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An Advanced Maturity of Parabolic Solar Collector Passive Enhancement Techniques

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A B S T R A C T

Renewable energy sources are seen as a viable alternative to traditional energy sources, which are quickly depleting and have negative environmental impacts from their excessive usage. Free thermal energy for medium to high-temperature production comes from solar power, a renewable energy source. Based on the effective solar power optical concentration, thermal or electrical energy may be extracted. Sunlight thermal energy has been the focus of more and more research. The parabolic trough collector is a globally accessible, time-tested technique for generating thermal energy. The factors affecting the enhancement techniques are represented by a perfect absorber design made from the best conductive material with perfect coating properties, and high-reflection performance mirror properties. This paper outlined the most promising investigations that have been conducted on parabolic-trough collectors and enhancement techniques. The design of the fluid's heat transmission mechanism, the Parabolic-Trough Collector (PTC), a reflector, a receiver, and thermal storage devices are all part of this. This article discusses parabolic trough collectors and the various uses they have. The PTC is now one of the most significant solar-powered heating applications available, widely used for both industrial and domestic applications under various operating conditions.

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1. Introduction

Now, renewable energy constitutes a substantial portion of the world's energy consumption, providing sustainable heat, electricity, and fuels for many applications [1,2]. The globe today is facing an energy crisis owing to the significant and continuing rise in energy consumption that exhausts existing energy resources [3]. Solar energy is poised to assume a pivotal position in the approaching future as a replacement for fossil-fuel power plants in stationary applications. Mitigating fossil-fuel usage is imperative due to resource depletion and environmental issues associated with increasing atmospheric carbon dioxide levels [4]. Unconventional sources of energy are extensively utilized across several sectors, encompassing both commercial and residential structures, to produce hot water and heat interior spaces [5,6]. Moreover, there exists a finite supply of traditional energy supplies, accompanied by a substantial increase in fuel costs and environmental issues. As a result of rising energy consumption and a growing worldwide population, the World Energy Council predicts that primary energy demand will quadruple by the year 2050. Heat use by dwelling is displayed as a percentage in Figure 1 [3]. Many countries are shifting away from using non-renewable energy sources to power contemporary conveniences, including air conditioning, water desalination, food chilling, heating, and electricity generation [7,8]. As its name implies, solar power is mostly generated by sunlight and is thus one of the most well-known forms of renewable energy. Renewable energy sources, such as solar and wind power, are being considered by various countries [9]. Solar power is a clean, sustainable, and easily accessible energy source for any country on the globe. Two main methods exist for capturing solar energy at the moment: photovoltaics and thermal energy systems. [10,11].

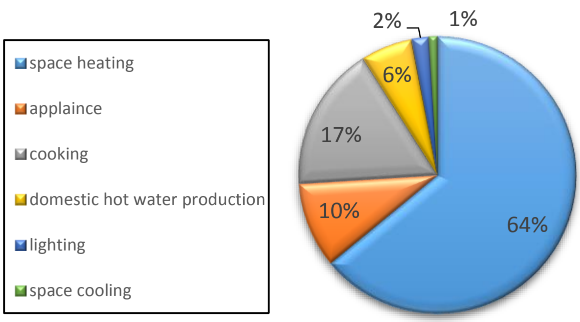


Figure 1. Heating and cooling energy usage by dwelling as a percentage [12]

