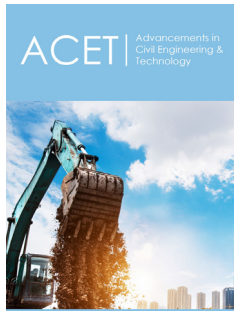# Enhancement Techniques of Parabolic Trough Collectors: A Review of Past and Recent Technologies

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Abstract

Parabolic Trough Collectors (PTC) are one of the most widely used technology amongst the solar thermal systems used by the power generation industry. In recent years, numerous scientific investigations have focused on this topic to assess the thermal performance and to improve its thermal efficiency. The current paper presents a short but concise review of the PTC system showing the recent and past studies in a quest to improve and enhance the thermal and optical efficiencies. We discuss briefly the techniques used for single and two-phase flow modelling, design variables and experimental processes. Furthermore, studies investigating the enhancement of thermal performance are critically summarized such as: use of nanofluids as a working fluid and passive heat transfer enhancement techniques (inserts for the solar receiver).

Keywords: Nanofluids; Parabolic trough collector; Passive heat transfer enhancements; Solar thermal energy

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Introduction

To tackle the climate change and global warming, the world needs to reduce its dependency on fossil fuels. In recent years clean, renewable and sustainable sources of energy such as solar, wind, tidal etc. have thus become widely popular. In particular solar thermal energy has emerged as a major contender in the quest to reduce CO_2 emissions especially for regions with hot tropical climate. The light or solar energy/heat from the sun can be harnessed to produce electricity via Photovoltaic Devices (PV) or Concentrating Solar Power (CSP) plants. The CSP plants operate on Direct Normal Irradiance (DNI), which is defined as the amount of received solar energy per unit area on the surface held normal to the rays of the sun. Depending upon the methodology to capture the suns energy, the CSP technology can be categorized into several technologies, four of the most common ones being; parabolic trough collectors (PTC: which is our focus), linear Fresnel reflectors, parabolic dishes and solar towers, in Figure 1.
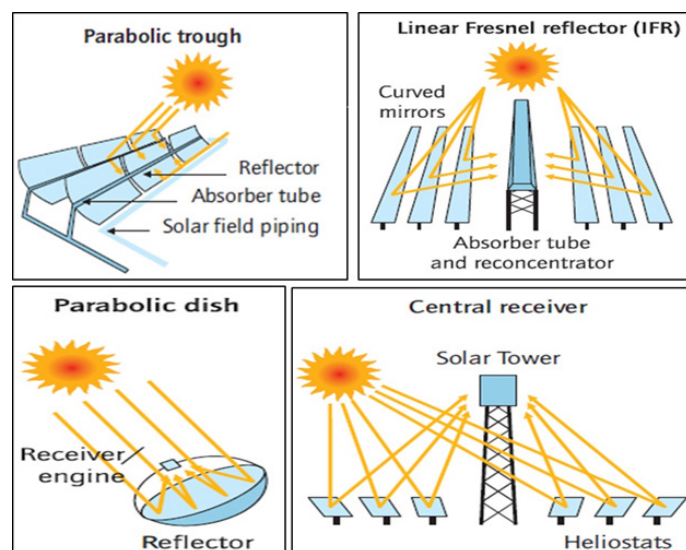

Figure 1: Current CSP types, Philibert and Frankl [1].

The PTC system consists mainly of three important sub-systems; the solar field, the storage system and the power block. The solar field can be categorized as a type of a large heat exchanger with the main components being the solar collector and the reflector surface. The reflector surface is generally made up of a series of mirrors that directs the solar energy to the solar collector. The solar collector then converts the absorbed incident solar radiation into thermal energy which is carried through the collector via the Heat Transfer Fluid (HTF). Within the solar collector, an absorber tube is generally made from a metal which is coated with black color to achieve larger solar absorbance and to reduce the thermal emittance. The absorber tube is encased within a glass envelope which is itself covered with an anti-reflective coating to reduce the heat losses by convection.

Thermal performance of PTCs

The absorber tube (also known as heat collection element (HCE)) is one of the most important elements in a PTC system; its thermal efficiency directly impacts not just the reliability of the plant but also the cost of energy production. Because of these reasons various methodologies of heat transfer enhancement are generally used within the absorber tube for the PTC system. The most commonly used techniques such as, changing the working fluid, use of nanoparticles and the use of inserts (swirl generators etc.), are reviewed below. A fourth methodology which is based on combination of nanoparticles with inserts is also becoming popular.

