A comprehensive review on Performance analysis of parabolic trough solar collectors

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Received: September 05, 2018 Accepted: October 21, 2018

ABSTRACT *Among the various available renewable energy sources such as wind, geothermal, tidal, bio mass, etc., harnessingof solar energy has become quite popular in most of the countries. Solar thermal systems are advantageous since it is easier to store heat than electricity on a large scale. Different collectors have been modeled, designed, fabricated and tested to operate in different range of temperatures such as low temperature collectors, medium temperature collectors and high temperature collectors. Several concentrated solar power technologies have been developed including the solar tower, the parabolic trough technology, solar dish and linear Fresnel systems. Among them, the parabolic trough solar collector is a proven technology used dominantly for both industrial process heat and power generation. Numerous research investigations both theoretical and experimental have been carried out for nearly more than three decades to enhance the optical and thermal efficiency of the system. The optical efficiency depends on the property of the materials such as reflectance of mirror, transmittance of glass cover, absorptance -emittance of receiver, intercept factor, geometry factor and angle of incidence. A few researcheswork on end losses have been carried out too. A huge opportunity for further investigation lies in the heat transfer enhancement of receiver tube, development of a low cost and highly rigid structure, less expensive and more accurate tracking mechanism. Investigations using passive methods to enhance the rate of heat transfer in heat exchanger domain have been carried out and hence a similar practice has been tried out in the receiver of PTC where some of the inserts used in heat exchanger have been tried out in the receiver tube of the PTC too. A review of such works has been presented in this paper along with the review of the other works carried out inthe enhancement of optical and thermal efficiency of the solar PTC.*

Keywords: *Parabolic Trough Collector, Performance Analysis, Optical Analysis, Thermal Analysis.*

1.Introduction

Solar energy is the world's most abundant source of energy, it has been shown to have significant potential to meet a considerable portion of the world's energy demand [1,2]. With 1.7×1014 kW of the sun's energy received by the earth surface, only 84 min of solar radiation was estimated to give 900 EJ which was equivalent to the world's energy demand for 2009 [1]. However, significant research and development efforts are still needed to overcome challenges associated with harnessing this resource [3]. These include developing efficient technologies for harvesting, cost effective and efficient energy storage options,optimization of hybrid energy systems working with solar energy and another renewable energy resource.Concentrating solar power (CSP) is an emerging technology and offers significant advantages such as built-in storage capability, high economic returns and reduced greenhouse gas emissions. The life-cycle co_2emissions of solar-only CSP plants are estimated to be 17 g/kWh while they are on the level of 776 g/kWh and 396 g/kWh for coal and natural gas combined plants, respectively [4].Although the investment costs of CSP plants are relatively higher compared to the conventional technologies, new plants are guaranteeing commercial maturity, increasedplant efficiency, and reduced levelized costs. With increasing installed CSP capacity, investment and energy costs are estimated to fall. The parabolic trough solar collector (PTSC) is a dominant technology available today in both commercial and industrial scale among the medium-temperature solar collectors. In comparison to other systems, Fig. 1 shows the temperature ranges of commonly used solar thermal systems [1].

Numerous manufacturing companies have focusedon this technology, Fresnel and parabolic dish technologies have become largely overshadowed. Feed-in tariffs and grant programs have driven the successful deployment of the technology, as well.Significant research and development efforts have been put into action to improve the technology and make it competitive with counterpart energy systems [5]. The PTSC technology has just maintained a substantial progress in mirror and receiver development, use of alternative heat transfer fluids (HTFs), identification of thermal storage options, and development of process design concepts [6].

Recent developments in the parabolic trough CSP systems [7,8] will raise the plant efficiency by reducing the optical and thermal losses and also by reducing the operation and maintenance costs. The reduced costs will establish a new era as a counter attack to the market that certain solar systemscannot touch, particularly for industrial process heat (IPH) [9,10] and desalination applications. The current status indicates that the research and development efforts, and the operational experience gained over in time will provide significant benefits to the increased deployment of the technology.

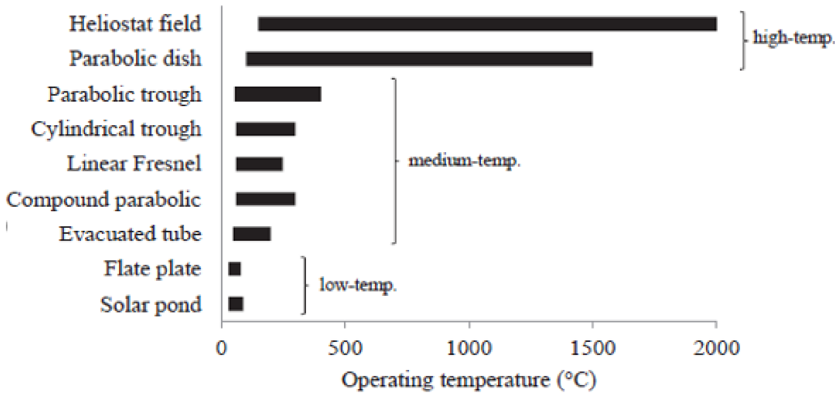

Fig.1Temperature ranges available with different solar technologies.

As introduced above, the operational experience gained with the PTSCs, and continued research and development efforts have made this technology the most commercially and technically mature of all the available CSP technologies. Meanwhile, a moderate number of studies on the analysis of PTSCs have contributed to the significant growth of this technology.

A significantly detailed review of the theoretical studies carried out on both the optical and thermal performance, and the studies on the performanceimprovement techniques which deal with the modification of the PTSC design, heat transfer augmentation by inserting turbulators and the use of nanofluids are consolidated and presented.

2. PARABOLIC TROUGH SOLAR COLLECTOR SYSTEMS

2.1 Background

Regarding the PTSC collector technology, the production of these systems dates back to the last quarter of nineteenth century. The first systems were used in small-scale facilities, with outputs lower than 100 kW, like steam generation and water irrigation. The PTSC technology was commercialized in the late 1970s and was deployed into the market in the 1980s [12]. In the early years, several companies manufactured and marketed a number of PTSCs which were developed for industrial process heat applications. During the period of 1984–1990, nine solar energy generating systems (SEGS), 14–80MWe in size and with a total installed capacity of 354MWe, were developed in Mojave Desert [7]. However, the average annual growth rate of the PTSC installations was almost zero from 1999 to 2006 due to numerous barriers against the diffusion of the technology. By 2006, the construction of the CSP plants emerged again with an 11MW plant in Spain, and a 64MW plant in Nevada. In 2007, about 90 systems for industrial process heat applications were reported in 21 countries with a total installed capacity of 25MWth. By the end of 2014, the number of installed industrial process heat plants reached 124 all over the world with a cumulative capacity over 93MWth [13]. Algeria, Egypt and Morocco have built integrated solar combined cycle plants, while Australia, China, India, Iran, Israel, Italy, Jordan, Mexico, South Africa and the United Arab Emirates are completing or planning projects [4,14]. Today, there are more than 97 plants at different levels of development based on the parabolic trough technology according to the database by NREL [14].

2.2 Fundamentals of PTSCs

A PTSC is a line-focus concentrator which converts concentratedsolar energy into high-temperature heat. Depending on the application,temperature up to 550 °C is achievable in these systems [15]. As demonstratedin Fig. 2, the PTSC assembly necessarily has several subsystemsto be functionally operated.

The PTSC has a mirror or reflector curved in the shape of a parabolawhich thus allows concentrating the sun's rays onto the focal line. Themirror is produced from different raw materials such as aluminum orlow iron glass to lessen the absorption losses. Not only solar-weightedreflectivity of the mirror but also its cost, durability and abradableproperties are important factors during the production of the collectormirrors.

