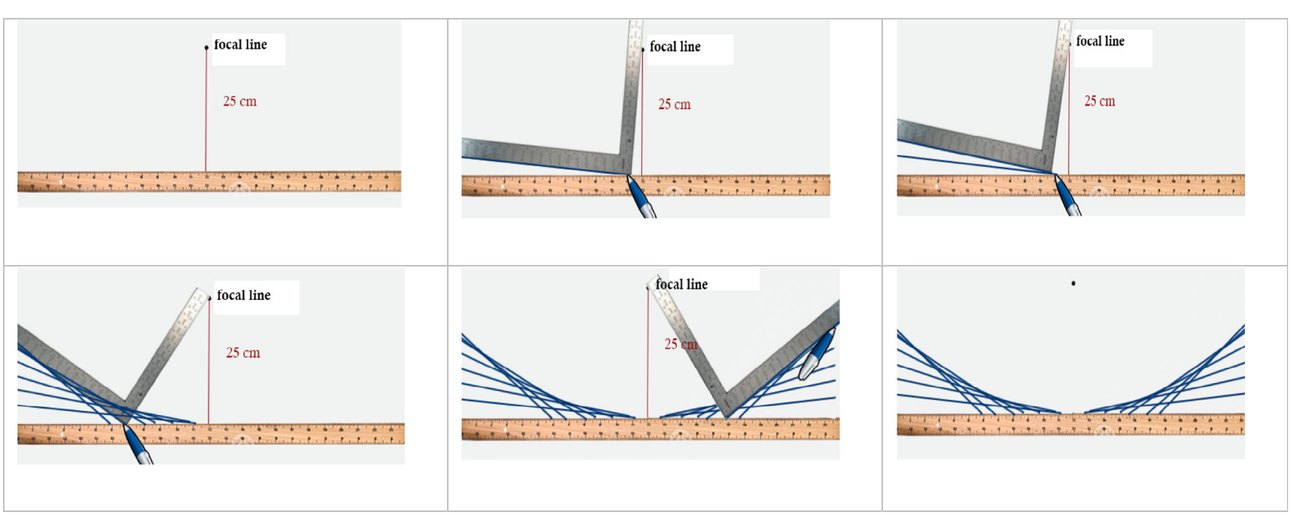

Fig. 4. Drawing of the PC parabola.

Fig. 5. The first model of the PC.

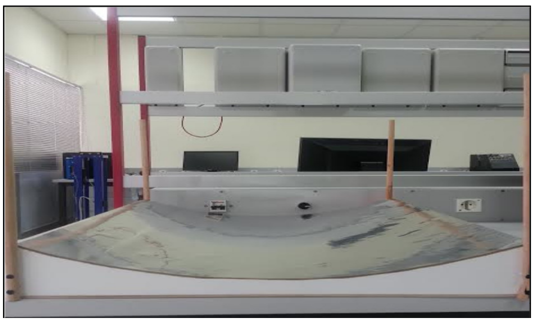

Fig. 6. The second model of the PC.

roll was purchased online, the thickness of the foil was really low and the weight was really light. Resultantly, it creased with time and lost its shine and burnish.

3.1.2. Using the stainless steel implementation

The final prototype was designed theoretically as a part of an ellipse with a semi-major axis $a = 90$ cm and the focus point from the origin f was designed to equal 40 cm so the semi-minor axis b was calculated using the following formula:

$$f = \sqrt{a^2 - b^2}$$

And equal to 74.83 cm as shown in Fig. 7.

The two dimensions and three dimensions models of the primary concentrator were designed using Rhinoceros software. The primary concentrator has a square shape when viewed vertically and has surface area of 47×52 cm. The design steps are shown in Fig. 7. Since the PCs are stationary, as the sun moves daily, their primary concentrated solar radiations will move in an east to west direction above the PC, where the secondary concentrator will be placed. The immobility of the PC makes its construction much less costly than conventional solar concentrators. Since the PC is on the ground, it does not have to be supported by metal superstructure required by most conventional solar concentrators. Instead, it can be cast in cheap wood. The upper surface of the primary concentrator is covered with concaved stainless steel super mirror with +90% reflexivity and thickness of 0.8 mm as a reflector.

