Techniques for Enhancing Performance of Parabolic Trough Systems: A Review

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Abstract - *Solar energy is a type of renewable energy source which is environmental friendly and helpful in sustaining the growing energy demand. Parabolic trough collectors are a conventional option used in various medium and high temperature applications such as water heating, heat engines, air conditioning, solar cooking, steam generation and solar drying for the exponentially growing residential and industrial sectors. This paper discusses the conventionally used materials and various components for parabolic trough solar collectors. Their effectiveness over the time can be improvised with the help of newly discovered alternative materials, geometrical orientation and new designs by means of which the overall performance of PTSC (parabolic trough solar collector) can be enhanced.*

Key Words: Concentrated Solar Power, Parabolic Trough Solar Collector, Reflector, Collector, Receiver, Heat transfer fluid.

1. INTRODUCTION

There are two types of energy sources: conventional and renewable energy. Conventional energy sources are coal, natural gas, oil, crude oil, etc. The use of conventional energy sources has several environmental and hazard aspects. Burning fossil fuels like coal and oil leads to photochemical pollution from nitrous oxide and acid rain from sulphur dioxide. It also produces greenhouse gases that cause the global warming phenomenon. Green energy provides environment friendly and non-polluting energy such as solar energy, biomass, wind, tidal energy, etc. Among these, wind energy is suitable for large-scale power generation because it requires coastal or mountain areas and high wind speeds. Biomass and tidal are also suitable for small scale purpose. Only solar energy has full potential to recover the existing power crisis without polluting our environment.

Solar energy is the conversion of energy from sunlight into the electricity. It can be classified into two types- solar photovoltaics (PV) and solar thermal, also known as concentrated solar energy (CSP). Concentrated solar power technology uses lenses or mirrors and a solar tracking system which focuses a large area of sunlight into a small beam. Photovoltaic cells convert light into electricity through the photovoltaic effect.

2. CSP TECHNOLOGY

In CSP technology, direct normal radiation from the sun is concentrated on HTF (Heat Transfer Fluid), which is then passed through a series of heat exchangers to produce superheated steam. This steam is converted into electrical energy in a conventional steam turbine. Some of the heat is also stored in some liquid or solid liquid media for use at night or during periods without sunlight. There are several CSP technologies, but their basic principle in generating electricity is the same. The CSP systems are classified into line focusing and point focusing type. In line focusing systems, solar radiation is concentrated onto a linear absorber tube or a series of tubes and tracked on single axis, to focus sun's radiation on the absorber tube. This is also known as single axis tracking technology. The Line focusing systems are further bifurcated into Parabolic trough system and Linear Fresnel reflector systems. While in the case of point focusing systems, all the concentrators concentrate the sun radiation at a focal point and it is further classified into solar tower type and solar dish type systems.

3. PARABOLIC TROUGH COLLECTORS

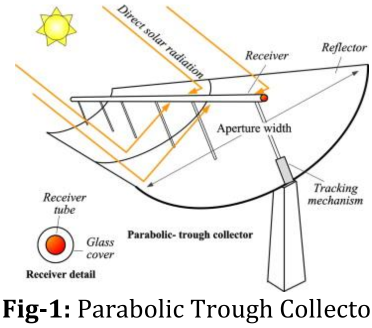


Fig-1: Parabolic Trough Collector

Parabolic trough collectors are a conventional option used in various medium and high temperature applications such as water heating, heat engines, air conditioning, solar cooking, steam generation and solar drying for residential and industrial sectors that have grown exponentially. About the conventionally used materials and the various components for the parabolic trough solar collector, effectiveness over time can be improvised with the help of newly discovered alternative materials and design structures, by means of which the performance of PTSC (Parabolic Trough Solar Collector) can be improvised. Parabolic trough system consists of several curved mirrors that focuses the sun's radiation onto a receiver tube containing a heat transfer fluid. This system has six major parts i.e., reflecting surface, absorber, support structure, tracking system, generation unit and thermal storage unit. It tracks the sun over the course of the day and reflectors, reflect the solar radiation and concentrate it onto a receiver tube that is located at the focal line of the parabola. The concentrated solar radiation increases the heat of HFT and then transforms into thermal energy. This paper suggests some of the methods and techniques studied by various researchers for enhancing the performance of PTC systems.

