International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://www.theaspd.com/ijes.php

Geometrical Modifications Of Absorber Tube Of Conventional Solar Parabolic Trough Collector Systems For Thermal Enhancement: A Complete Review

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Abstract
This review covers most of the techniques of improving the performance of solar parabolic trough collector systems using innovative geometries, novel heat transfer techniques, numerical simulation, and experimental verification. Fundamentally, the research considers the impact of geometrical configurations including fins, inserts, and innovative receiver geometries on system performance, as well as thermal performance. The studies show that trapezoidal receivers, dimpled tubing, corrugated absorbers, and wire coil inserts have major contributions in determining heat transfer rates and thermal efficiency. The use of external and internal fins, dimpled tubing, and turbulators, including twisted tapes and wire coils, significantly improves thermal performance, with some configurations achieving a significant increase in efficiency up to 40.74%. A comparison shows that the optimal configurations are dependent on factors like aperture width, fin geometry, and nanofluid concentration. Additionally, the use of nanofluids, especially copper or titanium dioxide nanoparticles, greatly improves performance by increasing convective heat transfer coefficients. This work illustrates the benefits of nanofluids and hybrid nanofluids as heat transfer fluids which significantly reduce the thermal gradients and the stresses they generate. These results represent a necessary step towards our pursuit of the sustainable harvesting of solar energy, enabling cost-saving approaches to large-scale solar applications and extending the pursuit of global carbon neutrality.
Keywords- *Parabolic Trough Collector, Turbulators, Protrudes, Fins, Nanofluids.*