The mathematical calculations of the focal line state that the focal line from the base of the PC is 40 cm, while practical measurements showed that the focal line was 30.1 cm from the base of the PC. The difference was 9.9 cm with an error of 24.75%.

3.2. Design and construction of the secondary concentrator

The SCs are used to further concentrate solar radiation and direct it to the ends of the solar collecting field. One SC is associated with every PC. The SC is oriented north–south parallel with the axis of the troughs of the corresponding PC. The function of each SC is to direct the solar radiation concentrated by the PC to the receiver. The secondary concentrator was designed mathematically in the same manner as the primary concentrator (please refer to the PC section above for more information). Three prototypes of the secondary concentrator were designed. The first one was a part of an ellipse with 90 cm semi-major axis, 34 cm semi minor-axis and a focal line of 82.9 cm from the base.

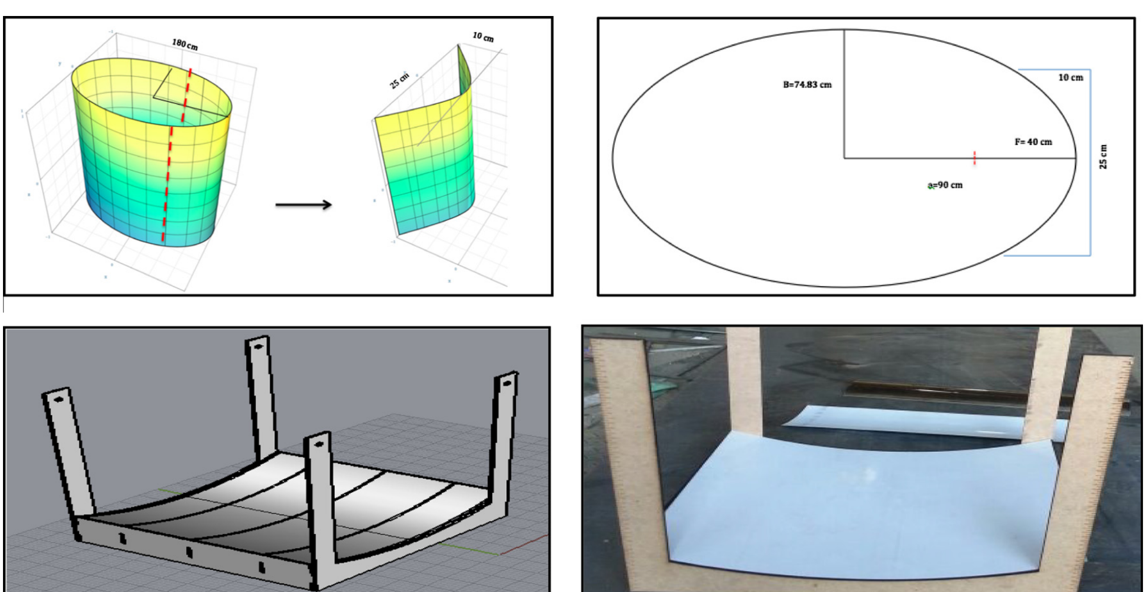

Fig. 7. The design steps of the PC.

The second one was a part of an ellipse with 40.6 cm semi-major axis, 35 cm semi-minor axis and focal line of 20 cm from the base. The third one was a part of an ellipse with a semi-major axis of 40.3 cm, a semi-minor axis of 35 cm and a focal line of 15 cm from the base.

As in the Reif system, the report between the size of the SC and the primary concentrator is 1:10, the size of the PC is 10 m × 10 m accordingly, the SC is 1 m *W* × 10 m *L*, the implemented prototype has the size of 52 cm × 47 cm and accordingly, the SC's width should be 4.7 cm. However, due to the small size and the thickness of the material (stainless steel with thickness of 0.8 mm) the size of 4.7 is inapplicable because the desired concavity cannot be approached. Thus, the width of the SC was increased to 15 cm in order to obtain an efficient system. The design was done using the Rhinoceros software for all the three prototypes.

