

A review of Thermal Performance of Solar Concentrator – the future needs

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Abstract

Abundant solar energy is freely available almost round the year in India. As per the current scenario of global warming and climatic change, solar energy is the cleanest source in nature. Concentrated solar power (CSP) has hardly contributed to the overall installed solar power capacity in the country. CSP technologies are Parabolic Trough Collector (PTC), Linear Fresnel Reflector (LFR), Paraboloid Dish and Solar Power Tower. This paper presents a review of CSP in solar parabolic dish concentrator to understand thermal aspect like thermal efficiency, optical efficiency, useful heat gain, heat losses, solar irradiation, etc. for various applications and current development. The current scenario of global CSP is discussed to meet the future challenges and need of the society.

Keywords: Concentrating solar power, parabolic dish, scheffler concentrator, heat transfer fluid

1. Introduction

Abundant solar energy is available almost round the year in India. During a day solar irradiation received on the earth is approximately $1000\text{W}/\text{m}^2$. The amount of irradiation could generate around 8500 TW worldwide and it is concluded that solar energy alone has the capability to meet the current energy demand. This is sustainable and economical energy source is available which can be utilized for domestic purpose. Among the solar concentrators, parabolic dishes have the highest efficiency in the conversion of solar energy to electricity with an efficiency of 29.4% achieved [19].

2. Thermal aspect of concentrated solar power

Hossein Mousazadeh et al. [1] reviewed the different types of sun tracking sun tracking systems and found the most suitable method of sun tracking devices in the form of polar axis and azimuth or elevation to improve the system efficiency. As per survey conducted to define the position of sun, they found a correlation between solar altitude angle, solar zenith angle and solar azimuth angle within accuracy of 0.001° . By Neglecting the atmospheric influence, the energy per unit area calculated for the fixed collector is $8.41\text{KWh}/\text{m}^2$ and for tracking collector it is $13.2\text{KWh}/\text{m}^2$ and reported the power consumption increase by 2-3%. K. Ravi Kumar and K.S. Reddy, [2] investigated the thermal performance of solar parabolic trough receiver with Therminol VP as working fluid and reported maximum heat transfer characteristic obtained at the top half receiver $H=0.5d_i$, $w=d_i$ and $\Theta=30^\circ$ based on the (write in words what H, w, d and Θ is) different types of geometrical parameters. The heat transfer characteristics enhances Nusselt number by 64.2% for optimum receiver compared with tubular receiver at Reynolds number of 31845 with pressure drop of 457Pa.

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LIU QiBin et al. [3] developed a parabolic trough solar collector system with synthetic oil as working fluid for the thermal power generation. They found solar collector efficiency in the range of 40-60% with variation of solar flux and flow rate of heat transfer fluid. It observed that 10% of total solar energy incident on collector with 180°C temperature difference between collector and ambient temperature. The convection and radiation loss decreases with time. A. Munir et al. [4] developed 8m² scheffler fixed focus concentrator for potential application in domestic as well as industrial configuration for medium temperature applications and mathematical model developed for two extreme positions of summer and winter in northern hemisphere. By comparative study of equinox parabola curve, the summer parabola is found to be smaller in size hence uses the top part of the parabola curve, while the winter parabola is bigger in size hence uses the lower part of a parabola curve to fixed focus. A. Fernandez-Garcia et al. [5] conducted survey of different types of parabolic trough collector along with applications to supply thermal energy up to 400°C to generate electricity. K. Lovegrove et al. [6] design and constructed a prototype of 500m² paraboloidal dish solar concentrator at Australian National University, Australia. A novel design developed to produce energy at minimum cost. It results for very high peak concentration ratio of 14100 and geometric concentration ratio for 95% capture of 2240, which was compared with SG3 dish. Rupesh J. Patil et al. [7] designed scheffler reflector water heater to satisfy domestic need about 100-200 litre per day with 8m² scheffler reflector. A 20 litre storage tank with Al-Cr thermocouple located in heater for the testing and performance, which results the average power of 1.30KW and efficiency of 21.61% with beam radiations of 742 W/m² attend maximum water temperature in the storage tank of 98°C.