After bending the mirror, a set of manufacturing processes suchas silvering, protective coating and gluing [16] are followed to improvethe solar-weighted reflectivity of the mirror. PTSCs have a characteristicthat all rays parallel to the collector's focal plane are reflected ontothe focal axis of the collector. The heat collection element (HCE) alsocalled the receiver is positioned at the focal axis of the mirror. It isbasically composed of an absorber and an envelope made of borosilicateglass surrounding the absorber. The absorber, usually a stainless-steeltube coated with a selective surface for better solar absorptance,transfers solar heat to a working fluid, i.e., HTF circulating through theabsorber. The envelope is coated by anti-reflective layer to reduce heatlosses by infrared radiation. The HCE has glass-to-metal seals and metalbellows to accommodate the differential thermal expansion between the steel tubing and the glass envelope. Moreover, the annulus betweenthe absorber and glass tubes can be vacuumed to minimize the convectiveheat loss between them. For a fully evacuated HCE, the vacuumpressure is about 0.013 Pa [7]. To ensure that no hydrogen replaces thevacuum in the HCE, getters are used to absorb gas molecules thatpermeate into the vacuum annulus over time.

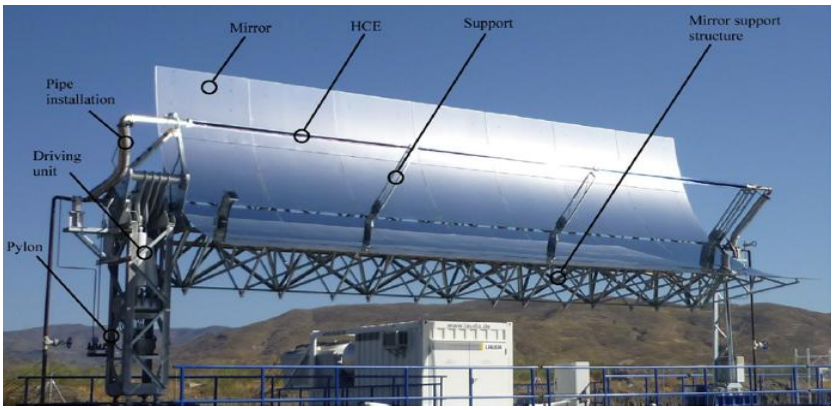

Fig.2PTC structure and components (Adapted from [17]).

The PTSC is supported bya constructional frame with pylons which keep the mirror stable. Supportsare used to hold the HCE in the focal alignment. Pipe installationsare made at the ends of the collector for connecting the HCE to theheader piping. The collector assembly is driven by a driving configuration(gear, jackscrew or hydraulic actuator) to position the collectorduring its tracking via a control unit.

3.PERFORMANCE ANALYSIS OF PTSCS

3.1. Location of the solar field

The geographical location of the installed parabolic trough collector affects the performance of the collector. Countries lying on the equator and closer to tropic of Cancer, Capricorn receive more direct beam radiation than that of the ones located away from the equator. The longitudinal and transverse incident angles of the solar insolation affect the performance of the collector too. Unlike dual axis tracking the single axis tracking does not nullify the incident angle effects and thus a loss of performance is always envisaged. Many authors have investigated the feasibility of the technology in their countries at different
locations. The viability analysis of standalone PTC plants in Indian conditions [10], the possibility of solar cooling in Athens climate [11] and potential of hydrogen production in Algerian climatic condition using parabolic trough collector [12] have been studied.

3.2. Rim angle and its effect

When the rim angle is changed, the focus to aperture ratio, which defines the parabola curvature, too changes. A larger rim angle (900) reduces the mean focal to reflector distance. Thus, the effect of slope and tracking errors are less pronounced on the beam spread. A smaller rim angle reduces the collector surface area, and increases the focal to reflector distance. This leads to a sacrifice in optical efficiency of the collector due to a wider image spread. Thus, an optimal rim angle is necessary for a satisfactory performance of the collector. An optimum rim angle of 65° for the PTC to be designed for a power plant for Indian conditions [10]. Standard curved mirrors have fixed rim angles whereas aluminum reflectors available as plain sheets need to be fabricated as per the design requirement.

3.3. Wind load, structural stability and tracking

The distortion of the parabolic structure due to wind load will decreasethe optical efficiency of the system. Now a day the glass mirrors are designed to withstand a maximum wind load of 37 m/s. A heavy rigid structure would perform better but result in higher initial cost and longer payback period of the installed system. A less rigid structure will lower the cost but distortion errors might be higher. Many investigators have tried different shapes of torque tube such as cylindrical hollow tube, box type structures [9,13]. Tracking accuracy is another parameter which determines the performance of the collector. A good tracking mechanism can have the tracking errors ranging from - 4 mrad to 4 mrad.

3.4. Optical analysis

The optical efficiency *is* related to the process of the photothermalconversion and can be defined as the ratio of the energy absorbedby the HCE to the energy incident on the collector's aperture. Itis basically the function of the reflectivity of the mirror (ρ), the transmittance of the glass envelope (τ), the absorptivity of the coating on the absorber surface (α) and the intercept factor of the mirror and HCEinteraction (γ).Although efficiency curves of solar collectors are usually measured at normal incidence, the incidence angle of a single-axis tracking collectorvaries during operation. In such a case, the effect of the incidenceangle should be taken into account since the variation of all the opticalproperties depend on it and can be correlated by a modifier called theincidence-angle modifier

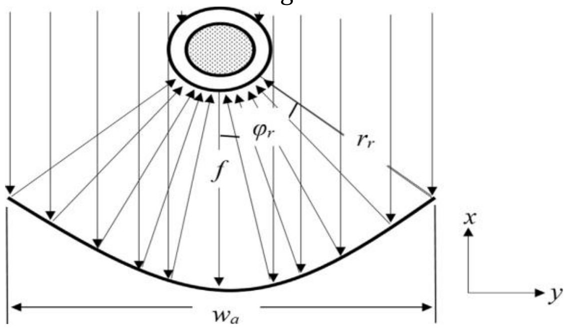

Fig.3Cross-section of a linear PTSC.

The optical efficiency includes the effect of incidenceangle and the end-loss factor which accounts for the spilling of radiationout at the end of line-focus collectors.In practice, the optical design of the trough collector is affected byseveral factors [22] including: apparent changes in the sun's width andincidence angle effects, physical properties of the materials used in HCEand mirror construction, imperfections (or errors) resulting frommanufacture and/or assembly, imperfect tracking of the sun, and pooroperating procedures. On the other hand, Mokheimer et al. [23] visualized the effects of the PTSC's components on the optical efficiencyas shown in Fig.4.

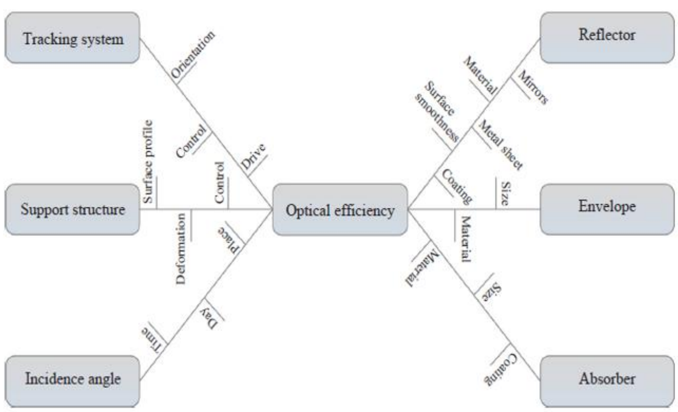

Fig.4Parameters affecting the optical efficiency (Adapted from [27])

During the optical analysis of PTSC systems, a number of parameterscan be determined, and their influences on the overall system performanceare investigated. These include the determination of the interceptfactor, optical efficiency, and the heat flux variation on the HCE asa function of the concentrator configuration (rim angle, HCE size, opticalerrors, sun shape, etc.). For these tasks, analytical and ray-tracingmethods have been used by numerous researchers. The next two sectionspresent how the analytical and ray-tracing methods are consideredand used in the analysis of PTSCs.

