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Review Article

Heat transfer enhancement techniques using different inserts in absorber tube of parabolic trough solar collector: A review

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ABSTRACT

Various collector technologies are prevalent for harnessing of solar energy. Some of the most common types are flat plate and evacuated tube collectors. Parabolic trough collectors are not commercialized other than large industrial set up because these collectors occupy larger land area along with higher cost of installation. It becomes important for the researcher to device new technologies that would reduce the cost and hereby promote sustainable renewable energy technologies. Heat transfer enhancement techniques like tube turbulators mainly twisted tape, wire coils, metal foam, corrugations, fins, and use of nano fluid are among the several alternatives. The present review focuses on research done in enhancement of heat transfer rate in PTC using above techniques considering the work done from 2015-2023. An effort has been made to compare the output of such techniques after exhaustive literature survey. The enhancement in heat transfer rate by dimensionless Nusselt number Nu/Nu_p. Where, Nu is the Nusselt number for PTC absorber tube when use with turbulator and Nu_p is the Nusselt number for plain absorber tube. Similar comparison is made for f/f_p which is related to friction factor encountered and when compared to smooth tube. From the literature it is evident that Nu/Nu_p has a range from 1.2-10 when using different turbulator and f/f_p has a range of 1.02-10.2 which is mainly dependent on geometry. These results prove efficacy of using tube turbulators in PTC absorber thereby promoting interest for further exploration especially with experimental investigation which is seldom reported in the literature. Moreover, previous research is not sufficient as direct comparison among these techniques is not reported. This critical study reports direct comparison of above techniques.

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INTRODUCTION

Parabolic trough solar collector is becoming popular in the current scenario because of its design and working efficiencies. To reduce radiation losses, the surface of collector is to be coated with reflective material which can be either metal or mirror. The incident sunlight falls on the surface of the parabola which eventually gets reflected and falls on the focal point. An absorber tube is kept along the length of the parabola at its focal point. The fluid which is intended to be heated flows through the absorber tube.

The heat transfer fluid which is usually thermal oil flows inside the tube wherein concentrated radiation is absorbed. Depending upon the geometry of the parabola and thermal property of fluid, the temperature increases manifold up to 400^{o}C [1,2]. Parabolic trough collector has wide application in the industrial sector and commercial sector. The applications are mainly found in areas of air heating, solar power generation and closed cycle heat exchange systems [3].

Normally, the absorber tube is made of metal and a concentric arrangement with glass tube as an outer tube. Vacuum is present between the concentric spaces of both the tubes. The presence of vacuum minimizes the heat losses. The receiver tube is also called as heat collecting element from where the heat is transferred to the fluid. So here, all modes of heat transfer take place as:

1) Radiation Heat transfer between glass tube and metal tube.
2) Conduction heat transfer through metal absorber tube.
3) Convection heat transfer between absorber tube and fluid.

Heat transfer enhancement has always been an area of research in thermal systems. The internal heat transfer in fluid plays a vital role for efficiency improvement. The current work reviews on use of turbulators inside the absorber tube of PTC. Turbulators are typically designed with surface features such as fins, ribs, or helical elements, which increase the effective surface area of the absorber tube, providing more contact points for heat exchange between the HTF and the tube's inner surface. Moreover, this turbulence promotes the better fluid mixing, and it also disrupts the formation of hydrodynamic boundary layer which is detrimental for better heat transfer rates.

Various techniques for increasing the rate of heat transfer mainly the use of twisted tapes, wire coils, porous metal foam and combination of above techniques with nano fluids. It is evident from literature that the use of such techniques enhances the heat transfer rate in PTC. The percentage of enhancement is represented by dimensionless Nusselt number which is denoted by Nu/Nu_p. Here Nu is Nusselt number for absorber tube with inserts whereas Nu_p is the Nusselt number for plain absorber tube. It is observed that this dimensionless factor has a range of 1.5 – 4.5 which means that use of turbulators enhances the heat transfer rates from 50% to 400%. An effort has been made to represent these figures after analyzing the graphs of literature and the same are incorporated in Table 8. However, on the contrary the use of these turbulators will also promote rise in pressure drop. The same is represented by another dimensionless parameter f/f_p where f is the friction factor for tube with turbulator and f_p is the friction factor for plain absorber tube. The above dimensionless parameter has a range from 1.1-10 as evident from the literature. The variation of percentage increment of Nusselt number and friction factor depends upon the geometry of insert used. The variation of dimensionless geometric parameters, such as twist ratio & width ratio in twisted tape, pitch ratio of wire coils and twisted tape and porosity of metal foam and concentration of nano fluid are of concern. Each of these techniques exhibits different behavior based on their geometry ultimately showing its influence on heat transfer rates and pressure drop which is mainly dependent on their geometry.

HEAT TRANSFER ENHANCEMENT

Heat transfer enhancement can be classified into many methods like active, passive and combination of both active and passive methods**.** Figure 1 presents the classification of these techniques.

Active method:

This heat transfer enhancement method is seldom used, as it requires additional external force for example magnetic field to disturb the light seeded particles in a flowing stream, external vibration etc.

Passive method:

In passive technology there is no requirement of any external force as it leads to thermal enhancement by increasing the surface area and residence time of HTF. This method includes inserts or turbulators sometime called as artificial methods like wire coil and twisted tape which produces swirling effect in the bulk of fluids [4]. In a plain absorber tube wherein the fluid flows, there will be formation of boundary layer which eventually is detrimental for the heat transfer capabilities. However, artificial methods like use of inserts and inner surface modifications like corrugations and use of metal foams, generates turbulence and prevents the formation of boundary layer thus enhancing the rate of heat transfer. The turbulence in the fluid flow will increase the Reynolds number by a significant extent thereby giving a remarkable rise in Nusselt number and increase in overall heat transfer coefficient.

Researchers have conducted studies on employing such techniques in PTSC absorber tube. Moreover, development in manufacturing technologies has made it convenient to use complicated geometries in absorber tube. Inserts like twisted tapes, internal fins, perforated plates, porous metal foams and wire coils have been proposed by various investigators. In the present manuscript, work done in this area have been considered between the period from 2015-2023 and review has been done on the numerical and experimental analysis of the inserts like wire coil, twisted tape,

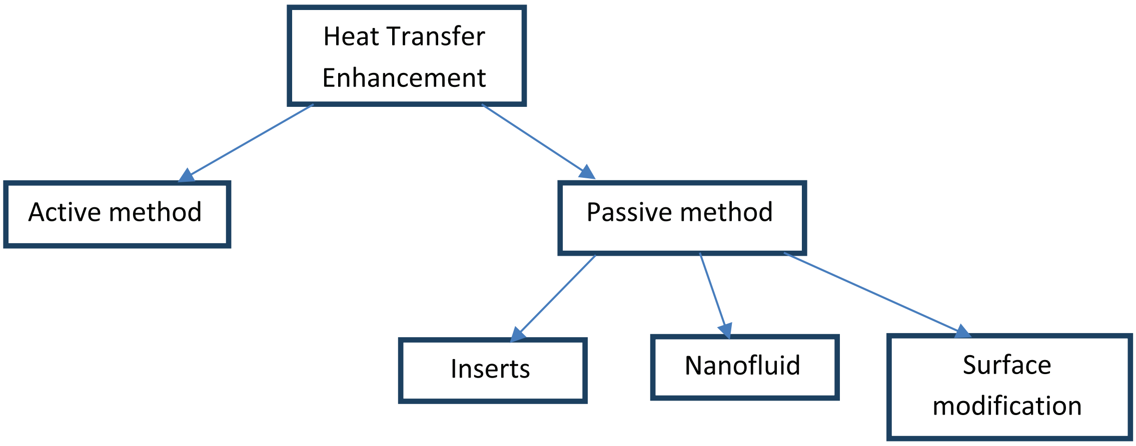

Figure 1. Heat transfer enhancement methods.

fins and porous metal foam and combination of inserts with nano fluid.

Data base of science direct, Taylor and Francis, ASME, springer etc. are referred using appropriate filters and considered references are thoroughly studied and scrutinized in this paper. The main objective is to present a detailed analysis of work done by researcher and outcomes of published research. Comparison has been made by analyzing the type of inserts which are widely used and moreover the enhancement obtained in heat transfer rate is represented by table indicating Nu/Nu_p whereas the friction factor comparison is represented by f/f_p. Aim is to provide an authentic presentation of work done in past so as to promote future research in the said area and assist in the selection of efficiency improvement techniques used in PTC.

As variety of enhancement technique are used by several researchers it becomes complicated for end user to select any appropriate combination for stipulated application. This work is supposed to be extended in a direction wherein a test rig shall be developed, and performance of parabolic collector shall be evaluated using different turbulators.

The outcome of the practical will be demonstrated and published in an effective manner which the researchers can refer for selection of appropriate technique. The research shall be proven imperative for development of sustainable mechanism for heat transfer enhancement of thermal system be it renewable or nonrenewable systems as such technologies lead to direct efficiency enhancement thereby lowering the system costs.

The forthcoming sections of this paper represents the advancements carried out in heat transfer enhancement methods used in PTC.

The content and layout of this paper are as follows:

- Review of work done by various researchers since 2015. Owing to its prevalence in applications the considered techniques are wire coiled inserts, twisted tape inserts, finned tube geometry, surface corrugations, porous metal foams and combination of nanofluid and turbulators.
- Key observations in performance using above mentioned techniques and discussion on use of mathematical, numerical and analytical method for study.
- Comparative analysis of above techniques in enhancement of Nusselt number and rise in friction factor.
- Conclusions.

Wire Coiled Inserts

Şahin et al. [5] studied the heat transfer and friction characteristics of a concentric tube heat exchanger with parabolic trough collector using wire coiled turbulators of different pitches. For a Reynolds number range of 3000-17000, results of numerical and experimental work are validated with one another. The Dittus boetler correlation for Nusselt number was used for analysis. Using wire coils of pitch distance 15, 30 and 45 mm, the thermal enhancement found to be increased by 2.28, 2.07 and 1.95 times respectively. Use of turbulators naturally increased the friction factor in all cases. Vahidifar and Kahrom [6] experimentally investigated the performance of heat exchanger tube by inserting wire coil and ring and observed the enhancement efficiecncy by 128%.

