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Design, Development and Testing a Solar Concentrator for Thermoacosutic Cooling Applications

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Abstract

The enduring development in remote areas requires more energy. It also calls for additional consideration of using the renewable energy in a better way. A Solar Energy Driven Thermoacoustic Refrigerator (SEDTAR) is a sound case for this mission. SEDTAR would consist of three major parts namely,
(1) solar concentrator -to convert solar radiation into heat.
(2) Prime Mover – a heat engine that generates high amplitude sound by heat.
(3) Thermoacoustic refrigerator –a heat pump where sound can pump heat up a temperature gradient.

In this article an effort has been aimed at developing the first part of the SEDTAR, the solar concentrator. A simple, cheap and easy to assemble concentrator that is capable of generating up to 500 watts/m^2 of heat density has been developed and field-tested. It also has concentration ratio about 20 with 50% optical efficiency and the temperature at the focus reaches up to 350 ^{o}C.

Introduction

The hunt in natural resources for cheaper sources of energy goes on nonstop. Solar energy is one of the very promising resources of all. Concentration to increase the merit of the incident sunrays is a mean that have been understudy for decades [1-5]. Emergent of a high efficiency solar concentrator is an issue of investment in money, technology and time. Concentrating solar power systems have many advantages over other competing power sources because they use components available today, have higher efficiencies, are environmentally benign. These systems rely on a secure, domestic, and endless source of energy. They can join with fossil technologies in hybrid power plants, provide jobs, promote local economic development and are popular with consumers.

Concentrators are one-dimensional, two-dimensional or three-dimensional. One-dimensional concentrators are the known flat plate thermal collectors. Parabolic trough is an example for two-dimensional concentrator with a line as a focus. A point focus can be achieved in three-dimensional concentrators (parabolic dishes). A receiver is usually positioned at the focus of the concentrator to collect the concentrated energy. The area of the collecting reflector to that of the concentrated image- the receiver- is called the concentrating ratio (CR). The CR in two-dimensional concentrators is moderately small, thus modest temperatures are generated at their receivers, usually in the range of a few hundred degrees Celsius. Applications are therefore limited in this temperature range to heating circuits, water distillers and power cycles using relatively large areas. In contrast, in three-dimensional concentrators where high CRs are possible, temperatures at the receiver could reach several thousand degrees. Concentration ratios of up to 50,000 have been reported [2]. Power generation –using three-dimensional concentrators- is possible at moderate scales that include Stirling, thermoelectric or possibly Rankine-type or Brayton-type cycles. The need for tracking system is not of such importance with three-dimensional concentrators. This paper describes the development of a solar concentrator (with investment minimization) with low to medium concentration ratio, that is anticipated to supply the driving heat for a thermoacoustic heat engine that will produce sound to drive a thermoacoustic refrigerator. Figure (1) shows a schematic diagram for the proposed SEDTAR.

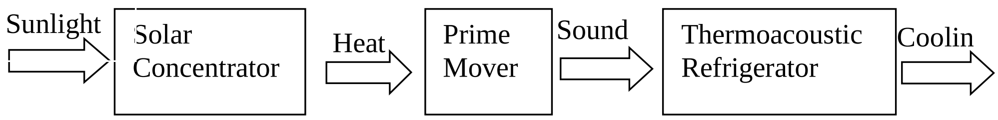


Figure 1: Schematic diagram for SEDTAR.

We used shiny parabolic dish as a solar reflector; it has high optical efficiency, high concentration ratio and low cost. A nickel black coated absorber is used to measure the heating power produced by the concentrator.

Design and Fabrication of the Concentrator

Variety for the reflector and the absorber were considered and we made selection based on the availability in the Egyptian market and the cost. Highly reflective materials are needed to cover the surface of the concentrator. A commercial TV satellite dish receiver is of parabolic geometry and is available in sizes from 0.5 m to about 3.5 m in diameter has been used. Few methods have been considered to change the existing dish surface to be practically reflective. These methods are:

(1) The dish can be electroplated with reflective metals, such as nickel or chrome. Due to limited dimensions of the electroplating units, this method is limited to maximum dish sizes of 0.5 m.
(2) The dish can be polished by means of multi-stage sanding and high-speed polishing techniques using solvents used in silver and plating workshops. The poor quality of the aluminum used in these commercial dishes limits the use of this method and it is costly to adopt.
(3) The dish can be painted with silver-colored paints or UV stabilized aluminized polyester foil of high reflectivity be pasted over dish surface. Due to weather situation in Egypt, this method is not reliable for long time, so these polyester foils need to be replaced periodically.
(4) Square pieces of high reflective mirror can be glued to the surface of the dish. Though the practicality and the simplicity of this method, it needs special care during gluing the mirrors to the dish surface to maximize the CR.