1. INTRODUCTION

Solar power is currently one of the prominent renewable energy sources, offering a clean means of addressing the growing global energy demand and environmental concerns. Among different solar power-related technologies, parabolic trough collectors (PTC) have become of great interest owing to their ability to concentrate solar radiation with high efficiency for medium-temperature applications. The researchers are targeting maximum heat transfer, minimum energy loss, and enhanced system efficiency, although they can lead to increased pressure loss and material consumption. This paper discusses research and development being carried out in PTC systems with substantial findings and possible solar thermal energy generation improvement. The 3D representation of PTC system with all of its components and arrangements can be perceived from **Figure 1**. Solar energy possesses ample potential to meet the energy requirements but, on the contrast, it is not at all an easy task to achieve optimum exergy from the sun. Different variations of insertions with modified geometrical configuration to enhance heat transfer augmentation employing nanofluids as heat transfer fluid (HTF) plays a crucial role. **Figure 2** clearly illustrates the cross-sectional view of the receiver tube of PTC. Loni et al. demonstrated the application of several unilateral receiver with cavity to conduct numerical investigation of parabolic solar collector. In this model, CFD simulation of a linear receiver with trapezoidal cavity was done analysing system for PTC in context to both optical and thermal aspects for evaluation, estimation and assessment of the performance at 25°angle and 55° angle respectively. Furthermore, a comparative study of thermal and optical improvement was done along with numerous alternatives possessing varying geometrical configuration in terms of specified tube shapes featuring cubical or V shape type structure and trapezoid of different orientation of angles with respect to axis. This study also aimed to optimize the solar parabolic trough collector system by conducting exergy and energy analyses with using soyabean oil base of mxene nanotechnology based ideal fluid with different varying constituents (0.025%, 0.075%, 0% and 0.125% by weight). This study was proved to be a boon regarding seventh development plan in Iran by optimum output contributing to the enhancement of performance of solar thermal energy by increasing thermal efficiency of the plants adding up significant amount of renewable energy for massive expansion of solar projects [1]. In depth analysis of parameters viz. insertion of different inserts inside the absorber tube with modifications of geometrical configuration, alternation of orientation of axis of insertion at different angles, changes tested with the different characteristics developed with respect to heat flow fluid will help to simplify complications and help researchers to reach their objectives smoothly. Hebba et al. proved to be a boon for the overall development of solar parabolic trough collector plants by enhancement of its performance incorporating numerous technologies viz insertion of inserts (wavy, twisted tape, corrugated and elliptical receiver, internal fins, wall detached and connected). Controlled parameters like materials of tube, tracking management, optical aspects characterization, use of different heat transfer fluid were also taken into consideration. With the variations of different range of speeds, the efficiency of tube was found to be modified [2]. In this current era of rapid modernization and industrialization in context to significant growth in innovative technologies worldwide to reduce carbon emissions and meet sustainable development goals it is inevitable to boost renewable energy generation through novel approach gathering appreciable interests from researchers to improve concentrated solar power plants. Yılmaz et al. used novel design considerations to enhance optical design and thermal characteristics to improve the performance of PTC system. Heat transfer enhancement incorporating numerous types of absorber tube configurations and modifications and enhancement of heat transfer rate with nanofluids were considerable [3]. Allam et al. examined that computing the enhancement of Nusselt number – as a parameter for evaluation of thermal performance augmentation and the impact on friction factor due to employing different variations of insertions were significant with optimum effectiveness. Heat transfer fluid exhibited different physical and chemical properties and enhanced heat transfer augmentation but it required more pumping power because of their high viscosity. Different variations of insertions with modified geometrical characteristics were tested without any nanofluids and could be used in future with nanofluids too [4]. To reduce extreme complications and minimize intricacies for optimum effectiveness and overall improvement of the performance in context to machineries equipped with modern based technology it is inevitable to adopt methods for the purpose of heat transfer augmentation in thermal sections of the devices. Ho et al. presented the controlled parameters in this research were nano ideal HTF, volume collection, geometrical configuration for novel fin, specified conditions of flow regime. Each fin possessed unique design definitely modifying thermo-hydraulic performance [5]. Kumaresan et al. targeted to design PTC which absorbed ample potential of solar concentrated radiation to be converted into useful energy. The numerical investigation was done to reduce induced heat losses minimizing heat loss with the employment of turbulators, nanofluid, selective coatings [6]. Nazir et al**.** represented a detailed and thorough experimental and numerical investigation to improve the performance of the system using numerous variations of modified turbulators with different characteristics each in the absorber tube. PEC and Nusselt number being pre-eminence for demonstrating hydraulic thermionic performance of the system. After the analysis of previous studies on this domain from the literature survey, newly designed turbulence causing element was taken for design consideration and its hydraulic performance was examined and validated through numerical simulation [7].Too et al. made a comparative study to examine the rate of thermal distribution with drop in pressure for same set of operating conditions along with considering both and without rate of temperature gradient augmentation techniques utilizing steady state heat transfer as the pre - requisite boundary conditions. Helium and carbon dioxide are taken into consideration as working gases for operating parameters. So, thermal gradients through walls and air flow can be mitigated or alleviated with such enhancement techniques [8]. Khan et al. conducted experimentation to demonstrate a numerical comparison and analyse the available methods of comparing the both energy and exergy performance for different modified geometrical configuration of absorber tubes with varying properties using Al_2O_3 or ideal working HTF being water to evaluate and predict the devastating nature of exergy because of fluid pressure build up with temperature inducing thermal stresses between the receiver wall and HT fluid temperature. Five different cases were considered for numerical investigation (smooth tube employed with nanofluid, tube with fin insertion using pure water as HTF, tube equipped with fins and using nanofluids as HTF, tube having twisted tape insertion using pure water as HTF and tubes with twisted tape insertion having nanofluid as HTF). An absorber tube equipped with twisted tape insertion and using nanofluids as HTF exhibited a significant enhancement in thermal efficiency by 72.6% to be followed upon by tube having internal fins demonstrating a thermal efficiency of about 72.10% [9]. Karimi et al. introduced a novel design to run air solar heater actively working on principle utilizing solar concentrated technology incorporating solar parabola dish consisting of a radial gap having shape of helical structure encompassing baffle positioned at the focal length of a parabolic solar dish serving the purpose of a receiver. The primary perspective relied upon absorbing abundant potential of concentrated radiation besides distributing the same to silicon-based oil. Transfer of thermal energy took place via heat exchanger connected through 2 fin series tube which were then made to be suspended in closed box alike structure of high heat flux with induced thermal stresses. This helped the system to develop medium and higher thermal gradients of air for providing numerous heat application along with the regulating air flow regime through the box. Certain controlled parameters took into consideration including inclusion of the oil mass flow rate, air mass flow rate and diameter of receiver aperture which provided the average thermal efficiency up to 60% [10].Dou et al. performed a numerical investigation and validated through CFD simulation to analyse the consequential impact of the same nanoparticles with two different base fluids. The cross - sectional thermal gradient of the absorber tube was significantly mitigated using synthetic oil or copper nanofluids as HTF. For low flow rate with high operating temperature thermal and exergy efficiency was significantly enhanced employing copper nanoparticles. Syltherm 800 as ideal working HTF was most optimum as the base fluid of nanoparticles [11]. Pranesh et al. conducted a detailed scientific investigation to review previous findings from the literature survey gap over the past five decades in the domain of harnessing solar thermal energy using CPC through adopting different innovative approaches including modified design, employment of numerous heat transfer fluid, experimentation and numerical simulation investigation, applications with the passage of history, current technology trends with latest developments. The paper served to guide the researchers for future prospects to expand the horizon of novelty with introduction of innovative applications to meet the requirements for industry 5.0 [12]. Fuqiang et al. presented to alleviate induced thermal deformation restrain for receiver tube in context to the rupture of glass enclosing covers. There was a brief insight of active and under construction solar projects in context to the PTC system in this study. [13]. Ajbar et al. conducted a detailed and thorough analysis to prepare this comprehensive review highlighting the perspective of past studies from the literature survey during the last four decades on the domain utilizing electronic based technologies to enhance the performance of PTSC system with optimum effectiveness. Future scope and applications were discussed for modified tube configurations, development of a novel ideal working fluids, including newly designed insertion, turbulators and baffles to enhance performance of the PTSC system. Data showcases using insertions yielded optimum effectiveness but increased the expenditure of the project by 5%. Heat transfer augmentation was achieved which lead to an overall increase in the thermal efficiency by about 8 to 15% [14].Gorjian et al. proposed some operating parameters to conduct scientific investigation which involved the modification of geometrical configuration with varying properties, inclusion of most ideal coatings for optimum and maximum absorption, modifying various alternation of position of axes and orientation including angles, employing nanotechnology equipped heat transfer fluid and using thermal energy storage techniques [15].Abdulhamed et al. mentioned the application of solar thermal energy generation for medium range temperatures up to 400°C with one of the most prominent and suitable solar concentrated technologies utilizing solar parabolic trough collector (STPC) system. The comprehensive review introduced modification of geometrical configuration of numerous insertion with varying properties each for the concerned operating parameters, employing novel designed techniques into consideration through examining various turbulators, baffles and using nanotechnology based ideal working heat transfer fluid to exhibit maximum efficiency contributing to performance enhancement and heat transfer augmentation mitigating induced thermal gradient at the wall of the tubes [16].The main purpose of this paper is to provide a comprehensive assessment of the recent advancements in the techniques to improve the performance of solar parabolic trough collectors. It attempts to investigate various methodologies, such as the use of nanofluids, geometry modifications of absorber tubes, and the use of inserts, to improve thermal efficiency. The study also highlights the importance of designing and operating parameter optimization for maximum heat transfer improvement while arresting pressure drop and energy losses simultaneously. This review article is divided into various categories which is presented in the below schematic diagram.