Diwan and Soni [7] numerically studied the performance of PTC using COMSOL Multiphysics considering wire coiled inserts. Heat transfer rates using various geometry of wire coiled inserts are studied considering water as working fluid. The Nusselt number enhancement is observed to be 104 – 330%. This enhances the overall heat transfer coefficient and ultimately the heat transfer rates. Moreover, using pitch of 8mm for wire coiled insert, the pressure drop is found to be in range of 55.23 Pa to 1311.79 Pa using different flow rates ranging from 0.013-0.099 kg/s. The rise in pressure drop increases the pumping power. Maximum increase of 12.6% is observed in friction factor. At lower mass flow rates, the value of Nusselt number remains almost unchanged up to 8mm pitch of wire coil but it goes on decreasing after 8mm up to 20mm of pitch. However, at 6mm pitch, the maximum value of Nusselt number is observed in case of higher mass flow rate and then it decreases linearly from 6mm coil pitch. It can be concluded that the selection of 6mm pitch is optimum for higher mass flow rates.

Yılmaz et al. [8] performed numerical study using Navier Stokes equation to analyze the performance of Parabolic Trough solar collector having large aperture and having absorber tube inserted with wire coil. A realistic heat flux profile on absorber tube was obtained using Monte – Carlo ray tracing method which was later coupled to FVM (Finite Volume method) based CFD tool. Pitch distance of 0.076, 0.114 and 0.152 m and 0.03, 0.033 and 0.036 width distance of wire coils are considered in the study. The earlier literature reveals that the sharp edge geometry yields better performance than circular or square. So, the contour selected for wire coil is triangular of 0.0076 m in size. This triangular cross section of wire stimulates fluid mixing and boundary separation which gives significant improvement in overall performance of the collector. The corresponding increase in efficiency is observed to be in the range of 0.4 – 1.4% when the flow rate is below 13m^3/hr. The thermal performance enhancement was observed to rise by 183%.

Porous Metal Foam Inserts

Valizade et al. [9] experimentally studied the performance of parabolic trough solar collector using copper metal foam in absorber tube. The comparison was made between full porous, semi porous, and non- porous foam absorber tube. The investigated parameters are thermal performance, temperature difference and friction factor. Different mass flow rates and inlet temperatures were considered as operating parameters. To validate the results, the performance of the collector is measured as per ASHRAE 93-2010 standards. There is significant increase observed in friction factor by use of porous metal foams. The maximum temperature difference observed are 12.2^{o}C, 8.8^{o}C and 3.3^{o}C in case of full porous, semi porous and non-porous absorber tube respectively. Decreasing the inlet temperature and increase in mass flow rates enhances the collector efficiency by a significant amount. Efficiency improvements of 171.2% and 119.6% are observed considering full and semi porous metal foams as compared to non-porous or plain absorber tube. Wang et al. [10] numerically analyzed the heat transfer characteristics of direct steam generation PTC using metal foam inserts. The thermo-hydraulic performances are analyzed by making variation in the layout (top/bottom), geometrical parameter and porous characteristic of metal foam. Here the insertion of metal foam is represented by dimensionless parameter H which is the ratio of height of metal foam h and diameter of tube D_i. With bottom orientation of H = 0.25, the rise in Nusselt number is observed to be 5-10 times but on the contrary the increment in friction factor is observed by 10-20 times. At H = 0.75 with top orientation Nusselt number increases about 10-12 times with rise in friction factor by 400-700 times and reduction in circumferential temperature difference on the outer surface of the absorber tube by 45% which ultimately reduces the thermal stresses. Reddy et al. [11] performed experimental investigation on porous disc enhanced receiver. ASHRAE 93-1986 test procedure was used for validation purpose. The pumping power is observed to increase by 0.05 Watt for per meter length of absorber tube owing to use of porous discs. The calculated efficiencies are obtained in the range of 63.9% - 66.66%. It is recommended in the study to use the porous disc receiver for process heat applications. Jamal-Abad et al. [12] investigated the experimental performance of PTC filled with copper foam of porosity 0.9 and pore density 30 PPI (pores per inch) in absorber tube of PTC. Nusselt number enhancement and friction factor increment was found by the insertion. ASHRAE 93 standards were used to measure the collector performance and volume flow rate of 0.5 – 1.5 Liter/min was used for experimentation purpose. The increment in efficiency was observed due to decrease in overall loss coefficient by 45% as less energy is lost. Khattar and Heyhat [13] conducted an exergy, entropy, environmental and economic analysis of direct absorption parabolic trough solar collector using different configuration of metal foam at different flow rate of heat transfer fluid. Along with enhancement in thermal efficiency, the addition of metal foam led to significant pressure drop. However, the insertion of metal foam reduces the manufacturing cost along with carbon print. Zheng et al. [14] investigated the thermo-hydraulic performance of parabolic trough solar collector with partially and fully filled porous media. The investigation was done numerically coupled with CFD code and found that partially filled porous insert yield better performance than fully filled metal foam. Peng et al. [15] developed numerical model using gradient metal foam inside the absorber tube and observed the thermal enhancement to be more than uniform metal foam. The Nusselt number increased by 43.7 - 81.26% with friction factor being 4.2 - 16.7 times more than that of smooth absorber. Due to non-uniform solar flux concentration thermal stresses are developed which led to the breakage of glass cover. So, the concept of metal foam as volumetric absorption reduces the circumferential temperature difference and henceforth the thermal stresses. Kumar and Reddy [16] numerically investigated the insertion of metal foam with varying radial thickness at lower portion of absorber tube and found reduction in circumferential temperature difference from 47% to 72% as compared to smooth absorber tube. Peng et al. [17] numerically analyzed the effect of novel insertion i.e., semi annular fin shaped metal foam inside the absorber tube of parabolic trough solar collector and also analyzed the different fin shape (rectangular, triangular and trapezoidal) and observed the result as rise in Nusselt number by 256.3%–838.7% and rise in friction factor by 440.3%–788.8% than plain tube receiver.

Twisted Tape Inserts

Okonkwo et al. [18] investigated the performance of PTC using modified absorber tube and found increase in het transfer coefficicent and reduction in circumferential temperature difference.

Jaramillo et al. [19] used the first and second law of thermodynamics to investigate the performance of PTC using wire coiled inserts. The investigated parameters are rate of entropy generation, thermal efficiency, friction factor and Nusselt number. With rise in twist ratio, heat transfer and thermal efficiency enhancement is not observed. However, these quantities are enhanced with decrease in twist ratio. Mwesigye et al. [20] performed numerical investigation of twisted tape inserts which are detached from wall. Efficiency rise of 10% and significant increase of 169% in heat transfer performance was observed. The analysis was done using FVM (Finite Volume Method) and k-ε model.

The Reynolds number rises with increase in twist ratio and with decrease in width ratio. The maximum reduction in the entropy generation rate was about 58%. The range for twist ratio and width ratio are taken as 0.5 – 2 and 0.53 – 0.91 respectively. Bhakta et al. [21] performed experimentation on parabolic solar water heater by using roughened surface in the receiver tube of PTC. The researcher used the nail twisted tape which is different than that of conventional twisted tape to enhance the overall efficiency of the collector. The twist pitch ratio of 4.78, 6.9 and 9.042 was examined and was found that lower the pitch ratio, higher is the performance enhancement. The pitch ratio of 4.78 was found optimum which enhanced the overall efficiency by 12.49%. Rawani et al. [22] used serrated twisted tape inserts for analytical study of PTC. Geometrical variation of pitch ratio 1, 2, 3 and 4 were examined with stipulated range of 0.06 kg/s to 0.16 kg/s of mass flow rates. It was observed that, at twist ratio 1, the Nusselt number and heat transfer coefficient enhances by 4.38 and 3.51 times respectively as compared to plain tube. Entropy generation rate, exergy efficiency, thermal efficiency and rise in fluid temperature were studied by developing equations for heat transfer considering fully developed quasi steady state conditions. Jafar and Sivaraman [23] experimentally investigated the thermal augmentation using nail twisted tape with twist ratio 2,3 and 4. Using nail twisted tape an increase in instantaneous efficiency of 27% is observed as compared to plain tube absorber. Thermal augmentation using twisted tape inserts are much reported in literature, but ring attached twisted tape is an emerging technology in the existing technique of passive augmentation. Isravel et al. [24] observed that performance of PTC is intensified using modified ring attached twisted tape. For all three types of twisted tape i.e., conventional, ring attached, and modified ring attached, it was observed that the Nusselt number increases by 5 – 40%, 11-101 % and 7-77% respectively. Higher pressure drop of 59-72% in ring attached and lower pressure drop 23-31% in modified ring attached twisted tape was observed. The modified ring attached twisted tape yields 24% more thermal enhancement than conventional twisted tape. Hosseinalipour et al. [25] presented numerical simulation of PTC using twisted tape and studied the reduction of circumferential temperature difference. Nusselt number and friction factor were the investigated parameters. It was found that by reducing twist ratio, Nusselt number and thermal performance factor enhances by 1 – 1.7 times and 0.8-1.1 times respectively with penalty of increase in friction factor by 1.8-4.1 times. The numerical simulation is conducted in the stipulated Reynolds number ranging from 10^4 -9.79x10^5 and clearance ratio and twist ratio are varied in the range of 0–0.5 and 2.5–10 respectively. Because of swirl generation and increase of fluid path length, Nusselt number and friction factor are maximum at lowest twist ratio. The reduction of 10-45% in circumferential temperature difference eventually lowers the thermal deformation in the receiver. Borunda et al. [26] applied the multi objective genetic algorithm approach for analyzing the performance of PTC with different twist ratio and observed that the best pareto optimal solution is achieved with twist ratio 1. The pareto optimal solution is required because at lower mass flow rate the efficiency is higher whereas the enhancement is lower and vice versa. Rawani et al. [27] analytically investigated the performance of cylindrical parabolic solar collector with twisted tape having constant tape ratio 4 at different solar insolation and concluded that there is increase in thermal efficiency with increase in insolation. Elton and Arunachala [28] developed Nusselt correlations for smooth tube and tube with twisted tape under realistic environmental condition. Therminol was used as heat transfer fluid with volumetric flow rate of 7 - 30 liter per hour and found enhancement in heat transfer rate. Thermohydraulic performance of parabolic trough solar collector was investigated by Arunachala [29] using twisted tape as of twist ratio 2.7, 4.1 and 5.2 for Reynolds range 544-1742 and found instantaneous efficiency 40% against 19% of smooth tube absorber with negligible pressure drop. Thapa et al. [30] conducted the experiment for thermal enhancement of parabolic trough solar collector by adopting passive technique. For this, multiple perforated twisted tape was investigated with different perforation ratio of 0.05, 0.15 and 0.25, twist ratio 3,4 and 5 and wing depth ratio 0.1, 0.2 and 0.3 for Reynolds range 3000 to 21000 with air as heat transfer fluid and found augmentation in thermohydraulic efficiency by 2.4 times than that of plain receiver. The large thermal gradient in the absorber tube led to thermal losses and ultimately affecting the thermal efficiency. Xiao et al. [31] proposed the curved twisted baffles inside the absorber tube that produces the longitudinal swirl which reduces the thermal gradient thereby increasing the overall efficiency of the parabolic trough solar collector. Muter and Al-Hadithi [32] numerically investigated the impact of twisted tape as insert in absorber tube and simulations were done in Ansys Fluent version 17. The performance parameters like useful heat gain, thermal efficiency and exit temperature were numerically investigated under the climatic condition of Fallujah city and found the higher efficiency in case of absorber tube with twisted tape rather than the plain absorber tube. Rawani et al. [27] numerically investigated the effect of twisted tape at different insolation and different mass flow rate on the thermal efficiency of parabolic trough solar collector. It was found that heat loss and outlet fluid temperature reduce with increase in mass flow rate whereas heat loss, useful heat gain and thermal efficiency increases with increase in insolation. Afsharpanah et al. [33] analyzed the multiple twisted tape with different geometry like perforated, square cut and V-cut numerically and performed simulations in commercial CFD code Ansys fluent using pressurized water as heat transfer fluid for Reynolds ranging from 10,000-20,000 and found the performance of square cut twisted tape is better in terms of thermo-hydraulic efficiency than other twisted tape.

