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Advancements in Concentrated Solar Power: A Review of Heat Transfer and Parabolic Trough Technologies

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Abstract: This review examines the advancements in concentrated solar power (CSP) technologies, focusing on their potential to meet energy demands sustainably while mitigating global warming. CSP systems, which harness solar energy through mirrors and lenses to generate high-temperature heat, offer a reliable alternative to fossil fuels. Key CSP technologies include Linear Fresnel Reflectors, Parabolic Dishes, Solar Towers, and Parabolic Trough Collectors (PTCs). Each system is assessed for its design, efficiency, and suitability in regions with high direct solar irradiance. Among these, PTCs are highlighted for their cost-effectiveness and thermal efficiency, with applications reaching temperatures up to 550°C, making them suitable for both small and large-scale implementations. The review also explores various heat transfer enhancement techniques, categorized into active, passive, and compound methods. Passive techniques, such as inserts, surface modifications, and nanofluids, are examined for their ability to increase heat transfer efficiency without external energy sources. Active methods like pumps, fans, and compound approaches are discussed for maximizing thermal performance. Advances in receiver design, including twisted tapes, wire coils, fins, and porous materials, are evaluated for their impact on heat transfer rates, thermal losses, and overall system efficiency. Additionally, the potential of nanofluids to improve thermal conductivity is explored. This comprehensive review underscores the importance of optimizing CSP systems to maximize efficiency, offering insights into innovations that could further enhance the adoption of solar thermal energy worldwide.

Keywords: solar thermal efficiency; parabolic trough collectors (ptcs); mitigating global warming.

Introduction

Global warming is the most essential concern nowadays, with repercussions like decreasing the amount of food that could be produced, rising sea levels, and changing weather patterns [1–4]. To combat global warming, it is necessary to discover clean, renewable, and sustainable energy sources to reduce carbon dioxide emissions. Solar thermal energy has been considered a practical solution for reducing our reliance on fossil fuels, reducing emissions that contribute to global warming, and providing human societies with electric power and systems of water heating, in addition to other industrial processes they require [5–8]. Concentrated solar power plants depend upon the direct normal irradiance representing the solar energy amount received for each unit area [9–11]. CSP plants can be designed to operate on a small or large scale, depending on the users' needs. They are particularly well-suited for use in sunny, dry regions. They can provide a reliable source of electricity if there is no sunshine, thanks to thermal energy storage systems [12].

This review aims to comprehensively analyze advancements in concentrated solar power (CSP) technologies, focusing on heat transfer enhancements for Parabolic Trough Collectors (PTCs) to improve thermal efficiency and promote sustainable energy. Objectives include evaluating major CSP systems—Linear Fresnel Reflectors, Parabolic Dishes, Solar Towers, and PTCs—for their design, efficiency, and suitability across applications. Additionally, the review investigates heat transfer techniques [13, 14], categorizing passive, active, and compound methods, and examines innovations in receiver design, such as twisted tapes, fins, and porous materials, for their impact on heat transfer. The potential of nanofluids to improve thermal conductivity in CSP systems is also assessed. This review addresses challenges and future directions in CSP scalability and cost-effectiveness, supporting clean energy goals and contributing to carbon reduction efforts worldwide.

1. Technologies for Concentrating Solar Power (CSP)

All approaches for CSP involve using mirrors or lenses to concentrate sunlight and convert it into electricity. These technologies have similar components, including a concentrator, a receiver, a heat transport medium or storage, and a power conversion unit. The main difference between the various CSP technologies is the shape and configuration of these components. Based on techniques that have been used in order to gather and concentrate solar radiation energy, the technology employed in CSP plants can be divided into four primary groups [15].

1.1. Linear Fresnel Reflectors

In concentrated solar power systems, individual reflectors are placed parallel to the ground so that every one of the reflectors is flat. It has a different focal length than its receiver. The spacing between reflectors is close to minimizing discontinuity in the reflective area or aperture. The reflectors' width has been optimized to allow access to reflectors for maintenance while being manageable to complicate a support or tracking structure. as shown in Fig. 1. In contrast, a reflector could be placed to be related to more than one.

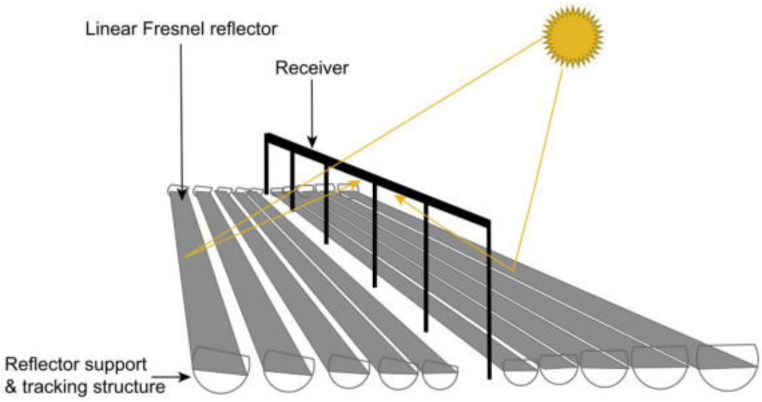

Fig. 1. - Linear Fresnel collector [15].

1.2. Parabolic dish

A parabolic dish collector is a solar thermal energy collector that uses a parabolic-shaped reflector to focus sunlight onto a central absorber tube. The reflector's parabolic shape allows it to focus sunlight onto a tiny area. The dish must follow the sun's movement to direct sun rays onto the receiver. These receivers can reach temperatures above 1,500°C, have concentrations between 600 and 2,000, and are the most efficient among all concentrated solar power (CSP) technologies [16].