We have adopted the third and the fourth methods throughout this work.

Reflectivity of two different kinds of commercial mirrors and an aluminized polyester foil were measured at normal incidence using JASCO V-570 spectrometer. Figure (2) shows the reflectivity of the three samples at wavelengths ranges from 200 nm to 2500 nm. Mirror M1 was chosen because of its relatively high reflectivity compared to mirror M2 and the aluminized polyester foil P1.

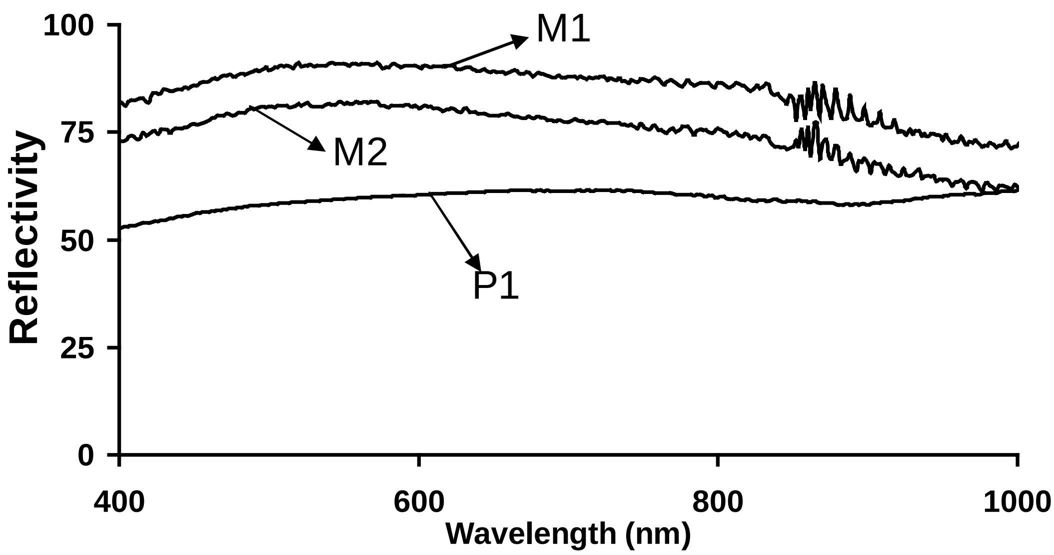


Figure 2: The reflectivity of two commercial mirrors and aluminized polyester foil.

The absorber is made of closely attached copper tubes of 4 mm diameter each. These tubes form a plate of an area 10x10 cm^2. The plate was electroplated with black nickel as a solar selective coating. Black nickel was favored over black chrome since black chrome is not reliable for long-term use much above 300 °C. The absorptance of the black nickel selective surface is 0.97 and its emittance (at 100 ^oC) is 0.14. The plate is enclosed in an envelope of borosilicate glass. This envelope protects the solar selective coating on the copper tubes and reduces convection and conduction heat losses. Evacuating the glass envelope will decrease heat losses by convection and conduction. In this experiment the glass envelope was not evacuated to simplify the manufacturing process.

The concentrator diagram is shown in Figure (3) where AA' is the aperture plane of the collector and BB' is the receiver. Efficient concentration requires that BB' should be sufficiently wide to capture all the reflected rays from the concentrator within ±δ from the normal. B and B' are located at the intersections of the extreme reflected beams from A and A' with the receiver.