Vishal R. Sardesh pande et al. [8] proposed test procedure for evaluation of thermal performance of point focus solar concentrator having an aperture area of 25m² based on latent heating with the phase change characteristic of water at constant operating temperature above 100°C which results in the system efficiency at 161°C is 47±3.5%. This procedure based on latent heating, so it can be used for characterization of line focus concentrator for steam generation.

Nestor Hernandez et al. [9] comparative study of conical, spherical and cylindrical receiver with made on ray tracing simulation to optimize the dimensions with the rim angle 90° for paraboloidal concentrator and characterization of receiver made on the basis of open loop and closed loop operation. It gives time constants of 110s and 140s for 4 and 3 lpm respectively. in closed loop efficiency is low but decreases with the temperature and in open loop efficiency increases with flow rate and diminishes with temperature. As per the analysis of different geometries the conical receiver is having good concentration rate and uniformity in radiation flux.

E. Venegas-Reyes et al. [10] presents a novel design for performance evaluation of solar parabolic trough concentrator with 45° rim angle and 5.8m² aperture area and water as working fluid. To understand the mechanical behavior, finite element analysis was conducted which results maximum stress of 7.37MPa for lateral load which is lower than permissible stress of aluminum 145MPa. The peak load efficiency is close to 60% with flow rate of 6 lpm at direct solar radiation of 865W/m² with 0° incident angle. The thermal performance of PTC was determined according to ASHRAE 93-1986, which results into overall heat transfer coefficient of 32.56W/m²K, heat removal factor of 0.935 and intercept factor close to 67%. Santos Gonzalez et al. [11] compound parabolic concentrator (12 CPC having aperture area 2.1m² acceptance angle 30° and concentration ratio of 1.8) has been designed to analyze thermal performance and dynamic behavior with one dimensional numerical analysis by using control volume method (Continuity, momentum & energy equation). The distribution and intensity of sun rays is determined

and obtained optical energy losses due to truncation is 6.7% with help of Monte Carlo ray tracking method. The experimentation gives useful energy gain of 1.47KW at mass flow rate of 12Kg/min with irradiance of 1026W/m². M. Alguacila et al. [12] developed a second generation parabolic trough to obtained more efficient generating system which operates above 400⁰C. To achieve higher temperature, Abengoa solar uses direct steam generation (DSG) in parabolic trough in the first stage heating upto 450⁰C and in second stage heating upto 550⁰C. It had built and evaluated a demonstration prototype plant of 8 MWht which is composed of an evaporator field (3 parallel loop) and a superheater field (2 loop) and oil as working fluid in order to work at 85 bar and 450⁰C to analyze control stability, receiver tube viability (analyzing mechanical behavior, optical performance and heat losses) and collector interconnection feasibility which results annual production of 140MW with lower thermal losses and improved efficiency.

Mahesh M. Rathore and Ravi M. Warkhedkar [13] proposed a new test standard to evaluate thermal performance of solar concentrator based on sensible heating of working fluid (Water) with 16 m parabolic scheffler reflector. It assumed optical efficiency of 85% and which varies from 52.38% to 26% with an error of $\pm 3.5\%$. The efficiency is higher at lowest operating pressure and it decreases as operating pressure increases. An mathematical model needs to be developed to find the radiation loss, as at high operating temperature radiation losses dominating over convection heat transfer. Ibrahim Halil Yilmaz et al. [14] experimental investigation conducted for the performance of parabolic trough solar collector array on 10.2 m² aperture area and renolintherm 320 as working fluid to evaluate the useful heat gain and the instantaneous thermal efficiency. The steady state and dynamic test were conducted which resulted into the peak thermal efficiency of 57% and optical efficiency of 56% in temperature range of 50⁰C to 200⁰C. The thermal efficiency is higher at lower inlet heat transfer fluid temperatures and heat loss from the receiver is lower relative to the higher temperature.

K. S. Reddy et al. [15] conducted an experimental investigation of thermal performance analysis on 20m² prototype fuzzy focal solar dish collector to find the performance of modified cavity receiver for different operating condition and estimate total heat losses. The overall heat loss coefficient is found to be 356 W/m² K. The maximum theoretical efficiency is 79.2% for no wind conditions and 78.2% and 77.8% for side-on and head-on winds speed of 5 m/s respectively. It results average thermal efficiency of the parabolic dish collector for the volume flow rate of 100 L/h and 250 L/h are found 69% and 74% for the average beam radiation (Ibn) of 532 W/m² and 641 W/m² respectively.