3.5. Thermal analysis

The aim of the thermal analysis in PTSCs is, in general, related tothe calculation of the surface temperature profile, the fluid temperature,the conversion efficiency of the absorbed solar radiation, and thedetermination of the HCE thermal loss.

3.5.1. Determination of heat flux and temperature profiles

Determination of the heat flux distribution on the absorber of theHCE is crucial in assembling a precise thermal model of a PTSC. Inpractice, the heat flux (q″) and temperature distributions around theabsorber tube are not constant or uniform. It has been shown in severalstudies that the heat flux distribution on the HCE is nonuniform aroundthe circumference of the absorber tube [24,25–29,30,31]. The determinationof the realistic heat flux profile is crucial to the accuratedetermination of the HCE thermal performance. The effect of the optical errors has a significant impact on the distributionof the heat flux on the absorber [32]. The distribution of theheat flux is affected by the intensity of the total optical errors whichacts to decrease the quantity of energy collected at increasing values. Atlower total optical error values, the shadow effect due to the HCE isquite salient. The parabola contour and sun tracking errors have negativeeffects on the LCR [33] as well as the other flaws being statisticallyeffective [22]. The LCR decreases with the increasing trackingerror which also changes the regularity of the LCR profileon the other hand, the heat flux distribution onthe absorber is nonuniform even if the sun is tracked properly. Thenonuniformdistribution of solar heat flux will have an effect on thethermal stress distribution and service life of the HCE. With highervalues of the incidence angle, the heat flux intensity will vary along thelength of the absorber [34].Furthermore, Khanna et al. [35] indicated that the differential risein HTF temperature increases the maximum deflection in the absorber.Determining an appropriatevalue for the rim angle can reduce the nonuniformity of the heat fluxdistribution and bending deflections [36]. Larger rim angles producesmaller deflections [35]. When the aperture width is increased, thecircumferential nonuniformity in heat flux intensifies. Arim angle of 110° can be considered as the optimum value for maximizingthe total absorbed flux as the width of the aperture is fixed, butit may not correspond to minimum mirror cost [34,36]. For the sake of increasing the maximum heatflux on the absorber, an optimum value should be determined withrespect to the assigned aperture width and rim angle combination.The temperature distribution around the absorber tube of the HCEfollows the same trend with the heat flux distribution as was shown byMwesigye et al. [37].

3.5.2. Thermal loss coefficient

In the evaluation of the overall heat loss from the HCE, the conceptof the thermal loss coefficient (UL) is used to simplify the analysis. The thermal characterization of the HCE is fundamental to accuratelydetermine the heat loss. Several studies in the literature have characterizedthe HCE thermal performance and determined the thermal loss coefficient.Gee et al. [38] developed a thermal model that shows how the HCEtype affects the thermal loss coefficient as a function of the absorbertemperature. The results for five different types of HCEs - the referencetrough, evacuated, xenon back-filled, heat mirror coated envelope, andreduced emittance selective coating - were obtained for a fixed absorbertube diameter. Antireflection and selective coatings (heat mirror coatedenvelope and reduced emittance selective coating) were shown to beeffective in the reduction of heat losses especially at higher absorbertemperatures. A back-filled HCE was more effective than the other typessince the use of a less-conductive gas reduces the heat transfer acrossthe annulus. While larger the absorber diameter leads to slight variationin the thermal loss coefficient, increasing the absorber-to-glass gap sizeinfluences the thermal loss coefficient favorably.Injecting inert gases such as argon and xenon have been shown toreduce the heat loss caused by the penalty associated with hydrogenpermeation. Prediction of the heat transfer characteristics of HCEs usinggas mixtures (hydrogen/argon, hydrogen/xenon) was modelled andtested experimentally by Burkholder [39].

3.5.3. Heat transfer analysis

The HCE of a PTSC is the central component, which is simplycomposed of the nested absorber tube in an envelope as shown in Fig.5, for the performance of the entire system.

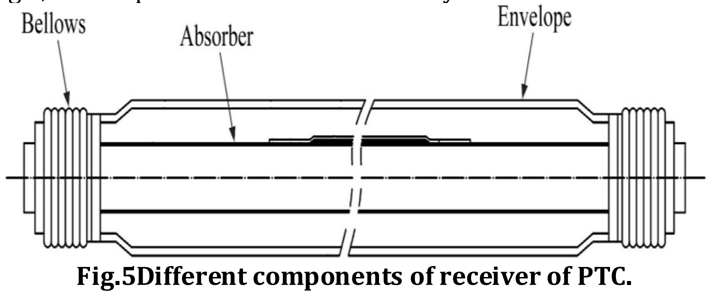

Fig.5Different components of receiver of PTC.

The heat transferanalysis of PTSCs mainly focuses on the prediction of the thermalperformance of the HCE. Inside the absorber tube, an HTF such as water,thermal oil, molten salt, gaseous, nanoparticle laden fluid or new alternativesis used for heat carrier [48]. The absorber tube is enclosed bya glass envelope, and the space between them is inherently filled withair but can be vacuumed to significantly reduce the heat losses. Theouter surface of the HCE is subjected to ambient conditions.Fig.6 shows the modes of losses on the cross-sectional view of thePTSC.

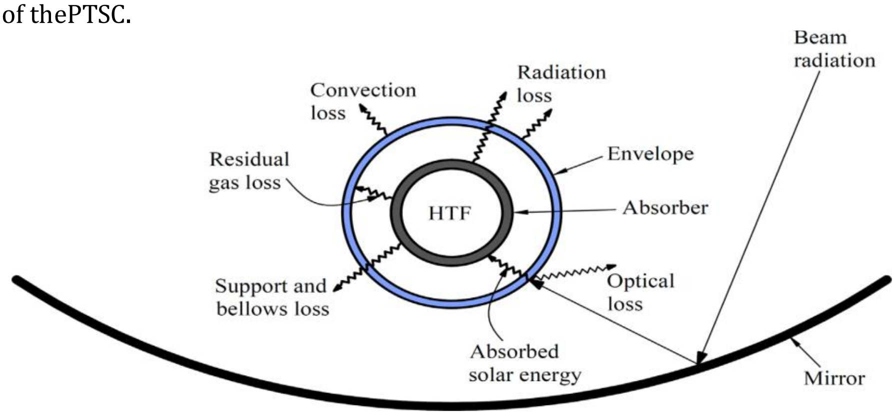

Fig.6Different components of PTC with heat exchange mechanism.

The heat transfer modeling of a HCE requires some assumptionseven if they can limit the accuracy of modeling outputs, but theseassumptions are needed to predict the system behavior. Each model hasits own characteristic assumptions, but the mutual ones include:
• fully-developed flow is present,
• the concentrator surface is specularly reflecting,
• no variation occurs in the collector dimensions such as constantdiameters,
• no free surface comes into existence inside the absorber,
• the fluid is assumed to be incompressible,
• the sky is assumed as a blackbody at an equivalent temperature forlong-wave radiation.