Corrugations and Internal Fins

Corrugation in the absorber tube is one of prominent technology in the field of passive heat transfer augmentation technique. Akbarzadeh and Valipour [34] experimentally analyzed the thermal performance using helically corrugated surface under ASHRAE standard 93-2010 in the Reynolds number range of 5000- 10000. The thermal and exergy efficiencies of PTC increased with the reduction in pitch ratio and with increase in rib-height ratio. At absorber tube with geometry ($P/D_h = 0.12$ and $e/D_h = 0.06$), the maximum efficiency of 65.8% is achieved. Thermal enhancement is also associated with friction factor increment of 35.5%-84.8%. Benabderrahmane et al. [35] investigated the thermal enhancement by placing the corrugated insert in the central portion of the receiver tube and found that the thermal enhancement is more than conventional absorber tube. The Nusselt number increment is 3.7 times than that of conventional absorber which makes the overall heat transfer augmentation in the range of 1.3-2.6.

Laaraba and Mebarki [36] investigated the impact of different fin geometry on thermal augmentation of PTC. The main objective was to study the effect of longitudinal fins in the lower half of the of the absorber tube and it was observed that 15mm fin length and 6mm fin thickness are optimum values giving better thermal enhancement by 8.45%. Bellos et al. [37] analytically investigated twelve longitudinal fins of different geometries and the parameters like Nusselt number, pressure losses and thermal performance index was compared with that of smooth absorber tube. The researcher examined the thermal efficiency, enhancement index and friction factor for the fin length ranging from 5 – 20 mm and fin thickness ranging from 2 – 6 mm. The impact of fin thickness is less intense than fin length. The combination of higher fin length and higher fin thickness led to higher thermal performance but with higher pressure losses. Optimal thermal efficiency is obtained in the case of 20mm fin length and 6mm fin thickness. Nusselt number is proved to be 2.65 times greater than smooth tube for 600 K inlet temperature. Under same temperature inlet condition, thermal efficiency and thermal enhancement index is found to be 1.27% and 1.48% respectively higher than that of smooth absorber.

Combined Effects of Different Inserts and Nano Fluids

Varun et al. [38] performed an indoor experiment in which two insert i.e. wire matrix and twisted tape were taken to observe thermo-hydraulic performance of PTC and the researcher also analyzed the impact of Nusselt number on receiver length. It was concluded that thermo-hydraulic efficiency of medium dense wire is maximum and twisted tape of twist ratio 3.37 give better PEC. A mathematical model was analyzed by Bellos and Tzivanidis [39] in Engineering Equation Solver to investigate the performance of inserts like internal fins, metal foam and dimpled absorber on the thermal enhancement of parabolic trough collector and observed the Nusselt enhancement of 2.5 times than that of smooth absorber. Bellos and Tzivanidis [40] analytically investigated the thermal performance of internal fins, perforated plate and twisted tape with syltherm 800 as HTF on both non-evacuated and evacuated tube. The result obtained in terms of thermal efficiency enhancement was higher for internal fins followed by perforated plate and twisted tape. High thermal losses are found in non- evacuated tube so there is high possibility of performance improvement margin and hence thermal enhancement found higher in case of non- evacuated tube collector. Using finite volume method Abbasian Arani and Memarzadeh [41] investigated the impact of combination of corrugated absorber tube and twisted tape as insert with nanofluid as heat transfer fluid was numerically investigated and found higher performance evaluation criteria as compared to smooth tube. Heyhat et al. [42] experimentally investigated the effect of nanofluid with metal foam as volumetric absorption medium. The thermal performance was examined at different concentration of Cuo/water nanofluid and found thermal efficiency rise by 13-95%. However, pressure drop is found to increase 50-80 times as compared to pure water. Ajbar et al. [43] developed thermal model to investigate the impact of eight different hybrid fluid on the outlet temperature and thermal efficiency of PTC where enhancement in thermal efficiency was observed to rise by 1.6%. The author investigated the performance taking syltherm 800 as base fluid. Among eight hybrid nanofluid, 1.5% Cu-1.5% MgO/Syltherm 800 shows higher Nusselt enhancement as compared to other hybrid nanofluid due to higher thermal conductivity and higher density. Hamada et al. [44] developed a novel parabolic trough solar collector with modification like coating the absorber tube with Cuo nanoparticle and black paint. Further inserting the fins in the outer surface of the tube and adding nano fluid with water as base fluid. The investigation was done to evaluate the thermal efficiency of PTC as compared to conventional PTC and found augmentation in thermal enhancement by 19.18% and 26.23% in finned type absorber tube and nano-coated absorber tube respectively. Heyhat and Khattar [45] carried out experimental investigation in the absorber tube of PTC by placing the different layout of porous copper foam at the center, lower half and periphery of the absorber tube and it was observed that if copper foam placed at center, then it yields higher thermal efficiency with penalty of pressure drop. However, considering the performance aspect, the placement of copper foam at the periphery is the optimal solution. Esmaeili et al. [46] numerically investigated and simulated the impact of combination of conical turbulator and hybrid nanofluid on the heat transfer rate and entropy generation in parabolic trough solar collector and it was observed that heat transfer rate increases by 36 % and entropy decreases by 33%. The novelty of the research was to investigate the innovative conical helical gear ring with Al_2O_3–Cu/water hybrid nanofluid. Dezfulizadeh et al. [47] concluded that numerical investigation consumes less time and less energy for checking the feasibility and thermal performance of inserts inside the absorber tube of PTC. This study explored the impact of combined twisted tape and hybrid nanofluid and found the maximum exergy efficiency at Reynolds number 1000 and at pitch ratio 2. The researcher introduced the innovation in the geometry of absorber tube of PTC wherein the elliptical cross-sectioned receiver has been used with turbulator and various parameters like exergy, performance index, energy efficiency has been obtained. Ghanbari et al. [48] numerically investigated the influence of different geometry of receiver tube with turbulators and magnetic hybrid nanofluid on the thermal performance of PTC in the Reynolds range from 18000 to 42000. The compound turbulator proved better thermal performance with magnetic hybrid nanofluid in the receiver of PTC. Chakraborty [49] numerically investigated the effect of spinning flower insert with six different types of working fluid and simulation has been done in ANSYS 22R Fluent. The entire investigation was done with the spinning insert speed ranging from 0 rad/s - 15 rad/s.at flow rate 0.016 kg/s -0.033 kg/s. The working fluid is nanofluid (combination of Al_2O_3, GO, CuO) with water as base fluid. The spinning flower selected are of different diameter with various sized holes are investigated and it was found that 6mm diameter of petal has obtained higher outlet temperature of 390K and higher heat transfer coefficient of 654W/m^2 at flow rate of 0.016 kg/s. Abed et al. [50] numerically investigated four strip of different geometry like large conical, small conical, rectangular and elliptical shape strips inserts in the receiver of PTC. The working fluid considered is nano fluid in which 6% of Sio_2 mixed in Therminol VP I which increase the output temperature of fluid thereby help in decreasing the absorber wall temperature. Among four strips, straight large conical strip yields maximum Nusselt enhancement up to 57% with base fluid and 62% with nanofluid. Pazarlıoğlu et al. [51] performed numerical investigation using the combination of turbulator like elliptical dimpled fins having different elliptical ratio ranging from 0.66 -1.66 and hybrid nanofluid with syltherm 800 as base working fluid to evaluate the exergetic, entropy and energetic generation in PTC and found the rise in Nusselt number by 38% as compared to smooth tube. The performance criteria index was obtained 1.81 with elliptical ratio 5/3. A CFD theoretical approach was used to model the performance of PTC. Darbari et al. [52] investigated the effect of different configuration of porous aluminum disc on the thermal performance of PTC. The pore size, diameter of disc and placing the disc at lower side or upper side of absorber tube affect the operational parameters of PTC. The fully porous disc yields better performance than the semi porous disc and yield PEC of 1.6. A detailed review has been given by Raja et al. [53] for increasing the efficiency of solar collector by using nanofluid, novel tube geometry, phase change material etc. Sahini et al. [54] numerically investigated the impact of alumina nanofluid in direct absorption solar evacuated tube and observed the outstanding performance of collector in terms of efficiency.