2. Solar thermal technology

One of the most abundant renewable energy sources is solar thermal energy, which may be utilized either directly or indirectly. Solar thermal and photovoltaic technologies enable the conversion of solar radiation into usable thermal energy and electrical power. There are two main types of solar thermal structures: concentrating and non-concentrating. Since the sun's rays are mostly diffuse when they hit Earth, non-concentrating devices may heat fluids to temperatures of 40 to 70 °C. Within this temperature range, you can meet some, but not all, of your home energy needs. The temperature of the energy used in industrial applications remains high. Because of their high concentration ratio, concentrating solar thermal systems may easily reach temperatures between 80 and 250 °C, making them ideal for meeting such needs. Because of operational economies of scale, most improvements to concentrated solar power (CSP) have focused on megawatt-scale energy generation. In thermal energy applications, however, solar power has a great deal of potential to supplant fossil fuels [13,14]. Solar thermal power is the method by which energy from the sun is transformed into heat. Figure 2 [15] demonstrates the process of converting solar thermal energy using a solar collector. Some of the radiated energy can be immediately or later stored for use in heating water or air for domestic, business, or industrial purposes. The graphic depicts one possible method of converting solar energy into mechanical labor [16,17].

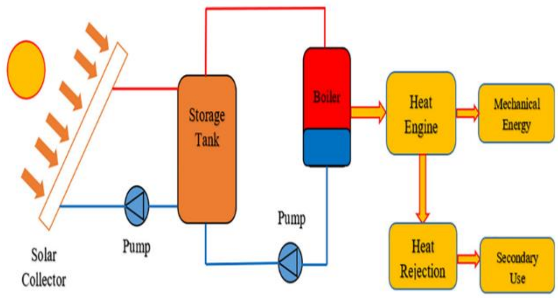


Figure 2. Solar thermal-conversion system [16]

There are a lot of benefits to using solar thermal energy for process heat in industrial settings. It reduces emissions of climate gases and our dependency on fossil fuels. [18].

3. Solar Collector

Active solar-powered heating systems rely on solar collectors. [19]. A collector for the sun is an apparatus to gather thermal energy from the radiance of the sun via absorption. The stored thermal power is transported via a circulating fluid and used for certain applications. Generally speaking, solar collectors can be either non-tracking or tracking. Collectors that do not track the sun's movement, sometimes called stationary or fixed collectors, do not move at all; in contrast, collectors that track the sun's route are designed to face perpendicularly to the ground. Solar collectors are classified as shown in Figure 3. In continuation of one kind of solar energy collector follows one axis at a time, whereas the other kind follows both axes at once. The three most prevalent types of non-track collectors are evacuated tubes, flat plates, and compound parabolic collectors. Some examples of single-axis tracking systems include cylindrical trough collectors, linear Fresnel reflectors, and parabolic trough collectors. On the other hand, examples of dual-axis tracking systems include central tower receivers, parabolic dish reflectors, and circular Friedel lenses [20].

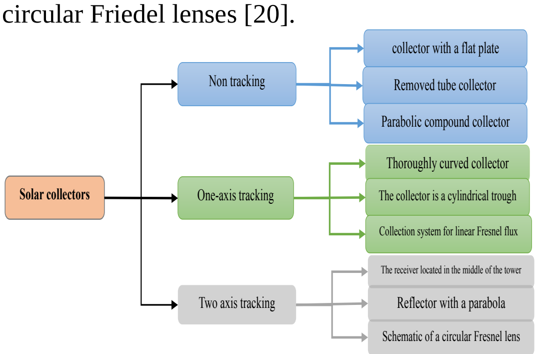


Figure 3. Classification of solar collectors [20]