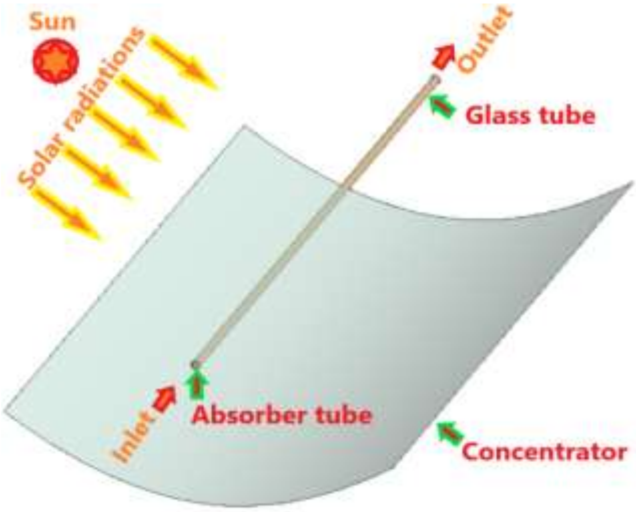

Figure 1. Representation of Conventional Parabolic Trough Collector.

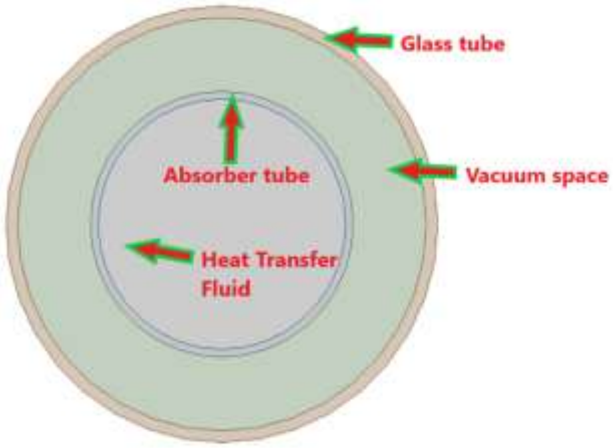

Figure 2. Cross sectional view of receiver tube.

2. Internal Protrudes for Convective Heat Transfer Enhancers

The combination of nanofluids with novel geometric configurations has been a proven method to enhance the efficiency of parabolic solar trough collectors (PSTC). Computational fluid dynamics modelling has been proven to be a successful means to model turbulent flow behaviour and optimize design parameters to achieve maximum energy harvesting. Arun et al. assessed improvement of solar PTC using controlled parameters namely dimpled tubes incorporating titanium oxide blended with water which was deionized by nature and calculated with the help of CFD simulation. The varying turbulent flow rates in the range of 0.5kg/min - 2.5kg/min in dimpled tube was studied. It was found that the convective heat transfer coefficient increased by 34.35% with the addition of TiO_2 nanofluids HTF. Nusselt number improved with the higher nanoparticle volume fraction. Collector efficiency was enhanced by 11% using nanofluids setting remarkable objective for harnessing solar thermal energy by improving its effectiveness [17]. Zou et al. carried out CFD simulation to investigate the research for novel designed parabola trough receiver using unilateral spiral ribbed inside absorber tube for better results. A specific comprehensive study was conducted to compare parabolic trough receiver employed with unilateral spiral ribbed and conventional straight smooth receiver respectively to evaluate thermal and hydraulic performance discovering parameters like rotational flow and local longitudinal vortex caused due to discontinuous spiral ribs to be prominent causes of heat transfer augmentation in unilateral spiral ribbed receiver. The temperature gradient decreased by 25% in the case of USR parabolic trough receiver. Modification of the following geometrical configuration followed by alternation of properties for pitch interval, rib height, radius of corner and spiral angle yielded optimal performance by 12.5% to be followed by 9.8%, 10.8 % and 30.1% respectively [18].