4. GEOMETRICAL STRUCTURAL IMPROVEMENT

4.1 New design of Parabolic Trough Collector

Numerous studies have shown that the accumulation of dust can invariably affect the performance of solar collectors and parabolic collectors. Frequent cleaning is necessary to ensure that the solar collectors perform evenly. Autonomous cleaning of parabolic trough collectors was not a viable option due to the shape of the trough and the existence of the receiving tube. Hence in one of the studies a new parabolic trough collector (NPTC) was designed and compared against the conventional parabolic trough collector (CPTC). The new trough uses the same kind of reflective material, vacuum absorber tube as conventional one but covered from the top and on both sides by Borosilicate glass. The idea of covering the top surface of the trough has two advantages: the first advantage is to optimize the heat loss in the trough by creating a greenhouse effect which will increase the temperature inside the parabolic trough. The second advantage of closing the trough is to facilitate the cleaning process of the trough after dust accumulates.

Fig-2: New Parabolic Trough Collector (Grami, 2018)

An experimental comparison between the conventional parabolic trough and the new designed trough collector is presented below:

4.1.1 Experiment 1

Both parabolic trough collectors were cleaned before the experiment, water was used as the heat transfer fluid, solar radiation was measured with a pyrometer installed on the roof during the experiment and the results of the experiment in terms of outlet temperature are shown in the figure. The figure shows that the NPTC has a higher outlet temperature compared to the CPTC. The outlet temperature for the NPTC started at 105 ° C and reached 123 ° C while for CPTC, the outlet temperature started at 55 ° C and reached 105 ° C, which is lower than the NPTC outlet temperature. The thermal improvement of the NPTC is approx. 14.4%.

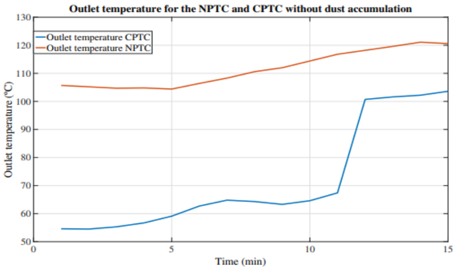


Fig-3: Outlet temperature for clean NPTC and CPTC (Grami, 2018)

4.1.2 Experiment 2

Fifteen days later, a second experiment without cleaning the parabolic collectors was carried out to investigate the effect of dust on the performance of the collectors and to demonstrate the importance of the cleaning process in solar concentrators. A comparative study was carried out between the two collectors without cleaning them. The outlet temperatures for both feeders are shown in figure. The graph shows that dust accumulation affects the performance of the concentrators as, the dust is an obstacle that prevents solar radiation from reaching the reflective surface. However, according to the diagram, NPTC again has a slightly better heat output than CPTC. Hence, the effect of dust is very important to performance. In this case, due to the accumulation of dust (from 123 ° C to 51 ° C), the NPTC showed a deterioration of about 60%, so that continuous cleaning is required to maintain the performance of solar energy concentrators.

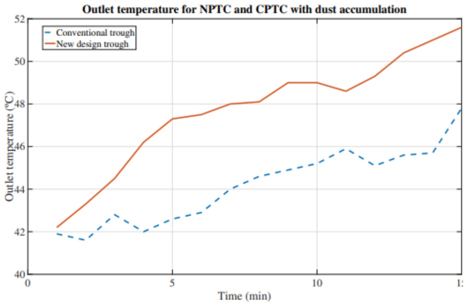


Fig-4: Outlet temperature for NPTC and CPTC with dust accumulation (Grami, 2018)

4.1.3 Experiment 3

To compare the two parabolic trough collectors, a third experiment was carried out using mineral oil as the heat transfer fluid. During this experiment the NPTC outlet temperature reached 223 ° C and the CPTC outlet temperature only 144 ° C. Thermal efficiency of NPTC was more than CPTC, hence, NPTC can be viewed as a thermal heat trap as it has a greenhouse effect. The percentage improvement using NPTC is about 35%, which is more important than using water as the heat transfer fluid. The newly developed parabolic trough collector (NPTC) has again proven its efficiency in terms of thermal heat. The flat cover on top of NPTC makes the cleaning process easy and can be performed with a small self-cleaning device.