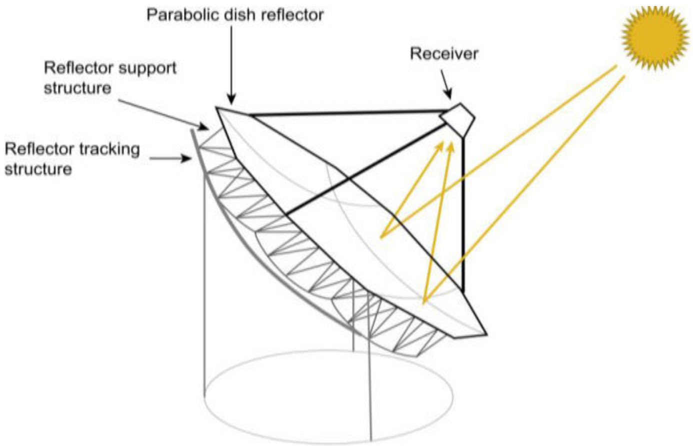

Fig. 2. - Parabolic dish collector [15].

1.3. Solar Tower

Solar towers are thermal power plants that use reflectors to focus sunlight on a central receiver at the top of the tower [17]. Concentrated sunlight makes electricity by heating a fluid, like water, to make steam that turns a turbine generator. The receiver absorbs a large amount of heat, reaching temperatures above 1,500°C [18]. The configuration of a solar tower is depicted in Fig. 3.

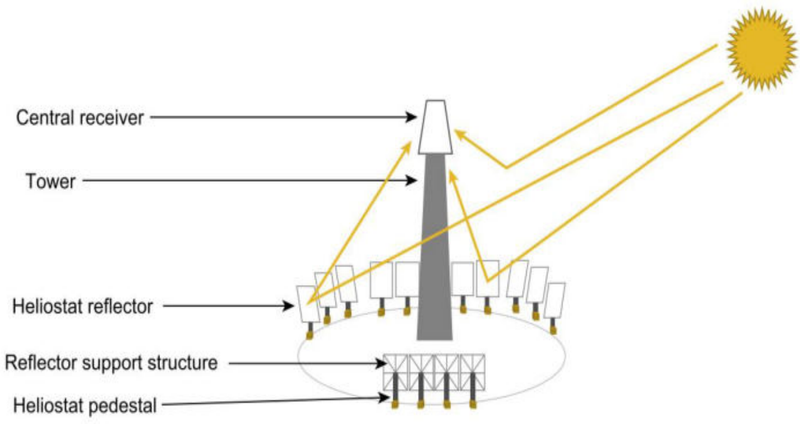

Fig. 3. - Solar tower [15].

2. Parabolic Trough Solar Collector (PTC)

PTC represents the oldest technology utilized in a broad range of applications. Particularly for levels of temperature that are as high as 400oC, PTCs can supply proper heat with high thermal efficiency with reasonable investment costs and are identified as mature and cost-effective technologies [19]. Therefore, this study will focus on this topic. Overall, CSP plants can effectively generate electricity using renewable energy and provide a reliable power source for various applications. However, they require a large amount of land and are typically only practical in areas with high levels of direct normal irradiance.

2.1. Fundamentals of PTCs

PTCs are line-focus concentrators producing high-temperature heat from concentrated solar energy. These systems can reach temperatures up to 550 degrees Celsius, though the exact maximum depends on the application. Figure 4 illustrated parabolic trough collector (PTC) system, the Heat Collection Element (HCE) is positioned precisely along the focal line of the reflective mirrors, serving as the central component responsible for thermal energy absorption. This element comprises a metallic absorber tube—typically constructed from stainless steel or a similar high-thermal-conductivity material—encapsulated within a vacuum-sealed borosilicate glass envelope to minimize convective and conductive heat losses. The absorber tube is designed to carry a heat transfer fluid (HTF), such as synthetic oil or molten salt, which facilitates the efficient transport of absorbed solar energy to downstream thermal conversion systems. Strategically mounted on the collector's structural supports, the HCE plays a critical role in maximizing optical-to-thermal energy conversion, and its precise alignment within the optical axis ensures optimal intercept of concentrated solar flux reflected by the parabolic mirrors.

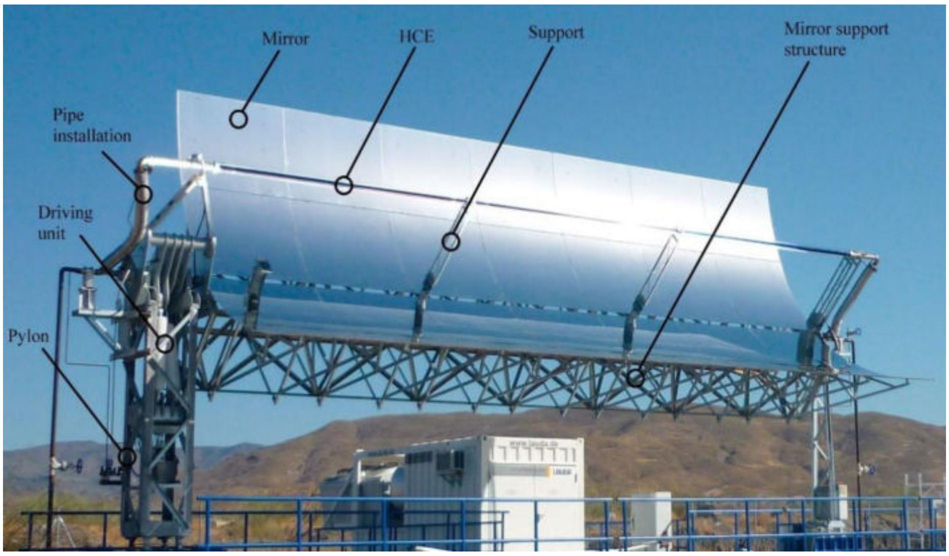

Fig. 4. - Parabolic trough collector system [20].