The concentration ratio is governed by

$$CR = \frac{AA'}{BB'} = \frac{a}{b} \qquad (1)$$

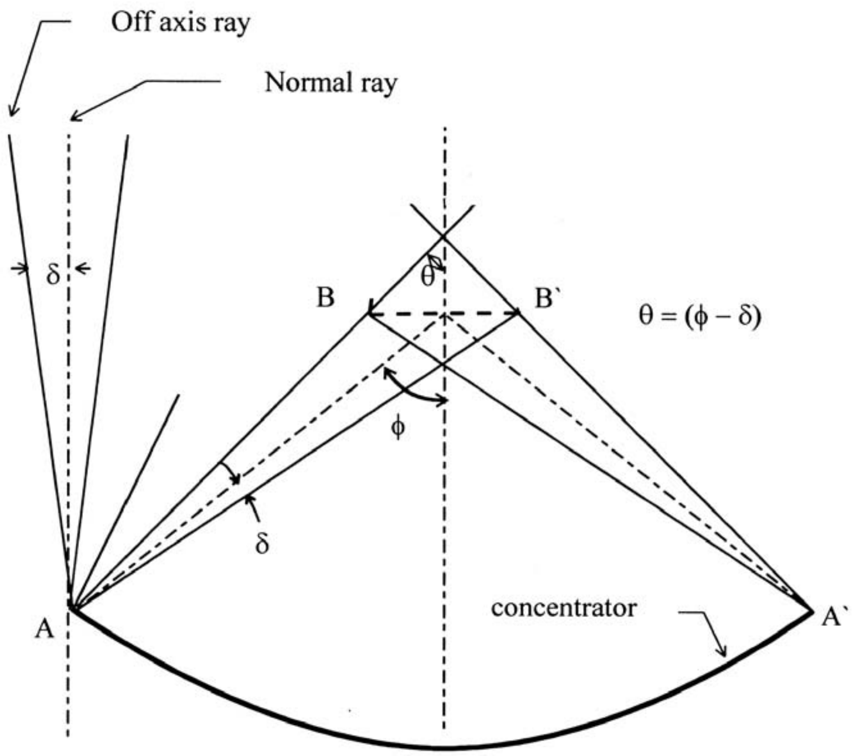


Figure 3: A schematic diagram of the concentrator.

where a is half the aperture width of the concentrator AA' and b is half the aperture width of the receiver BB'.

For a reflector of a parabolic section, the focal length (*f*) is defined by the equation of the surface [6]:

$$y^2 = 4fx \qquad (2)$$

where y axis is the axis of the reflector.

The distance r from a point on the reflector to the focus is given by [6]:

$$r = \frac{2f}{1+\cos\phi} \tag{3}$$

The aperture width of the concentrator (a) is the projection of AA' on the plane perpendicular to the incident rays and is given by

$$a = r\sin\phi = \frac{2f\sin\phi}{1+\cos\phi} \tag{4}$$

and from figure (3) we have

$$b = a - \frac{2f\cos\phi\tan(\phi-\delta)}{1+\cos\phi} \tag{5}$$

so,

$$CR = \left(1 - \frac{\tan(\phi-\delta)}{\tan\phi}\right)^{-1} \tag{6}$$

It is evident that CR increases as tolerance angle (δ) decreases (for a fixed rim angle). It is also obvious that δ depends on the receiver width.

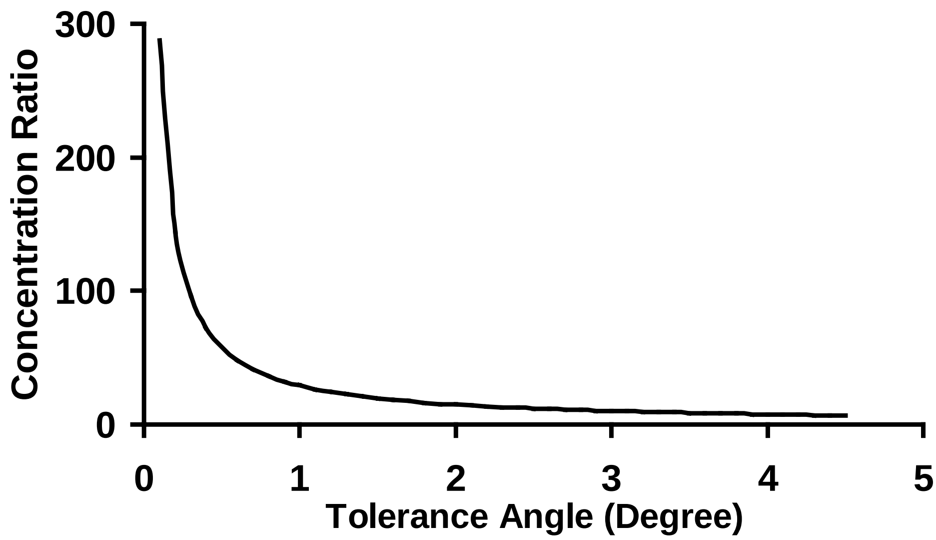


Figure 4: The concentration ratio as a function of the Tolerance angel at Rim angle of 45^{o}.