4. Parabolic Trough Collector

Due to the high temperatures and concentration ratio of sunlight, several nations have begun using solar-powered PTC for heating purposes. This helps sustain electrical power plants. [21]. A game-changer in the energy sector, concentrated solar power (CSP) eliminates the need for nuclear power and fossil fuels by converting concentrated solar radiation into heat for thermal fluids or electrical generation [22]. A conventional PTC has a metallic base, a linear tubular receiver, and a parabolic concentrator that runs in a straight line [23]. By allowing the sun's rays to penetrate completely perpendicular to the line of symmetry, the pelvis helps to concentrate them along the focal line. This method makes the best use of incident solar irradiation throughout the summer, when the sun's potential is at its peak [24]. Using this focal line as a guide, a heat transfer fluid-filled receiver pipe is positioned along the pipe walls to capture concentrated solar energy. An orientation monitoring mechanism for the sun's rays is included inside the collector to keep them perpendicular to its axis. In Figure 4, we can see the PTC in action. [25] As a fluid moves through the tube, it soaks up the concentrated heat of the sun, increasing both its enthalpy and the temperature of the tube wall [26, 27]. Surfaces that reflect light, such as polished aluminum or silver-coated metal, are common components of reflecting surfaces. The inability to focus diffuse radiation onto the collecting plate makes parabolic channels less useful for this purpose than flat plates. When clouds roll in or the sun's rays aren't directly above, their effectiveness drops. To remedy this shortcoming, monitoring equipment is set up. With the aid of the monitoring component, the reflectors can follow the sun's path throughout the day and maintain the proper concentration. The receiver is often constructed of black metallic material to ensure optimal absorption efficiency [28]. How well PTSCs work is dependent on how well the material used to make the absorption tubes conducts heat [29]. Optimal thermal efficiency requires precise design and the use of lightweight materials that are both mechanically robust and thermally conductive [30, 31].

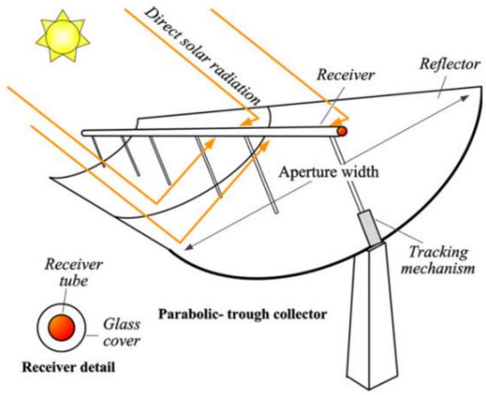


Figure 4. Schematic of PTC [25]

5. Technology That Improves Heat Conduction

Techniques for enhancing the transfer of heat are crucial for energy conservation and the utilization of appropriate energy sources [32]. There have been a lot of new methods developed to improve heat exchanger performance in response to the demand for such improvements. To enhance heat transmission, one can employ either active or passive techniques. The active approach can only improve heat transmission with the help of an external energy source. To improve fluid turbulence, passive heat transfer requires a small amount of energy extraction from the system, rather than an external energy source. These methods improve the flow treatment in a way that increases the convective heat transfer coefficient. Turbulence boosters increase the heat transfer rate by making the flow more turbulent, which enhances fluid mixing and helps to remove the thermal boundary layer. Several agents that increase turbulence, include synthetic roughness [33, 34], baffles [35, 36], the fins [37, 38, 39], the ribs [40, 41], barriers [42,43,44], the rib-groove arrangements [45, 46], tape that is twisted [47, 48], turbulent generators [49, 50], the blocks [51, 52], the wings [53, 54], spiraled wires [55, 56], the swirling rings [57, 58], and swirl devices like containers [59], have been analyzed.

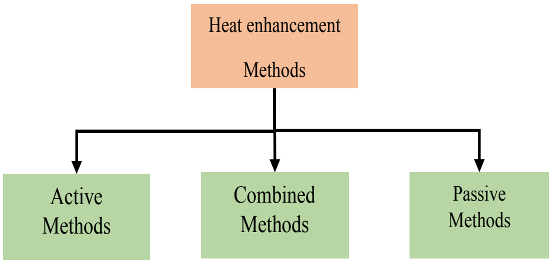


Figure 5. Classification of Various Heat Transfer Enhancement Methods [32]

6. The PTC Application

PTCs are utilized in various industrial applications and are categorized into primary classes, as seen in table 1 [60]. In thermal usage, the gathered heat is put to direct use for a particular process. Concentrating photovoltaics are now a topic of research, however, solar energy is mostly used for heat control in commercial and industrial settings. Recognizing the presence of small-scale installations and companies worldwide that produce PTC for PV uses is essential [61,62]. table 1 describes the PTC applications, including the type of PTC used.