The flow inside the absorber tube involves forced convection whoseflow pattern can be in single-phase or two-phase. Unlike two-phaseflow, single-phase flow is considered in most of PTSC systems since thephase of the HTF does not change during operation. However, directsteam generation (DSG) collector systems involve two-phase flowwhich results from boiling of water in the absorber tube. The flow regime is much complicated in these systems as compared to the formersince both the liquid and the vapor are forced to flow together.Table 2 shows the governing equations which are mostly usedin modeling the HCE's heat transfer performance.

3.5.4. Single-phase steady flow

The single-phase flow provides reliability in operation and controllability of the exit temperature of PTSC systems.In this modeling approach, the temperature gradient isconsidered to be significant only across the radial direction of the HCE

rather than the axial and circumferential directions. The energy balanceequations can be defined by conserving energy at each surface of theHCE.

Qabsorbed solar = Qresidual + Qradiation, abs + Qsupport, bellow
Qbeam radiation = Qoptical + Qconvection + Qradiation,env
Qheat loss = Qconvection + Qradiation,env + Qsupport,bellow

Forristall [21], in his extensive study, used also the 1-D approach toinvestigate how design conditions and operating parameters affect thePTSC performance. These efforts were significant to identify the designparameters which affect the performance the most and to show whichdesign conditions influence the performance significantly and should bethe focus of any performance improvement.The summary of the results is given in Table 1.

Table 1 Summary of parametric studies [41]

Design option or parameter	Evaluation range	Results and comments
Absorber base material	304/316L, 321H, B42 copper, and carbon steel	• Negligible effect on the HCE perfomance, yet material selection material strength, corrosion properties, installation ease, coating cost considerations.
Selective coating	• Luz black chrome and cermet • Solel cermets	• The improvements in coatings have improved HCE performance. • HCE perfomance would be sensitive to any variance in selective properties.

Annulus gas type	Vacuum, air, argon, and hydrogen	• Vacuum gives the best result. • Filling the annulus with an inert gas is better than air. • Hydrogen permeation can degrade HCE performance.
HCE condition/wind speed	• Vacuum, loss vacuum, and broken envelope • 0–20 mph	• A broken glass envelope gives unfavorable performance results, especially with windy conditions. • Wind has little influence on HCE performance when the annulus vacuum is intact, but does when the vacuum is lost.
Annulus pressure	• Air and hydrogen • 0.0001–760 torr	• Vacuum levels less than < 0.1 torr show negligible improvements from the 0.0001 torr level. • HCE performance declines appreciably with pressures of 100 torr or greater in the annulus. • If hydrogen in present, HCE performance is even more sensitive to annulus pressure.
Mirror reflectance	0.8–0.935	• The trough performance drops appreciably with solar weighted reflectivity less than 0.9. • Keeping mirrors clean is very important to solar collector assembly performance.
Incident angle	0–60°	• Trough performance is very sensitive to solar incident angle.
Beam radiation	300–1100 W/m^2	• Trough performance very sensitive to beam radiation. • Factors such as atmospheric pollutants and particulates should be considered when choosing a solar site.
HTF flow rate	100–160 gpm	• HCE performance has weak dependency to HTF flow rate.
HTF type	Therminol VP-1, Xceltherm 600, Syltherm 800, 60–40 Salt, and Hitec XL Salt	• Trough performance has weak dependency to HTF type. • Operation of the HCE at higher temperatures decreases the HCE performance yet increases the power cycle efficiency.
Envelope diameter	• Vacuum and lost vacuum • 0.08–0.165 m	• An optimal diameter leads to minimize the heat losses. • Influence of diameter on heat loss is more sensitive under lost vacuum. • Clearance for absorber pipe bowing needs to be included.
Temperature and heat flux variation along HCE	39.0–740.5 m	• Temperatures along the length of the HCE increase in a slightly nonlinear. • Radiation heat transfer fluxes increase nonlinearly. • Optical losses per unit HCE length remain constant.

3.5.5. Single-phase transient flow

So far, only the cases of single-phase steady flow operation havebeen reviewed. However, most PTSC systems operate under transientconditions due to the heating of collectors from start-up to shut-down ofa daily operation. Moreover, the intermittent nature of the drivingenvironmental conditions will not allow the PTSC to operate steadilyfor prolonged periods.Several studies have considered the lumped-capacitance analysis[42-48] for analyzing the transient characteristics of PTSCs. Thelumped-capacitance analysis involves the transient energy balanceequations defined for the various parts of the collector at uniformtemperatures. The control volume "A×Δx" for the analysis of the HCEunder transient conditions is shown in Fig. 16.

The governing equationsused for this analysis can be expressed as: A number of studies have considered the transient nature of operationin PTSCs. Unlike 3-D model conducted in [49], a number ofresearchers have developed 1-D energy models for experimental validation,and for the subsequent implementation of these models intoparametric analyses. The variation in the HCE temperature [50,51],HTF temperature [13,50–57], HTF mass flow rate [51,53], HTFtype [54,55], solar radiation [55], energy collected [48,56,57]energetic efficiency [51,53,53,56], and exergetic efficiency [51]were considered in these studies to analyze their influence over thedynamics of a specified PTSC.The governing equations describing the 1-D transient behavior ofthe PTSC can be expressed on the control volume given in Fig. 7.For HTF:

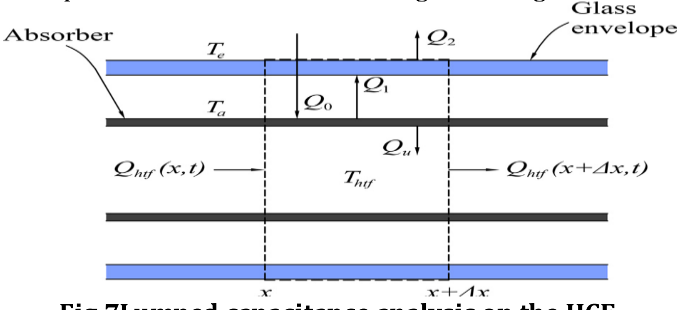

Fig.7Lumped capacitance analysis on the HCE.

On the other hand, different modeling tools have been widely usedfor the dynamic simulation. TRNSYS (TRaNsient SYstem Simulation)[58], SAM (Solar Advisor Model) physical model [59], multi-purposephysical system modeling language, Modelica [60,61] are widelyaccepted and validated programs. A good example for modeling and cosimulationof a PTSC plant is available in [136] where SolTrace (forMCRT modeling), TRNSYS and Modelica tools are coupled, and thedynamic performance of the plant was investigated elaborately.For the single-phase flow transient analysis of the PTSC, two differentmodels have been used. In the lumped-capacitance model, thetemperatures of the collector parts vary with time but remain uniformthroughout the time. It is less complicated than the 1-D model whichconsiders the variation of temperature with time as well as with theaxial position.

3.5.6. Two-phase steady flow

One of the obstacles in using thermal oil is its maximum temperaturelimit, called film temperature, which limits the operating temperatureup to about 400 °C due to chemical degradation. Although theoperation of the PTSC technology is well understood and highly developed,further improvements and reducing its cost are limited due totemperature range, necessary components for the oil loop, and parasiticloads during operation. The pros and cons of using thermal oils as HTFsin PTSC systems can be found in the literature [63,64–67] with detail.On the contrary, DSG and the use of molten salts are possible solutionsthat offer higher temperature operation and maintain betterthermal efficiency.

There are possible operation concepts as schematically shown inFig. 8.