The focal length of the PC is 22–24 cm from the base of the reflector. The SC is placed in a point after that focal point where the concentrated radiations disperse a bit again. The design steps are shown in Fig. 8. The reason behind that is to allow the SC to re-concentrate the radiation to the metal sheet as shown in Fig. 9.

Mathematically, it is found that the focal line from the base of the SC is 15 cm, practical measurements showed that the focal line ranges from 19 cm from the base of the PC. The difference was −4 cm with an error of 26.6%.

Although the modification was done to the SC's width provided more efficiency to the system, on the other hand, it caused it to be heavier than planned, resulting in the wooden supporting trusses designed attached to the PC previously to concave to the inside and become not able to carry the weight of the metallic SC. Additional metallic supporting trusses were designed using stainless steel as well. The final product is shown in Fig. 10.

3.3. Controlling system

The SC movement needs to be translated in the horizontal west–east direction over the period of each solar day. This movement insures that the SC is correctly positioned at each time, so that the solar energy focused by the PC is reflected by the SC to the metal sheet, which measures the temperature. This movement is achieved by using only horizontal displacements. The concentration system is comprised of the primary and SC, and the geometry of the tracking requirements can be summarized in the following: (i) at any given time, the PC has a single extended focal line, and through the course of the day, that extended focal line moves from west to east; (ii) the SC needs to face the radiation from the PC; and (iii) the directed focal line of the SC needs to coincide with the focal line of the PC.

The SC moves west to east in such a way that it's redirected focal line coincides with the focal line of the PC. Over the day, the extended focal line of the PC moves from west to east, as shown in Fig. 11.

The special relationship between the primary and SC described above can be achieved by west to east translational tracking of the SC with some form of rotational movement. The east-facing surface is used from the start of the day until middle of the day; the SC only needs to shift slightly west.

As shown in Fig. 12, the support metallic rod holds up the SC. The SC is attached to a controlled rubber belt with a junction, which lets the SC move freely along the support metal rod. Each day, as the sun crosses over the primary concentrator, the focal line of the concentrated solar radiation moves across the focal plane and the SC moves along in a similar manner just above this focal plane. A fixed control cable serving as a control system for moving along the east–west axis runs parallel to the support metal rod. This movement is achieved by using a stepper motor, the entire mechanism being economical and simple since the control is centralized.

The controlled stepper motor moves the main belt attached to the gear, which result in a circular movement of the rod leading to the movement of the sided pulleys. The rubber belt attached to the sided pulleys causes the secondary concentrator to move either forward or backward depending on the direction of the stepper motor shaft (Fig. 13).

After the end of the solar day, the tracking movement is reversed to allow the SC to be repositioned to the start of day position. The interfacing circuit diagram is shown in Fig. 14.

The proposed solar concentrating system design has the following key properties:

(i) *Cost-effectiveness:* The most important advantage of the nSCS is that its capital cost is substantially less (roughly 30–50% of current costs) of existing SCSs, with similar energy efficiency. It requires no large-scale structural support