Methodology for Analysis

This section presents the numerical and analytical model adopted widely for performance analysis of PTC. As evident from all numerical study Yılmaz et al. [8] used the realizable $k - \varepsilon$ model which gives accurate results because of additional terms. The prediction of separated flows and flow with secondary complex features is feasible using realizable $k - \varepsilon$ model, which makes it better compared to other $k - \varepsilon$ models. Furthermore, the author used MCRT ray tracing for estimation of non-uniform heat flux on the absorber tube.

As compared to work done using other augmentation geometry like twisted tape and corrugations, the author has used tetrahedral mesh which eventually reduces the computation time. Moreover, the author also performed mesh dependent study to predict more accurate results.

The Reynolds number is predicted using standard correlation which may not be feasible for wire coils owing to generation of vortices in flow field which will give rise to turbulence, instead Nusselt correlation using regression analysis is presented.

Şahin et al. [5] used standard correlation for Reynolds number which again needs more insight due to insertion of wire coils. This is the only study reported in the literature to use $k - \varepsilon$ turbulence model, which eventually becomes inadequate for estimation of numerical friction factor.

Diwan and Soni [7] presented numerical simulation of PTSC using wire coiled insert. The Nusselt number correlation used is given in Table 2.

It is valid for a large range of Reynolds number from 80-90000. Instead, correlation suggested and validated by Manglik and Bergles which is presented in Table 2 are better to use owing to limited range of Reynolds number suggested.

Numerical and analytical study of PTSC using porous metal foam is not reported in the literature. The Experimental studies conducted by Valizade et al. [9] and Jamal-Abad et al. [12] have used the ASHRAE standards

Table 1. Requirement of environmental conditions based on ASHRAE standards

Parameter	Range
Solar Heat flux W/m^2	>800
The fraction of diffusion	20% max.
Wind velocity (m/s)	2 m/s to 4 m/s

for determination of performance parameters of parabolic trough solar collector using porous metal foam. The detailed description of environmental conditions and its corresponding range to predict the collector efficiency as per ASHRAE 93 standards is given in Table 1 [53].

ASHRAE standard suggests performing the test according to specified conditions and various range of inlet temperature. The corresponding equations considered to eventually calculate the efficiency of the collector is given below [53].

$$Qu = mcp(T_o - T_i) \tag{1}$$

The useful energy collected from the collector is given by equation 2 [55].

$$Qu = F_R\left(A_a G_i \eta_o - U_l A_r \left(T_i - T_a\right)\right). \tag{2}$$

Here Qu is the energy gain, A_a denotes the area for solar absorption. For the case of PTC, it will be the projected area of the absorber tube. F_R is the heat removal factor and η_o is the optical efficiency. The solar irradiance is taken as G_i and U_l is the overall loss coefficient.

The thermal efficiency and collector heat removal factor is obtained using equations 3 and 4 respectively [53].

$$\eta = F_R\left(\eta_o - U_l\left(\frac{T_i - T_a}{G_i C}\right)\right) \tag{3}$$

$$F_R = \frac{mc_p}{A_{ri}U_l}\left[1 - \exp\left(\frac{-A_{ri}U_l\bar{F}}{mc_p}\right)\right] \tag{4}$$

Where $\overline{F}$ is the collector efficiency factor.

The heat transfer phenomena in PTC pertains to analysis of complex problem with variable flux encountered. To achieve dynamic similarity between prototype and model it becomes imperative to predict the performance of such system using numerical approach which gives a near accurate prediction of heat transfer rate in PTC.

Primarily researchers have used conservation equations of mass, momentum, and energy to predict system behavior, these are partial differential equations which are solved using appropriate tools and solution scheme considering the stipulated boundary conditions.

Depending on the problem, the mathematical expressions differ with initial and boundary conditions, these PDE's are used for determining the change in time over which the heat spread through the space.

Moreover, simple heat transfer problems can be solved by analytical method like D Alembert or variable separation method, but these methods are not as accurate as the numerical approach. Also, the iteration and convergence become tedious and difficult in analytical method whereas the numerical approach give fast and accurate result owing to availability of commercial software package like ANSYS fluent. Researchers have options to choose from FEM, FVM, FDM and boundary element method. The common objective of any numerical method applied in heat transfer problem solving is to achieve approximate solution of the governing equation to achieve convergence in lesser time. The result obtained in numerical approach assist the development of prototype PTC effectively. The accuracy of numerical method depends on the quality of discretization. Detailed description of equations and corresponding solution methods used in solving PTC heat transfer problem is described here subsequently.

Researchers have used finite volume-based approach for numerical analysis of PTC with twisted tape insert [20]. It is quite evident from literature that realizable k-ε turbulence model is used for analysis with hexahedral elements and SIMPLE algorithm is used for pressure velocity coupling. The second order upwind scheme is preferred for solution purpose. In realizable k – ε model, two additional equations are solved for transport of turbulent kinetic energy and turbulent dissipation rate thereby more adopted in comparison with standard k-ε model. The eddy viscosity effects are also considered in research. The considered equation for numerical analysis is widely adopted Reynolds averaging Navier Stokes equation which is given by equation 5, 6 and 7 [20].

Conservation of mass:

$$\frac{\partial}{\partial x_i}\left(\rho \bar{u}_i\right) = 0 \tag{5}$$

Conservation of momentum:

$$\frac{\partial}{\partial x_j}\left(\rho \overline{u_i}\,\overline{u_j}\right) = -\frac{\partial \bar{p}}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\mu_{eff}\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) - \frac{2}{3}\mu_{eff}\frac{\partial \overline{u_i}}{\partial x_i}\delta_{ij} - \rho\overline{u_i u_j}\right) \tag{6}$$

Conservation of Energy:

$$\frac{\partial}{\partial x_j}\left(\rho \overline{u_j} C_p \overline{T}\right) = \frac{\partial}{\partial x_j}\left(\lambda \frac{\partial \overline{T}}{\partial x_j} + \frac{\mu_t}{\sigma_{h,t}}\frac{\partial C_p \overline{T}}{\partial x_j}\right) + \overline{u_j}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \overline{u_i}}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) - \frac{2}{3}\mu_{eff}\frac{\partial \overline{u_i}}{\partial x_i}\delta_{ij} - \rho\overline{u_i u_j}\right] \tag{7}$$

$$\rho \overline{u_i}\,\overline{u_j}$$

Are the Reynolds stresses and u_i, u_j are the velocity components. The Boussinesq approach is the most common technique for estimation of Reynolds stresses which is represented by equation 8 [20].

$$\rho\overline{u_i}\overline{u_j} = \mu_t\left(\frac{\partial\overline{u_i}}{\partial x_j}+\frac{\partial\overline{u_j}}{\partial x_i}\right)-\frac{2}{3}\left(\rho k-\mu_t\frac{\partial\overline{u_k}}{\partial x_k}\right)\delta_{ij} \quad (8)$$

The energy equation for the solid domain under examination is given by equation 9 [20].

$$\lambda\nabla^2 T = 0 \quad (9)$$

The corresponding equation for turbulent kinetic energy is given by equation 10 [20].

$$k = \frac{1}{2}\left(\overline{u'^2}+\overline{v'^2}+\overline{w'^2}\right) \quad (10)$$

The eddy viscosity effects are also taken into consideration for analysis and is to be determined by the equation 11 [20].

$$\mu_t = \rho c_\mu\frac{k^2}{\varepsilon} \quad (11)$$

As described above in most of the numerical studies, the realizable k-ε model is used for turbulence modeling. The transport equation for turbulent kinetic energy is given by equation 12 [20].

$$\frac{\partial}{\partial x_j}\left(\rho k\overline{u_j}\right) = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon \quad (12)$$

The flow will generate a velocity gradient due to which there is generation of turbulent kinetic energy which is given by equation 13 [20].

$$G_k = \rho u_i' u_j'\frac{\partial\overline{u_j}}{\partial x_i} = \mu_t S^2 \quad (13)$$

Since the realizable k-ε model considers generation of turbulence kinetic energy also with dissipation rate, henceforth the dissipation rate transport equation is given by equation 14 [20].

$$\frac{\partial}{\partial x_j}\left(\rho\varepsilon\overline{u_j}\right) = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma k}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+c_1\frac{\varepsilon}{k}G_k-\left(c_2+\frac{c_\mu\eta^3\left(1-\eta/\eta_o\right)}{1+\beta\eta^3}\right)\rho\frac{\varepsilon^2}{k} \quad (14)$$

Here the strain rate S is calculated using the equations 15,16 and 17 [20].

$$\eta = S\frac{k}{\varepsilon} \quad (15)$$

$$S = \sqrt{2s_{ij}s_{ij}} = \sqrt{\frac{G}{\mu_t}} \quad (16)$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial\overline{u_i}}{\partial x_j}+\frac{\partial\overline{u_j}}{\partial x_i}\right) \quad (17)$$

$C_1 = max\left[0.43, \frac{\eta}{\eta+5}\right]$, $\eta = S\frac{k}{\varepsilon}$, $S = \sqrt{SijSij}$, $C2 = 1.9$, where $\sigma k = 1, \sigma\varepsilon = 1.2$

The values of constants in equation 14 are taken appropriately from the literature.

However, in work done by Mwesigye et al. [20], there is direct estimation of convective heat transfer coefficient and assumed to be uniform, instead it would be more realistic to calculate heat transfer coefficient from Nusselt number which is eventually determined from Reynold number which alters depending upon the fluid path, type, and geometry of twisted tape. Moreover, the correlation for Nusselt number and friction factor as suggested by Mwesigye is done using regression analysis and henceforth only valid for a typical range of Reynolds number. The generalized equations are more preferred owing to coverage of large variation in non-dimensional parameters.

Hossenalipour et al. [25] validated the numerical result with that of experimental correlation used by Manglik and Bergles [56]. Jaramillo et al. [19], Bhakta et al. [21] and Jafar and Sivaraman [23] performed experimental study in twisted tape insert used in PTSC. However, Jaramillo et al. [19] considered same Reynold no. for plain and enhanced tube and Nusselt correlation is changed only considering twist ratio. This prevents the occurrence of more realistic result. The author also studied entropy generation which is suggested to be good value if within 1, which is in line with previously published results by Mwesigye et al. [20]. Direct comparison of performance is not feasible since researchers have used different geometry like wall detached tape, serrated twisted tape, and nailed twisted tapes. Use of Guoy stodola theorem for estimation of entropy generation is done by Rawani et al. [22]. Jaffar and Sivaraman [23] performed experimental investigation but the theoretical analysis is done using basic correlation which are advisable only for plain tube conditions. Moreover, the correlation for Nusselt number was developed using Response Surface Methodology approach to generate a polynomial equation.