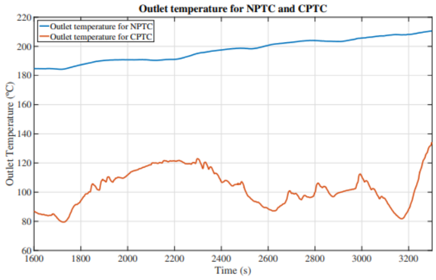


Fig-5: Outlet temperature for NPTC and CPTC with oil as HTF (Grami, 2018)

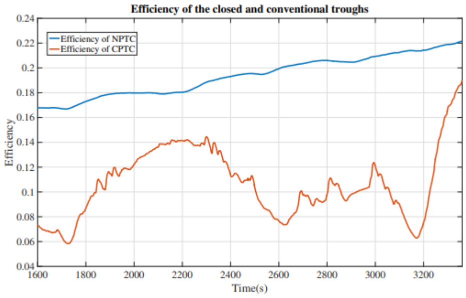


Fig-6: Efficiency of the CPTC and NPTC (Grami, 2018)

Table-1: Comparison of experiment results

Experiment no. / Outlet temperature	Experiment 1	Experiment 2	Experiment 3
Outlet temperature of CPTC	105 ° C	48° C	144 ° C
Outlet temperature of NPTC	123 ° C	51 ° C	223 ° C

From the above results, the new designed parabolic trough collector showed a noticeable improvement in terms of thermal efficiency as compared to CPTC and has less effect of dust accumulation as shown in table-1 as well as makes the cleaning process easy.

4.2 Eccentric Tube Receiver

An eccentric tube receiver was constructed to reduces the thermal stresses. The center of the internal cylinder surface of the concentric tube receiver was moved upward (or at other directions) at a different location from the center of the external cylinder surface. Therefore, the wall thickness of the bottom half section of tube receiver would increase without adding any mass to the entire tube receiver. The increase of wall thickness would not only strengthen the tube to increase the resistance to thermal stress, but also enlarge the thermal capacity, which in turn will reduce the non-uniform temperature distribution condition. Ray-thermal-structural sequential coupled numerical analyses were performed to obtain the concentrated heat flux distributions, temperature distributions, and thermal stress fields of both the eccentric and concentric tube receivers. The numerical results indicated that adopting the eccentric tube as the metal tube of the PTC system can reduce the effective thermal stress up to 41.1% and also decrease the thermal deformation of the receiver tube.

4.3 Two axis rotation

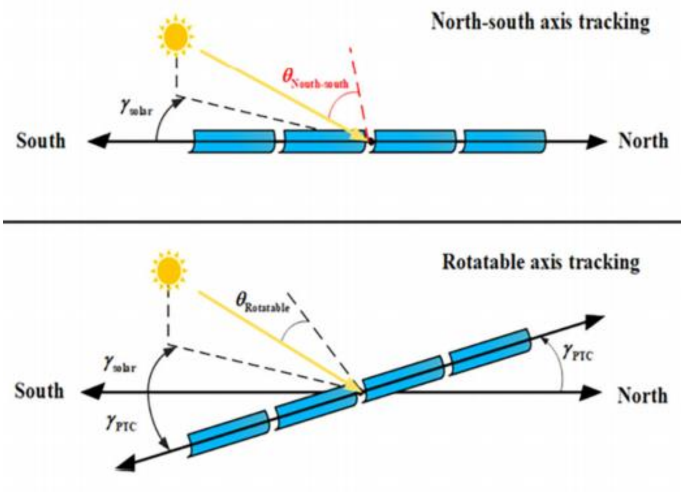


Fig-7: Two axis rotation

A huge amount of energy is wasted if sunrays are not concentrated on the absorber coatings. Hence, a study was proposed in which a rotatable axis system was compared against the conventional fixed axis system in North-South direction under the Chinese climate. This proposed idea of rotatable axis reduced the energy destruction and thus the energy efficiency of the PTC was enhanced by 3% annually. It was because the angle of the PTC was easily perpendicular to the sun location with rotating axis as compared to the fixed one. However, another researcher studied experimentally the effect of performing tow-axes tracking system compared with a fixed-axis system oriented in the South direction under the Greece climate and the solar energy collected was enhanced up to 46.46% with the proposed system.