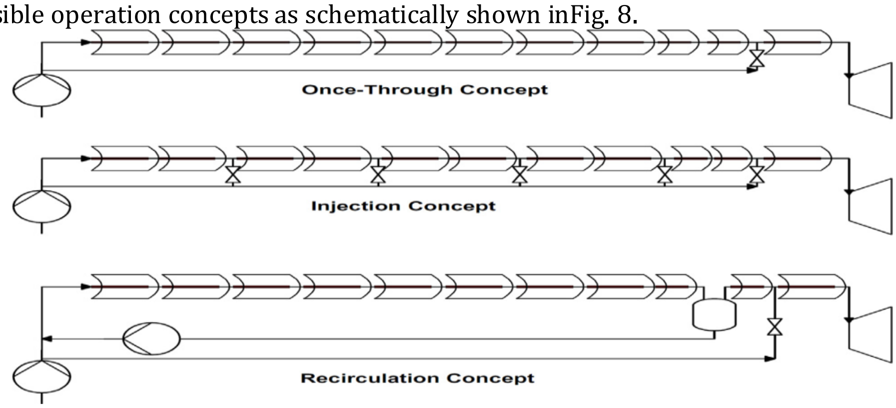

Fig.8Possible operation concepts through PTC

The two-phase flow in a DSG collector exhibits different flow patterns,including stratified, wavy, slug, intermittent, annular and apossible dryout [64].

3.5.7.Two-phase transient flow

In DSG systems, the flow characteristics are more complex comparedto the single-phase flow owing to the flow instabilities that
happen in case of disturbances in the solar radiation or local shading byclouds passing over the solar field for a limited time. At this point, thetransient modeling becomes more valuable for predicting the responseof the solar field since the lengths of the single-phase, two-phase, anddry steam regions are significantly affected by the dynamic conditions.This issue causes thermal stability problems in the field, and largefluctuations in the outlet temperature and steam flow rate, as well. In this context, the use of time-dependent modeling tools is preferred. As the complexity of the system becomes higher, modeling and simulation of such systems provides significant information. Estimating the system behavior by experimental methods when the facilities involved are large is always notfeasible. Moreover, the experimental approach is expensive, time-consuming,and might have significant uncertainties. An accurate model can be developed to predict the system's dynamic reaction, and to assess the subsequent control strategies as presented by Alguacil et al. [68]. Numerous studies have been performed to describe the transient behavior of the DSG PTSC systems. These studies can be categorized in terms of characterizing start-up or shut-down of daily operation of DSG
systems, prediction of the thermal instabilities, and control strategies ofDSG facilities. A number of these numerical models were principallydeveloped based on energy balance [65,69] or mass, momentum andenergy balances [70,71–73]. Lumped-capacitance model [159],quasi-steady dynamic models [160] were developed in the remainingstudies.

4. PERFORMANCE ENHANCEMENT TECHNIQUES

Improving the performance of PTSC systems is one way of ensuringreduced system cost, improved overall system efficiency, minimizedHCE temperature gradient, and subsequently improved system reliability.Because of these benefits, many researchers have considered anumber of heat transfer enhancement techniques to improve thethermal performance of PTSCs. The performance of a PTSC can be enhancedby either changing its optical design or HCE properties, includingaugmentation techniques [76]. In recent years, thermal enhancementin the HCE properties has been widely considered by manyresearchers rather than the optical design. In this section, all the effortsfound in literature, including both the optical and the thermal improvementsare presented.

4.1. Novel designs

The novel design studies have been especially focused on eitherincreasing the optical efficiency to capture most of the absorbed radiationor decreasing the heat loss from the HCE by partially insulating the HCE. In order to increase the absorbed radiation, differentcavities with different shapes, including V-shaped, cylindrical, triangularwere proposed. These cavities have positive effects on the opticalefficiency, but the thermal efficiencies of these new HCEs need to beenhanced. On the other hand, the overall heat loss for filled-air HCEswas reduced by at least 20% [77,78,79] using partial insulation.

4.2. Passive heat transfer improvement

Convective heat transfer enhancement in the HCE's absorber tubehas received considerable attention due to the associated benefits. It hasbeen shown in a number of studies that heat transfer enhancement onthe HCE improves overall performance, reduces the absorber tubetemperatures and temperature gradients. Despite these benefits, thereare a number of drawbacks such as increasing parasitic loads associatedwith the increased pressure loss, vibration, and adding extra manufacturingcost. Several researchers have investigatedthe use of passive heat transfer enhancement techniques inthe absorber of a PTSC. some studies focused on the variationof the absorber tube design while the others considered the use of insertsin a plain absorber tube. It can be easily seen that most studiesavailable in the literature were performed numerically and their applicationto actual PTSC systems still needs to be demonstrated experimentallyor using field tests.

4.3.Enhancement of optical efficiency of the trough

4.3.1. Coating of selective surface on receiver tube

The optical efficiency is the ratio of the energy absorbed by thereceiver to the energy incident on the aperture of the collector. It dependson the optical properties of the materials, the geometry of thecollector and the various imperfections arising from the construction ofcollector [80]. Numerous works have been carried out in enhancing theabsorptive and minimizing emissive properties of the selective surface.The synthesis of selective coatings is much more tedious than that ofanti-reflective and protective coatings for mirrors, glass and aluminumsheets because the absorptance and emittance are surface propertieswhich are strongly dependent on temperature and wave length andaffected by micro structure too [81–83]. The coatings developed needto be chemically and structurally stable at operating temperatures,durable and ideal for a longer period of time, environmentalfriendly,safe to handle and quite inexpensive. Selective coatings have beenclassified as intrinsic, semiconductor-metal, multi-layer, cermet's ormetal dielectric composite material and textured surfaces [84–86].It is observed from the extensive review on selective surface coating by vapor deposition method carried out [20] thatamong the various materials investigated for mid-temperature range,coating of Ni-NiO on Al yielded the maximum absorptivity of 0.96,(ε100°C=0.10), and coating of graphite on Cu, Ni, Ti and Ag resulted ina minimum emissivity of 0.01–0.02, (α=0.71–0.80). The DMD absorbers can be Cr_2O_3used for metals like Cr, Zr, Mo, Al, Pt,Ni and dielectrics Al_2O_3, MgO, MgF_2[6] stated that Pyromark coating is the one that has commercially demonstrated higher cost effectiveness.

4.3.2. Coating of anti-reflective surface on glass tube

For many years the anti-reflection coating has been used in opticalindustries to improve the quality of image and reduce the glare of theglass. In solar applications the concentric borosilicate glass tube aroundthe absorber should have a good transmissivity property. The coating ofselective surface on the glass has improved the transmissivity fromaround 92% to 96% [5]. The modeling of anti-reflection coatings andprinciples of operation have been reviewed and explained by McCleodand Hecht [80,89]. The processes for developing anti-reflective coatings have almost been saturated and the properties are close to optimal. The authorsdesigned and prepared novel multifunctional (MF) coatings thatpresent anti-reflection (AR) and self-cleaning (SC) capacity.A new methodto adjust refractive index of nano-porous silica films is reported. Abroadband antireflective coating with average reflectance 1.5% in thesolar energy spectrum has been obtained [90]. In this study, the basecatalyzedsol was modified by acid-catalyzed polysiloxane and nano-TiO2. The maximum transmittance of the antireflective solar glass withsingle layer coating is about 95.02% at 565 nm wavelength, which isabout 3.36% higher than the substrate glass [91].Silica films were preparedby sol-gel process and later an expression for coating thickness wasdeveloped. Two methods for preparinggels in the silicate systems are described; gelling colloidal silicasol and polymerization of alxoysilane. In this work the effect of microstructureof the deposited film on varying the precursor structure,solvent composition or deposition conditions is described [92].Silicafilms were fabricated by dip-coating onto silicon and glass substratesand the film properties such as thickness, stability, water-precursorratio, sol aging time were monitored followed by interpretation of filmbehavior [93]. The advantages and disadvantages of sol – gel processhave been discussed in this paper [94]. Thus, the transmittance valuesand the sol – gel coating methods have been briefly reviewed.