3. External Protrudes for Radiative Heat Transfer Enhancers

Different geometrical tube designs of the absorber tubes, with different fin diameters and with different fin spacings are studied to analyse their impacts on heat transfer and system efficiency. Other alternative geometrical configurations such as corrugated and S-shaped receiver tubes are investigated based on their capacity to enhance heat transfer and fluid flow. This research illuminates the efficiency of the modified absorber configurations and addresses future research directions such as hybrid nanofluids, advanced geometrical configurations, and cost-effective fabrication processes for efficient solar thermal energy harvesting. Limboonruang et al. discussed a numerical study on seven models of Cu absorber tube each with different properties and characteristics for achieving optimum effectiveness by enhancing modifications of design for external fin tube demonstrating higher thermal efficiency. Finned tubes with small diameter yield higher thermal efficiency than those with large diameter. With the increasing number of fins, the 40.7%enhancement in efficiency was observed [19]. Fuqiang et al. mentioned that corrugated tube with unsymmetrical external convex specification for employment in SPT collector exhibited optimum rate of heat transfer. Numerical results demonstrated the enhancement of heat transfer factor by 148%. Optimization was achieved for restraining of Von Mises induced thermal strain evaluated at 26.8% [20]. Bitam et al. used novel designed shape receiver tube which represented that there were variations obtained both in the longitudinal and circumferential directions on the outer surface as a consequence of the distribution of heat density on the parabolic trough collector system equipped with S - Curved / Sinusoidal receiver tube. On the contrast, for the case of conventional straight smooth tube, variations were seen only for the circumferential direction. The mean value for the Nusselt number increased exponentially in the range of 45% to 63% along with friction coefficient increasing by less than 40.8% establishing performance evaluation criteria (PEC) of approximately 135% [21].Khan et al. primarily focused to achieve net optimum energy efficiency by numerically investigating the consequential impact of a novel corrugated absorber tube employed with hybrid nanofluid as an ideal working heat transfer fluid (HTF) on energy efficiency of double fluid PTSC system. The controlled parameters involved inclusion of numerous modified geometrical configurations of corrugated absorber tube with varying properties each to exhibit optimum design consideration for different values of Reynolds number (Re) and studying nanotechnology-based nanoparticles volume fraction. It was deduced that using corrugated absorber tube enhanced energy efficiency both in the case of single and double fluid PTSC system. Moreover, at higher values of Reynolds number (Re) optimum effectiveness was seen in the case of double fluid PTSC system. Higher concentration of nanoparticles yields maximum energy efficiency [22].

4. Internal Fins as Surface Extenders

Internal fins, pin fins, toroidal ring, and helical-shaped units are few geometric extensions considered for enhancing heat transfer efficiency and fluid dynamics. Bellos et al. used 12 varying internal fins with modifications to carry out comparative study with the smooth absorber. The research was performed for internal fins with thickness of two mm, four mm and six mm while length specification being five mm, ten mm, fifteen mm and twenty mm respectively. Fin with 4mm thickness and 20mm length was found to be most suitable as per thermal enhancement index. This study showcased that fin lengths are more important than fin thickness to achieve optimum results [23]. Zhao et al. conducted experiment to present that for internal pin fin both air temperature and pressure drop were exponentially much higher in comparison to smooth tube. The temperature of air reached 266°C for rate of flowing at 93Nm^3/hr at 900 W/m^2 of concentrated radiation [24]. Bellos et al. performed CFD simulation using SolidWorks Flow to investigate LS -2 PTC employed with internally finned absorbers at numerous operating conditions. A study of was carried out between smooth case fins and twelve different variations of longitudinal fins with different geometrical characteristics. It was concluded that the thermionic performance got enhanced with higher pressure losses due to thickness and greater length [25]. Ahmed et al. introduced numerical simulation to examine impact of an SPTC absorber incorporating ring of toroidal structure shaped internally. Nine different models of absorber tube were taken into the design consideration. Thermionic efficiency achieved optimum rise by 3.7% and energy efficiency was computed at 1.8% [26]. Ahmed et al. used unique design to demonstrate the impact of incorporating toroidal rings operating with gases like air, carbon dioxide and helium respectively in an absorber tube. 9 various strategies focusing upon modification for absorber tube was examined to do a comparative study with the smooth absorber tube. Newly designed tube with altered geometrical configuration of diameter ratio 0.88 and 0.90 were proven to be the most optimum cases for thermal efficiency. For an absorber tube with toroidal rings employed with helium yields optimal energy efficiency of 41.23% with diameter ratio being 0.90. It was observed that helium being the most ideal HTF to minimize pressure drop to be followed upon by carbon dioxide and air respectively [27]. Liu et al. opted a novel approach with six different arrangements of ribbed tube

