A Comparative Study On The Efficiency Of Concentrating Solar Thermal Technologies In Use At Different Geographical Locations

Pankaj Kumar[1] , Krishna Kumar Sinha[1] , M. K. Gupta[1]* , M. K. Banerjee[1]

[1]Department of Energy and Electrical Engineering, Suresh Gyan Vihar University Jaipur-302017, India.

Abstract: - A comparative study on the efficiency of concentrating solar thermal (CST) technologies is carried out. Modelling of experimental data at five different locations of India is employed to calculate the absorbed thermal energy by each of four different types of preselected collectors; the collectors for each of the selected locations, thermal losses are calculated. The total thermal energy accessible from the collectors, i.e., the thermal yield of each collector, has been computed using the results obtained thus far. The thermal efficiency of a collector is defined as the ratio of the actual thermal yield to the potential amount of collectable thermal energy (solar radiation x aperture area). The efficiency of collectors that use tracking systems to follow the sun throughout the day is calculated using direct normal solar irradiation. In contrast, the efficiency of compound parabolic collector is calculated using both global and diffuse irradiance. The performance simulations used to produce the data for the comparisons give, as the output, yield and thermal loss data on an hourly basis over a complete year. This data used to calculate the average annual yield or average annual thermal efficiency shows that newly designed parabolic dish collector is superior to others in respect of thermal efficiency. In order to ensure the best possible comparison between collector types, only the performance of individual collector has been considered without regard to other factors, such as solar field losses or boiler efficiency, that are specific to an actual installation.

Keywords: Solar collectors, solar irradiance, efficiency, latitude, modelling

1. Introduction

It is known that direct normal incidence as well as direct horizontal incidence is functions of locational latitude and the time in a day. Since the available solar energy changes with geographical locations, it is prudent to conduct the proposed study at different locations of country so that a pragmatic comparison of the efficiency of technologies as function of latitude is possible; this entices the authors to select five different locations in India with installation of four different technologies. Thus, the performance assessment of different solar thermal technologies at different quantum of available solar energy will become possible. Table 1 shows the selected locations for the study long with the available solar energy at the concerned locations [DNI and DHI].

Table 1: Available solar radiation at the five chosen locations [1]

Location	Latitude	DNI (kwh/m2/day	DNI (kWh/m2/annum	DHI (kwh/m2/day	DHI (kWh/m2/annum
Jaipur	26.95°	4.85	1772	2.26	826
Bhopal	23.25°	4.69	1712	2.25	820
Kolkata	22.55°	3.58	1308	2.42	883
Pune	18.55°	4.76	1739	2.26	824
Madurai	9.95°	5.10	1863	2.17	790

The known technology configurations like 'Linear Fresnel Reflector (LFR)', 'Parabolic Trough Collector (PTC)', 'Compound Parabolic Collector (CPC) and Parabolic Dish Collector (PDC) are taken in consideration for the proposed study. The construction and operating principles of the selected CTCs are elaborately enumerated elsewhere [2-15]

In view of the dynamism involved in evolution of modified version of the selected technology class, due attention is paid to choose those technology configurations which are not only of latest development but also are in use with proven performance; in contrast with PTC, LFR and CPC the PDC used for the present study is an exception in the sense that the one used for the study is attached with a Tubular Cavity Receiver of high efficiency; although such type of PDC configuration is proven of worth in laboratory scale scientific projects, there is no report of its applications in industries. It is for this reason the present investigation looks for the performance efficiency of TCR integrated PDC which is made up with different design parameters [3,4].

Performance monitoring of the individual technology type, already in use at various locations, makes it apparent that there is further scope to improve the performance level of the PDC technology suitable change in design. It is for this reason the present investigation is carried out to optimise the hardware design parameters of TCR integrated PDC technology and to compare its efficiency with the other types at the five chosen locations [5-9].

The present paper reports the results of comparison among the four different technologies, inclusive of the newly designed PDC and thus, deals with the assessment of the performance of the above four class of solar thermal technologies with newly designed PDC installations at the aforementioned five locations. However, the design parameters of the technology used are kept undisclosed for obvious reason of possible infringement of IPR [9-13].