4.3.3. Reflectivity of the mirror

The reflective surfaces are coated with silver followed by copperand a few layers of paint to enhance the durability of the highly polishedmirror surface of reflectivity 94.5% and aluminum reflectivesheets of reflectivity 88%. Commercial suppliers of curved glass with4mm thickness are RIOGlass [95], AGC Solar Mirrorand 1mmthickness RONDA Glass [96]. The mirrors are indented to be used formid and high temperature range. Highly polished aluminum reflectorsof 0.3mm and 0.4mm thickness are commercially available for the lowtemperature range AlMIRA [97], ALMECO [98]. The optical efficiency ofthe Ronda mirror is observed to be as close as 99.5%.

4.3.4. Intercept factor of the absorber tube

The intercept factor is the ratio of the energy intercepted by thereceiver tube to the energy reflected by the highly polished mirror oraluminum reflector sheet. It depends on many factors such as size of thereceiver, surface errors of the reflecting surface and the solar beamspread. Several investigatorshave carried out numerical analysis of flux distribution around the receiver[99,100]. The first ever PTC datesback to 1870 with an aperture area of 3.25m2, driven by a 373-wattengine built by a Swedish engineer John Ericsson in United States. Heexperimented with different fluids from water to air. From there onwards,development of commercial collector started in response to theoil crises that happened in 70's.

4.3.5. Incorporating secondary reflector

The primary concentrator either a mirror or aluminum polishedsurface reflects the incident radiation on to the receiver. The radiationflux intercepted by the receiver depends on factors such as rim angle ofthe collector, surface errors of the primary concentrator, tracking accuracyof the mechanism and rigidity of the structure to withstand windand self-load. Spillage or scattering of highly concentrated radiationaround the receiver will lead to a great loss of optical and thus thermalefficiency. Many works to capture the spillage of radiation have beencarried out by positioning the secondary reflector in the close vicinity ofreceiver. The investigation of several designs has resulted in the improvementin thermal efficiency related to the benchmark design ranging from0.8% for seagull shaped secondary reflector to 1.6% for a aplanaticmirror. Even though aplanatic mirrors gave the best performance, evena simple reflective glass surface could yield an increase in thermal efficiencyof 1.0% [101].

4.3.6. End losses and dual axis tracking

The optical efficiency is dictated by the geometric factor of thecollector, which is the decrease in the aperture area due to abnormalincidence effects, blockages, shadows and loss of radiation beyond theend of receiver. Radiation falling on the edge of the concentrator oppositeto the sun cannot reach the absorber tube and this is called theend effect. Attempts to prevent the concentrated radiation falling awayby placing an opaque plate on either side of the trough have failed dueto the fall of shadow which in a way reduces the aperture area. Ming liet al., have studied the end loss effect of parabolic trough collectors andsuggested the methods to reduce the losses by extending the absorbertube, setting an end plane mirror, etc. A collector oriented in north – south direction and located in and around the equator, the end loss is smaller for the whole year in comparison to the east-west oriented one [101]. With increase intrough length, the end loss effect is gradually decreased. A tracking mechanism isemployed to track the sun throughout the day to minimize the longitudinaland transverse incident angle losses. Four different modes oftracking namely tilted N-S axis, polar N-S axis with E-W tracking,horizontal E-W axis with N-S tracking and horizontal N-S axis with E-Wtracking. Jie Sun et al., numerically investigated the double axisPTC and proposed an optimized tracking strategy [103].

4.3.7. Enhancement of thermal efficiency of the trough

An effort to minimize heat loss by convection issuccessful by the utilization of an evacuated receiver tube. Selectivesurface coatings on the receiver have minimized the radiation losses byreducing the emissivity property of the surface [104]. Numerous researchinvestigations on enhancing the thermal efficiency of receiverhave been attempted apart from the efforts to minimize the losses [105].The investigation of enhancement of heat transfer in heat exchangershas been widely carried out and similar investigations of heat transfercoefficient and pressure drop have been performed on the receiver tubeof a parabolic trough collector by many authors.

4.3.8. Nanoparticle laden fluid flow

Another way to improve the thermal performance of PTSCs ismodifying and improving the thermophysical properties of the HTFrestriction with conventional HTFs (such as water, oil, molten salt) dueto their inherently low thermal conductivities. The thermal conductivitiesof metallic particles, metallic oxides and carbon nanotubesare extraordinarily higher than those of the conventional fluids availableand dispersing a very small amount of guest colloidal particles i.e.,nanoparticle (with average sizes<100 nm) in the conventional HTFscan have significant impacts on the optical [106] and thermophysicalproperties of the host fluid [107]. Precise prediction of the thermophysical properties of the synthesizednanofluids is essential to ensure acceptable results in modelingand simulation studies. There are various theoretical models in theliterature that can be used for this purpose.

In nanofluid related studies of PTSCs, some of thesecorrelations have been used extensively for the estimation of specificheat [108,109], the viscosity [110,111], and thermal conductivity[112–114,115,116]. There is however need for the experimental determinationof thermal physical properties with nanoparticles dispersedin commonly used HTFs, especially at higher temperatures andpressures, since these studies are not widespread.

4.3.9. Nanofluid in conventional PTSC

As the popularity of nanofluids increases, its applications in differentareas such as solar energy, heat exchanger, fuel cell, nuclear

reactors, medical field have widened. The application of nanofluids insolar thermal systems is becoming prevalent. A recent review by Vermaet al. [106] presents the studies on the use of nanofluids in solarthermal collectors. Recently, the nanofluid researches have also beenextended to PTSCs since one of the barriers to the development of thetechnology is its high cost. Hence, improving performance and consequentlyreducing the cost of these systems will increase their deployment.Using nanofluids instead of conventional HTFs could beseen one of the possible ways to improve performance.In summary, the nanofluids enhance the heat transfer performanceof the HCE due to increasing extinction capability of the base fluid.Moreover, increasing the volume fraction of hosted nano particles has apositive effect on the improvement of the convection heat transfer

coefficient of the HTF and reducing thermal stresses on the HCE howeverthis will affect the stability of nanofluid leading to agglomerationand also will result in increased pumping power requirement accompaniedby reducing the total collector efficiency. For this reason, thevolume fraction of the nanoparticle should be optimized for effectiveheat transfer enhancement for the PTSC. Moreover, most studies rely on correlations derived for otherbase fluids which may or may not be applicable to thermal oils operatingat high temperatures in terms of PTSCs. Therefore, there still existopportunities for research on the use of nanofluids in PTSCs. The mostpressing ones include the investigation of thermophysical properties ofthermal oil-based nanofluids at high temperatures and pressures, andthe use of nanofluids in actual systems working under field operatingconditions.

4.3.10. Nanofluid in DARS

In contrast to the conventional PTSC, Khullar et al. [117] introducedan idea of harvesting the solar radiant energy through the use of ananofluid-based concentrating PTSC (NCPTSC). This concept is directlysimilar to the conventional PTSC only the exception of the HCE inwhich the absorber tube being made of metallic material is replacedwith a glass tube as shown in Fig. 9.