Table 1. Potential uses for solar power and various types of solar collectors [60]

Application	System	Type of collector
Hydrogen powered by the sun.		
Systems for thermosyphons	Inactive one	FPC
Storage for integrated collectors	Inactive one	CPC
The direct movement Systems for Heating Water in an Indirect Way	Active	FPC, CPC
System for air	Active	ETC FPC, CPC
	Active	ETC FPC
Cooling with solar energy		
Adsorption apparatuses	Active	FPC,CPC
Adsorption apparatuses	Active	ETC FPC, CPC ETC
Reusing saltwater using solar energy		
Solar stills	Inactive one	-
Multistage flash (MSF)	Active	FPC, CPC ETC
Multiple-effect boiling (MEB)	Active	FPC, CPC ETC
vapor compression (VC)	Active	FPC, CPC ETC
Industrial heat for processes		
Water and air systems in industrial settings	Active	FPC, CPC, ETC
Systems for producing steam	Active	PTC, LFR

Climate control in enclosed spaces		
Hot water for heating and water heating services	Active	FPC, CPC ETC
The air systems	Active	
Water systems	Active	FCP
Systems that use heat pumps	Active	FPC, CPC ETC FPC, CPC ETC
System for solar thermal power		
Systems for collecting parabolic troughs	Active	PTC
Systems of parabolic towers	Active	HFC
Systems of parabolic dishes	Active	PDR
Thermal solar panels	Active	HFC, PDR
Systems for solar chemistry	Active	CPC, PTC, LFR

This section provides an overview of PTC models, including their key characteristics, uses, manufacturers, governmental institutions engaged in their creation, and commercial availability.

6.1. Research on the Parabolic Solar Collector System: An Experimental Study

Chafie et al. [63] constructed and fine-tuned a system for thermal efficiency, the (PTC). We hand-picked this heat transfer oil because of its superior thermal performance, low vapor pressure, and foundation of high-quality mineral oil. One method of transferring heat is utilizing heating oil. With a focal distance of 0.835 m and proportions of 2.7 m wide by 4 m long, the PTC is an impressive structure. A 4-meter-long steel absorber tube with a selective coating makes up the PTC receiver. The absorbent tube is protected by a glass cover with a thickness of 3 mm and an inner diameter of 120 mm. You may see the solar PTC schematic in Figure 6. Nothing existed in the annular space that had previously contained the absorber tube and its glass cover. For an absorber tube with an area proportionate to its surface area, the concentration ratio is 11.77. (from the aluminum reflector to the steel container). On sunny days, the performance assessment levels were 41.09%, whereas on rainy days, they dropped to 20.91%. A total of 55.1% of PTCs were efficient. The total comes to $4,346. The trials took place at Tunisia's Research and Technological Center of Energy.

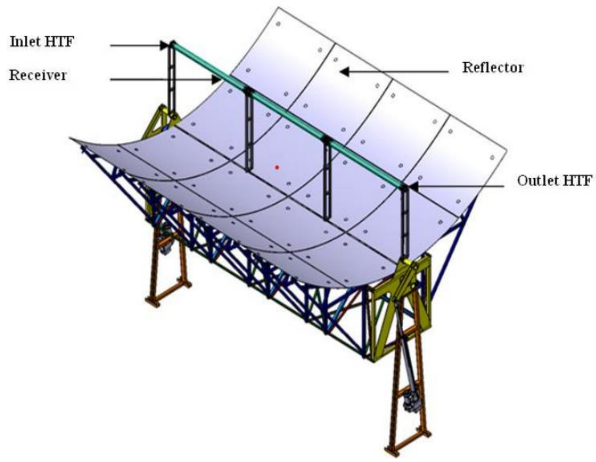


Figure 6. Design of a PTC [63]

Zou et al. [64] studied the effectiveness of a small PTC (w = 1 meters, di = 0.023 meters, do = 0.026 meters, rated flow = 0.5 m^3/h,) with a DNI of 720 W/m^2, employing a reflecting mirror and an aluminum receiving tube, under cold experimental circumstances. Figure 8 shows the experimental setup. The receiving conduits were either an uncoated double-glazed evacuated tube or a coated double-glazed evacuated tube. The average thermal effectiveness of a painted double-glazed vacuum-sealed tube was 30%, compared to 33% for an unpainted double-glazed evacuation tube.