It is clear that the CR is a function of the rim angle (ϕ) and the tolerance (δ). High concentration ratio is achieved by using smaller receiver and in turn smaller tolerance angle as shown in Figure (4). It is also achievable by using large rim angle as shown in Figure (5). Large rim angle entails closer receiver to the center of mass of the collector which leads to more mechanically stable system. Generally the optimal rim angle of parabolic trough concentrators for flat receivers is in the range of 40-60^o. Small tolerance necessitates precise tracking system to grant efficient concentrator [7]. So, a careful trade off between high rim angle and small tolerance is needed to design an efficient concentrator.

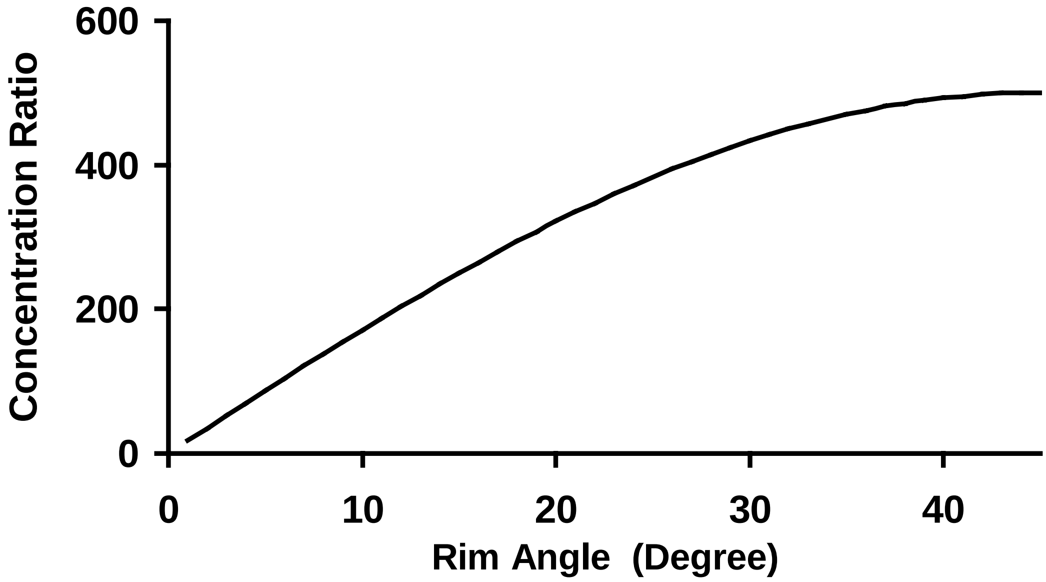


Figure 5 : The concentration ratio as a function of the Rim angle.

A commercial TV satellite dish of 1.7 m diameter covered by M1 mirror was used as a reflector. The reflector has a rim angle of 28^o and tolerance of 1.3^o ± 0.2^o . These angles yield concentration ratios of the range 16-22.

Evaluation of Collector's Performance

To estimate the temperature at the focal point of the concentrator, simple calculations to determine the incident radiation absorbed on the receiver at the focal point were made using the following equation [6]:

$$Q_{incident} = I_{direct}\ \rho\ \alpha\ CR \qquad (7)$$

where;

I_{direct} is the direct solar irradiation (as seen by the reflector),

ρ is the mirror reflectivity,

α is the receiver absorptivity, and
CR is the concentration ratio.

Knowing the emittance of the absorber (ε) one can calculate the emitted power per unit area from the receiver (E) [6]

$$E = \varepsilon \, Q_{incident} \tag{8}$$

Using Stefan-Boltzmann Law,

$$E = \sigma \, T^4 \tag{9}$$

where;

σ is Stefan-Boltzmann constant ($5.67 * 10^{-8}$ W/m^2. K^4), and
T is the temperature of the receiver.