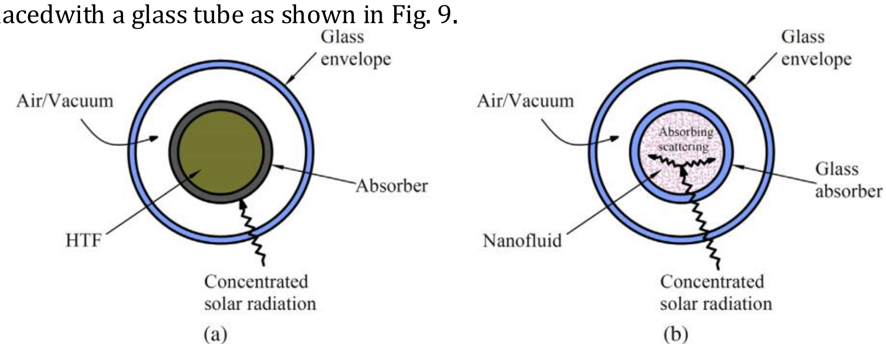

Fig.9(a) Conventional HCE. (b) Nanofluid-based HCE.

Therefore, both absorber and itsenvelope consist of transparent glass material which makes the HCEdirectly interact with incident radiation, for this reason it is named as adirect absorption receiver system (DARS).Addition of nanoparticles to the host fluid significantly increases theextinction capability of the fluid resulting in an enhanced solarweightedabsorption relative to that of the host fluid alone [118]. Thus,the combination of any nanoparticle and host fluid can exhibit differentsolar absorption capabilities by virtue of solar intensity attenuation ratewithin the medium.Incase the volume concentration is low, the optical efficiency suffers notable to capture the whole reflected radiation. In order to get maximumsolar absorption yielded from the DARS, the volume fraction and thediameter of the DARS should be tailored properly. Table 2 reviews thestudies made on the DARS and its performance indicators.

Table 2. Summary of studies with DARS

Reference	Nanofluid	Result
Khullar et al. [332]	Al/Therminol VP-1	Adding only 0.05% nanoparticle into the base fluid improves the thermal efficiency of the DARS between 5% and 10% relative to the conventional PTSC.
Toppin-Hector and Singh [333]	Graphene/Therminol VP-1, Al/ Therminol VP-1	Graphene has better solar absorption capability than aluminum. The DARS is able to deliver heat at 265 °C.
Ghasemi and Ahangar [335]	Cu/Water	The optical and thermal efficiencies almost level off beyond the volume concentration of 0.015%.
De Risi et al. [336]	CuO + Ni/Gas	A maximum thermal efficiency reaches 62.5% which gradually lowers beyond the mass flow rate of 2.5 kg/s.
Kasaeian et al. [337]	MWCNT, nanoslica/Ethylene glycol	MWCNT/ethylene glycol achieves about 10% higher thermal efficiency than the nanoslica/ethylene glycol nanofluid at optimum conditions. The optimum volume fraction for MWCNT and nanosilica is found to be 0.5% and 0.4%, respectively.

Althoughits optical efficiency is better than the conventional one, it has muchhigher heat loss particularly at elevated temperatures. Thus, its usagefor high temperature applications (e.g.>250 °C) may not be feasiblefor efficient energy harvesting. Rather, it can be suitable for mediumtemperature IPH applications. It is essential to say that the structure ofthis collector may have some problems in practice due to operationalreliability. Most failures of HCEs are especially the breakage of the glassenvelope due to the circumferential temperature gradients in the absorbertube and mechanical stresses on the HCE. For example, th elimited maximum temperature difference on the LS-3 HCE is 50 K tomake sure the safety in operation [119]. Recently, improved glass tometal seal designs have put into practice to reduce breakage problems.

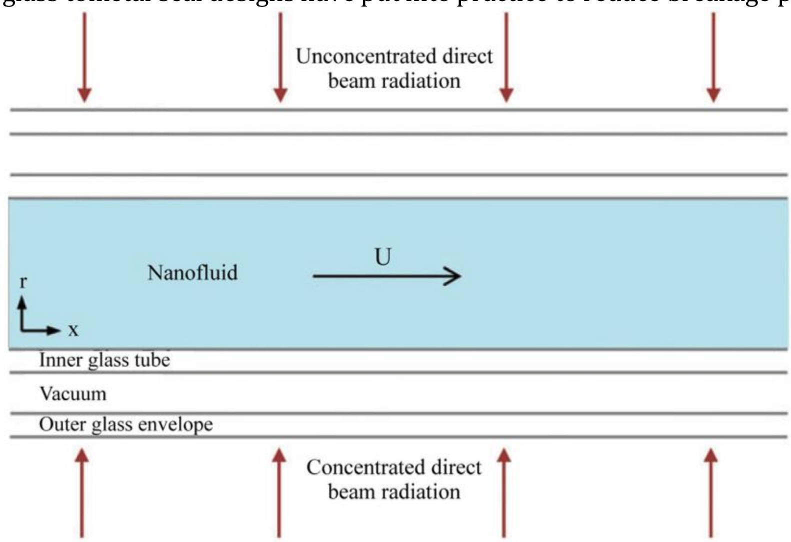

Fig.10Section view of the DARS.

5. INSERTS

Heat transfer enhancement techniques are classified as active, passiveand compound methods [120]. In the active method either of thefollowing techniques are adopted to enhance the heat transfer.

- Vibrating the heat transfer surface,
- Rotating the surface,
- Creating a pulse on fluid surface,
- Applying electrical or magnetic field across the heat exchanger,
- Injecting a fluid in the bulk fluid flow-single phase,
- Removal of vapor-two phase.

In passive method no additional energy is consumed unlike theactive method to enhance the heat transfer rate.

5.1. Inserts for heat transfer enhancement in PTC.

Numerous researchinvestigations of heat transfer enhancement, friction factor andpressure drop incorporating passive inserts and/or modifying theprofile of receivers have been carried out in heat exchangers and theresults have been found encouraging. Similar investigations have beenperformed in PTC receiver with various configurations of inserts andreceiver profiles.

5.2. Porous configuration.

The porous configurations of insertshave been numerically and/or experimentally investigated by variousauthors. The configurations investigated are porous disc and porousinserts of square, triangular, trapezoidal and circular geometries,porous rings, porous media and perforated plate inserts. The porousdisc incorporated receiver was analyzed for different orientations,

angles, height and distance between discs and the findings showedthat the disc oriented at an angle of 300 exhibited better thermalperformance than the others [121,122]. Two conventional and fourreceivers inserted with porous discs were experimentally analyzed.The results revealed that the receivers with porous disc perform betterthan the conventional ones [123]. Porous inserts of 4 differentgeometries were investigated out of which the trapezium porousinserts exhibited an enhanced performance [124]. The porous ringinserts when investigated exhibited a good heat transfer performancecharacteristic too [125] whereas the porous media had just a slightincrease in the heat transfer [79]. The perforated plates placed centrally increase in the heat transfer [126]. The perforated plates placed centrallyin the absorber tube serve to increase the thermal efficiency by 1.2–8%for inserts of porosity 0.65 and flow rates lower than 0.01205m3/s[127].

5.3. *Twisted tapes.*

The inserts with the different geometrieshave been investigated either numerically or experimentally such astwisted tapes, twin counter/co twisted tapes, louvered twisted tape,wavy type inserts and helical inserts. The performance of countertwisted tape is found to be better than co twisted tape and in general theheat transfer rates of both the inserts are 17.8–50% higher than singletwisted tape inserts [128]. The absorber with twisted tapes,louvered twisted tape [129], helical inserts [130], wavy inserts [131] andabsorber with molten salt along with twisted tapes [132] exhibit a betterperformance than the plain tube.