(a)

(b)

Figure 7. Photographs of some experimental devices (a): double-glazed evacuated tube, while the second (b) is an uncoated double-glazed evacuated tube [64]

A revised design of PTC was executed by Maryam Ibrahim et al. [65]. The findings from the PTC-designed rig show that the PTC functions effectively as a water heater and can achieve commendable thermal performance under Iraqi environmental conditions. The updated PTC comprises five lines. All channels will possess identical dimensions to those of an individual conduit. The entire region of area of the parabola will be 1 m². The parabolic trough panel was composed of ferrous material and covered with chromium to resemble the glass mirrors. The total thickness of the plate was one millimeter, as well as the measurements of the curve were as follows: The width of the curve: 20 cm; focus length: 5 cm; the length of the curve: 1 m; weight: 48.4 kg. All things considered, the fluid intake and exit areas, the quantity of heat captured, the rates of convectional heat transfer, and the heating effectiveness of the collection would be most affected by the minimum volume flow rates of water, in that order.

Figure 8. Parabola trough collector designed by Maryam Ibrahim et. al [65]

SPTC operating fluids were thoroughly examined by Bello's et al. [66] over a broad temperature range of 300-1,300 K, the parabolic trough collector is analyzed thermally and experimentally. A variety of working fluids were investigated and their best mass flow rates determined. Hydrogen permeated with pressure, vaporized nitrate salt, liquid sodium, oxygen, carbon dioxide, and helium were among them. With an input temperature of 800 Kelvin, the findings show that liquid sodium reaches the global exergy maximum efficacy of 47.48%. For moderate to low temperatures up to 550 Kelvin, forced water is the ideal working medium. However, at temperatures beyond 1100 Kelvin, the only possibilities are carbon dioxide and helium. The analyzed PTC is a commercial collector's the European Troughs ET-150, and the evaluation is conducted using the EES tool.

6.2 Passive Enhancement Techniques on SPTC

Diwan and Soni [67] conducted a computational analysis of the PTC's impact wire coiled insert within its absorber tube. For pitching measures of (six, seven, eight, nine, ten, twelve, fifteen, seventeen, and twenty) millimeters, the total flow rate varied between 0.01388 kg/s and 0.099 kg/s, with a constant water input temperature of 313 degrees Kelvin. In testing the improved heat transmission and friction coefficients over the tube's absorption, with pitching amounts ranging from 6 to 8 mm. They were preferred for reduced rates of flow. The pitching measurement of eight millimeters was deemed appropriate for elevated rates of flow.

Jaramillo et al. [68] presented experimental and analytical results of a passive technique for improving PTC heat transmission utilizing twisting tape. The examination was conducted at Te-mixco, Morelos, Mexico. Their findings indicated that using twisted ribbon enhanced heat transmission when the twist ratio approached one, and with low Reynolds values. Figure 9. Schematic depiction of the twisted ribbon inserts.

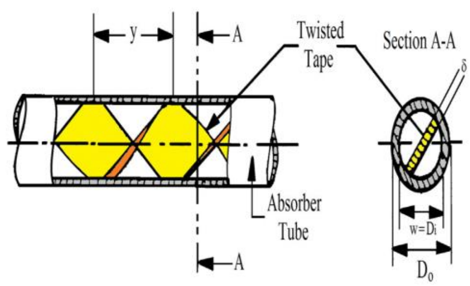


Figure 9. Schematic illustration of the twisted tape insertion [68]