2.2. Reflector

This element includes high specular reflectance (over 88%) mirrors and structural components that reflect solar energy onto the receiver. The mirrors are typically made from low-iron float glass (about 4mm thick) of the large solar transmittance. They are silvered from the back and coated by selective coatings to maximize their durability and solar reflectance (SR = 0.930). Besides mounting structures, installation significantly affects overall plant performance [21]. In the previous articles, an analysis of reflecting coatings (for mirrors) and the general qualities of various materials was conducted, including an examination of techniques for applying reflective and selective coatings (SCs; for receivers) [22].

2.3. Receiver tube

The solar receiver tube represents a primary component of the solar thermal production systems; the PTC receiver tube is positioned at a point where the focal line of the parabolic mirror lies. In most cases, stainless steel is used for the tube material. A selective coating is applied to the outside of the tube. This coating has high absorptivity but low emissivity. Fig. 5 illustrates the absorber tube with a glass cover over it [23], which makes the outer layer transparent and anti-reflective to solar radiation, contributing to increased tube functionality. It is also capable of reducing convection and radiation losses [24].

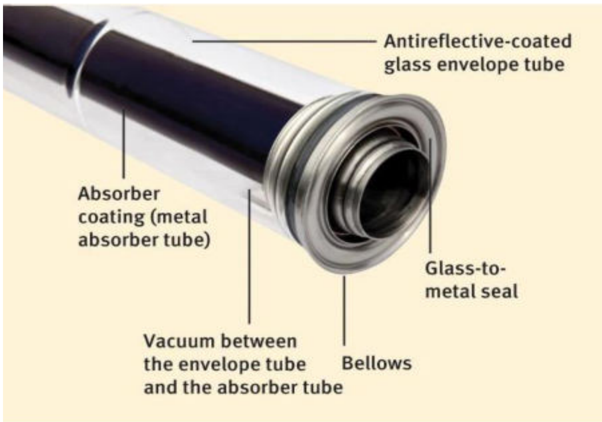

Fig. 5. - Typical receiver tube regarding the PTC [23].

2.4. Heat transfer fluid

The heat energy is relocated from the receiver to the storage system through a transmission fluid. Depending on the operating conditions and design. The choice of this fluid is essential. This fluid must have high thermal conductivity and capacity, low viscosity, low thermal expansion, low toxicity, minimum corrosive activity, and thermal and chemical stability throughout its entire operating temperature range and be environmentally friendly [25,26]. PTCs function at temperatures ranging from low to moderate, with the working fluid achieving temperatures of 50 to 400 degrees Celsius. This temperature range is one in which various industrial activities are carried out [18].

2.5. Solar tracking system

The device also includes one-axis solar tracking to align the trough with the sun's light and ensure that the maximal amounts of radiation are reflected on the focal line [27]. The parabolic troughs have been rotated to follow the sun's day-to-day path across the sky and optimize solar heat uptake.

2.6. Supporting structure

The primary purpose of the supporting structure is to fix the components of the complex, providing rigidity and stability to the entire system. The structure is generally made of structural materials such as steel or aluminum. From a structural perspective, the PTC supporting structure consists of three parts: the primary support (columns, piles, and box), the frame, and the receiver brackets, as shown in Fig. 6 [28].

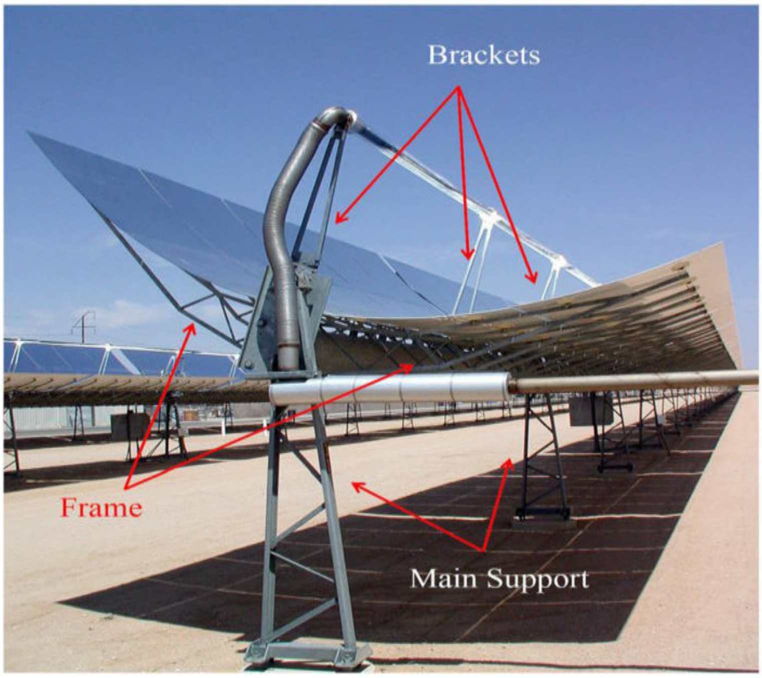

Fig. 6. - Structural division of the PTC.

The parabola's shape must be preserved, and the receiver must be moved to lie on the parabola's focal line. The structure's design is of the utmost importance because bending and torsion imbalances significantly impact the entire system's performance.