Various equations of Nusselt number are used by researchers which are represented in below table.

Owing to wide variation in used correlations, it becomes difficult to make direct comparison of results.

Table 2. Nusselt correlation used by researchers

Sr. No.	Author	Type of insert	Nusselt correlation
1	Jafar and Sivaraman [23]	Twisted tape	$Nu = 9.83 + 1.21\,\mathrm{Re} - 1.42Y - 0.22\,\mathrm{Re}\,Y + 0.42\,\mathrm{Re}^2 - 0.24Y^2$
2	Rawani et al. [22]	Twisted tape	$Nu = 1.86(\mathrm{Re}\,\mathrm{Pr})^{0.33}\left(dri/L\right)^{0.33}$
3	Mwesigye et al. [20]	Twisted tape	$Nu = \dfrac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/8)^{0.5}(\mathrm{Pr}^{2/3}-1)}$
4	Jaramillo et al. [19]	Twisted tape	$Nu = 0.224\,\mathrm{Re}^{0.66}\,\mathrm{Pr}^{0.4}\left(\dfrac{y}{w}\right)^{-0.6}$
5	Diwan and Soni [7]	Wire coils	$Nu = 0.132\left(\dfrac{p}{d}\right)^{-0.372}\mathrm{Re}^{0.72}\,\mathrm{Pr}^{0.37}$
6	Manglik and Bergles [56]	Twisted tape	$Nu = 4.631\left(\dfrac{\mu_b}{\mu_w}\right)^{0.14}\left[0.4935\{\mathrm{Pr}(\mathrm{Re}_a/y)^{3.475}\}^{0.53} + \left(1+0.0954Gz^{0.8685}\right)^{2.63}\right]^{0.2}$

Also change in geometry makes it non feasible to make direct comparison.

Seldom experimental work is reported in the literature using fins inside absorber tube of PTSC. This is in account of manufacturing difficulties and associated economic costing which cannot be justified unless adopted commercially. Akbarzadeh et al. [34] used ASHRAE standard 93 which is widely accepted, and performance parameters can be measured effectively. Moreover, Bejan number which is universally adopted standard for measurement of entropy generation is used in this study. numerical investigation is performed, wherein, realizable k-ε model is solved using FVM approach and SIMPLE algorithm which is widely adopted in CFD studies. However, in work done by Laaraba et al. [36], there is no mention of Reynold number correlations which will differ in case of corrugations. Also, the fins are only used in lower half of the tube, which is the only case referred in this literature, hence validation with theory should be done with experimentation. Moreover, fins with different geometry can be explored like circular, trapezoidal etc., which provides more prospects for further research. Bellos et al. [37] has considered Reynold number using standard correlation which may differ with results considering fins in the flow path. For numerical analysis Benabderrahmane et al. [35] coupled MCRT method with FVM which gives more realistic numerical accuracy. The MCRT is widely used method for estimation of reflected radiation. It can be deduced from available literature that fins has more scope as far as experimental work is concerned. The numerical method adopted for analysis using fins is same as that which is mentioned above.

Furthermore, the researchers have also analyzed the entropy generation rate in PTC [14,31]. The entropy generated is due to heat transfer and fluid friction within the fluid flow in the absorber tube of the PTC. A simple equation comprising both the irreversibility is given by [14] and is represented as equation 18.

$$\dot{S}_{gen} = \left(\frac{Q_{loss}}{T_{amb}} + \frac{Q_u}{T_{in}} - \frac{I_b}{T_s}\right) + \left(\frac{\dot{m}}{\rho}\frac{\Delta P}{T_{amb}}\right) \tag{18}$$

The first bracket in the above equation represents irreversibility due to heat transfer considering finite temperature difference. Whereas the second term in the equation is due to the fluid friction encountered. The parenthesis is well supported by representation of the pressure drop term appearing in the second bracket.

Comparison of Inserts

Different inserts performances are compared in Table 3-6 shows comparison of wire coil inserts, metal foam, twisted tape, corrugated and finned absorber respectively. Whereas, Table 7 summarizes the performance considering combinations of nano fluids and inserts.

Comparative Analysis

Most research is done using numerical approach and seldom experimental work found in literature. Table 8 gives the comprehensive review of heat transfer enhancement performance using different inserts in the absorber tube of PTC. Performance parameters are Nusselt number enhancement (Nu/Nu_p), friction factor increment (f/f_p) and performance evaluation criteria (PEC). PEC is the ratio of Nusselt number enhancement and friction factor increment. Higher the PEC, better will be the performance of collector.

Effect of Different Turbulators on Fluid Flow Behaviour

This section intends to present the physical behavior of fluid flow while using the turbulators. The explanation for

Table 3. Comparison of wire coiled inserts

Author	Investigation method	Working fluid	Key observations
Sahin et al. [5]	Experimental method and numerical simulation by three dimensional CFD computer code	Air	This study is limited to Reynolds number ranging from 3000 to 17000.With increase in Reynolds number and with decrease in pitch distance, the Nusselt number increases with penalty of pressure drop. Heat transfer enhancement is 2.28 times better than smooth tube.
Diwan and Soni [7]	Analytical and simulation in COMSOL Multiphysics(R) 4.4	Water	Heat transfer performance is analyzed at different mass flow rates and for different pitch values of wire coil and it is observed that Nusselt number increases by 104 - 330%.
Yılmaz et al. [8]	Monte-carlo ray tracing and CFD tool	Therminol VP -1	The insert used is triangular cross-sectioned wire coil which eventually enhances the heat transfer rate by 183%

Table 4. Comparison of metal foam inserts

Author	Investigation method	Working fluid	Key observations
Valizade et al. [9]	Experimental study. ASHRAE Standard 93-2010 is utilized to compute the performance parameters	Water	Thermal enhancement using copper foam with full porous and semi porous foam is investigated experimentally and found full porous arrangement yield thermal efficiency of 60.23% and semi-porous yield 49.42%.
Wang et al. [10]	Experimental	Water	Metal foam placed at different location of absorber tube is investigated experimentally and it is observed that metal foams inserted at the top of the receiver tube yield better performance in which it is found that Nusselt increases by 10–12 times with the increase of friction factor by 400–700 times than that of plain absorber tube.
Reddy et al. [11]	Experimental	Water	Thermal performance analyzed using six different receiver configuration and found Collector efficiency improved by 63.9 to 66.6%.
Jamal et al. [12]	Experimental	Water	The overall loss coefficient decreases by 45% which eventually increases the thermal efficiency of the collector.
Khattar and Heyhat [13]	Experimental	Water	An exergy, entropy, environmental and economic analysis of direct absorption parabolic trough solar collector is investigated using different configuration of metal foam at different flow rate of heat transfer fluid.
Zheng et al. [14]	Numerical	Mixed nitrate molten salt	Enhanced receiver tube (ERT) was numerically investigated with different porous insert configuration and found ERT with partially filled porous insert yield better performance than ERT with fully filled porous insert.
Peng et al. [15]	Numerical	Syltherm 800	Gradient metal foam used as heat transfer enhancement technique in PTC and it is observed that Nusselt number enhances by 43.7% - 81.26%
Kumar and Reddy [16]	Numerical	Superheated steam	The metal foam insert led to reduction in circumferential temperature difference from 47% - 72% and PEC obtained is 5
Peng et al. [17]	Numerical	Syltherm 800	The novel design, semi annular fin shape metal foam is investigated and observed increase in Nusselt number by 256% - 838% with rise in friction factor from 440% - 778%.

Table 5. Comparison of twisted tape inserts

Author	Investigation method	Working fluid	Key observations
Jaramillo et al. [19]	Analytical investigation is performed using first and second law of thermodynamics. The analytical model is supported with experimental results. Empirical correlations of Nusselt number is used.	Water	The analytical investigation done using twisted tape of four different twist ratio 2.5,3,3.5 and 4 at temperature range of 70-110 º C. Heat transfer and thermal efficiency enhances as twist ratio decreases with the penalty of pressure drop.
Mwesigye et al. [20]	Numerical analytical investigation based on finite volume method with K-€ model.	Water	The thermal performance of PTC is analyzed using Wall detached twisted tape in the Reynolds number ranging from 10260 -13,53, 000 and it was observed that the thermal enhancement is 1.05 to 2.69 times more than that of plain receiver.
Bhakta et al. [21]	Experimental	Water	The experimental investigation carried out using nail twisted tape of different nail pitch ratio of 4.787, 6.914 and 9.042 respectively. It is observed that the instantaneous efficiency reaches to 64.8% at nail pitch ratio 4.787 and decreases with increase in nail pitch ratio.
Rawani et al. [22]	Analytical	Therminol VP-1	Heat transfer coefficient with serrated twisted tape insert increases by 4.38 times to that of plain tube at twist ratio 1 and at mass flow rate of 0.6kg/s.
Jafar and Sivaraman [23]	Experimental. Response surface metho using central composite design was applied to develop emprirical relationship for predicting Nusselt number and friction factor.	Water	Nusselt number increases by 20 - 30% with nail twisted tape as compared to plain twisted tape and thermal efficiency increases by 27% with nail twisted tape as compared to plain tube.
Isravel et al. [24]	Experimental	Water	Modified ring attached twisted tape yield better heat transfer enhancement than ring attached and conventional twisted tape insert. The thermal enhancement for modified ring attached twisted tape and simple ring attached twisted tapes are 24% and 19% respectively more than the conventional twisted tape.
Hosseinalipour et al. [25]	Numerical simulation using ICEM software performed by solving mass, momentum and energy conservation equation using appropriate boundary conditions.	Steam	The effect of geometrical parameters like twist ratio of twisted tape is investigated numerically on the thermal performance of PTC and it is observed that Nusselt number increases by 1.0-1.7 times more than that of plain receiver tube.
Borunda et al. [26]	Numerical-Genetic algorithm	Water	The multi objective genetic algorithm approach is applied for analyzing the performance of PTC with different twist ratio and observed that the best pareto optimal solution is achieved with twist ratio 1. The pareto optimal solution is required because at lower mass flow rate the efficiency is higher whereas the enhancement is lower and vice versa.
Rawani et al. [27]	Numerical	Thermic fluid	Analysis done on different mass flow rate, different solar insolation and at different twist ratio reveals heat loss, fluid outlet temperature and useful heat gain reduces with increase in mass flow rate and increases with increase in solar insolation
Elton and Arunachala [28]	Experimental	Therminol VP1	The experiment was conducted for Reynolds number range 2300-25000 at different twist ratio and at different volumetric flow rate ranging from 7 to 30 liter per minute. The Nusselt correlations is developed for smooth tube and tube with twisted tape under realistic non uniform heat flux.