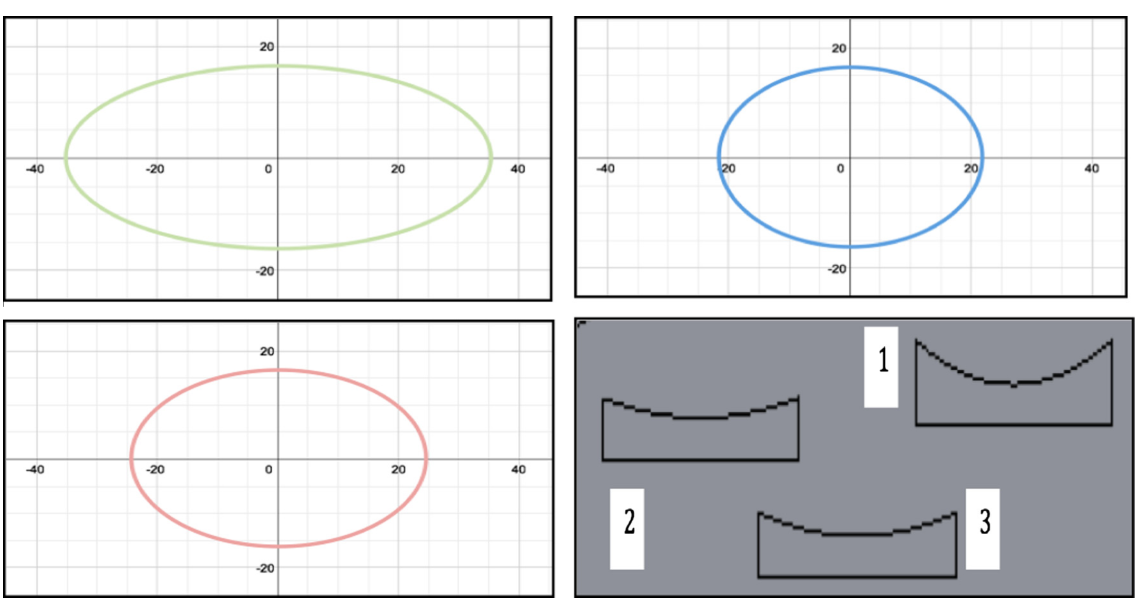

Fig. 8. The design steps of the SC.

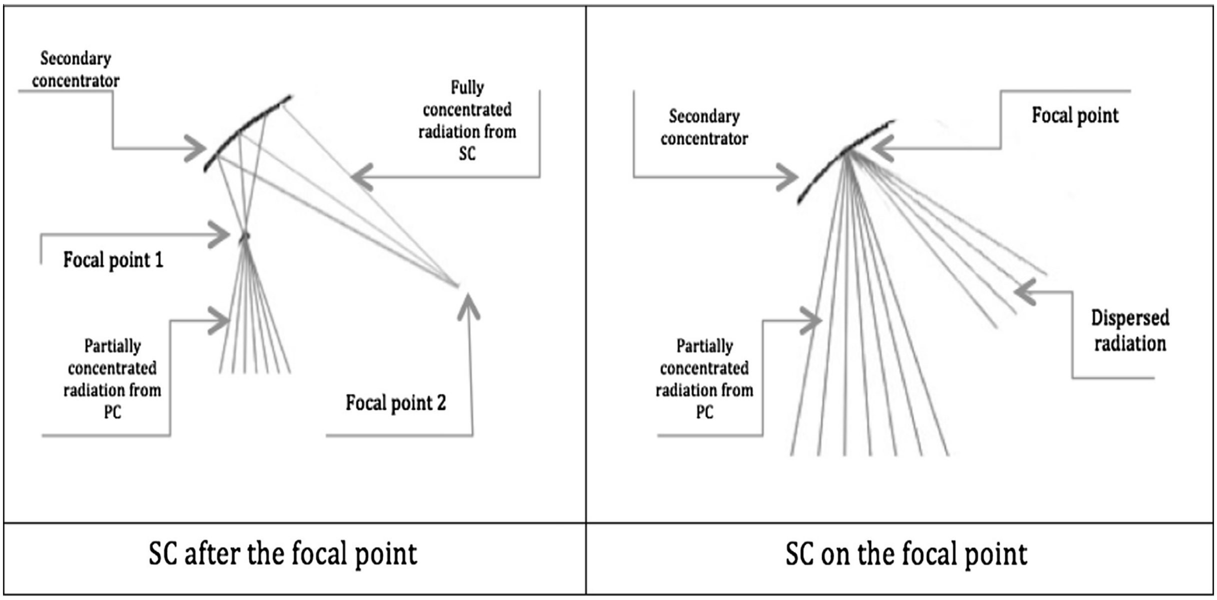

Fig. 9. The secondary concentrator on and after the focal point.

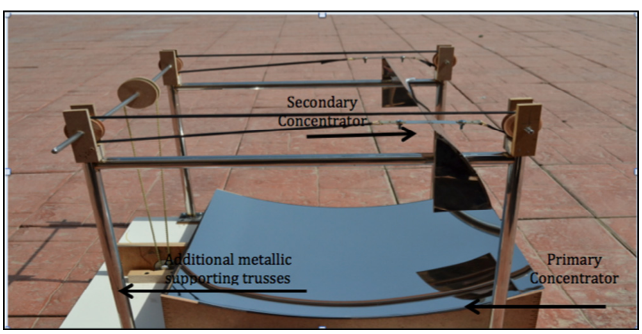

Fig. 10. SC supporting metallic structure.

structures, which vastly decreases construction costs. In contrast, most prior PCs require costly support structures and tracking systems.