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://www.theaspd.com/ijes.php

at low Re with varying properties in PTC. The output revealed induced thermal stresses minimizing heat losses, reducing temperature and maximising thermal efficiency by about 80.1%, 177°C and 1.9% respectively [28]. Chakraborty et al. introduced helical shaped absorber tube with and without turns employing water and alumina equipped water as ideal working HTF for operating parameters at varying flow rate of 0.025kg/second - 0.25 kg/second. The controlled parameters for the design consideration involved inclusion of a smooth absorber tube on contrast with three different absorber tube with modified geometrical configuration consisting of 15, 20 and 25 turns respectively [29].

5. Concentrics Turbulators as Vortex Creators

Recent research identifies the efficiency of nanofluids, porous media, and innovative geometrical configurations in improving heat transfer efficiency and minimizing pressure losses. Methods like the addition of metal foam, helical screw-tape, and conical strip inserts have been found to be effective in inhibiting thermal gradients and fluid mixing. Siavashi et al. observed for significant enhancement in copper nano particles at volume of 0.015 fraction resulted in increasing Nusselt number by 12% and friction factor by 1.2%. Half - porous receiver tubes exponentially yielded Nusselt number to 10.6 enhancing friction fraction to 5 times when compared to the usage of non-porous receiver tubes. [30]. Ghasem et al. employed CFD with Syltherm 800 as HTF to obtain Nusselt number increment with rings [31]. Kumar et al. examined for the porous disc line receiver in PTSC. With variations of geometrical configuration namely orientation of axis, angle(h), distance between discs(w), disc height, heat flux, pressure drop was calculated as 457 Pa and heat transfer got increased by 64.3% [32]. Bellos et al. used CFD SolidWorks simulation for turbulators, inserts, internal fins with copper oxide nanofluids as HTF. It was observed that the nanotechnology based working fluid yielded 0.76% thermionic efficiency augmentation. Insertion of internal fins exhibited an enhancement in thermal efficiency of about 1.10%. [33]. Yılmaz et al. represented SPTC with large apertures (to exhibit significant concentration ratios) to improve thermal performance. It was obtained that the inclusion of wire coil inserts with flow rate being less than 13m^3/h, thermal efficiency improved in the range between 0.4 - 1.4% leading to overall increase of heat transfer performance by 183% [34]. Kumar et al. represented that the metal foam insertion increased average energy efficiency by 3.71% whereas 2.3% for available energy efficiency respectively [35]. Saedodin et al. studied numerical simulation of STPC with helical shaped turbulators at wall. It was observed that for the inlet velocity of 0.32 m/sec; models with two to six number of elements exhibit higher thermal efficiency than plain PTC by 6.6, 13.2, 20.6 and 27.6% respectively. The second phase of this research involved variations in geometrical configuration of cross - section namely rectangular, triangular. For rectangle shape cross section, with inlet velocity of 0.2 m/second, 29% improvement in thermal efficiency was achieved [36].Peng et al. examined inserting some portion of foam composed with metal gradient. Results revealed that Nusselt number got enhanced by about 43.7% to 812.6% and energy efficiency by 92.6 %. when employing GMF insertion in the parabolic trough receiver tube [37]. Chang et al. used salt in the molten state as HTF. For the value of H = 0.8 the performance evaluation criterion was reduced in the range of 1.84 to 1.68 times over a plain PTR under a certain operating Reynolds number thereby making the PTR more reliable with maximum effectiveness [38]. Xiao et al. considered numerical investigation for A1 baffle to examine mean net optimum efficiency and exergy efficiency as 0.52% and 0.22% respectively [39]. Song et al. employed helical screw - tape insertion to determine a simulation of heat flux dissipation at external area of wall for absorber tube evaluating consequential impact for solar incident angle. Output showcased transverse angle, β altering flux being dissipated at higher rate when compared to longitude angle (φ). The relative change in heat loss (Q_{loss}) was increased significantly for transversal angle about 11.567 m_{rad} as the inlet temperature rise contributing to the optimum temperature rise on absorber tube (T_{max}) leading to a significant radial thermal gradient [40]. Feng et al. used numerical CFD simulation for modified mini – channel with fluid flow mixing due to the generation of swirl flows from both the wire coil and twisted tape insertion. A case with maximum enhancement for temperature gradient augmentation in the ratio of 4.11 - 4.83 was observed. Under the same operating conditions, the overall thermal performance was optimum for low rates (< 9.292 g/second) [41]. Ou et al. used conical strip insertion which was investigated and validated utilizing CFD simulation. The actual efficiency rose significantly by about 3.3% for the drop in the temperature gradient of tube wall by 168K when compared to that of the smooth PTR [42].