3. Heat Transfer Enhancement Techniques

The economic viability of solar thermal systems dramatically depends on the processing and use of input solar heat. The heat losses from the receiver of PTC primarily affect the system's overall performance [29]. Different strategies for improving heat transmission have been discovered and classified as one of three types [30],[31].

3.1. Active methods

External forces such as surface vibration and magnetic fields are applied in this method for heat transfer enhancement, such as:

- Pumps: Circulating a heat transfer fluid (HTF) with a pump can help raise the rate of heat transfer by moving the fluid through the system more quickly, which can be particularly effective in systems where the heat transfer fluid is not naturally circulated, such as in a closed-loop system;
- Fans: Blowing air over a heat exchanger can help to increase the heat transfer rate through convection, which can be achieved using a fan or other mechanical means to move the air;
- Electrical heating elements: Directly heating a substance using an electrical heating element can also increase the heat transfer rate, which could be accomplished using a variety of heat elements, including resistance and induction heat elements.

Overall, active heat transfer enhancement methods rely on external energy sources, such as mechanical or electrical devices, to increase the heat transfer rate. These methods can be effective in certain situations but may also increase the system's complexity and cost.

3.2. Passive method

This method does not require any external power input, and the additional power needed to enhance the heat transfer is taken from the available energy in the system, which ultimately leads to a fluid pressure drop. A good heat exchanger design should have efficient thermodynamic performance. Here are some examples of passive approaches to heat transfer enhancements:

- Materials with high thermal conductivity: Using materials with high thermal conductivity could help enhance the heat transfer rate by allowing heat to be more efficiently conducted through the material. For example, metals such as copper and aluminum have high thermal conductivity, making them good choices for heat exchangers and other heat transfer devices;
- Enhanced surface area: Another strategy for improving heat transmission efficiency is to raise the area of the heat exchanger. Fins or other surface modifications that increase the surface area in touch with heat transfer fluid can be utilized to accomplish this goal;
- Insulation: Insulating a system can help to decrease heat loss and optimize heat transfer efficiency. For example, insulating a pipe can prevent heat from being lost to the surrounding environment, transferring more heat to the desired location.

Overall, passive methods of heat transfer enhancement depend on the natural properties of the materials and system to improve heat transfer efficiency rather than requiring external energy sources. They are generally more straightforward and cost-effective than active methods but may be less effective in certain situations.

3.3. Compound Method

This method uses passive and active methods to enhance heat transfer. These methods can be particularly effective in situations where more than one method is needed to achieve the desired level of heat transfer efficiency. Compound methods of heat transfer enhancements involve using materials with high thermal conductivity and surface enhancements, such as fins, to increase the surface area in touch with heat transfer fluid. Other compound methods involve using insulation to reduce heat loss and a pump to circulate the heat transfer fluid more quickly.

Compound approaches of heat transfer enhancements combine the advantages of active and passive approaches in a single system, allowing for more efficient heat transfer and particularly useful in situations where a single method alone is insufficient.

4. Uses of Inserts in the Receivers

The usage of inserts in a concentrated solar power (CSP) system can improve heat transfer rates through enhancement of effective heat transfer area, creating swirling motion in the flow, and increasing turbulence with a lower in the thermal boundary layer thickness when metallic turbulators are inserted into the absorber system of the PTC system. Additionally, this method can lower the temperature of the outer absorption wall, reducing heat loss and improving thermal efficiency [18,19]. Increased effective heat transfer area: Inserts, such as turbulators or other surface enhancements, can increase the effective heat transfer area by presenting more surface areas to improve the system's efficiency by allowing more heat to be transferred from solar collectors to HTF. Swirl generation Inserts can also create swirling motion in heat transfer fluid flow, which can help increase the heat transfer rate by generating turbulence in the flow, which can help mix the fluid and enhance heat transfer by convection.

According to [34], heat transmission may increase by 17.5% compared to a smooth absorber by employing two different kinds of fins (longitudinal and porous). Researchers have conducted several computational studies on how inserts affect the rise in heat transfer. The numerical studies are built on codes for computational fluid dynamics (CFD), and other researchers utilize different software packages. There are four types of inserts: circular/porous inserts, fin-type inserts, twisted tape-type inserts, and others. These types will be covered in the second chapter of this study.

5. Literature Review

In past research, the focus was on the absorber tube to improve the device's thermal efficiency. The literature will also look up passive methods, such as changing the shape of the receiver tube or putting inserts inside the tube. In addition, nano-fluids as an HTF will be discussed, as will the impact on PTC's thermal performance.

5.1. Use Direct Inserts

Twisted Tapes Inserts

The first and second laws of thermodynamics and flow rate variety of 1 to 6L/min are used to calculate PTC thermal-hydraulic performance, which is done using twisting tape inserts, as shown in Fig. 7. The best thermal performance was achieved at the lowest torsion ratio (1 to 5). The enhancement is due to the increased flow of vortices that cause turbulence [35]. It has been considered how the twist ratio in the PTC receiver tube affects heat transmission and friction coefficients numerically. They noticed that louvered twisted tape had greater Nu and friction factor than the standard tube. The heat transfer coefficient improved by reducing Reynolds number and twist ratio, with the highest findings recorded for a 2.67 twist ratio and Re= 5000 [36]. Experiments and numerical simulations have been utilized to study pressure drop and heat transfer using regular twisted, perforated, U-shaped, and V-shaped tapes. The maximum Nu was found at the V-shaped bars with dr = 0.03, w = 0.45, which is 2.03 times the smooth tube and 2 times the tube with conventional twisted strips [37].