Annie Hofer et al. [16] summarised the review based on the characteristics of the different steady-state, quasi-dynamic and fully dynamic testing methods and presents current advancements, assets and drawbacks as well as limitations of the evaluation procedures. They reported characterisation of 12 testing procedure heat transfer fluid 67% for thermal oil, 50% for pressurised water and 8% for evaluation method with molten salt. S. Ravelli et al. [17] developed prediction performance of 5MWe direct steam generation solar power plant based on TRASYS, Thermoflex and Octave simulation. It results high pressure and low pressure isothermal efficiency of 71% and 78% respectively with net power 5.0MW and electric efficiency of 22.3% but 2.6% higher fossil fuel consumption.

Safa Skouri et al. [18] FORTRAN program developed for three pilot sun tracking system developed to follow the sun position on azimuth and elevation angle for solar parabolic concentrator. Which results solar direct irradiation is 60% of global irradiation within tracking accuracy of 2.5mrad. Hamza Hijazi et al. [19] designed a low cost parabolic solar dish concentrator with small to moderate size for direct electricity generation. Three diameters of the dish; 5, 10 and 20 m were investigated and the focal point to dish

diameter ratio is set to be 0.3. Stress analysis was carried out to optimize the dimension of dish under the effect of dish weight and wind force.

Anil Kumar et al. [20] reported a step by step procedure for designing of reflector parabola and calculated thermal efficiency with receiver capacity upto 200⁰C for medium temperature applications. A comparative study of energy and exergy analysis was conducted. Jun Wang et al.[21]proposed 2-stage dish concentrator system (paraboloid and hyperboloid) for CSP plants based on overlap method to improve radial flux concentration ratio ($b=15498$) and intercept factor ($g=0.78$). Mun Soo Na et al. [22] developed thermal performance of solar concentrator based on 45⁰conical angle for different mass flow rates (0.03, 0.06 and 0.1Kg/s) and 0.785m² aperture area. The maximum efficiency at an optimum flow rate of 0.06 kg/s found was 85%.Song Yanga et al. [23] constructed tailor made receiver coupled to two stage dish concentrator with 20m diameter, intercept radiation upto 312 KW for optical and thermal aspects. The obtained result was compared with conventional receiver intercept radiation of $3.8 \times 10^5 \text{W/m}^2$, optical efficiency of 77.8%, thermal efficiency of 85.2%, solar to thermal efficiency of 68.6%, convective losses from 33.3% to 39.4% and net heat flux absorbed in pipe is 11.9%.Mohammed H. Abbood et al. [24] investigated thermal and optical performance of three parabolic trough collector placed in series with two axes sun tracking mechanism, two borosilicate glass tube receiver to generate hot water and moderate temperature steam. Thermal performance evaluated according to ASHARE 93-1986(RA91) and efficiency of evacuated and non evacuated glass receiver obtained were 50% and 18.8%. Thirunavukkarasu Venkatachalam, M. Cheralathanstudy [25] observed thermal performance of conical cavity receiver of 16m² scheffler type dish concentrator with different aspect ratio (0.8, 1.0 and 1.2) and average beam radiation above 600W/m² to evaluate energy efficiency, exergy efficiency and overall heat loss factor. For the aspect ratio 0.8 to 1.0, energy and exergy efficiency was reduced by 20% and 8.5% and when aspect ratio was 1.2, the energy efficiency and exergy efficiency increased by 4% and 7.6% respectively.

Li-Chao Xu et al. [26] investigated operating parameter for solar collector with 1.8m² area and 24 all glass evacuated tube connected in parallel and proposed a low cost solar collector for steam generation. When temperature of the steam is 130⁰C and 140⁰C at solar irradiation of 800W/m², the collector efficiency is 0.43 and 0.55. The steam temperature is maintained at 130⁰C, if irradiation above 500W/m² and steam production of 2.25Kg/m².KarimaGhazouani et al. [27] a parabolic trough collector were designed and evaluated for indirect steam generation with 10.8m² aperture area and one axis sun tracking mechanism. A mathematical model has been developed to evaluate thermal performance which results absorbed energy 552.73W, thermal energy efficiency varies from 24% to 28% for parabolic trough solar power plant (PTSSP), average concentration factor 200 and 8Kg/h steam generated [27]. The aim of this paper is to study and review of thermal aspects like thermal efficiency, optical efficiency, useful heat gain, heat losses, etc. of concentrated solar parabolic, specifically parabolic dish concentrator and current statistics of CSP.