6. Lower Lateral Surface for Utilizing Heat Concentrator Surfaces

Current research efforts direct towards enhancing PTC system thermal efficiency through design innovations and novel materials. Several research studies emphasize the need for heat exchanger geometry to enhance temperature gradients and efficiency. The application of nanofluids and internal fins with modifications is also investigated using CFD simulations. Nain et al. investigated to compute thermal index factor for a PST heater employed with heat exchanger which was U in shape with and without fins were taken into the design consideration alternatively; made up of copper and aluminium respectively. It was located at the focal length of parabolic trough constituted with nickel coated stainless steel. The performance factor for copper heat exchanger exhibited enhancement and was better than Al made heat exchanger [43]. Chakraborty et al. used numerical investigation for thermal efficiency optimization for LS2 model solar PTC system utilizing a smooth and helical absorber. Employing helical shaped tube reached optimal rate of heat transfer by 71% for the same length of parabolic trough including smooth absorber PTC. Thermionic and exergy efficiency were 10% and 5%, respectively as compared to smooth type absorber [44]. Chakraborty et al. showcased a numerical investigation with CFD simulation utilizing ANSYS 23 software for four different cases involving three models with different specified fin in comparison of a model employed with tube without fins to predict the impact of nanofluid particles for a PTSC to demonstrate thermal convenience. The tubes and the fins were subjected to rotation with spinning rates in the range of 0 radian per second to 15 radian per second for the mass flow rate of operating working medium range 0.15 kg/second to 0.60 kg/s. Thermionic performance exhibited an improvement factor of 47.45%, Nusselt number improvement factor enhancement of about 55.45% respectively for (Re) = 4739.3 for Nanofluid 6 than Nanofluid - 1[45].Pandey et al. conducted CFD simulation for eleven different operating set to analyse impact of new insertion yielding optimum enhancement for thermionic performance of the PTC system evaluating thermodynamic and hydraulic characteristics. For the usual operating parameters of the concerned boundary conditions for arc - plug insertion at R =1 and R = 1.6060 a thermal efficiency was achieved varying in the range of 73.09% to 67.55% and 67.78% to 65.37% respectively.[46]. From the above review, the schematic diagram proposes the numerical simulation procedure for the modified PTC.

7. CONCLUSION

The overall objective of this extensive research is to explore and examine several modifications and advancements of the conventional PTC system with emphasis on thermal performance and efficiency improvement, and thereby attempting optimization of thermal energy collection and utilization of solar energy for medium to high-temperature applications. The research explores an array of changes including the use of novel geometric forms, advanced computing techniques and nanofluids. One of the most vigorous research fields involves the utilization of nanofluids in the context of non-traditional geometrical designs of absorber tubes. The use of various inserts like twisted tapes, fins, eccentric rods, helical screws, and corrugated surfaces in absorber tubes increases coefficients of heat transfer and reduces thermal stresses and thereby provides an entry to more even temperature profiles. Techniques like Finite Volume Techniques coupled with Monte Carlo Ray Tracing yield valuable insights into the complex interaction between optical, thermal, and structural parameters and thus enable serious evaluation of performance parameters under varied conditions. The simulations conducted allowed for an investigation that corrugated absorber tube saves energy considerably, especially at high Reynolds numbers. In addition, novel material utilization, best design philosophy, and new analysis techniques have great potential for increasing solar thermal system efficiency. The overall outcome highlights the dominant role of accurate numerical information in the PTC system design, thus a solid foundation for future developments and use of solar thermal energy. With the world moving towards cleaner and renewable energy, this information will be the stepping stone to the creation of the next solar system that will be efficient and sustainable in addressing future energy demands.

REFERENCES

[1] R. Loni, M. Sharifzadeh, Performance comparison of a solar parabolic trough concentrator using different shapes of linear cavity receiver, Case Studies in Thermal Engineering 60 (2024) 104603.

[2] U. Hebbal, B. Soragaon, G. Rathnakar, A.N.M. Das, L.R. Thippeswamy, N. Nagabhushana, C.D. Prasad, A.A. Aden, Principal difficulties with parabolic trough collector systems and performance-boosting strategies: A comprehensive review, International Journal of Thermofluids 25 (2025) 101009.

[3] I. H. Yilmaz, A. Mwesigye, Modeling, simulation and performance analysis of parabolic trough solar collectors: A comprehensive review, Applied Energy 225 (2018) 135-174.