5. SURFACE MOFIFICATION

5.1 Collectors

5.1.1 Silver Coated Glass Mirror

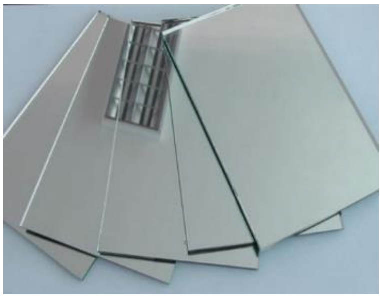


Fig-8: Silver Coated Glass Mirror

The most commonly used collector material is a silver-coated glass mirror. One of the types of glass used is low iron flat glass with a relatively flat surface that can be made by a flat process and has a reflectivity of 0.896. Silver glass mirrors tend to deteriorate when stored outdoors because silver corrodes. Therefore, they must be adequately protected, otherwise their reflectivity will deteriorate. Glass mirrors are very fragile and therefore difficult to handle in large plates which are made up of single piece hence, they are made from mirror fragments that reduce the reflectivity of the collector opening due to the gaps. Mirrors have a reflectivity of 0.93. These high quality, low iron glass mirrors can be expensive.

5.1.2 Acrylic Mirror Sheets

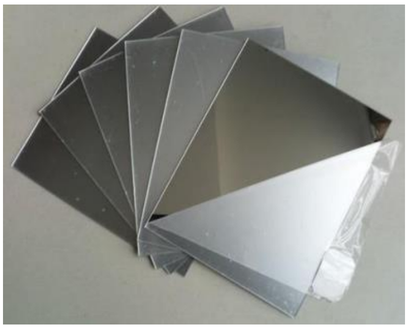


Fig-9: Acrylic mirrors

After researching reflective materials that can be used for collectors, acrylic mirrors seemed to be noteworthy for using reflective materials for collectors. Acrylic is nothing but polymethylmethacrylate (PMMA). A study was conducted by NREL and 3M Company on inexpensive, long-life solar reflectors that contained various reflector materials such as acrylic, silicone, fluoropolymers, polyacrylonitrile (PAN), polycarbonate, and polyester films. Out of which Acrylic was found to be remarkable in its performance and reassuring from a cost per performance point of view and its weight is half of glass mirrors. Reflectivity for acrylic mirrors is high, 99%.

5.2 Absorptive Coating

5.2.1 Black Matt Coating

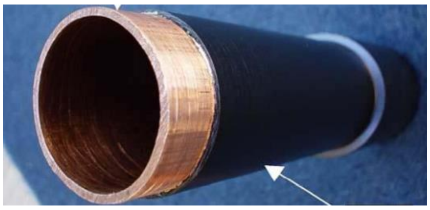


Fig-10: Black Matt Coating

Black matt is one of the most widely used absorbents. The spray method is used to apply matt black to any metal. It has been tested that the Black matt coating deteriorates the thermal conductivity and also that the absorptivity of the black matt decreases with decreasing wavelength of the imposed light. The absorptivity of Black matt is 6-7% lower than Black Chrome, Black Nickel and Chrome coatings.

5.2.2 Black Copper

Black Copper is suitable for use as a coating on copper. It can be applied on any the required metal by electroplating method.

Characteristics: -
- Absorptivity = 0.97 -0.98
- Emissivity at 100°c = 0.02
- Stability in vacuum is up to 370 °c
- Stability in air is up to 250°c

5.2.3 Black Chrome

The chemical composition of black chrome is 75% chromium and 25% chromium oxide. It is Suitable for plating over copper, Stainless Steel & Bright Chromium and can be applied on these metals by electrodeposition/electroplating technique.

Characteristics: -
- Absorptivity = 0.97
- Emissivity at 100°C = 0.09
- Stability in vacuum is up to 400 °C
- Stability in air is up to 350°C

5.2.4 Black Nickel

It is composed of Zinc and Nickel with small amounts of carbon, nitrogen and sulphur. Emissivity is high therefore it needs to be coated on initial plating of bright nickel for decreasing the emissivity to 0.06 and for corrosion protection.