Carrying out these simple calculations the temperature at the focal point of the concentrator was estimated to be around 350 ^oC.

Using the optical properties of the materials used in fabricating the collector and the absorber, the optical efficiency η_o can be calculated theoretically and measured experimentally. The overall efficiency of the concentrator under steady state conditions is given by [6]

$$\eta = \eta_o F_R - \frac{U_L F_R (T_{in} - T_{amb})}{I_{eff} CR} \tag{10}$$

where F_R is the heat transfer factor, U_L is the heat loss coefficient, I_{eff} is the effective solar irradiance and T_{in} and T_{amb} are the fluid inlet and ambient air temperatures respectively. I_{eff} is given by [6]

$$I_{eff} = I_b \cos\theta_{in} + \frac{I_d}{CR} \tag{11}$$

where I_b is the beam radiation , and I_d is the diffuse radiation. When $T_{in} = T_{amb}$

$$\eta = \eta_o F_R = \frac{\dot{m} C_f (T_{out} - T_{in})}{I_{eff} CR} \tag{12}$$

where $\dot{m}$ and C_f are the mass flow rate and the specific heat of the circulating fluid respectively, T_{in} and T_{out} are the inlet and outlet temperatures of the fluid .

Testing of the Concentrator

The prototype has been installed at New Bassaisa Community in Ras Sidr, Sinai, Egypt. The New Bassaisa Community is a Non Governmental Organization (NGO). The concentrator was located in a spot where there was access to sunlight and it was kept with its absorber aligned east– west with the tilt angle equal to the latitude of the place (35^o) towards south so as to maximize the useful solar energy. Figure (6) shows the concentrator during assembly and testing. The collector has been focused manually and the maximum power/temperature measurements were done at noontime. Using Eq. 6 the concentration ratio was estimated to be in the range of 17 to 20. The maximum temperature of 350^oC was measured at the focus using a copper-constantan thermocouple. This finding agrees with the temperature calculations carried out from equations 7-9.