3. Concentrated solar power (CSP)

Concentrated solar power systems generate sustainable power by using mirrors or lenses to concentrate a large area of sunrays onto a small area. This concentrated heat is utilized to heating pure substance, which in turn changes enthalpy and phase, which drives steam turbine connected to electric generator or prime mover [29-35].

The most common technologies for concentrated solar power (CSP) are parabolic trough collector (PTC), Linear Fresnel Reflector (LFR), Paraboloid Dish (PD) and Solar Power Tower (SPT). Among four PTC and LFR are based on line focus system while paraboloid dish and solar power tower two point focus systems. Paraboloid dish receiver made up of four components is concentrator, receiver, stirling engine and generator. The power conversion unit consists of stirling engine, receiver, and generator.

The sun rays striking on solar Paraboloid dish operated with two axes sun tracking system. It captures highest solar radiation and optical efficiency of 94% with concentration ratio from 500 to 200 which is then transferred to receiver located at the focal distance. This results into the higher solar to electric efficiencies. In the CSP, parabolic concentrator have an excellent potential amongst other technologies which in results 31.25% solar to electric efficiency. The PDR based Solar Industrial process heating system can be installed at automobile industrial plants with high DNI values to make automobile production more green and environment friendly [28].

4. Heat transfer fluids(HTFs)

To generate higher thermal performance which results in higher solar to electrical efficiency, heat transfer fluid (HTF) plays a vital role. In CSP, the heat is collected from the receiver by a thermal energy carrier called heat transfer fluids. The HTF can directly drive a turbine for production of power or can be used in a heat exchanger to transfer heat to another fluid known as the cycle fluid. Desired properties and characteristics of a HTF are: high boiling point, low melting point and thermal stability, low vapour pressure (<1 atm) at high temperature, low viscosity, low corrosion with metal alloys used to contain the HTF, high heat capacity for energy storage, high thermal conductivity and low cost. The HTFs is based on type of material used water/steam, organics and molten-salts.

4.1. Water or steam

A less cost of electricity production with the water or steam use as HTF and working fluid of cycle which removes the complexities from the system and leads to enhanced efficiency. Water as working fluid used in world's largest CSP plant.

4.2. Organics

To achieve higher thermal performance organic materials are also used widely as HTFs in CSP systems. Therminol VP1 (Biphenyl/Diphenyloxide) is commonly used in commercial CSP systems. Biphenyl/Diphenyl oxide is a eutectic mixture of two very stable organic compounds; Biphenyl (C₁₂H₁₀) and Diphenyl oxide (C₁₂H₁₀O).

4.3. Molten-salts

Molten salt is most widely used as working fluid to achieve higher temperature more than 500⁰C and excellent properties like heat capacity, low vapour pressure and corrosive property and good thermal and physical properties at elevated temperatures. The most common molten salt as HTF is a mixture of 60% NaNO₃ and 40% KNO₃. The drawback of molten salt is high melting point also salt freeze and blocks the pipeline during winter. To overcome these drawbacks, it needs to provide auxiliary arrangement which increases the operational as well as investment cost.

5. Current scenario of CSP in India

Compare to photovoltaic technology, CSP technology yet not adopted widely in India. Following are some reasons which responsible for this:

1. Low investor confidence
2. Lack of indigenous manufacturing
3. Unreliable solar data
4. Low availability of skilled labour
5. Higher cost

Following table shows the current statistics of the CSP in India according to capacity (MW), current status and technology used.