Research was done to determine the impact of the angle of incidence of the solar beam and the heat transfer rate when a helical screw-tape was inserted. The results showed that the transverse angle influences the energy flow more than the longitudinal angle. Also, the rate of heat loss in a smooth absorption tube is six times that of the tube's helical tape inside [38]. A tape with various nail-type twist ratios for a solar water heater concentrator has been utilized in the tube. The empirical findings indicate that the most significant overall thermal efficiency of 12.027 percent was reached with the shortest twist pitch ratio of 4.7870 [39]. An experiment was conducted with different flow rates and the idea of putting nail twist tape into the absorbent tube. The results were compared to see how smooth tube, tube with regular twist tape, and tube with nail twist tape had been used regarding thermal performance. Depending on the findings, the Nu improved by 10 to 15 percent when the smallest twist rate was 2, but it went up by 20 to 30 percent when nail twister tape was used [40]. Researchers studied a small-scale industrial PTC that used twisted tape in a receiver tube to improve performance. A genetic algorithm technique was used to analyze the efficiency of the first and second laws. It was discovered that increasing the flow rate causes thermal efficiency to increase. However, this rise is offset by a fall in the enhancement factor caused by the high-pressure drop [41]. Numerical studies showed that wall detached twisted tape increases the absorber's heat transmission performance. At the minimum torsion ratio, heat transmission and fluid friction increase due to mixing along the lengthy spiral route. The absorber's circumferential temperature differential was decreased by 4 to 68%, and the heat transmission was enhanced by 1.05 to 2.69 times [42]. They evaluated the influence of the twisting ratio and clearance ratio on the thermal performance of PTC utilizing molten salt as an HTF with turbulent flow from 5,000 to 25,000. Also, the temperature of the receiver wall could go down at the lowest clearance ratio of 0 to 1.

The higher Nu value has also been 2.9 times greater than a standard tube at a twisting ratio 2.5 [43]. Using standard or perforated twin twisted tapes could improve friction factor and heat transmission. The impact of altering the Reynolds number between 10,000 - 20,000 and the holes (N = 0, 1, 2, and 3) Dual twisted tapes improved the Nu by 9%. On the other hand, perforating TTs significantly impacts the friction factor, decreasing it by up to 396 percent [44].

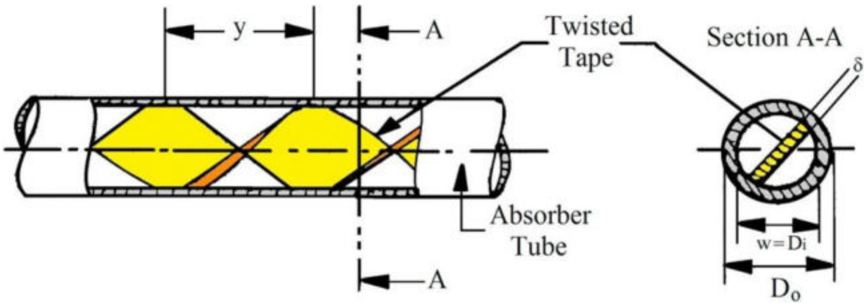

Fig. 7. - Schematic of the twisted tape insert [35].

The Indian Institute of Technology evaluated a cylindrical parabolic collector (CPC) system using a twisted tape and different flow rates, Reynolds numbers, and torsion ratios. The result showed that the value of y = 5 has the lowest skew ratio and the greatest Nu [45]. Using the twisted, curved tape increases heat transmission, as researchers discovered that at the height of 7 mm, the tape has a superior thermal performance of around 37% compared to the standard case [46].

Wire Coil

Due to the rise in heat transfer area and turbulence, wire coils improve thermal performance, but the wire pitch, distance between subsequent coils, and flow rate must be considered [14,47,48].

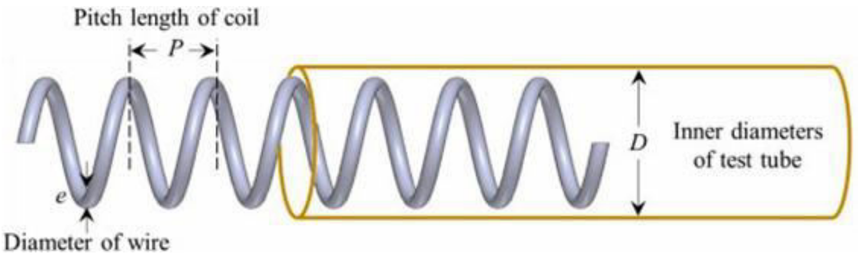

Fig. 8. - Wire coil insert.

Simulations using COMSOL Multiphysics with different flows for the absorbent tube of the PTC system with the insertion of wire coils with different pitches found that the coil increases flow turbulence and both Reynolds and Nu, with Nu increased by 104% - 330%, indicating a heat transfer coefficient improvement [49]. The friction coefficient and Nu for wire coils and twisted tape tubes have been analyzed experimentally and numerically. The Nu and f in twisted-tape tubes rose by 38–57% and 148–202% compared to regular tubes, whereas in wire-coiled tubes, they increased by 75–94% and 685–792%. Numerical research reveals that a twisted band or coil may increase tangential velocity [50]. Improved PTC efficiency was modeled with wire coil inserts inside the receiver 9-meter-wide parabolic trough collector with an 80-degree rim angle. When the flow rate decreases by 0.0036 m3/s, heat transfer efficiency increases by roughly 183%, while thermal effectiveness increases by 0.4% to 1.4% [51].