Thermal performance by changing working fluids

Majority of the solar thermal power plants (STPP) with PTC systems around the world which are currently operational use thermal oil as HTF with the maximum working temperature of 398 °C. Low vapour pressure, affordable price, long lifetime and good thermal stability are the obvious reasons for using thermal oils in the STPP. However, this does not mean that thermal oils are the best working fluid; limitation of temperature (around 400 °C), environmental toxicity and flammability are some of the key drawbacks when using thermal oils. Alternative HTFs that have been examined in the literature instead are; liquid-water/steam, pressurized gases and molten salts. Some of these investigations and their key findings highlighting the advantages and disadvantages compared to thermal oils typically used in the STPP are summarized in Table 1.

Table 1: Effects of changing Heat Transfer Fluid (HTF) on the thermal performance.

Ref.	Working Fluid	Details of Findings
[2]	Syltherm 800 oil and water	Thermal loss of the collector was lower when using water than those predicted by using Syltherm 800 oil.
[3]	Therminol VP1, Xceltherm 600, Syltherm 800, 60-40 Salt, and Hitec XL Salt	Effect of working fluid was smaller than other parameters. The maximum thermal efficiency was provided by Xceltherm 600 and Syltherm 800, but these fluids are relatively expensive.
[4]	Molten salt, water, oil	Better efficiency has been obtained by using water.
[5]	Syltherm 800, XLT, Santotherm 59, Marlotherm X, and Therminol D12.	The Syltherm 800 can be operated at a temperature higher than 700K, while the working fluids marlotherm X and syltherm XLT can only be operated at a temperature less than 700K; whereas, others can operate between 650K and 750K.
[6]	Syltherm 800, XLT Santotherm 59, LT, Marlotherm X, Therminol D12, and Marlotherm SH.	The most appropriate choice was Syltherm 800 which provided the maximum range of (700-800) K. The highest cost when using Santotherm LT was 129US $/kW h/day. Moreover, the best HTF was Syltherm 800 from the thermal capacity point of view.
[7]	Pressurized nitrogen and synthetic oil	A slight difference in the net electrical power between fluids, only (-0.91%), while the gross electrical production per year was the same.
[8]	Gas	The highest temperature reached by the gas was 400 °C which cannot be reached by the synthetic oil.
[9]	Molten salt compared with the results of PTR70	It was deduced that the heat loss of the examined tube using PTR70 is smaller than that of using molten salt.
[10]	(S-CO_2) using Rankine and Brayton cycles	The collector efficiency in two cycles increased to 81.93%-84.7% (Rankine cycle) and 18.78%-84.17% (Brayton cycle).
[11]	Thermal oil, water	The performance obtained by water was better than that measured by oil.
[12]	Pressurized water, Therminol VP-1, nitrate molten salt, sodium liquid, air, CO_2 & helium.	The performance of liquids was higher than that of gases. The pressurized water is the most appropriate fluid for temperature up to 500K while sodium liquid is better for temperatures up to 1100K.

Thermal performance by adding nanoparticles

One of the most commonly used technique to improve the thermal performance in PTCs is to add metallic or non-metallic nanoparticles inside the base working fluid; the mixture then referred to as nanofluid. These nanoparticles having different thermal properties than that of the base fluid results in a more efficient nanofluid thereby improving the overall thermal performance of the absorber system. Besides this, the nanoparticles also help in the reduction of the thermal stresses inside the absorber tube. However, agglomeration of nanoparticles in certain parts of the system results in higher pressure drops with raised power pumping requirements. To overcome this problem, the volume fraction of nanoparticles needs to be optimized for efficient heat transfer augmentation. A summarized review of previous studies is shown in Table 2 illustrating the use of nanofluids in the PTCs. Numerical modelling approaches either treat the nanofluids as a single phase or a two-phase model; the latter being more accurate. However, regardless of the treatment, the selection of thermos-physical properties of the nanoparticles is of paramount importance.

Table 2: Effects of nanoparticles Concentration Ratio (CR) on the thermal performance of Parabolic Trough Collector (PTC).