2. Collector Parameters

In the contemplated modelling of thermal yield from various CST technologies, a nominal mirror area of 5000m² is taken inconsideration with adjustment for maintaining compatibility actually available collector sizes for relevant technology. Apart from the size of solar field which aids in realistic simulation, the thermal losses are to be considered for simulation work. The thermal losses taken for the simulation is based on the average temperature of heat transfer fluid; in view of the fact that HTF gets heated during operation, the average temperature is such calculated that the temperature of HTF increases by 50°C. Thus, simulation temperature is less than the collector's output temperature by 25°C. A soiling factor of 97% has been considered for all technologies with the presumption of uninterrupted operation during daytime [10-15].

3. Simulation Tools

SAM simulation software, a powerful and versatile simulation environment for the calculation and analysis of renewable power projects is used to determine the yield of the collectors. System design parameters are used as inputs and accordingly performance prediction is done by SAM software. To simulate and reflect the real metrological conditions on site, a weather reference year called the Typical Metrological Year (TMY) is used as the basis of the calculation. To make up the TMY, key weather data for previous fifteen years, as available from the results of a joint MNRE/NREL project, has been used verification of authenticity the SAM simulation results so that the tool can be employed for real life comparison of technology efficacy.

4. Results and Discussions

The average annual efficiency (%) and daily energy yield, are measured in kWh/m², for each of the above technologies over a range of temperatures. In spite of the fact that within the chosen range of temperature, one or other technology may not be able to operate at high efficiency, such design of experiments is done to examine if the results of contemplated comparative study is true and consistent under all possible operative conditions. The variation of efficiency against the operating temperatures of four CTC is shown in Figs 1-5. It is clear from the figures for all locations that the performance efficiency of newly designed PDC is considerably higher than all other technologies. Moreover, it is also apparent that other CPC technology, other three technologies do not show much change in efficiency over the experimental temperatures till 250°C. In contrast, the efficiency of CPC technology decreases with temperature and this observation is consistent for all the selected locations.