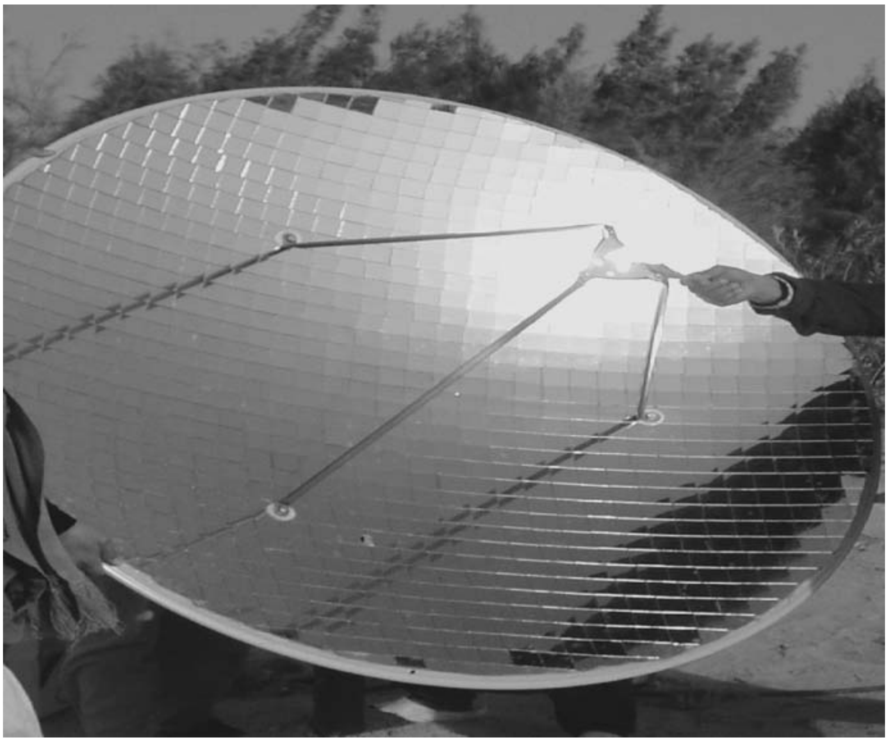
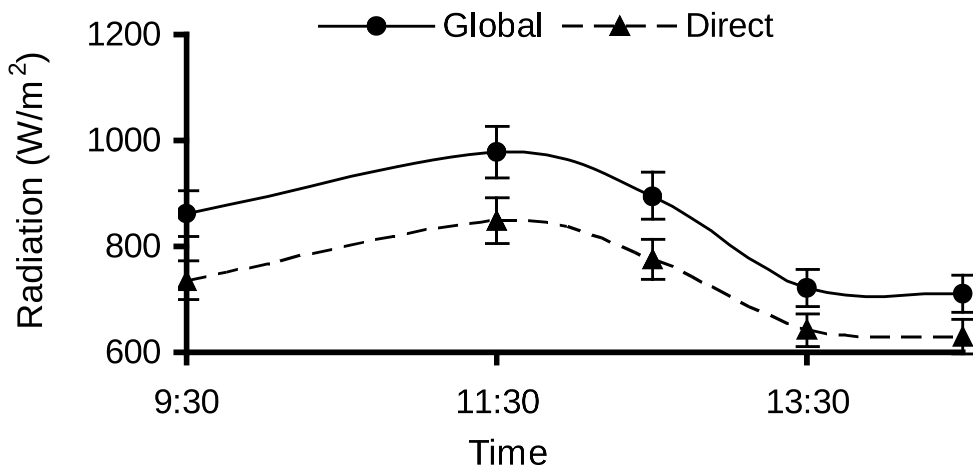
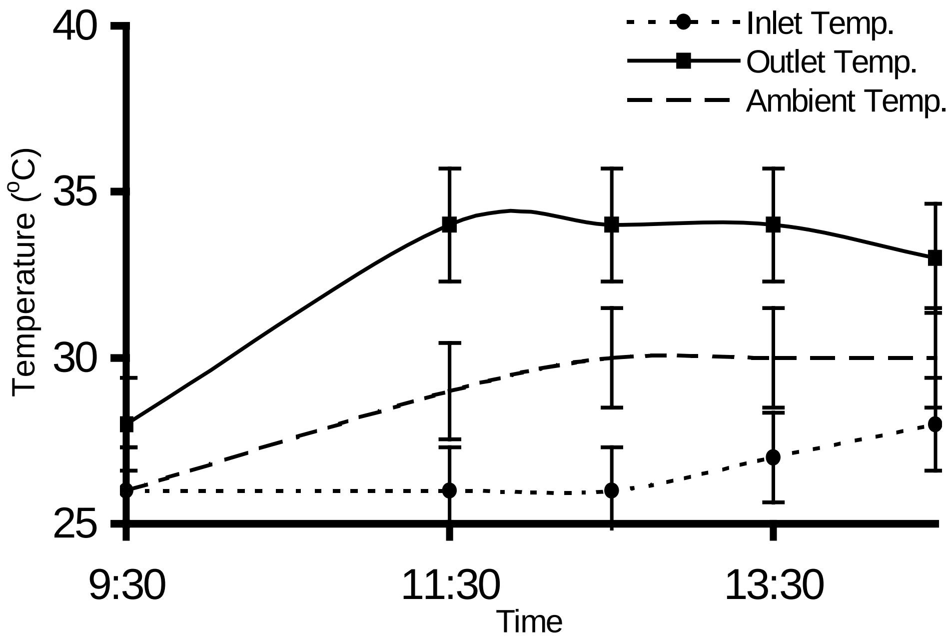


Figure 6: Photographs of the concentrator at the installation site during testing.

Thorough measurements were carried out with the collector operated in an open fluid loop mode. The flow rate was monitored using a graduated container and a stopwatch. Control valve was used to adjust the flow rate of water through the absorber. The inlet, outlet and ambient temperatures were measured using thermometers. The global radiation (I_G) and the beam radiation (I_b) were measured using a pyranometer and pyreheliometer respectively (the global radiation is the sum of the beam and diffuse radiation). The measurements were carried out on clear sunny days. The performance curves are shown in figures (7) a and b.Using steady state values of $\dot{m}$, T_{in}, T_{out} and I_{eff} the efficiency of the concentrator is calculated. The efficiency is then graphed against $(T_{in} – T_{amb})/ I_{eff}$. The experimental data points were fitted to a straight line using the least square fitting method. The line was extrapolated and from the Y-intercept the optical efficiency was determined to be 0.50 ± 0.02 and U_LF_R is 14.8 (W /°C m^2) as shown in Figure (8).