(ii) *Low Energy Loss and High Efficiency:* It has been estimated that the total optical loss <59.7% (this is the percentage of concentrated solar energy that reaches to the interior of the solar receivers as compared to the solar insolation (direct solar energy from the sun) including all geometric, optical, thermal, solar field losses and IAM correction). This figure of <59.7% loss and 40.3% efficiency is typical for many conventional solar concentrator systems. Since the Kingdom of Saudi Arabia receives about 5.78 kW h/m^2 average solar insolation per solar day, the proposed nSCS will produce approx. $0.403 * 5.78 = 2.32$ kW h/m^2 average concentrated solar energy per solar day (Note, as usual, there is further

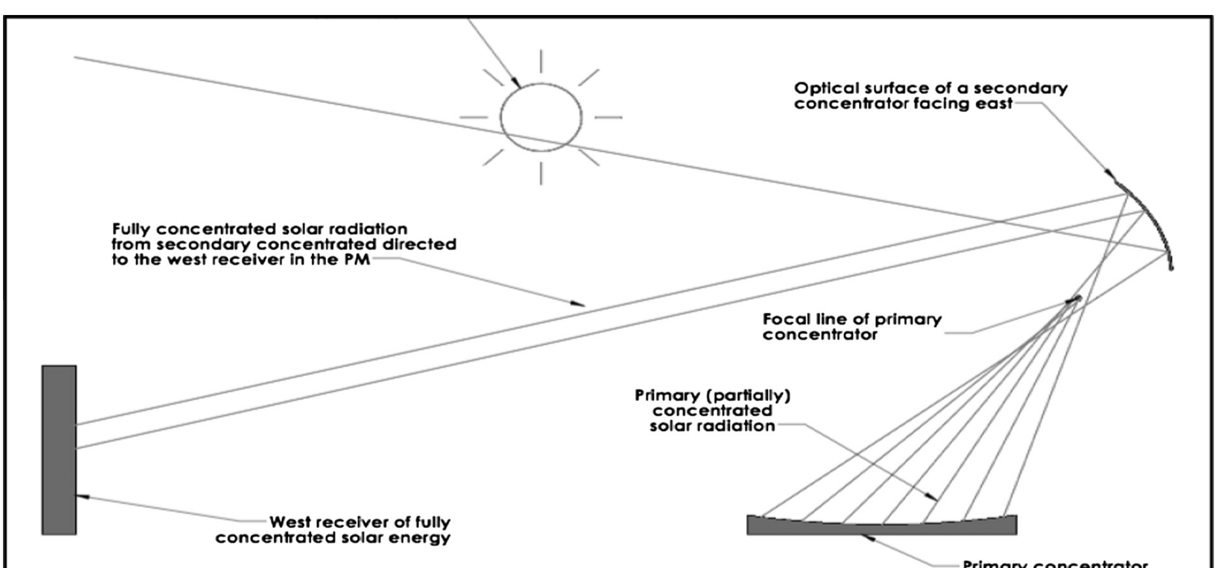

Fig. 11. The illustration shows the required positioning of the SC so that its focal line coincides with the focal line of the PC.