They were investigated using a coiled wire with an equilateral triangle cross-section and air as the transmission fluid. There was a 36% increase in efficiency when the pitch-to-diameter ratio was one, and the length-to-width ratio of the equilateral triangle to the tube's diameter (a/D) was 0.08920. The best system operation was found when the Reynolds number for all coiled wire inputs was smaller, resulting in a more compact heat exchanger [52]. Testing the inserts for coil wire turbulators was done experimentally and numerically. Seven pitch distances were simulated numerically. At pitch distances of 15, 30, and 45, the thermal increase was 2.28, 2.07, and 1.95 times that of a standard tube [53]. Experiments were performed using a serrated wire coil (DC) of 34.40, 41.20, and 47.90mm in diameter and pitch lengths (PC) of 10, 20, 30, and 40 mm to explore characteristics of the heat transfer and airflow friction in a pipe with the wire coils. With diameter ratio (DR)= 0.94 and pitch ratio (PR)= 0.1969, the optimum thermal fulfillment is achieved at Re = 5112 [54]. An experimental investigation involves wire coils with rectangular and circular cross-sections of varying pitches with air as the transmission fluid inside an elliptical tube. According to the findings, rectangular cross-section wire coils have a higher Nu value, friction coefficient, and thermal efficiency increase of 15%, 3%, and 14% than circular cross-section wire coils because the shape of a rectangular cross-section increases the strength of the air's turbulence [55].

Use Porous Materials

Solar energy systems may make use of porous materials for a variety of purposes. It is possible to increase heat transfer by using high-conductivity materials like metallic foams, metal porous metals, and other materials with high thermal conductivity, which work well to mix flow and have an acceptable pressure drop [56]. Employed the porous substance in the solar PTC absorber for its heat-conducting qualities. The results indicated that the incorporation of the porous medium enhances heat transmission capabilities, although the pressure decreased markedly. The domains of heat transport, thermal conductivity, and turbulence effects exhibit significant enhancement. The optimal heat transfer coefficient with a notable drag occurs under the parametric parameters of w = di, H = 0.5di at h = 30°. At a Reynolds number of 31.845 and a pressure loss of 0.0663 Psi, an enhancement of 64.2% in the tube-receiver Nusselt number is attained for the optimal recipient [57]. Three-dimensional simulations were used to investigate the impact of metallic foam on the PTC absorbent tube. The optimal thermo-hydraulic performance, accounting for increased flow resistance, is achieved when H = 0.25 with the insertion of metallic foam into the tube, resulting in an increase of approximately 5 to 10 times alongside a rise in f by 10 to 20 times, while the PEC ranges from 1.40 to 3.20 [58].

PTC was evaluated with six diverse receiver designs in an experiment test. The porous disc was optimized for all receivers to increase PTC efficiency and decrease receiver angular thermal gradients. The collector efficiency ranges from 63.9 % to 66.66 % [59].On the solar air collector, an experiment was done with porous absorbent tubes made of corrugated iron, and another study was carried out with non-porous absorbent tubes made of aluminum mesh. According to the findings, the solar thermal efficiency was approximately 61 percent during the middle of the day, and the temperature that this collector could reach was 41 percent [60]. They utilized the porous medium of charcoal to improve the thermal efficiency of the solar air heater. As a result of these studies, the thermal increase was 30% greater than in the model that did not contain the porous medium [61].

This study used a 3D turbulent flow model to simulate employing (syltherm800) fluid to transmit heat in the PTC absorber tube. They numerically simulated an absorber tube with porous rings. A porous ring receiver tube's heat transfer and thermal efficiency are more significant than a smooth one. It was also noticed that the Nu enhanced with the size of the rings. The thermal performance factor was at its highest when H was equal to 0.8, Re was equal to 30,000, and the space between rings was double that of the inner ring [62]. Copper foam was used in the solar collector's receiver tube to assess its performance within a range of flow rates from 0.0083 to 0.025 L/s. It was discovered that raising the flow rate improves efficiency and reduces the loss coefficient by 45 percent [63]. Three absorber tubes were used: porous, semi-porous, and nonporous. With an intake temperature ranging from 20C to 40C, a working fluid selection of 0.3 - 1.6 L/min was used. Thermal effectiveness improves with increased flow rate and reduced inlet temperature. Semi-insert and full-insert thermal efficiency increases were 119.6% and 171.2%, respectively. The most significant temperature differences were 12.2C, 8.8C, and 3.3C, namely porous, semi-porous, and nonporous [64].

Use Fin type inserts

Several researchers have investigated how the presence of fins influences thermal performance. They have examined fins that are wavy, pinched, porous, and longitudinally flat.

In a study using porous fin geometry on the tube's lower side, researchers found a slight rise in pressure drop as the coefficient of heat transfer augmented. Tee tubes have been observed under the various shapes of the inserts (circular, triangular, square, and trapezoidal). The researchers noticed a slight rise in pressure drop as the heat transfer coefficient increased. Results have shown that at 6.4 kg/s flow rate, trapezoidal inputs increased heat transfer by approximately 13.8% [65]. They put pin fin arrays on the absorber tube's bottom side to increase heat transfer and reduce circumferential temperature differences. Numerical results have shown that the average Nu has been increased by up to 9%, and the overall performance factor has been increased by up to 12% [66].

Simulated by Solid works using longitudinal fins of varying lengths (5, 10, and 15) in parabolic trough collectors and verified with carbon dioxide, air, and helium gas. The results showed that although fins increased pressure drop, they boosted thermal efficiency. A fin with a height of 10 is most suited for use, especially with helium as a transport fluid [67]. A new tube insert in the absorber tube with star-shaped geometric features was developed to enhance this insert's shape. The fin length ranged from 15–30 mm, while the fin thickness ranged from 3–5 mm in 16 instances. The Nu and heat transfer factor may be enhanced by 60%, and thanks to these improvements, thermal losses might be cut by 14%. For star inserts, a 5 mm fin thickness is ideal. The recommended fin length for the star insert is 20–30 mm [68].