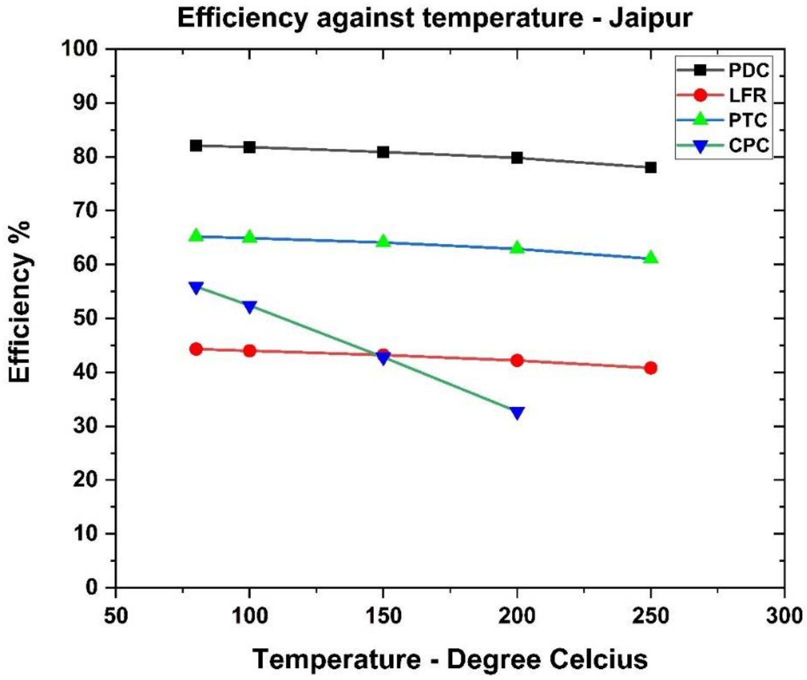

Figure 1: Efficiency vs. temperature at Jaipur

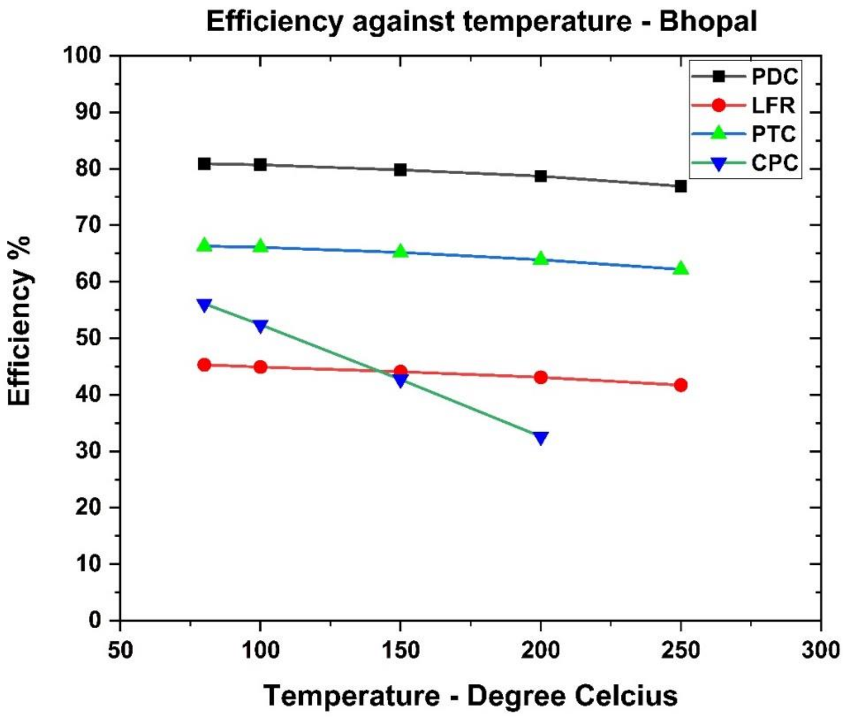

Figure 2: Efficiency vs. temperature at Bhopal

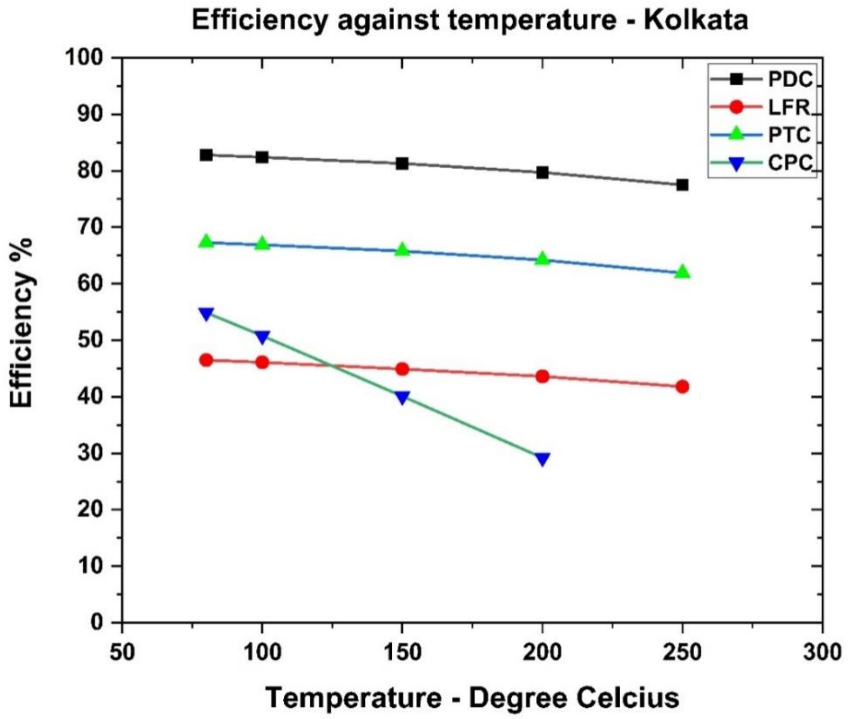

Figure 3: Efficiency vs. temperature at Kolkata

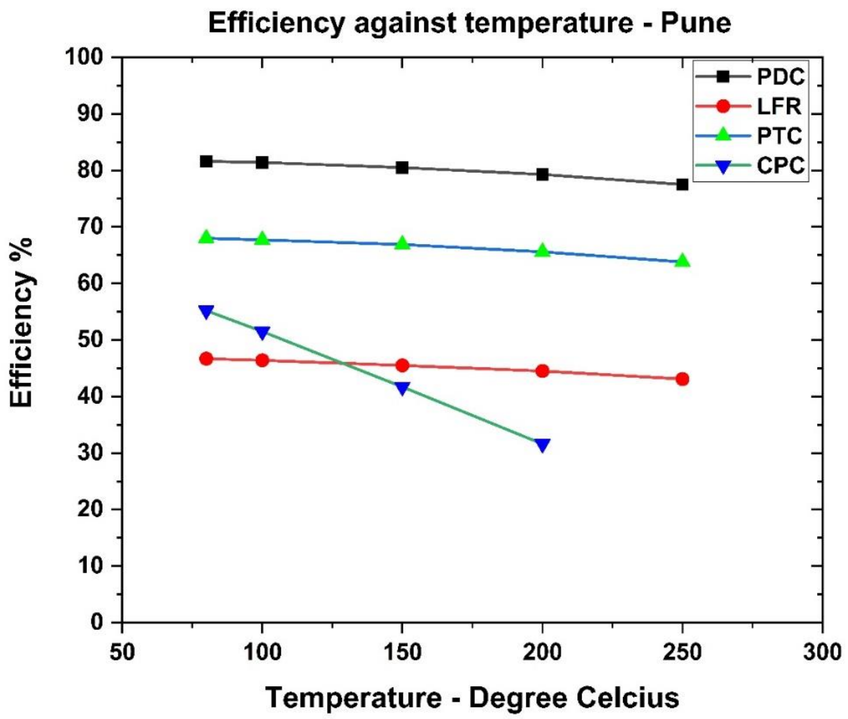

Figure 4: Efficiency vs. temperature at Pune

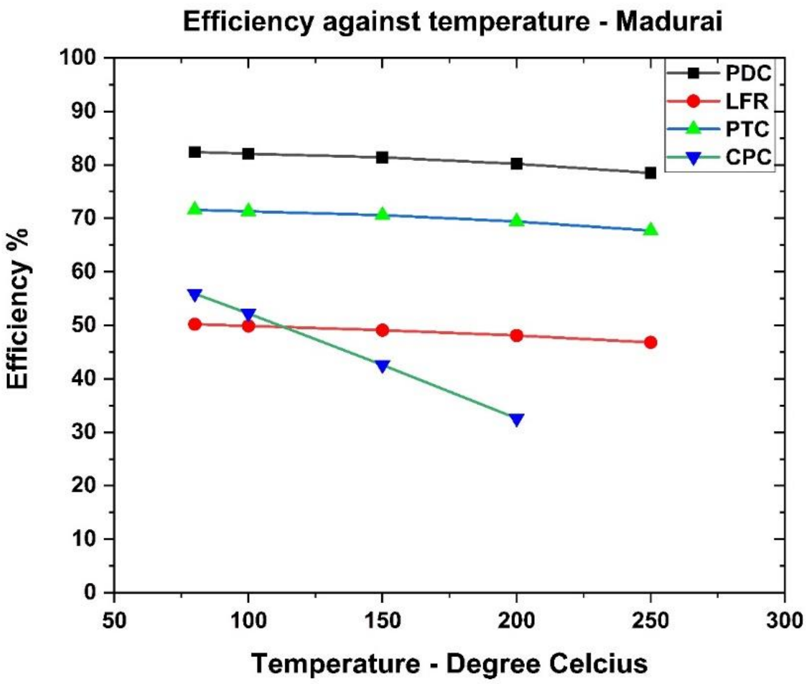

Figure 5: Efficiency vs. temperature at Madurai

In order to gather a better understanding about the deliverable thermal efficiency, it is required to fix such a temperature where all the chosen technologies are known perform consistently well. Thus, the annual thermal energy yield for each of the four selected technologies are calculated by considering a constant aperture area of 5000m², and such calculations are done for a temperature of 150°C. Data are collected from all the five locations selected for the study and the results are shown in Fig.6. It is revealed from Fig.6 that the annual yield for PDC with the new design parameters is much higher than all the other technologies irrespective of quantum of availability of solar energy as evidenced by similar observations for all the five locations. It may be noted that the selected test temperature lies in the upper operating region of CPC whereas it is at the lower regime of the operating temperatures for the other three tracked collectors.