Characteristics: -
- Absorptivity = 0.92 – 0.98
- Emissivity = 0.08 – 0.68

- Stability in air up to 300°C

6. ABSORBER TUBE MODIFICATION

6.1 Receiver Tube

6.1.1 Non - Evacuated Receiver Tube

The Losses due to air movement over hot receiver surfaces are convection losses. These losses can be reduced by placing a glass cover or an acrylic cover concentrically over the receiver tube. The envelope results in the reduction of convection losses only, by the method of conduction through any medium between the hot surface of the receiver and the atmosphere, which in this case is air. They have a lower receiver efficiency as there are more losses, i.e., conduction and convection losses. The non-evacuated pipes cannot be used for temperatures above 250 ° C, as the losses are not that critical up to this point.

6.1.2 Evacuated receiver tube

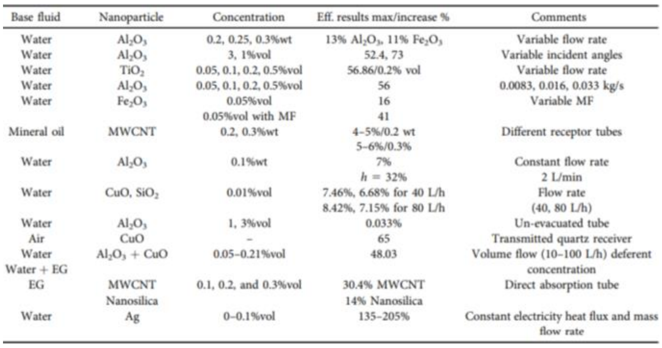
Fig-11: Evacuated tube

A low-iron borosilicate glass tube is used as a cover for the metal receiving tube. The low-iron borosilicate glass tube has a permeability of 95. The evacuated tube minimizes exponentially line and convention losses and provides a relatively higher thermal output than non-evacuated receivers. The proposed receiver tube has a selectively absorbent coated copper inner tube and a clear borosilicate outer tube. Evacuated pipes are used in a high temperature range of 450 ° C, since thermal losses are critical in this temperature range.

6.2 Heat Transfer Fluid

HTF is a crucial factor in a solar thermal power plant as it directly influences the tube receiver efficiency, determines the type of thermodynamic cycle, as well as the thermal energy storage technology that must be adopted. Synthetic thermal oil is commonly used as an HTF in the tube receivers but it has an upper temperature limit of 400 °C, if it is operated beyond this limit, the hydrocarbons breakdown quickly and generate hydrogen, which would reduce the overall HTF lifetime and induce build-up of sludge or other by-products that reduce the system heat transfer efficiency and increase maintenance cost. Using water as HTF needs more sophisticated control strategies and concepts. While molten salt has high melting point which results in high operation and maintenance costs for freeze protection. An effective method to overcome this barrier is using nano-sized particles (1–100 nm) suspended in HTF to improve their effective thermal conductivity. The commonly used nanofluids in applications contain the following nanoparticles: Al2O3, ZnO, Cu, Au, TiO2, Al, Fe2O3, CuO, SiO2, NiO, Ag and Fe, etc.

Table-2: Nanofluid specification and main findings results (Al-Oran, 2020)



Base fluid	Nanoparticle	Concentration	Eff. results max/increase %	Comments
Water	Al_2O_3	0.2, 0.25, 0.3%wt	13% Al_2O_3, 11% Fe_2O_3	Variable flow rate
Water	Al_2O_3	3, 1%vol	52.4, 73	Variable incident angles
Water	TiO_2	0.05, 0.1, 0.2, 0.5%vol	56.86/0.2% vol	Variable flow rate
Water	Al_2O_3	0.05, 0.1, 0.2, 0.5%vol	56	0.0083, 0.016, 0.033 kg/s
Water	Fe_2O_3	0.05%vol 0.05%vol with MF	16 41	Variable MF
Mineral oil	MWCNT	0.2, 0.3%wt	4–5%/0.2 wt 5–6%/0.3%	Different receptor tubes
Water	Al_2O_3	0.1%wt	7% $h = 32\%$	Constant flow rate 2 L/min
Water	CuO, SiO_2	0.01%vol	7.46%, 6.68% for 40 L/h 8.42%, 7.15% for 80 L/h	Flow rate (40, 80 L/h)
Water	Al_2O_3	1, 3%vol	0.033%	Un-evacuated tube
Air	CuO	–	65	Transmitted quartz receiver
Water	Al_2O_3 + CuO	0.05–0.21%vol	48.03	Volume flow (10–100 L/h) deferent concentration
Water + EG				
EG	MWCNT Nanosilica	0.1, 0.2, and 0.3%vol	30.4% MWCNT 14% Nanosilica	Direct absorption tube
Water	Ag	0–0.1%vol	135–205%	Constant electricity heat flux and mass flow rate