Table 5. Comparison of twisted tape inserts

Author	Investigation method	Working fluid	Key observations
Arunachala [29]	Experimental	Syltherm 800	The experiment was performed for Reynold range 544-1742 at different twist ratio of 5.2, 4.1 & 2.7 and observed maximum instantaneous efficiency of 40% at twist ratio 2.7.
Thapa et al. [30]	Experimental	Air	The thermo-hydraulic performance was investigated with twisted tape having different perforation ratio and different wing depth ratio for Reynolds range 3000-21000 with four number of twisted tapes. The optimal combination for maximum Nusselt enhancement was found at twist ratio 3, perforation ratio 0.05 and wing depth ratio 0.3
Xiao et al. [31]	Numerical	Syltherm 800	The novel inclined curved twisted baffles were investigated and found the overall efficiency increases by 0.52% and exergy efficiency increases by 0.22 %.
Muter and Al-Hadithi [32]	Experimental	water	The experimental investigation is carried out in finding thermal performance of collector using twisted tape of fixed twist ratio 4 and observed rise in thermal efficiency by 44%.
Afsharpanah et al. [33]	Numerical	Pressurized water	Multiple twisted tape with different geometry like perforated, square cut and V-cut numerically investigated for Reynolds number ranging from 10,000 to 20,000 and found the performance of square cut twisted tape is better in terms of thermo-hydraulic efficiency than other twisted tape.

Table 6. Comparison of corrugated and finned tube absorber

Author	Investigation method	Working fluid	Key observations
Akbarzadeh and Valipour [34]	Experimental using ASHRAE 93 standard 2010	Water	Analysis is done on different geometry of corrugations. Thermal performance increases but with penalty of friction factor increment by 35 to 84%. Investigation is limited to Reynolds number ranging from 5000 to 10000.
Benabderrahmane et al. [35]	Numerical	Water	The overall thermal performance enhances using corrugated surface and increase in Nusselt number is 3.7 times more than that of smooth absorber.
Laaraba and Mebarki [36]	Simulation done by solving Navier stokes energy conservation equation.	Syltherm 800	Improvement in thermal efficiency by 8.45%. The impact of fin length as compared to fin thickness is more on thermal efficiency
Bellos et al. [37]	Analytical and simulation in solid works	Syltherm 800	The analytical investigation is carried out of different fin length and of different fin thickness and it is observed that the optimum fin length is 20 mm and thickness 4 mm. Thermal enhancement index increases by 1.27%.

wire coils, twisted tapes, porous metal foam and combination of these inserts with nano fluid is subsequently presented. There is a tangible geometrical parameter difference amongst these turbulator device. The wire coils are measured mostly in terms of its diameter and pitch ratio and the twisted tapes are measured in terms of width ratio and twist ratio. Both devices will exhibit different influence on fluid flow. The boundary layer separation happens in both the techniques; however, the twisted tape will give better enhancement because of the width factor which covers major surface area thereby promoting better heat transfer as compared to wire coils. As mentioned, the researchers have also used porous metal foams within the absorber tube. The influencing factors are pore size and porosity of the foam. More the porosity higher will be the turbulence generated. This section also presents the use of these techniques with hybrid nano fluids. However, in this case the heat transfer enhancement not only depends on the type and geometry

Table 7. Comparison of nano fluid with inserts

Author	Investigation method	Working fluid	Key observations
Ajbar et al. [43]	Analytical	Hybrid nanofluid	Insertion of hybrid nanofluid with syltherm 800 as base fluid proved better working fluid for thermal enhancement in PTC due to its higher thermal conductivity and other thermal properties.
Hamda et al. [44]	Experimental	CuO/water	Novel PTC was developed by inserting fin in the outer side of absorber tube and coating the absorber tube with copper oxide and black paint and to reduce convection loss by air, the annular part is filled with graphite. This design gives average efficiency of 35.8% as compared to conventional PTC
Heyhat and Khattar [45]	Experimental	water	Impact of placing different layout of copper foam inside the absorber tube was investigated and it was observed that the location of placing, geometry of copper foam and porosity play important role in thermal efficiency of PTC. The central location of copper foam yields higher efficiency but it also lead to higher pressure drop so optimal solution was based on PEC.
Esmaeili et al. [46]	Numerical	Hybrid nanofluid with water as base fluid	The objective is to investigate the innovative design of helical conical gear ring with hybrid nanofluid, and it was observed that heat transfer coefficient increases by 57.3% and entropy decreases by 33%.
Dezfulizadeh et al. [47]	Numerical	Multi walled carbon nano tube-Graphine oxide/Syltherm 800	Various types of cross-section like circular tube, horizontal elliptic and vertical elliptic absorber tube have been investigated with combined twisted tape insert and hybrid nanofluid particles and it had been observed that performance evaluation criteria obtained in all cases are more than 1.
Ghanbari et al. [48]	Numerical	Nanofluid with base fluid water	The geometry of receiver was modified using turbulator and its impact was investigated along with hybrid nanofluid on thermal performance of PTC and found the compound coiled turbulator has significant impact on the performance.
Oveepsa Chakraborty [49]	Numerical	Nanofluid with base fluid water	The research investigated the effect of spinning flower insert with six combination of nano fluid particles in terms of outlet fluid temperature and heat transfer coefficient and it is observed that 6mm diameter of petal yields higher outlet temperature of 390K and higher heat transfer coefficient of 654W/m^2 at 0.016 kg/s with nanofluid.
Abed et al. [50]	Numerical	Therminol VP I	The combination of nanofluid with swirl generator enhanced the thermal efficiency of PTC. This research introduced the novel design of four strips of different geometry and found the large straight conical strip yield maximum Nusselt enhancement up to 57% with base fluid and 62% with nanofluid.
Pazarlıoğlu et al. [51]	Numerical	Syltherm 800 as base fluid	Numerical research is to investigate the effect of different types of working fluid and geometrical modification of absorber tube using dimpled fins to evaluate the thermo-hydraulic behavior of PTC. The thermal efficiency enhances from 74% to 80%.
Darbari et al. [52]	Numerical	Syltherm 800	The author investigated the impact of porous aluminum disc having different shape, diameter, pore sizing and spacing between two discs on the thermal performance of PTC and observed that the PEC is 1.6 using fully porous disc.

Table 8. Comprehensive review of different turbulators

Author	Investigation Method	Type of insert	Geometry of insert	Working fluid	Reynolds number range	Findings			Geometry of PTC
						Nu/Nu_p	f/f_p	PEC	
Şahin et al. [5]	Experimental	Wire coil	Pitch-15,30,45mm	Air	3000-17000	2.2 at 15mm and Re-7000	1.5	1.9	-
Diwan and Soni [7]	Analytical and simulation	Wire coil	Pitch-6 to 20mm Wire dia-1.2mm	Water	100-750	2.8 at 8mm pitch	1.3	2.5	L-250mm Di-19.5mm
Yılmaz et al. [8]	Analytical and simulation	Equilateral triangular cross sectional Wire coil	Pitch-0.076,0.114,0.152 Width-0.03, 0.033, 0.036mm	Therminol VP -1	10,000-40,000	1.5	2.67	1.08	L-5m Width-5m φ-80°
Valizade et al. [9]	Experimental study.	Copper Metal Foam	Porosity-0.95 PPI-10 Día of foam-22mm	Water	100-2500	2.12	5.98	1.17------	L-1.5m Width-0.7m Focal-0.175m φ-90°
Wang et al. [10]	Numerical	Copper Metal Foam	Porosity-0.91,0.95,0.97 PPI-5,20,40	Superheated steam	200000-1,000,000	5	10	2.3	L-2m Width-5m Di-0.06m Do-0.07m φ-70°
Reddy et al. [11]	Experimental	Porous disc	Porous disc height 0.308m Thickness-2mm	Water	1000-10,000	-	2	-	L-3m Width-2.5m Di-0.054m Do-0.06m φ-65°
Jamal-Abad et al. [12]	Experimental	Copper Metal Foam	Porosity-0.9 PPI-30 K-399 W/mK Día of porous media-28mm	Water	500-2000	1.5	6.98	1.11	L-1.28m Width-1m Thickness-1mm φ-90°
Khattar and Heyhat [13]	Experimental	Copper Metal Foam	Porosity-0.95 PPI-10 Diameter of porous media-22mm	Water	-	-	-	-	L-1.5m Width-0.7m Do-26mm. φ-90°
Zheng et al. [14]	Numerical	Metal Foam	Porosity-0.97,0.95,0.94 PPI-5,10,20,40	Mixed nitrate molten salt	20000-1000000	2.83	4.5	1.71	Di-18.6mm Do-21mm. Absorber tube-Alloy 800H