To determine the optimal number and location of rectangular inner fins with thickness (2 mm) and length (10 mm). After that, they concluded that using three fins at the bottom of the tube was the optimal design because it increased the thermal efficiency by 0.51 percent [69]. It investigated how the inner longitudinal fin also has a flat and sinusoidal lateral surface of the PTC tube, affecting its thermal performance. The Nu, friction coefficient and thermal enhancement were determined using numerical analyses. This convective augmentation technique resulted in a consistent fluid temp distribution and decreased the absorber's ambient temperature. The Nu enhancement has been 25 % with flat fins and 78 % for fins with sinusoidal lateral surfaces. In addition, the maximum Nu enhancement increased from 57 to 210 percent when Tin dropped to 300 K because the fluid reaching the absorber at a low temperature can better utilize the energy of a source of heat (solar energy) [70].

An experimental investigation of three PTC receiver tubes, the smooth tube and two tubes with pin fins of varying heights and axial pitch, was conducted using air as heat transfer fluid. A finned inner tube's temperature and pressure drop were more significant than a smooth tube's. With a flow rate of 93 Nm3/h, the average air temperature was 266. According to the findings, the maximum exergy was obtained with a fin length of 3.50mm and an axial pitch of 1.8 mm [71]. Comprehensively investigated novel PTR performance with a star-shaped insert in an absorber tube. Results regarding exergy, thermal, and collector efficiency have been discussed. It has been shown that heat loss drop has been as high as 14%, and pumping work has still been deficient (16W), even though pressure drop has been obvious [72].

Other Types of Turbulator Inserts

The effects of the perforated plate inserts in a solar PTC with Syltherm800 as the heat transfer fluid revealed a rise in the percentage between 1.2 and 8 in the modified thermal efficiency when using perforated plate inserts [73]. In this analysis, researchers conducted a scientific experiment on an absorber tube equipped with hinged blades as the variable. The work aims to determine the energy transfer rate for various mass flow rates and intensities of sunlight. In this experiment, the working fluid that was used was distilled water. Under identical conditions, the researchers found that the efficiency of the new absorber tube ranged from 67.970 percent to 70.820 percent. In contrast, the efficiency of the smooth tube (which did not contain any inserts) was between 58.77 percent and 61.70 percent [74].

The insertion of a corrugated tape with a sinusoidal shape into the PTC tube has been simulated. A corrugated tape insertion increased the PEC and Nu by 2.11 and 3, respectively, and the heat loss was reduced by 33%, reducing heat stress in the absorber structure [75]. A PTC absorber tube with a conical strip insertion is examined numerically for its thermal-hydraulic and thermodynamic efficiency. This study investigates the influence of geometric characteristics on performance. Using four different fluid input temperatures, the conical strip inserts significantly increase heat transfer, increasing the Nu by 45 to 203 percent. The heat loss was reduced by up to 82.10%. The inserts create a significant increase in pressure drops, with a friction factor of 6.17–17.44 times that of a smooth PTC absorber [76]. In the presented work, the receiver tube regarding the PTC with internal toroidal rings has been investigated to improve heat transfer. Nine different receiver types were determined to affect the heat transfer rate considerably. In addition, at various input temperatures and fluid flow rates, the absorbed tube's fully turbulent heat transfer properties were numerically analyzed and confirmed. It was found that a thermally efficient ideal receiver has a diameter ratio of 0.88 as well as a pitch size (2d). Whereas the receive diameter ratio (0.92) and pitch size are the most energy-efficient, the improvement in efficiency for the thermally efficient and energy-efficient ideal cases is 3.74 and 1.88 percent, respectively, while the increase in Nu is 2.330 and 1.490 times higher when compared to smooth absorber tube [77].

5.2. Surface Modifications of The Tube

They looked at how turbulence flow, and heat transmission was altered with or without helical fins inside the tube and protrusions and dimples on the surface of Fig. 9 in terms of heat transfer, as tubes with dimples do better than tubes with protrusions or helical fins. When the Reynolds number increased from 1104 to 2104, Nu and coefficient of friction increased from 56% to 77% and 44% to 64%, respectively [78].

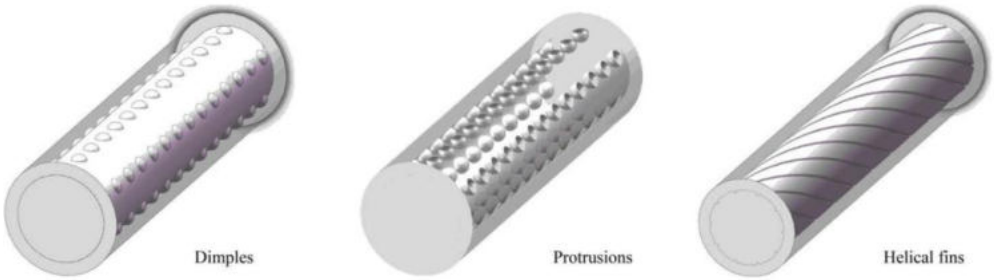

Fig. 9. - The schematic of dimples, protrusions, and helical fins [78].