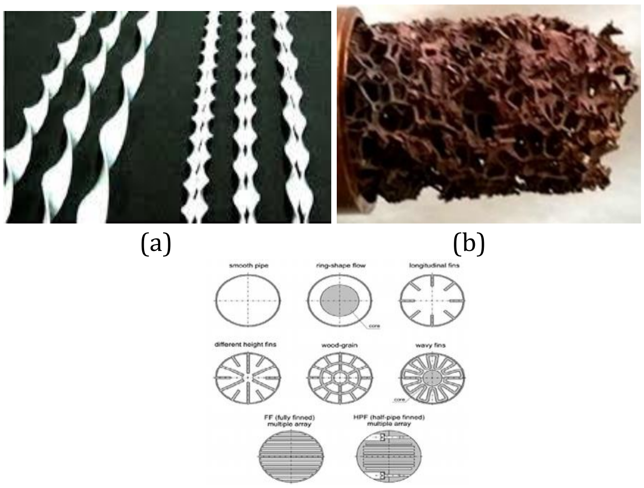
Several researchers experimentally studied the behaviour of HTF by adding the nanoparticles of different compositions and concentrations as shown in table-2. Some of them are listed below:

1. Nanoparticles consisting of oxide aluminium and iron based water of concentrations (0.2, 0.25, and 0.3%) on weight base. Major results showed enhancements on the thermal efficiency using nanofluids Al2O3/H2O reaching up to 13%, while it reaches 11% using Fe2O3/H2O.
2. Nanoparticle of Al2O3 in a base fluid of water under the effect of variables incident angle and volume concentration were observed. The maximum thermal efficiency observed reached 63.4% for water, 73% for alumina oxide under volume concentration 1%, and 52.4% for the alumina oxide under volume concentration 3%.
3. Nanofluid of TiO2 was mixed with ionized water at different concentrations (i.e., 0.05, 0.1, 0.2, and 0.5%), and various flow rates. The thermal efficiency enhanced up to 8.66% and convective heat transfer coefficient up to 22.76% for 0.2% volume concentration and 0.0667 kg/s mass flow rate.

Similarly, other studies were also conducted which are explained in [1]

6.3 Inserts Model and Surface Modification Experimental Works

Surface geometric modifications and flow inserts are the oldest methods of improving heat transfer in various applications. The effect of using these criteria within the receiver was aimed at making the flow more turbulent, whether using different flow model inserts such as twisted tap, porous material or disc, a wire coil and wavy insert or by surface modification in the internal or on the surface of the receiver (e.g., dimpled and internal fins).



(a) (b)

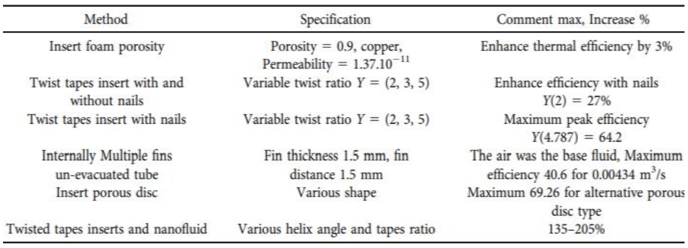
(c)

Fig-12: Insert models:

(a) twisted tapes
(b) copper foam porous
(c) internal fins

The table-3 describes the major parameters of different methods and results of the experiments performed by various researchers by using different kind of inserts such as copper metal foam, twisted tapes with nails, internal fins, porous discs and surface modification of receiver tubes given in [1].