[4] M. Allam, M. Tawfik, M. Bekheit, E.E. Negiry, Heat transfer enhancement in parabolic trough receivers using inserts: A review, Sustainable Energy Technologies and Assessments 48 (2021) 101671.
[5] M.L.G. Ho, C.S. Oon, L.L. Tan, Y. Wang, Y.M. Hung, A review on nanofluids coupled with extended surfaces for heat transfer enhancement, Results in Engineering 17 (2023) 100957.
[6] G. Kumaresan, P. Sudhakar, R. Santosh, R. Velraj, Experimental and numerical studies of thermal performance enhancement in the receiver part of solar parabolic trough collectors, Renewable and Sustainable Energy Reviews 77 (2017) 1363-1374.
[7] M.S. Nazir, A. Shahsavar, M. Afrand, M. Arici, S. Nizetic, Z. Ma, H.F. Oztop, A comprehensive review of parabolic trough solar collectors equipped with turbulators and numerical evaluation of hydrothermal performance of a novel model, Sustainable Energy Technologies and Assessments 45 (2021) 101103.
[8] Y.C.S. Too, R. Benito, Enhancing heat transfer in air tubular absorbers for concentrated solar thermal applications, Applied Thermal Engineering 50 (2013) 1076-1083.
[9] M.S. Khan, M. Yan, H.M. Ali, K.P. Amber, M.A. Bashir, B. Akbar, S. Javed, Comparative performance assessment of different absorber tube geometries for parabolic trough solar collector using nanofluid, Journal of Thermal Analysis and Calorimetry 142 (2020) 2227–2241.
[10] R. Karimi, T.T. Gheinani, V.M. Avargani, Coupling of a parabolic solar dish collector to finned-tube heat exchangers for hot air production: An experimental and theoretical study, Solar Energy 187 (2019) 199-211.
[11] L. Dou, B. Ding, Q. Zhang, G. Kou, M. Mu, Numerical investigation on the thermal performance of parabolic trough solar collector with synthetic oil/Cu nanofluids, Applied Thermal Engineering 227 (2023) 120376.
[12] V. Pranesh, R. Velraj, S. Christopher, V. Kumaresan, A 50-year review of basic and applied research in compound parabolic concentrating solar thermal collector for domestic and industrial applications, Solar Energy 187 (2019) 293-340.
[13] W. Fuqiang, C. Ziming, T. Jianyu, Y. Yuan, S. Yong, L. Linhua, Progress in concentrated solar power technology with parabolic trough collector system: A comprehensive review, Renewable and Sustainable Energy Reviews 79 (2017) 1314-1328.
[14] W. Ajbar, A. Parrales, A. Huicochea, J.A. Hernandez, Different ways to improve parabolic trough solar collectors' performance over the last four decades and their applications: A comprehensive review, Renewable and Sustainable Energy Reviews 156 (2022) 111947.
[15] S. Gorjian, H. Ebadi, F. Calise, A. Shukla, C. Ingrao, A review on recent advancements in performance enhancement techniques for low-temperature solar collectors, Energy Conversion and Management 222 (2020) 113246.
[16] A.J. Abdulhamed, N.M. Adam, M.Z.A.A. Kadir, A.A. Hairuddin, Review of solar parabolic-trough collector geometrical and thermal analyses, performance, and applications, Renewable and Sustainable Energy Reviews 91 (2018) 822-831.
[17]. M. Arun, D. Barik, H. Ahmad, I. Alraddadi, M.A. Shenashen, Z.A. Khan, Parabolic trough solar collector technology using TiO2 nanofluids with dimpled tubes, Case Studies in Thermal Engineering 61 (2024) 104840.
[18] B. Zou, Y. Jiang, Y. Yao, H. Yang, Thermal performance improvement using unilateral spiral ribbed absorber tube for parabolic trough solar collector, Solar Energy 183 (2019) 371-385.
[19] T. Limboonruang, M. Oyinlola, D. Harmanto, N. Phunapai, Optimizing the configuration of external fins of solar receiver tubes for the solar parabolic trough collector, Applied Thermal Engineering 263 (2025) 125317.
[20] W. Fuqiang, T. Zhexiang, G. Xiangtao, T. Jianyu, H. Huaizhi, L. Bingxi, Heat transfer performance enhancement and thermal strain restrain of tube receiver for parabolic trough solar collector by using asymmetric outward convex corrugated tube, Energy 114 (2016) 275-292.
[21] E.W. Bitam, Y. Demagh, A.A. Hachicha, H. Benmoussa, Y. Kabar, Numerical investigation of a novel sinusoidal tube receiver for parabolic trough technology, Applied Energy 218 (2018) 494-510.
[22] M. Khan, I.N. Alsaduni, M. Alluhaidan, W.F. Xia, M. Ibrahim, Evaluating the energy efficiency of a parabolic trough solar collector filled with a hybrid nanofluid by utilizing double fluid system and a novel corrugated absorber tube, Journal of the Taiwan Institute of Chemical Engineers 124 (2021) 150-161.
[23] E. Bellos, C. Tzivanidis, D. Tsimpoukis, Thermal enhancement of parabolic trough collector with internally finned absorbers, Solar Energy 157 (2017) 514-531.
[24] Z. Zhao, F. Bai, X. Zhang, Z. Wang, Experimental study of pin finned receiver tubes for a parabolic trough solar air collector, Solar Energy 207 (2020) 91-102.
[25] E. Bellos, C. Tzivanidis, D. Tsimpoukis, Multi-criteria evaluation of parabolic trough collector with internally finned absorbers, Applied Energy 205 (2017) 540-561.
[26] K.A. Ahmed, E. Natarajan, Thermal performance enhancement in a parabolic trough receiver tube with internal toroidal rings: A numerical investigation, Applied Thermal Engineering 162 (2019) 114224.
[27] K.A. Ahmed, E. Natarajan, Numerical investigation on the effect of toroidal rings in a parabolic trough receiver with the operation of gases: An energy and exergy analysis, Energy 203 (2020) 117880.
[28] P. Liu, J. Lv, F. Shan, Z. Liu, W. Liu, Effects of rib arrangements on the performance of a parabolic trough receiver with ribbed absorber tube, Applied Thermal Engineering 156 (2019) 1-13.
[29] O. Chakraborty, B. Das, R. Gupta, S. Debbarma, Heat transfer enhancement analysis of parabolic trough collector with straight and helical absorber tube, Thermal Science and Engineering Progress 20 (2020) 100718.
[30] M. Siavashi, M.V. Bozorg, M.H. Toosi, A numerical analysis of the effects of nanofluid and porous media utilization on the performance of parabolic trough solar collectors, Sustainable Energy Technologies and Assessments 45 (2021) 101179.
[31] S.E. Ghasemi, A.A. Ranjbar, Numerical thermal study on effect of porous rings on performance of solar parabolic trough collector, Applied Thermal Engineering 118 (2017) 807-816.
[32] K.R. Kumar, K.S. Reddy, Thermal analysis of solar parabolic trough with porous disc receiver, Applied Energy 86 (2009) 1804-1812.
[33] E. Bellos, C. Tzivanidis, D. Tsimpoukis, Enhancing the performance of parabolic trough collectors using nanofluids and turbulators, Renewable and Sustainable Energy Reviews 91 (2018) 358-375.