Table 8. Comprehensive review of different turbulators

Author	Investigation Method	Type of insert	Geometry of insert	Working fluid	Reynolds number range	Findings			Geometry of PTC
						Nu/Nu_p	f/f_p	PEC	
Peng et al. [15]	Numerical	Gradient Metal Foam	Outer layer thickness-10.7mm Inner layer thickness-30.9mm	Syltherm 800	200000-1000000	5.4	10.4	2.5	L-4.06m Di-64mm Do-70mm.
Kumar and Reddy [16]	Numerical	Metal Foam with varying radial distance	PPI-5-40 Porosity-0.97,0.95,0.91 Radial distance-0.25,0.5,0.75	Superheated steam	-	10	8	5	L-4.06m Width-5.76m Di-0.05m Do-0.07m
Peng et al. [17]	Numerical	Semi annular fin shaped m Metal Foam	Rectangle, triangular, trapezoidal	Syltherm 800	200000-1000000	6	6.2	3.2	L-5m Di-66mm Do-70mm
Jaramillo et al. [19]	Analytical investigation	Twisted tape	TR-2.5,3.3.5,4	Water	2700-21000	2.21	7.21	1.14	L-4.8m Width1.06m Di-2.32cm Do-2.54cm
Mwesigye et al. [20]	Numerical investigation	Wall detached Twisted tape	TR-0.5 to 2 Tape thickness 0.001m	Water	260-1353000	3.16	5.3	1.8	Di-6.6cm Thickness-0.24cm
Bhakta et al. [21]	Experimental	Nail Twisted tape	Length of nail 0.02m Día of nail 0.004m Thickness of NTT-0.0012m	Water	-	---	------	------	L-1.2m Aperture area 2.03m2 Di-0.023m Do-0.025m φ-67.25°
Rawani et al. [22]	Analytical	Oblique delta winglet Twisted tape	TR-1 to 4	Therminol VP-1	3000-9000	3.1	----	1.04	L-7.8m Widht-3m Do-0.043m Di-0.03m
Jafar and Sivaraman [23]	Experimental.	Nail Twisted tape	TR_2,3,5 Thickness-1.5mm Length of nail-11mm Día of nail-1.5mm	Water	-	2.8	1.8	2.3	L-2m Widht-1m Di-12mm Do-12.5mm
Isravel et al. [24]	Experimental	Ring attached Twisted tape		Water	6000-16000	2.32	1.83	1.90	-
Hosseinalipour et al. [25]	Numerical	Twisted tape	TR-2.5 to 10 Thickness-1mm	Steam	10000-100000	1.7	1.8		L-4m Di-50mm Do-70mm

Table 8. Comprehensive review of different turbulators

Author	Investigation Method	Type of insert	Geometry of insert	Working fluid	Reynolds number range	Findings			Geometry of PTC
						Nu/Nu_p	f/f_p	PEC	
Borunda et al. [26]	Numerical-Genetic algorithm	Twisted tape	-	Water	-	-	-	-	L-4.8m Width-1.003m Di-2.32cm Do-2.54cm Φ-90 °
Rawani et al. [27]	Numerical	Twisted tape	TR-4	Thermic fluid	-	-	-	-	L-3.6m Width-1.25m Di-0.038m Do-0.04m
Elton and Arunachala [28]	Experimental	Twisted tape	TR-3.48,5.42,7.36	Therminol VP1	2300-25000	-	-	-	-
Arunachala [29]	Experimental	Twisted tape	TR_5.2,4.1,2.7 Width of tape 0.024m Thickness-0.0014m	Syltherm 800	544-1742	-	-	-	L-1.2m Di-0.023m Do-0.025m Aperture area $1.98m^2$
Thapa et al. [30]	Experimental	Multiple perforated and winglet Twisted tape	Perforation ratio-0.5,0.15,0.25 TR-3,4,5 Wing depth ratio-0.1,0.2,0.3	Air	3000-21000	1.75	1.02	1.7	L-1m Di-81mm
Xiao et al. [31]	Numerical	Inclined curved baffle Twisted tape	L-0.069m Height of baffle 0.005m	Syltherm 800	10,000-20,000	1.58	9	0.7	Width-6m Di-0.06m Φ-80 °
Muter and Al-Hadithi [32]	Experimental	Twisted tape	TR-4 L-2m Pitch-0.085m	water	-	-	-	-	L-2m Width-3.48m Do-0.022m Thickness-0.0195m
Afsharpanah et al. [33]	Numerical	Twisted tape	Normal, perforated, Centre clear, square & V cut double twisted tape	Pressurized water	10000-20000	1.2	1.28	1.11	
Ajbar et al. [43]	Analytical	Hybrid nanofluid	Nanofluid	Base fluid-Syltherm 800	10000-90000	1.5	1.3	1.37	L-7.8m,W-5m, Φ-64.8

Table 8. Comprehensive review of different turbulators

Author	Investigation Method	Type of insert	Geometry of insert	Working fluid	Reynolds number range	Findings			Geometry of PTC
						Nu/Nu_p	f/f_p	PEC	
Hamda et al. [44]	Experimental	Nanofluid, fins	Thickness of fin-2mm,length of fin-1cm	Water and nanofluid copper oxide					Aperture-3.24m2,
Heyhat and Khattar [45]	Experimental	Copper foam	Pore diameter-10,20PPI and porosity-95%	water	700-2500	1.33	7	0.7	L-1.5m, W-0.7m, Φ-90°
Esmaeili et al. [46]	Numerical	Conical ring and nanofluid	-		5000-10000	2.4	3.5	1.6	L-1m
Dezfulizadeh et al. [47]	Numerical	Combined twisted tape and hybrid nanofluid	-	Multi walled carbon nano tube-Graphine oxide/ Syltherm 800	5000-20000			1.68	L-300mm
Ghanbari et al. [48]	Numerical	Hybrid nano fluid and turbulator	-	Base fluid-water	18000-42000	2.25	2.4	1.68	L-1500mm
Chakraborty [49]	Numerical	Spinning flower with nanofluid	Diameter of petal of flower-12-36mm	Base fluid-water	2000-16000	-	-	-	L-7.8m, w-5m Φ-70°
Abed et al. [50]	Numerical	Strips and nanofluid	Large, small, rectangular, elliptical conical strip	Therminol VP I	25000-100000	1.5	-	-	L-4m,W-8m, Φ-95°
Pazarlıoğlu et al. [51]	Numerical	Dimpled fins and hybrid nano fluid	Elliptical ratio-0.6-1.66	Syltherm 800 as base fluid	10000-30000	1.6	1.24	1.49	L-7.8m,D_o-70mm and D_i-66mm
Darbari et al. [52]	Numerical	Porous disc and nano fluid	Full disc and half disc of 22mm diameter	Syltherm 800	5000-45000	1.25	0.75	1.4	L-7.8m, W-5m, Φ-70°

of inserts but also on the thermal properties of concerned nano fluid. The detailed physical effects of these kind of techniques are further explained in the below sub sections.

Wire Coil

Extensive research is done on wire coil inserts in heat exchanger and flat plate solar collectors but very few literatures available on the use of wire coil inserts in parabolic trough solar collector. Use of wire coil produces helical flow at the periphery of the tube. The generated centrifugal forces super impose the rotational flow or swirl flow on the axial central flow. This centrifugal force produces movement of heated fluid from boundary towards axis thus augmenting heat transfer.

In wire coil, only two geometrical non-dimensional parameters are considered which can influence the thermo-hydraulic behavior. They are pitch ratio and wire diameter ratio. Depending on the geometrical criteria of PTC, various co-relations are proposed by researchers for friction factor and Nusselt number. However, an exact experimental evaluation is necessary to analyze the performance in different regimes of laminar, transition and turbulent flow. The co -relations established for wire coil are dependent on flow regimes and boundary condition. Not only the geometrical aspect of wire coil affects the performance, but the location of wire coil inserts from the tube wall also affect the thermo-hydraulic behavior of fluid. If it is placed close to the tube wall region, it interrupts the development of boundary layer which can increase the turbulent intensity but along-with it can lead to the erosion of the tube wall. And if the wire coil is placed far from the tube wall i.e., more clearance between tube wall and insert then there will be bypass flow and eventually fluid mixing diminishes and turbulent intensity also get reduced which ultimately reduce the heat transfer rate.

The numerical investigation carried out on the shape of wire coil i.e., triangular, trapezoidal, equilateral triangle cross-section which give wide scope of investigation to researchers for carrying out the experimental performance of such geometry of wire coil. The wire coil with different pitches ranging from 6mm to 45 mm investigated at different mass flow rate have found enhancement of approximately 1.01 to 1.08. There is more scope of research to investigate by varying the wire diameter ratio and on using wire matrix of different material in PTC.

Twisted Tape

Twisted tape is one of the most promising inserts used in heat exchanger, absorber tube of solar flat plate collector and parabolic trough solar collector. This insert causes the partial blockage of fluid flow which increases the swirl motion, and this led to the increase of turbulence and eventually heat transfer rate. Moreover, the use of twisted tape leads to the reduction in absorber wall temperature with a rise in outlet temperature of heat transfer fluid which results in the rise in thermal efficiency of the collector.

Twist ratio is the most effective parameter which influence the thermo-hydraulic behavior of the fluid. Numerous investigations are done numerically and experimentally for laminar and turbulent region with different fluid like water, air, thermic oil etc. Number of modifications are done in the plain twisted tape and found nail twisted tape [21,23], serrated twisted tape [22], ring attached twisted tape [24], perforated twisted tape [30] which yields better performance than the plain twisted tape. Nusselt and friction factor co-relations are established for wide range of Reynolds number and further based on twist ratio and boundary condition like uniform wall temperature and uniform heat flux condition. Manglik and Bergles [56] established the Nusselt and friction factor co-relations under both uniform wall temperature and uniform heat flux condition considering the reduction in area of fluid flow, tape thickness and formation of swirl velocity whereas other researchers have mainly focused on twist ratio.

Novel design like inclined curved baffle, multiple perforated with varying winglet, square and V-cut double twisted tape are investigated numerically which provides base for experimental studies. Aluminum is mostly used for manufacturing twisted tape due to its lighter weight and high thermal conductivity henceforth there is future scope for investigating other materials.

Porous Media

The application of porous insert in direct absorption solar system enhances the solar absorption. When low radiation absorption coefficient is encountered, the volumetric absorption placed a significant role. Mostly copper foam is used as porous media in fluid like water with combination of nano-fluid as its thermal conductivity is high. The porosity and pores per inch play important role in volumetric absorption of solar radiation as the rays enter the pores and collide with the internal surface thus getting absorbed by the working fluid which enhance the outlet temperature of the fluid which eventually rises the thermal efficiency.