Gong et al. [69] conducted studies that proved the efficacy of incorporating pin fin arrays into the receiving tube to enhance heat transmission in the parabolic trough. Conducted studies that proved the efficacy of incorporating pin fin arrays into the receiving tube to enhance heat transmission in the parabolic trough. We used the MCRT, which stands for Monte Carlo Ray Tracing approach. To ensure the accuracy of the numerical findings, they were cross-referenced with experimental data from the DISS testing facility in Spain using the Finite Morphology Technique. The results demonstrated a maximum comparison error of 5%. Quantitative studies illustrated that the incorporation of a pin-fine tube featuring an insertion design would significantly enhance the transmission of heat efficiency within the absorption tube in the parabola trough receptor. Upon installation of the rotor receiver with pin fin arrays, the mean Nusselt value may increase by as high as nine percent, along with the comprehensive transfer of heat efficiency. The coefficient might rise by as much as twelve percent.

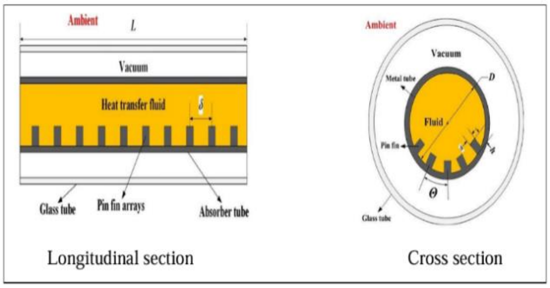
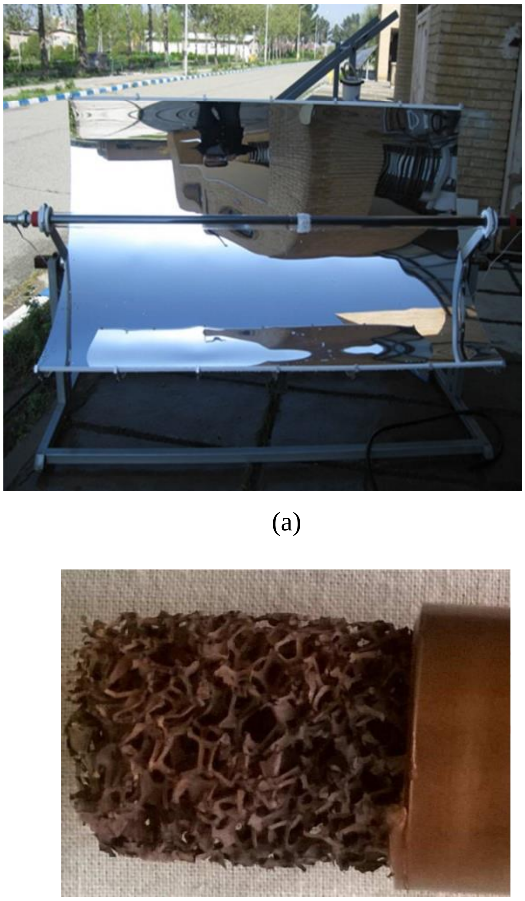


Figure 10. Illustrations of the absorber tube using pin fin arrays insertion [69]

Jamal-Abad et al. [70] used porous material made of copper foam inside the SPTC's absorption tube. The main objectives of the experiment were to test the effectiveness of SPTC and to determine its friction factor and Nusselt number. A 1.28-meter-long parabolic reflector with a 1-meter-wide aperture was built. As seen in Figure 11, the reflecting component is a 1 mm-thick steel mirror. Foam made of copper has a porosity degree of 90% and a porosity density of 30%. Using the ASHRAE 93 standard, to evaluate the solar collector's performance, the experiments were conducted with flow rates varying from half a liter per minute to one and a half liters per minute. It was demonstrated that the collector's efficiency improved as the mass flow rate increased; the same effect was also seen when copper foam was injected into the absorber. At what time an absorber is packed with metallic foam, the total loss coefficient UL reduces by forty-five percent. This results in increased efficiency due to reduced energy loss.