5.4. Modified receiver profile.

The circular receiver of the PTCis replaced by internally finned tube, asymmetric outward convexcorrugated tube, dimpled tubes, dimple - converging – divergingtubes and modified receiver with hinged blades and investigatednumerically or experimentally for the performance. The analysis ofinternally finned tube showed that the plant efficiency increases [133]. A

similar type of insert was investigated with gaseous HTF such as CO2,air and Helium in absorber of Euro trough ET -150. Helium was foundto produce optimal results amongst the other gases [134].The asymmetric outward convex corrugated tube had asignificant increase in heat transfer [135]. Dimpled tubes oninvestigation reveal that deep dimples perform better than shallowones [136]. Dimpled -converging – diverging tubes were tested with HTFsuch as water, thermic oil and nano fluids. An increase in thermalefficiency of just 4.25% was observed for nano fluids where as it was4.5% for the other fluids [137]. Experimental study on receiver withhinged blades demonstrated an increase of thermal efficiency by 9%more than conventional receiver [138]. Numerical analysis of heattransfers in the trough receiver with and without helical fins,protrusions and dimples shows that dimple tubes have betterperformance than the other receivers [139].

5.5. Other configurations.

The otherinserts examined werevortex generators, metal foam, pin fin and multi fin array. Thermalloss of the novel receiver with vortex generator reduces by1.35–12.10% than the plain absorber tube [140]. Investigation ofplacing metal foams in the absorber tube has resulted in increase ofNusselt number [141]. Analysis of solar air heater with half- pipe finarrangement resulted in increase in the efficiency by 14% compared toplain tube arrangement [142]. Arranging pin fin arrays in a PTC receiverincrease the Nusselt number by 9% [143]

5.6. Similar inserts used in heat exchanger for heat transferenhancement.

The technique of using passive inserts to enhance theheat transfer coefficient of the fluid and thus the thermal efficiency ofthe system was initially practiced in a heat exchanger exclusively ashell and tube heat exchanger. Many researchers have tried differentinserts and a few of which are similar in shape have been investigatedin both the absorber tube and heat exchangers. Such types of similarshapes of inserts ar e presented in Table 6.

5.7. Some of heat exchanger inserts which are not tried in PTCabsorber. Geometries of inserts which have so far been investigated ina heat exchanger and never been tried in a parabolic trough receiver arepresented in Table 7. This table provides enormous opportunities forresearchers to carry out heat transfer and pressure drop investigationusing the same shapes.

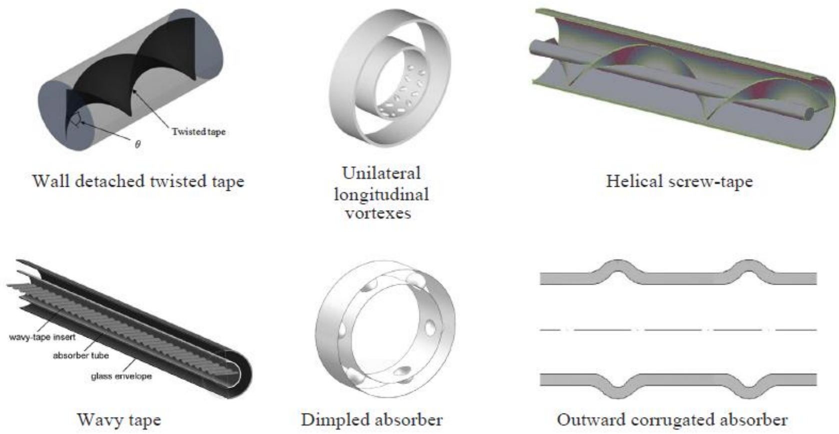

Fig.11 Different PTC inserts

6. CONCLUSION

Parabolic trough solar collector systems have emerged as technicallyand commercially developed CSP systems.

In this paper, researchstudies aimed at the performance ofPTSCs to characterize their optical and thermal performance have been reviewed and presented. All the current research and developmentefforts are essential and are mainly aimed at further improving theperformance of PTSC systems to reduce their costs and make themcompetitive with other conventional energy systems. From the reviewed studies, it is clear that the optical performance ofthe PTSC system also requires significant attention relative to thethermal performance.The optical and thermal analyses offer a better insight into the co-optimizeddesign of a PTSC and its performance improvement. It is alsoshown that heat transfer modeling is not only useful for the enhancementof the thermal performance but also for the thermal stress analysisof the HCE.It is also clear from the literature that obtaining precise heat fluxand temperature distribution profiles on the HCE's absorber tube isparamount for both single and two-phase flows to keep track of thetemperature gradients and maintain the operational safety. However, itshould be noted that the flow pattern of two-phase systems is muchmore complex compared to the single-phase one, thus its control isdifficult. These flows can be analyzed under steady-state to view theoperational limits or under transient analysis to provide knowledge onthe long-term performance of a PTSC. It can be said that the steadystateanalysis helps mainly in the design stage whilst the transientanalysis is useful especially in the simulation of the actual field conditions.To increase the overall performance of the PTSC, different designconsiderations have been proposed in the literature. The performanceof the PTSC is improved by either manipulating its optical design or thethermal properties. It should not be forgotten that even a minor improvementin the performance can induce significant returns for largescaleplants. All the research efforts undertaken so far are clearly presentedin this paper. There are still significant research opportunities toimprove the current state-of-the-art PTSC technologies that support thedevelopment of innovative concepts in the collector, HCE, and HTFs.The optical performance of new concepts could possibly be analyzed indetail for improved optical efficiency. Evacuated HCEs have relativelymuch air-leakage and breakage problems especially with higher temperaturegradients. Improved air-filled HCEs have lower costs andhigher reliability in operation hence the research studies on this subjecthave gained priority nowadays. The challenge of achieving uniformtemperature profile on the HCE is another open research field requiringattention. New concentrator structures require reduced costs, improvedoptical accuracy and improved reliability. There are several studies inthe literature on the structural analyses of PTSC systems, but there existpotential gaps that could be fulfilled. Heat transferaugmentation techniques such as inserting turbulators, modification ofthe absorber tube and using nanofluids are increasingly being considered,however, the extensive demonstration of most consideredtechniques has not been done experimentally. There is therefore roomfor research studies on the investigation of several heat transfer enhancementtechniques experimentally and under actual operatingconditions in order to fully justify any commercial implementation to PTSCs.

7. FUTURE PROSPECTS FOR RESEARCH IN PTC AND ECONOMIC ASSESSMENT MODELS

The detailed literature review of parabolic trough collector hasgiven a deep insight on the research works carried out in enhancementof optical and thermal efficiency. The forth coming section high lights the gapavailable for future research work in the improvement of the performanceof PTC.

● Investigation of coatings to minimize the adhesion of dust particles
● Enhancement of the stability of selective surface coatings due tothermal and environmental degradation
● Work on prevention of corrosion of reflectors and increase in the lifespan of reflectivity property of mirrors
● Design of an indigenous and economical automated tracking system
● Synthesis of gas Nano fluids and analysis of their feasibility throughperformance study
● Inserts analysed in heat exchangers can be investigated in absorbertube
● Investigation of multiple passive inserts in receiver tube
● Investigation of an optimal combination of nanofluids and inserts
● Performance investigation of cavity receivers with nano HTF
● Effect of uncertainty of assumptions on assessment results
● Impact of uncertainty on market revenues and techno economicanalysis of CSP systems

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