Ref.	Np	HTF	(CR) (%)	Main Achievements
[13]	Al_2O_3	Ionic Liquids	0.18, 0.36, 0.9	0.9% of CR, thermal conductivity enhanced by about 11% and heat capacity by 49%.
[14]	Al_2O_3	synthetic oil	0, 1, 2, 3, 4, 5	11.5% and 36% increase in the heat transfer coefficient (HTC) using 5% of CR for single-phase and two-phase model respectively.
[15]	Al_2O_3	synthetic oil	1, 3, 5	Considerable increase in the heat transfer coefficient recorded with increasing CR.
[16]	Al_2O_3	synthetic oil	0-4, 0-6, 0–8	The thermal efficiency reached 76% with CR of 8% and the maximum efficiency was recorded at the smallest temperature and minimum Renumber.
[17]	$CuO-Al_2O_3$	water	CuO:0.1-0.3 Al2O3: 4,6,8	The extinction coefficient increased with increasing the CR of nanoparticles.
[18]	Al_2O_3	Sylthem 800	0 - 4	10% enhancement was obtained in the collector efficiency at CR of 4%.
[19]	NiO	Biphenyl, diphenyl oxide	Wt%: $(1,5,10)10^{-4}$	Increasing the heat transfer coefficient up to 50% and thermal conductivity up to 96%.
[20]	$CuO +-Al_2O_3$	Water, water-EG	0.05, 0.1, 0.2	The thermal efficiency is higher in the case of dispersing only in water since the mixture of water-EG has a disadvantage of boiling and freezing temperature which is higher than those of pure water.
[21]	Al_2O_3	synthetic oil	0, 0.01, 0.03, 0.05	The absorber deformation decreased moderately from 2.11 mm to only 0.54 mm by increasing the CR to 0.05%.
[22]	Al_2O_3 Fe_2O_3	water	0.20, 0.25, 0.30	The thermal efficiency enhanced by 13% and 11% respectively, higher than the pure fluid.
[23]	TiO_2	water	0.05, 0.1, 0.2	The thermal efficiency enhanced by 8.66% at CR of 0.2%.
[24]	MWCNT	oil	0.2, 0.3	The thermal efficiency enhancement was 5-7% when using CR of 0.2%.
[25]	Al_2O_3, CuO, TiO_2	Syltherm 800	3,5	The thermal efficiency enhanced by 1.46, 1.25, and 1.40 using Al_2O_3, CuO, and TiO_2, respectively.
[26]	Cu	Therminol ®VP-1	0, 1, 2, 4, 6	At CR 6%, Heat transfer rate and the system thermal efficiency enhanced by 32% and 12.5% respectively, whereas, the entropy generation decreased up to 20-30%.

Effects of swirl generators on the thermal performance

The usage of swirl generators inside a receiver is a passive method that is used to enhance the convective heat transfer rate. These devices could be twisted tapes, fins, coils, wires and spiral grooved tubes etc. The flow in such devices has important features such as; intense mixing of the near-wall region flows with main-stream flow and reduction of the thermal boundary layer. Improved overall thermal efficiency of the PTC, cost minimization and improvement in the system reliability are added further benefits of such passive enhancers. A comprehensive summary of such inserts is presented in Table 3 including the enhancement of both thermal and optical performances.

Table 3: Effects of insert types.

Ref.	Typical output	Enhancements by Inserting Swirl Generators Compared with the Typical Receiver					
		Gain in Output	Type 1	Gain in Output	Type 2	Gain in Output	Type 3
[27]	ηth (%): 57.21- 66.96	58.98-67.59	Bottom insert	59.41-67.78	U-shaped	60.5- 67.43	Inclined insert
[28]	Nu (%) FF (%)	Nu (%): 37%	Twisted tape (TT)	Nu & FF 150 & 210	louvered TT	-	-
[29]	Nu: 229.46- 1286.37	Nu: 374.63-1766.11	Porous rings	-	-	-	-
[30]	Nu & Thermal performance	9 % & 12%	Arrays of pin fins	-	-	-	-
[31]	Nu: 229.46-1286.37	Nu: 318.41-1501.22	Two segmental rings	Nu: 337.87-1613.77	Three segmental rings	-	-
[32]	HTC & pressure drop (PD)	490-2200 & Up to 1850	Trapezoidal fins	500-2300 & Up to 2400	Circular fins	490-2200 & Up to 1600	Triangular Fins
[33]	Nu (%)	16	TT & 0.3% of Al_2O_3	20	Nail TT & 0.3% Al_2O_3	-	-
[34]	HTC (%) & Entropy generation	25.53 & -29.1%	Dimpled TT	58.96 & F.F 5.05%	Dimpled TT & Al_2O_3	-	-
[35]	Nu (times) & FF (times)	1.3-1.8 & 1.66	Triangular fins	1.3-1.8 & 1.57	Rectangular fins	-	-
[36]	Exegetic performance & ηth	42.7% &70.82%	longitudinal fins with helium	40.76% & 70.54%	Longitudinal fins with air	41.97% & 69.93%	Longitudinal fins with CO_2
[37]	Nu (%)	(56-75)%	0.6% of Fe3O4	(59-73)%	TT	(63-7)%	TT and 0.6 % of Fe_3O_4

[38]	Performance evaluation criteria (PEC)	1.23-1.37	Dimples	1.125-1.225	Helical fins	1.13-1.41	Protrusions
[39]	Heat losses (Watt)	26.6	V-cavity receiver	16.3	V-cavity with fins	-	-
[40]	Nu (times), FF (times) & PEC	10-12, 400-700, 1.1-1.5	metal foam (H=0.75 top)	5-10, 10- 20, 1.4-3.2	metal foam (H=0.25 bottom)	-	-

Summary

To effectively enhance the optical and thermal efficiencies of PTCs, some possible solutions from the literature are summarized in this paper related to improvement of the thermal properties of HTF and manipulation of the optical design of HCE.

Acknowledgment

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