Using a hollow V-shaped absorber with rectangular fins improved heat transmission. The heat transfer fluid was heated from 109.8 to 110.9, and the surface absorber was cooled from 136.2 to 121.5. It has been noted that the sunshine cannot escape since it may often be reflected in the triangle [79] developed an asymmetrical external convex corrugated tube absorber for PTC. Compared to the standard tube receiver, it was discovered that using the improved tube as the absorber could significantly minimize heat stress and improve heat transfer performance. In addition, the maximum von Mises thermal stress restriction has been 26.8%, while the maximal total heat transfer performance factor increase has been 148% [80]. Simulating the receiver tube with a dimpled surface and a constant Reynolds number while varying the Grashoff number from 109 to 3.2×1010 led to an increase in the performance assessment criterion to 1.3, which indicates that the reinforcement ratio rose as the Nu grew, at the expense of a 1.01–1.14 rise in friction coefficient [81].

The spiral corrugated suction tube was utilized to increase heat transfer, and research was carried out to determine how the degree of pitch and height to diameter influenced heat transfer. According to the research, a thermal efficiency of 65.8 percent could be achieved at the height of pitch (DH = 0.12) and at the height of ripple (P/DH = 0.06), where there was a reduction of 44 percent in the amount of heat lost in comparison to the standard tube [82]. They suggested using a hollow, arc-shaped receiver tube, where they studied the effects of the angle of inclination and the width of the aperture. Since the angle of inclination and the width of the opening have a significant effect on how much heat is lost by natural load, they found that 50–70 is a good range for the width of the opening for this type because manufacturing costs go up when the width of the opening gets smaller [83]. A numerical analysis of flow and heat transfer in the PTC with turbulence-inducing objects in the receiver tube was carried out. The pipe's elements feature a helical profile. The element cross-sections studied were rectangle, triangular, trapezoid, and quasi-triangular. According to the results, the case with a rectangle cross-section at Veinlet = 0.2 m/sec had the best thermal efficiency by 29% [84].

Use of Nanofluid

Researchers have studied the uses of Nanofluids as heat transfer fluids because traditional fluids like water, oil, and others have low heat conductivity, reducing the overall performance of systems due to the thinness of the thermal layer. Nanofluids in conventional liquids contain solid nanoparticles (1-100 nm) [85]. Nanofluids combine conventional liquids with metallic nanoparticles, such as copper, titanium dioxide, ammonia, silicon dioxide, and other standard nanoparticles [86].

Because an enormous number of studies have been conducted to investigate these fluids and the advantages that can be gained from utilizing them to achieve higher levels of thermal efficiency, we will focus on some of the studies conducted to provide a concise overview of their findings. An empirical study has been carried out to enhance the heat transfer and coefficient of friction by inserting a twisted tape into an absorbent tube and employing HTF, water, and silver Nanofluid. Results show increasing friction and Nu factor by 1.0-1.75 times and 1.25-2.10 times [87]. When three types of HTFs were tested in a converging-diverging tube, the researchers indicated that the Nanofluids improved thermal efficiency by 4.25 percent. However, the design's functional purpose improved thermal efficiency by 4.55 percent. According to the research, this application is recommended for high-temperature situations [88].

The use of mono- as well as hybrid Nano-fluids in PTC as a heat transfer fluid boosts thermal efficiency value by 1.8 percent for the hybrid Nanofluids and 0.7 percent for the mono Nanofluids at temperatures range of 300 K - 650 K [89]. When the vortex generator was used with and without Nanofluids, the researchers found that the use of the largest vortex generator (H30mm-30-N4) with 6 percent SiO_2 resulted in the most significant overall efficiency and thermal energy improvement, with 14.62 percent and 14.47 percent, respectively, compared to the other options [32]. Examined the effects of two Nanofluids, CuO-H_2O and TiO_2-H_2O, as well as three pure fluids, which are ethylene glycol, water, and thermal oil, on an absorbed tube that has been equipped with a triangular cross-section in addition to forward perforated ring steps. Analysis was done on the working fluid effect, nanoparticle volume concentration, step inner diameter, and step spacing.

The maximal level of thermal efficiency ranged between 67% and 76.50% when 4% of CuO-H_2O Nano fluid was used and flowed through a tube with inserts [90]. The influence of a hybrid Nanofluid (Cu/SBA-15) was examined to ascertain the energy and exergy efficacy of a PTSC absorber tube fitted with turbulators. According to CFD investigations, heat transfer improvement is less for low Reynolds number values (less than 3500). Beyond this, average Nu rises in comparison to smooth absorber tubes. At noon, the highest energy and exergy efficiencies were 65% and 5%. These values were 2% and 1% higher than in the usual case [57].

Conclusion

This comprehensive review demonstrates that Concentrated Solar Power (CSP) systems represent a viable and sustainable solution to global energy challenges, particularly in reducing greenhouse gas emissions and dependence on fossil fuels. Among the various CSP technologies explored - Linear Fresnel Reflectors, Parabolic Dishes, Solar Towers, and Parabolic Trough Collectors (PTCs) - PTCs emerge as the most mature, cost-effective, and widely adopted for medium- to high-temperature thermal applications. The study emphasizes that enhancing the thermal performance of CSP systems relies heavily on advanced heat transfer strategies. Passive techniques such as surface modification, internal inserts, and nanofluids offer significant improvements in heat transfer without additional energy input. Active methods—such as forced circulation using pumps or fans - provide further enhancement but at the cost of increased complexity and energy consumption. Compound methods, which integrate passive and active approaches, yield the highest thermal efficiency gains. Notably, innovations in receiver design - such as the implementation of twisted tapes, wire coils, porous materials, and various fin configurations - contribute substantially to reducing thermal losses and increasing heat transfer rates. Furthermore, the integration of nanofluids with enhanced thermal conductivity has shown measurable gains in system performance, particularly at elevated temperatures. Overall, sustained innovation in heat transfer enhancement and system design is imperative for maximizing the efficiency and scalability of CSP technologies, thereby advancing the global transition toward clean, renewable energy systems.

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