Table 1: Various CSP plants in India according to capacity, current status, capacity [29]

| Project | Technology type | Capacity (MW) | Current status |
|------------------------------|-------------------|---------------|--------------------|
| Godawari Solar Project | Parabolic trough | 50 | Operational |
| Megha Solar Plant | Parabolic trough | 50 | Operational |
| National Solar Thermal Power | Parabolic trough | 1 | Operational |
| Diwakar | Parabolic trough | 100 | Under construction |
| KVK Energy Solar Project | Parabolic trough | 100 | Under construction |
| Abhijeet Solar Project | Parabolic trough | 50 | Under construction |
| Gujarat Solar One | Parabolic trough | 25 | Under construction |
| Rajasthan Solar One | Parabolic trough | 10 | Under construction |
| ACME Solar Tower | Solar tower | 2.5 | Operational |
| Dhursar | Fresnel reflector | 125 | Operational |
| Dadri ISCC Plant | Fresnel reflector | 14 | Under construction |

6. Global CSP worldwide

As per the statistical data of global CSP, following are the graphical representation of CSP worldwide and global capacity of CSP. Figure 1 represents Spain and USA producing 2300MW and 1758 MW of accumulative CSP compared with other countries are too higher whereas India producing 229MW. Figure 2 represents the CSP global capacity is going to increasing from year by year. It found 0.04 gigawatt-hour during 2007 which increase and recorded in 2017 was 12.8 gigawatt-hour [36].

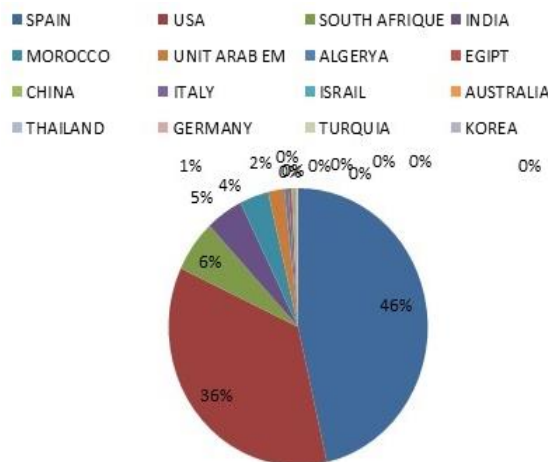


Figure 1: CSP worldwide

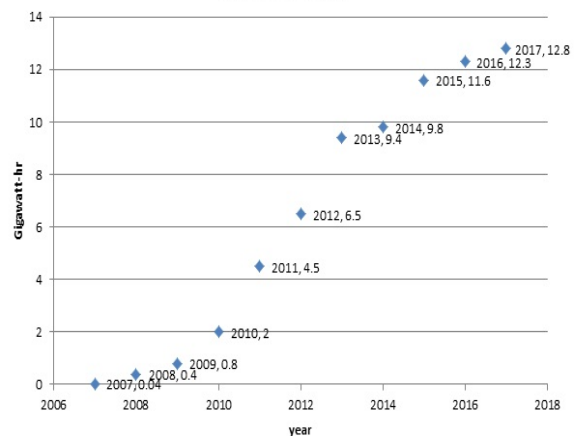


Figure 2: Global capacity of CSP

7. Conclusion

Thermal aspect of CSP has been studied based on various parameters like thermal efficiency, optical efficiency, useful heat gain, heat losses, solar irradiation, etc. for verified applications of different temperature ranges to satisfy future needs. CSP having a great potential compared to other technologies which in results solar to electric efficiency at 31.25%.As per the review it concluded that the CSP with paraboloidal dish concentrator giving a higher temperature ranges applications as compared with other technologies. The heat transfer fluid is reported in this paper. Many of researcher conducted experimentation by using water as working fluid and obtained higher thermal performance for domestic and household application with temperature range upto 250⁰C, but molten salt is best suited to heat transfer fluid which results industrial fluid applications for higher temperature ranges (above 250⁰C).

The present world electricity consumption is 18000TWh/y which is very low as compared with the global technical potential of concentrating solar power amounts to almost 3,000,000 TWh/y. CSP plants with large solar fields and thermal energy storage in desert is capable of producing electricity with capacity up to 8000 hours per year. Solar electricity imports from deserts and semi-deserts to large centers helps to reduce greenhouse gas emissions and to stabilize electricity costs all over the world. Finally there is an imperative need to develop CSP with optimistic parameters to satisfy future need of the society.

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