Table-3: Inserts types and surface receiver modifications enhancement (Al-Oran, 2020)



Method	Specification	Comment max, Increase %
Insert foam porosity	Porosity = 0.9, copper, Permeability = $1.37.10^{-11}$	Enhance thermal efficiency by 3%
Twist tapes insert with and without nails	Variable twist ratio $Y = (2, 3, 5)$	Enhance efficiency with nails $Y(2) = 27\%$
Twist tapes insert with nails	Variable twist ratio $Y = (2, 3, 5)$	Maximum peak efficiency $Y(4.787) = 64.2$
Internally Multiple fins un-evacuated tube	Fin thickness 1.5 mm, fin distance 1.5 mm	The air was the base fluid, Maximum efficiency 40.6 for 0.00434 m^3/s
Insert porous disc	Various shape	Maximum 69.26 for alternative porous disc type
Twisted tapes inserts and nanofluid	Various helix angle and tapes ratio	135–205%

7. SUMMARY TABLE

Sr. No.	Research paper/ Year of publication	Area of research
1	Recent experimental enhancement techniques applied in the receiver part of the parabolic trough collector – A review. [2020]	Enhancing thermal performance of PTC using nanofluid, receiver surface modification, and inserts models
2	An extensive review of various technologies for enhancing the thermal and optical performances of parabolic trough collectors. [2020]	utilization of nanofluids for improving thermal properties
3	Experimental Investigation of New Designed Solar Parabolic Trough Collectors. [2018]	Investigation of New Designed Solar Parabolic Trough Collectors
4	Literature Review and Analysis of Improvisations in Parabolic Trough Solar Collector. [2019]	Using of alternative materials for collector, reflector and absorptive coating
5	Progress in concentrated solar power technology with parabolic trough collector system: a comprehensive review. [2017]	Enhancing thermal performance of PTC using nanofluid, receiver surface modification, and inserts models
6	An overview of concentrated solar power (CSP) technologies and its opportunities in Bangladesh. [2017]	Concentrated solar power (CSP) technologies
7	Parabolic trough solar collectors: A general overview of technology, industrial applications, energy market, modeling, and standards. [2020]	Thermal performance analysis methods and components used in the fabrication of collector
8	Advances in Parabolic Trough Solar Power Technology. [2002]	Future of parabolic trough solar power plants
9	An Experimental Study of Modelling and Fabrication of an Autonomous Solar Parabolic Trough Collector. [2018]	Experimental study of modelling and fabrication of an autonomous solar parabolic trough collector
10	Concentrating Solar Power Systems with Advanced Thermal Energy Storage for Emerging Markets. [2016]	CSP plant storage
11	Concentrating Solar Thermal Power Technologies: A Review	Concentrating Solar Thermal Power (CSP) Technology

12	Sizing and siting of a concentrating solar power plant in an unbalanced radial distribution system. [2020]	Sizing and siting of a concentrating solar power plant
13	Feasibility Analysis and Design of a Concentrated Solar Power Plant. [2018]	Technical and financial details for setting up a parabolic trough CSP plant
14	Concentrated Solar Power Technology and Thermal Energy Storage: A brief Overview of Nascent Sustainable Designs. [2019]	Developments in the concentrated solar receivers and the future direction in the receiver technology
15	Evaluation of Concentrated Solar-Thermal Generation for Provision of Power System Flexibility	New institutional arrangement to exploit generation flexibility

8. CONCLUSIONS

PTC systems plays a key role in solar thermal energy. Numerous technologies and distinct strategies have been investigated to enhance the general overall performance of the PTC optically, thermally and hydraulically, using experiments, simulations, or analytical approaches. The performance of PTC systems can be enhanced using two main approaches: improvement in thermal performance, and optical performance. Based on the research investigations discussed in this review paper, it can be concluded that the utilization of nanofluids in HTFs, receiver surface modification, absorber coatings and insert model improves the thermal properties of the PTC systems. While the use of newly designed parabolic trough collector and alternative collector materials enhances the optical performance of PTC system and hence, the overall performance of the system can be achieved.

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