(A)



(B)

Figure 7: The performance curves of the concentrator.

Using steady state values of $\dot{m}$, T_{in}, T_{out} and I_{eff} the efficiency of the concentrator is calculated. The efficiency is then graphed against $(T_{in} - T_{amb})/ I_{eff}$. The experimental data points were fitted to a straight line using the least square fitting method. The line was extrapolated and from the Y-intercept the optical efficiency was determined to be 0.50 ± 0.02 and $U_L F_R$ is 14.8 (W /^{o}C m^2) as shown in Figure (8).

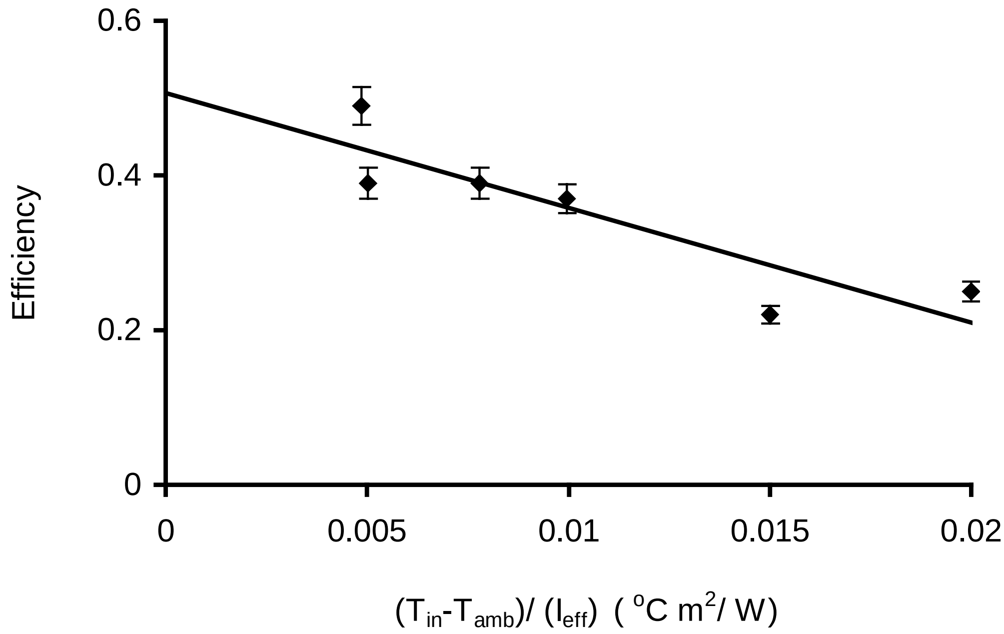


Figure 8: The experimental efficiency curve of the concentrator.

Conclusion and Recommendations

Fabrication of low cost concentrator is achieved. The concentrator has concentration ration of 20. The optical and thermal performance of the prototype is quite encouraging. An optical efficiency of 0.50 ± 0.02 is accomplished. Improving the reflective surface of the collector (increasing the reflectivity and the optical precision) can enhance this efficiency. High thermal losses have been observed. These losses can be minimized by evacuating the glass envelope and by optimizing the gap between the absorber and the envelope. Net thermal power density of more than 400 watts/m^2 has been achieved. The prototype has been verified to supply enough thermal power to run a SEDTAR prototype.

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References

[1] Winston R. Principles of solar concentrator of a novel design. Solar Energy 1974; 16; 89–95.
[2] Winston R. Ideal flux concentrators with reflector gap. Applied Optics 1978;17(11); 1668–1669.
[3] McIntire WR. Elimination of the optical loses due to gaps between absorber and their reflectors. Proceedings As/ISES AnnMeet 1980,pp. 600–4.
[4] McIntire WR. New reflector design which avoids losses through gaps between tubular absorbers and their reflectors. Solar Energy 1980; 25; 215–50.
[5] Khonkar HE, Sayigh AAM. Optimization of the tubular absorber using a compound parabolic concentrator.Renewable Energy 1995;6(1); 17–21.
[6] Duffie John and Beckman William. Solar Energy Thermal Process, John Wiley and sons. ISBN 0-471-22371-9
[7] L.-C. Valdes. Competitive solar heat engines, Renewable Energy 29 (2004) 1825–1842.