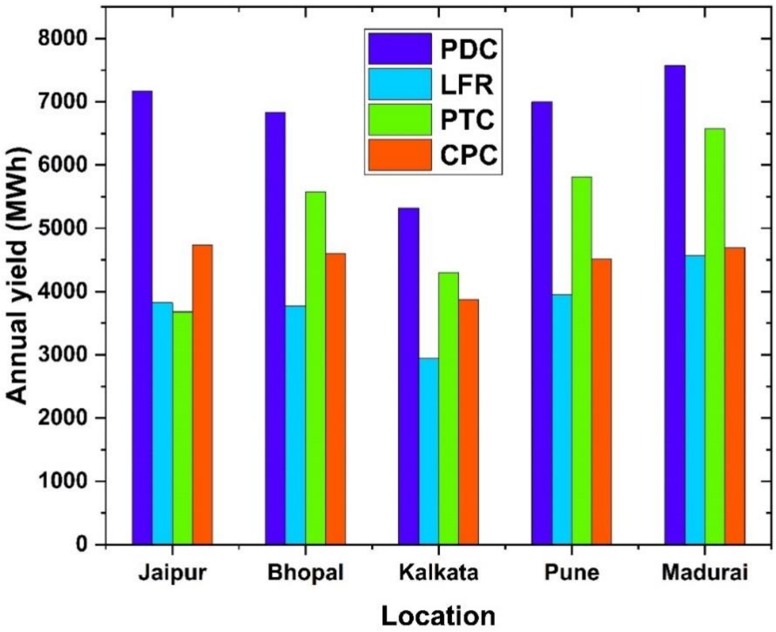

Figure6: Annual yield at 150^{0}C output temperature by location

Table 2 shows the values of peak thermal power of the chosen Concentrating Solar Thermal (CST) technologies at a chosen DNI value of 850W/m² without consideration of incidence angle. Moreover, it is assumed that the mirror as well as receiving surfaces are highly clean.

Table 2: Peak thermal of CTC technologies

Concentrator	Temperature (^{0}C)	Peak thermal power (MW_{th})
Parabolic Dish	250	3.6
Fresnel	250	2.6
Parabolic Trough	250	3.3
CPC	100	2.5

As stated earlier, on the basis of the collector of 5000m², the simulation work is carried out under preselected operating temperatures. Fig.7 furnishes the mode of variation in annual thermal efficiency of CST technologies with changing latitudes at a fixed output temperature of 150°C. It is observed that the output efficiencies of all the CST technologies are sensitive to latitudes which implies that all other conditions remaining same the efficiency of any CST technology is to be different for different geographical locations around the globe. In general, for lower value of latitudes, the collector efficiency is increased although the degree of such variation depends upon the technology in use. In this respect, the designed PDC is found to be least sensitive; this indicates that the design parameters of PDC used for the present investigation is able to give rise to almost similar efficiencies irrespective of the latitude of the place of installations

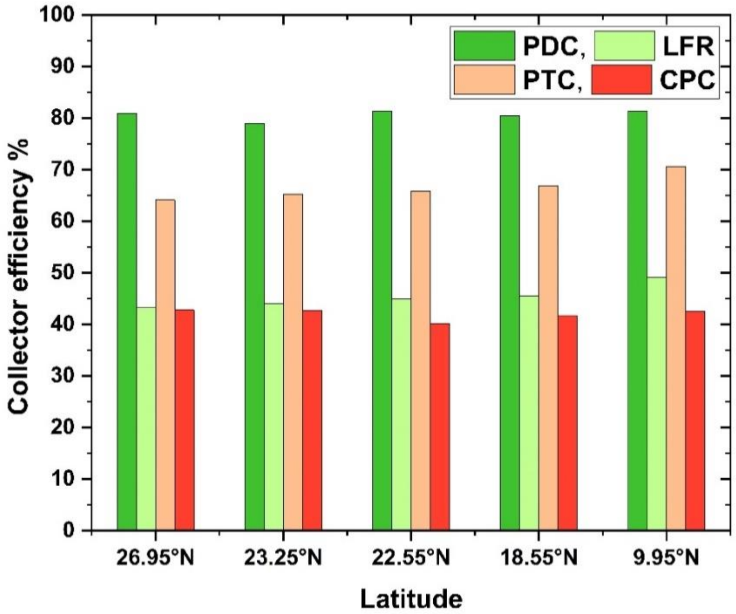

Figure 7: Location wise variation of efficiency of four CTCs at 150°C output temperature as a function of latitude