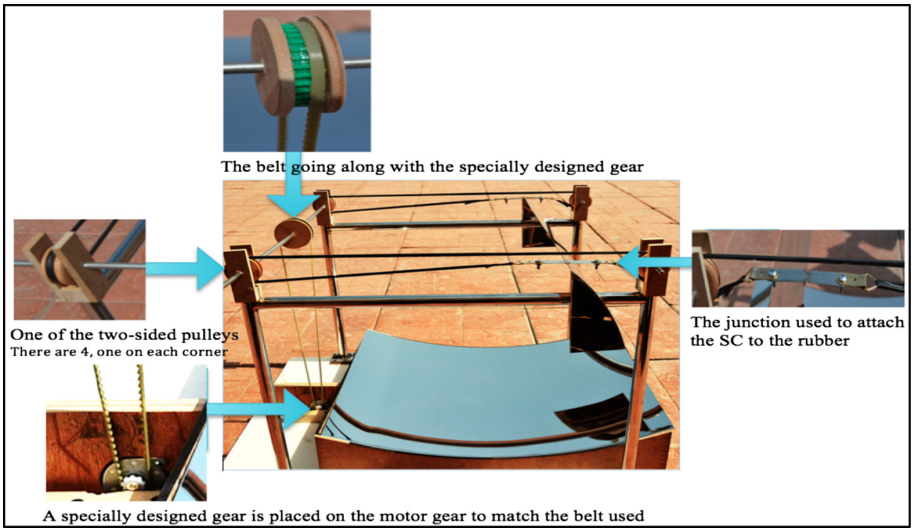

Fig. 12. Stepper motor attached to the gears.

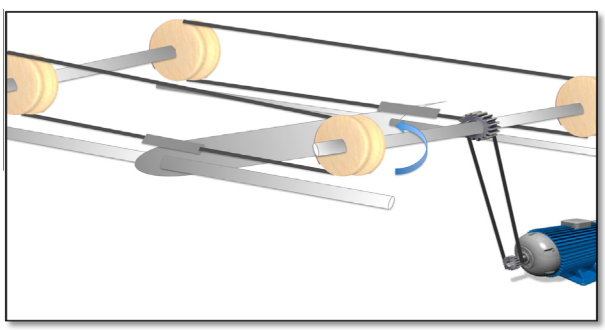

Fig. 13. The control mechanism.

subsequent loss typically across the heat transfer system and also due to subsequent the energy conversion from heat energy to other forms of energy).

(iii) *Highly Durable:* Due to the immobility of the PCs, their primary composition is concrete, and their horizontal placement is on the ground which minimizes the exposure to wind.

(iv) *Scalable to Very Large Systems:* The system is scalable to very large plants (e.g., utility electrical power systems and desalination plant applications) with the potential for high capacity factors.

(v) *Compact Land Use:* Multiple of SCSs can be combined in a compact scalable fashion which leads to a significant reduction in land use (approx. by a factor of 2).