The geometric parameter like porosity, thickness of foam and position of foam on upper side or lower side of receiver have been investigated numerically and experimentally [13]. Major work has been done on copper foam having porosity ranging from 0.01 to 0.98 and PPI ranging from 5 to 40. Peng Hao et al. [15] numerically investigated the novel design of PTC with Gradient metal foam having two layers with varying thickness and found PEC from 1-3. Moreover, Kumar and Reddy [16] numerically investigated the impact of copper foam with varying the radial distance ranging from 0.25 - 0.75m on thermal enhancement of PTC. This novel design has proven better in context to thermal enhancement numerically, which give further insights to explore the feasibility of the inserts as well as to establish the tradeoff between heat transfer enhancement and pressure drop.

Corrugations and Internal Fins

Seldom literature is found on use of corrugations and internal fins. These techniques are known to enhance the heat transfer rates but the geometry is mostly concerned with the modification in the absorber tube itself. These types of geometry are limited due to its manufacturing anomalies which increases the costs incurred. Hence, major research in such kind of techniques is limited to numerical approach as experimental investigation could not be proven cost effective.

Combination of Inserts with Nano Fluids

Nano fluids are known to exhibit thermal properties which enhances the rate of heat transfer by mixing it with base fluid which is mostly water. The nano particles like Aluminum oxides and copper oxides are primarily metal particles which have higher thermal conductivity and subsequently mixed with based fluid using various mixing methods. The use of such nano particles in fluid will conduct the heat more effectively which promotes better heat transfer rates in solar collector. This also leads to saving in the amount of fluid used and further decreasing the overall size of collector for the given rate of heat transfer required. The concentration of nano fluids also plays a crucial role as higher concentration will increase the viscosity of the fluid which will affect the hydraulic behavior of the system. The concentration should be optimum to promote better heat transfer while keeping the power required for fluid flow to be minimum. Use of the technique like nano fluid and inserts combined will greatly enhance the thermal performance of the collector.

Commercial Applications of Parabolic Trough Collector

PTC has wide scope in power generation in many countries because of its high concentration ratio and high temperature output. PTC with aperture area 3.3m^2 is used for water heating purpose yielding temperature range from 50 to 200 ^{o}C in food industry [57]. IIT Madras developed PTC for industrial application in the area of space heating, space cooling, desalination but not yet commercialized [58]. A small sized parabola trough collector of aperture area 2.07m^2 with concentration ratio 9.93 has been investigated experimentally for solar dehumidification purpose in university of Pakistan [59].

Through exhaustive literature survey wide applications of PTC is found, though not commercialized. Numerical analysis and seldom experimental investigations on thermal enhancement are reported with use of tube turbulators but there is no evidence about commercial and industrial applications using such techniques.

CONCLUSION

This paper presents the application of heat transfer enhancement techniques in absorber tube of parabolic trough solar collector using different inserts. The period considered for study is from 2015- 2023 which includes very recent study done in the said field. The current literature reveals the discussion on wire coil, twisted tape, porous metal foam, corrugations and fins and combined effect of these techniques with nano fluids. The below points summarize the major findings of this study.

- The performance evaluation criteria of dimensionless Nusselt number and friction factor are studied in this literature. Based on performance graphs the values of Nu/Nu_p and f/f_p are deduced. The Nu indicates Nusselt number for augmented tube with inserts whereas Nu_p indicates Nusselt number for plain tube. Since the use of inserts enhances the thermal performance, this factor will always be greater than 1. It is found from the literature that use of turbulators gives the value of Nu/Nu_p ranging from 1.1-10 which shows the percentage rise in Nusselt number from 10% to 1000% as compared to plain tube. On the contrary use of such turbulators will also rise the pressure drop across the length of tube. This rise in pressure drop is indicated by f/f_p where f shows the friction factor encountered for augmented tube whereas f_p indicates the friction factor for plain tube. This ratio is observed in the range of 1.02 – 10.1 Henceforth, the percentage rise in friction factor is from 10% to 1000%. Here it becomes imperative for researcher for selection of optimum geometry of such tube turbulators.
- The use of tube turbulators will increase in internal swirl flow which enhances the local Reynolds number and since the Nusselt number is further dependent on Reynold number, there is enhancement observed in all the case using different turbulators.
- Experimental, Numerical, and analytical methods are used by researchers for studying the influence of tube turbulators. Each method has its own advantage and drawbacks. The experimental techniques require costs to be incurred which limits the detailed investigation. The numerical techniques though easier for exploration owing to commercially available software packages are limited since validation of the results would further require experimental investigation.
- There is no evidence of any stipulated approach to justify the performance of the collector. However, ASHRAE 93-2010 standards are commonly used by researchers to measure the efficiency of the collector.
- The analytical method needs more insights as far as performance evaluation of Parabolic trough solar collectors are concerned. This is owing to the fact that various researchers have proposed different Nusselt correlation for different kinds of inserts. This limits the direct comparison for performance prediction. However, if numerical investigation is validated by analytical and experimental approach then the used Nusselt correlations can be justified.
- The experimental studies reveal that the modified twisted tape like nail twisted tape, serrated twisted tape, yields better performance than plain twisted tape. The nail twisted tape yields Nusselt enhancement by 2.8

times. Moreover, the use of square cut dual twisted tape insert stimulates more heat transfer rate than single plain twisted tape by 16%.

- The numerical studies reveals that the use of equilateral triangular cross sectioned wire coil gives better performance than the simple helical coiled wire with 1.08 performance evaluation criteria.
- The use of copper as porous media having 0.95 porosity with 28mm diameter gives Nusselt enhancement by 2.12 times compared to plain absorber tube. The gradient metal foam with varying radial distance is investigated and 0.25 m is found to be optimum which led to Nusselt number enhancement and PEC by factor 10 and 5 respectively. Major numerical simulation is done using ANSYS Fluent, however, use of heuristic methods like Artificial neural network, Genetic algorithm etc. are adopted for prediction and optimization.
- Literature pertaining to commercial application with use of inserts are not reported. However, if patented and eventually penetrated in the commercial market, it has good potential as the overall area reduction for required heat duty will lower the installation cost.

Future Scope of Work

Heat transfer enhancement is always a topic of interest for thermal systems performance. Moreover, heat transfer enhancement in solar collector has been an area of significance since the collectors are devices which incurs large capital investments which demands their optimization as far as their thermal performance is concerned. Based on the literature, the prospects of the work are:

- Major investigation has been made using twisted tapes, wire coils, porous metal foam, corrugations and fins and nano fluids. Other than these, use of wire matrix can be explored which are seldom investigated.
- Different geometry in case of wire coils and twisted tapes can be considered like equilateral cross section wire coils and trapezoidal wire coils whereas in twisted tapes several geometrical modifications like perforations, cuts along the periphery, twin geometry and varying twist ratio along the length of tube can be explored.
- Experimental investigation of combined effect of different geometry along with use of hybrid nano fluids can be explored.
- It is evident from the study that, the rise in Nusselt number using such techniques is accompanied by corresponding rise in friction factor and eventually decrease in flow pressure. The researchers can explore various methods to establish a tradeoff between heat transfer enhancement and pressure drop.

NOMENCLATURE

PTC	*Parabolic Trough Collector*
HTF	*Heat transfer fluid*
CFD	*Computation Fluid Dynamics*
H	*Height (m)*
GO	*Graphine Oxide*
p/D_h	*Pitch Ratio*
e/D_h	*Roughness height*
PEC	*Performance evaluation criteria*
MCRT	*Monte Carlo Ray Tracing*
Q_u	*Useful heat gain* (W/m^2)
$\dot{m}$	*Mass flow rate (kg/s)*
Cp	*Specific heat (J/kg K)*
A_a	*Aperture area* (m^2)
A_r	*Receiver area* (m^2)
G_i	*Solar Irradiance* (W/m^2)
U_l	*Overall loss coefficient* (W/m^2K)
D_{ri}	*Inner Diameter (m)*
L	*Length of collector (m)*
Pr	*Prandtl Number*
Gz	*Graetz number*
D_{ro}	*Outer Diameter*
T_{amb}	*Ambient temperature (K)*
T_s	*Apparent sun temp. (K)*
c_p	*Specific heat capacity (J/kg/K)*
k	*Turbulent kinetic energy* (m^2/s^2)
S	*Modulus of the mean rate-of-strain tensor (1/s)*
S_{ij}	*Rate of linear deformation tensor, (1/s)*
ε	*Turbulent dissipation rate* (m^2/s^3)
λ	*Fluid thermal conductivity (W/m/K)*
σ_k	*Turbulent Prandtl number for k*
μ_{eff}	*Effective viscosity (Pa-s)*
i,j,k	*General spatial indices*
η_o	*Optical efficiency*
$\bar{F}$	*Collector efficiency factor*
A_{ri}	*Inner area of absorber* (m^2)
ρ	*Density* (kg/m^3)
FVM	*Finite volume method*
Nu	*Nusselt Number*
Nu/Nu_p	*Nusselt number enhancement ratio*
f/f_p	*Friction factor increment ratio*
T_{amb}	*Ambient temperature (K)*
I_b	*Beam radiation* (W/m^2)
μ_t	*Turbulent viscosity (Pa-s)*
T_s	*Surface temperature (K)*
Q_{loss}	*Heat loss (W)*
S_{gen}	*Entropy generation*
G_i	*Solar irradiance* (W/m^2)
T_i	*Fluid inlet temperature (K)*
T_o	*Fluid outlet Temperature (K)*
R	*Reflectivity*
W	*Aperture width (m)*
T_{fm}	*Mean fluid temperature (K)*
Re	*Reynold number*
K	*Thermal conductivity (W/m-K)*
A_c	*Cross sectional area* (m^2)
ΔP	*Pressure drop (Pa)*
u_i, u_j	*Averaged velocity components (m/s)*
u', v', w'	*Fluctuations from mean velocity (m/s)*
x_i, x_j	*Spatial coordinates (m)*

$-\rho\overline{u_i'}\overline{u_j'}$	*Reynolds stresses (N/m²)*
δ_{ij}	*Kronecker delta*
η	*Turbulence model parameter (=Sk/ε)*
$\sigma_{h,t}$	*Turbulent Prandtl number for energy*
φ	*Rim angle*

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declare that they have no known financial interest or personal relationships that could have appeared to influence the work reported in this paper.

ETHICS

There are no ethical issues with the publication of this manuscript.

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