5. Conclusions

The authors conclude that regardless of the latitude of the place of installations, the parabolic dish of new design parameters exhibit the highest annual efficiency at all temperatures within 75°C to 250°C; this is followed by the parabolic trough collector. It is inferred that CPC technology shows a continuous decline in efficiency with temperature and exhibits lowest efficiency from a temperature of 120°C upwards. It is further concluded that cosine effect caused by the sun brings about at least a 5% decrease in performance between a system located in the southernmost parts of India and one located in the north. This effect is lower in the sky especially in winter (northern hemisphere) and as a result the sun's rays tending to shine "along" the axis of the linear collector rather than arriving at 90° to it. The authors further conclude that in general, the collector efficiency of all the systems is increased with lowering of latitude and the degree of such variation depends upon the technology in use. In this respect, the designed PDC is found to be least sensitive; hence it is concluded that the design parameters of PDC used for the present investigation is able to give rise to almost similar efficiencies irrespective of the latitude of the place of installations.

Reference

[1] Garcia, Dário, Dawei Liang, Joana Almeida, Bruno D. Tibúrcio, Hugo Costa, Miguel Catela, and Cláudia R. Vistas, 2022, Elliptical-Shaped Fresnel Lens Design through Gaussian Source Distribution" Energies 15, no. 2: 668.

[2] Coughenour B.M., Stalcup T., Wheelwright, B., Geary, A., Hammer K., Angel R., 2014, Dish-based high concentration PV system with Köhler optics. Opt. Express, 22, A211–A224.

[3] El Majid B., Motahhir S., El Ghzizal A., 2019, Parabolic bifacial solar panel with the cooling system: Concept and challenges. SN Appl. Sci. 1, 1176.

[4] Xie, W.T., Dai, Y.J., Wang, R.Z., Sumathy, K., 2011, Concentrated solar energy applications using Fresnel lenses, A review. Renew. Sustain. Energy Rev. 15, 2588–2606.

[5] Cosbyn R.M., 1977, Solar Concentration by Curved-Base Fresnel Lenses; Ball State University: Muncie, IN, USA, .

[6] Ahmet Çağlar, 2016, Design of a Parabolic Trough Solar Collector Using a Concentrator with High Reflectivity, Proceedings of the 2nd World Congress on Mechanical, Chemical, and Material Engineering (MCM'16) Budapest, Hungary, DOI: 10.11159/htff16.152

[7] Xinglong Ma, Hongfei Zheng, Shuli Liu, 2019, A Review on Solar Concentrators with Multi-surface and Multi-element Combinations, Journal of Daylighting, 6, 80-96. http://dx.doi.org/10.15627/jd.2019.9

[8] Parvathi Gorantla, B. Janarthanan, J. Chandrasekaran, 2016, International Journal of Innovative Research in Science, Engineering and Technology, Vol. 5, Issue 11.

[9] Mehrdad Khamooshi, Hana Salati, Fuat Egelioglu, Ali Hooshyar Faghiri, Judy Tarabishi, Saeed Babadi, 2014, A Review of Solar Photovoltaic Concentrators, International Journal of Photoenergy,

[10] Emetere M. E., Emetere J.M., and Ometan O.O., 2019, A short review on solar concentrator for energy generation in tropical coastal belt, Journal of Physics: Conference Series 1378, doi:10.1088/1742-6596/1378/4/042027

[11] Wang, L., Yuan, Z., Zhao, Y. et al. 2019, Review on Development of Small Point-Focusing Solar Concentrators. J. Therm. Sci. **28,** 929–947,

[12] Tiwari G. N, Atheaya D, Tiwari A., 2017, Review on solar thermal power concentrators. MOJ Solar Photoen Sys 1(3).

[13] Meng Tian, Yuehong Su, Hongfei Zheng, Gang Pei, Guiqiang Li, Saffa Riffat, 2018, A review on the recent research progress in the compound parabolic concentrator (CPC) for solar energy applications, Renewable and Sustainable Energy Reviews, Volume 82, Pages 1272-1296, https://doi.org/10.1016/j.rser.2017.09.050.

[14] Nayab Bushra, Timo Hartmann, 2019, A review of state-of-the-art reflective two-stage solar concentrators: Technology categorization and research trends, Renewable and Sustainable Energy Reviews, Volume 114, 109307.

[15] Hussein N. Jabbar, 2021, A Review on Parabolic Solar Concentrator Trough And Parabolic Solar Concentrator Dish, Journal of Mechanical Engineering Research and Developments, Vol. 44, No. 5, pp. 381-386.