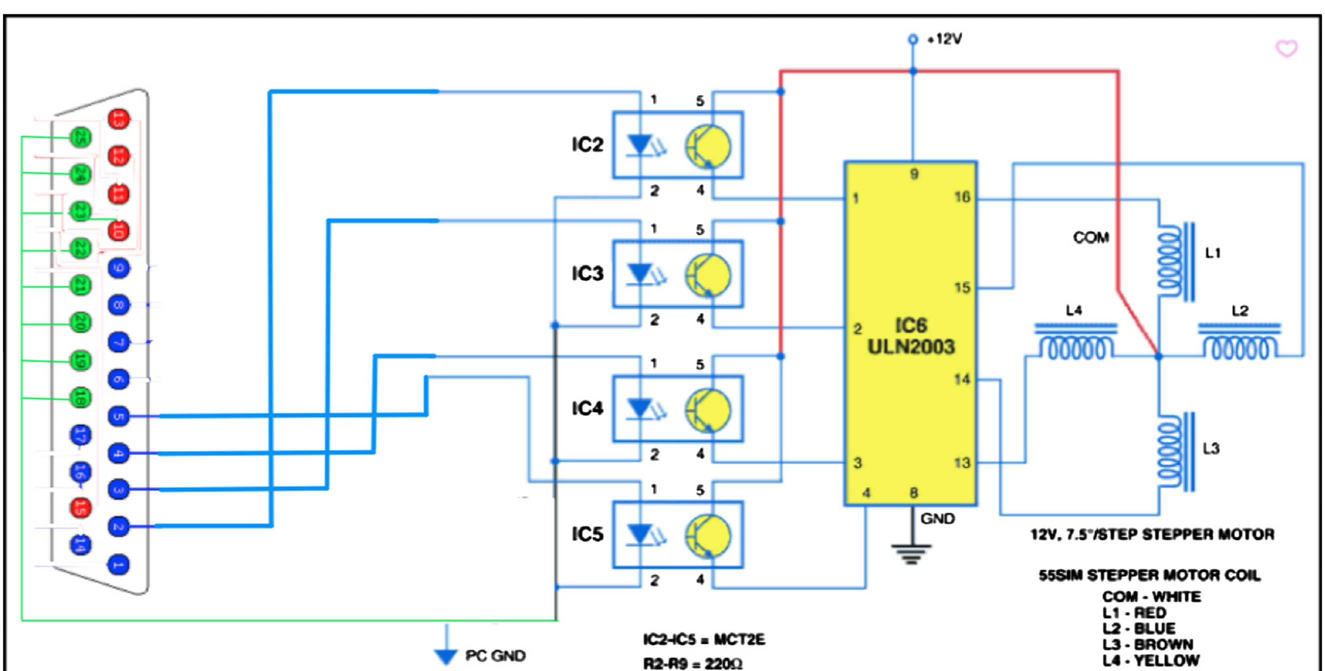

Fig. 14. Interfacing circuit for controlling the stepper motor.

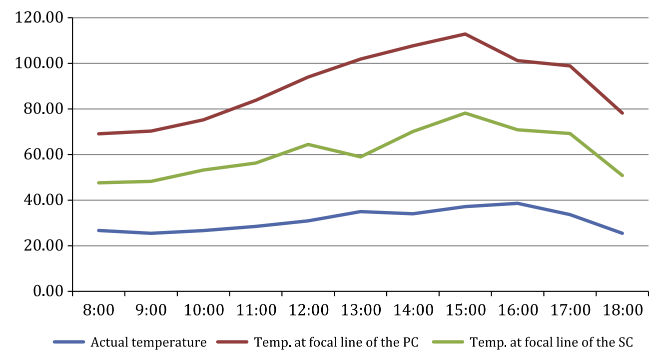

Fig. 15. The average temperature measurements in different times of the day for 15 days.

(vi) *Uses Well-Developed and Commercially Available Components:* While novel in overall design, it uses a number of well-established and already commercialized key components (such as ReflecTech reflective film, Schott tube receivers for RET elements, (Therminol VP-1 synthetic oil for the thermal energy fluid (HTF)) and therefore substantially reduces project risk.

(vii) *Provides Conventional Concentration Performance:* The system has an adjustable design, capable of a variety of solar concentration ratios ranging up to 40:1 or more. The REC tubes typically used by conventional SCS (for conversion of infra-red solar energy to heat energy), allow the proposed SCS to directly and simply substitute for conventional (solar trough and solar tower) concentrating systems at considerably lower manufacturing and maintenance cost.

(viii) *Broad Applicability:* The challenge of designing energy-efficient and cost-efficient SCSs is critical to a wide variety of solar technologies, including both solar-desalination and solar-thermal electrical power. To provide the broadest base of application, our SCS provides concentration of a wide spectrum of solar radiation, including IR (for example for solar-desalination and solar-thermal electrical plant applications), as well as UV and VIS (for example for PV electrical power plant applications).

4. Results and discussion

After the system was designed, implemented and each component was tested, the last step is to determine the performance of the overall prototype. In this case, the PC was giving an obvious focal line, the SC is also reflecting a focal line. The second focal line that was reflected by the SC can be seen clearly on the receiver. It was noticed that the second focal line is larger in area but has less density. This is due to the fact the SC is not completely in focus. This is another problem might need to be addressed in a future research.

In order to determine the overall efficiency, different temperature readings were taken during the day and the focal line was changing in a range of 3 cm. This readings include: the actual temperature, the temperature at the focal line of the PC and the temperature at the focal line of the SC. The results are presented below (see Fig. 15).

The results that we got are reasonable, but less than expected due to the imprecision of the handmade installation of the prototype.

5. Conclusion

In this work, a prototype of a solar concentrating system was implemented using collaboration and co-learning techniques. The scope was to develop an efficient and cost effective system which can be easily used in different areas. The three main parts of the system (primary concentrator, secondary concentrator and the controller) were successfully implemented and they were working properly. The immobility of the primary concentrator allowed construction using much less costly material comparing with other solar concentrating systems. The mechanism that was designed in the prototype was working perfectly, even though in the design step we have faced some high error when comparing the theoretical calculations with the practical measurements. In the end, the overall results were relatively satisfying.

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