[34] I.B.H. Yılmaz, A. Mwesigye, T.T. Goksu, Enhancing the overall thermal performance of a large aperture parabolic trough solar collector using wire coil inserts, Sustainable Energy Technologies and Assessments 39 (2020) 100696.
[35] B.N. Kumar, K.S. Reddy, Numerical investigations on metal foam inserted solar parabolic trough DSG absorber tube for mitigating thermal gradients and enhancing heat transfer, Applied Thermal Engineering 178 (2020) 115511.
[36] S. Saedodin, M. Zaboli, S.S.M. Ajarostaghi, Hydrothermal analysis of heat transfer and thermal performance characteristics in a parabolic trough solar collector with Turbulence-Inducing elements, Sustainable Energy Technologies and Assessments 46 (2021) 101266.
[37] H. Peng, M. Li, X. Liang, Thermal-hydraulic and thermodynamic performance of parabolic trough solar receiver partially filled with gradient metal foam, Energy 211 (2020) 119046.
[38] C. Chang, A. Sciacovelli, Z. Wu, X. Li, Y. Li, M. Zhao, J. Deng, Z. Wang, Y. Ding, Enhanced heat transfer in a parabolic trough solar receiver by inserting rods and using molten salt as heat transfer fluid, Applied Energy 220 (2018) 337-350.
[39] H. Xiao, P. Liu, Z. Liu, W. Liu, Performance analyses in parabolic trough collectors by inserting novel inclined curved-twisted baffles, Renewable Energy 165 (2021) 14-27.
[40] X. Song, G. Dong, F. Gao, X. Diao, L. Zheng, F. Zhou, A numerical study of parabolic trough receiver with nonuniform heat flux and helical screw-tape inserts, Energy 77 (2014) 771-782.
[41] Z. Feng, Z. Li, Z. Hu, Y. Lan, S. Zheng, Q. Zhang, J. Zhou, J. Zhang, Combined influence of rectangular wire coil and twisted tape on flow and heat transfer characteristics in square mini-channels, International Journal of Heat and Mass Transfer 205 (2023) 123866.
[42] G. Ou, P. Liu, Z. Liu, W. Liu, Performance analyses and heat transfer optimization of parabolic trough receiver with a novel single conical strip insert, Renewable Energy 199 (2022) 335-350.
[43] S. Nain, V. Ahlawat, S. Kajal, P. Anuradha, A. Sharma, T. Singh, Performance analysis of different U-shaped heat exchangers in parabolic trough solar collector for air heating applications, Case Studies in Thermal Engineering 25 (2021) 100949.
[44] O. Chakraborty, S. Roy, B. Das, R. Gupta, Effects of helical absorber tube on the energy and exergy analysis of parabolic solar trough collector – A computational analysis, Sustainable Energy Technologies and Assessments 44 (2021) 101083.
[45] O. Chakraborty, S. Nath, Numerical study on solar trough collectors: Optimizing heat transfer with ternary nanoparticles in ionic base fluid and spinning tube fins, Renewable Energy 236 (2024) 121473.
[46] M. Pandey, B.N. Padhi, I. Mishra, Numerical simulation of solar parabolic trough collector with arc-plug insertion, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 43 (2020) 2635–2655.