(a)

(b)

Figure 11 Experimental apparatus (a) parabolic trough collector. Copper foam is utilized as a porous medium [70]

6.3 Enhancement of Parabolic Solar Collector Systems by Using Phase Change Materials

A solar-powered water heater shown in Figure 12, with an 80-liter storage tank and a vacuum tube collector was used in an experimental investigation by Nasir et al. [71] to heat twelve kilos of black Iraqi paraffin wax to liquefaction, which was done in a heat exchanger at 45 degrees Celsius. Various working conditions were employed to provide a changeable imposed flow of water rates of two hundred, three hundred, and five hundred L/h. The findings indicated that complete wax melting requires 3–4 hours during summer and 14–16 hours in winter. The melting period was inversely related to the water flow velocity and directly related to the magnitude of radiation from the sun.

Figure 12. The experimental rig [71]

Esapour et al. [72] utilized a multi-tube heat exchange device which is shown in Figure 13. The solidification and melting of a phase transition material combined with a metal foam were examined. It was investigated how the growing number of internal pipes, their arrangement, and the metallic foam's porosity affected the heat storage unit's thermal properties. It was discovered that PCM with metal foam is more affected by an increase in internal pipes than PCM alone. Increase the rates of melting and solidification substantially.

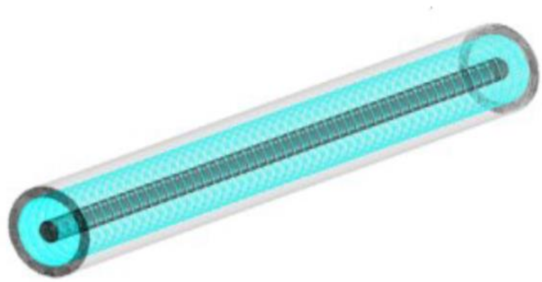


Figure 13. physical model configuration (Esapour et al., 2018) [72]

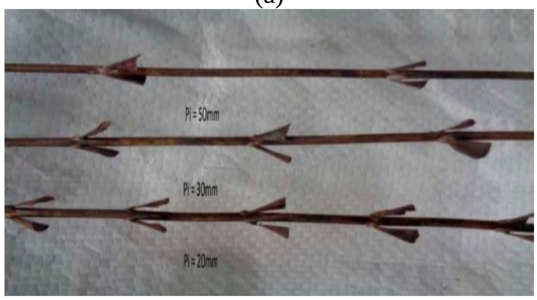
Olubunmi et al. [73] investigated a solar heater experimentally and found that its performance improved after adding 45°C paraffin wax-containing copper tubing. Water was the fluid of choice for the siphon method, which transferred heat. The findings showed that there was more hot water available than in the water-only case. The next day, when using PCM, the water temperature was 57.6 degrees Celsius, but with plain water, it was only 46.5 degrees Celsius. The highest temperatures reached during the charging procedure were 54.5 degrees Celsius for the water-only case and 65 degrees Celsius for the PCM case.

6.4 Hybrid Enhancement Techniques on SPTC

Venkatesaperumal et al. [74] performed experimental investigations on solar parabolic trough collectors. Implementing a hybrid approach of thermal enhancement through a ribbed tube receiver integrated along with coned tape inserts. An 8 mm proposition and 2 mm corrugated height ribbed tube receiver was used in conjunction with three different pitches of coned tape inserts—20, 30, and 50 mm—to measure the SPTC's thermal performance.

A straight tube and a ribbed tube receiver were used for the tests, and were performed at different mass flow rates. The heat exchange rate was enhanced by convection in every scenario involving the coned tape inserts. With a PC of eight millimeters and an HC of two millimeters, the SPTC performed admirably with the ribbed tube. And the coned tape insert (PI = twenty millimeters). The testing findings indicated that the highest achievable Nusselt number, the frictional factor, immediate effectiveness, and heating efficiency for CT-I3 were 177 percent, 38 percent, 26.92 percent, and 9 percent, respectively., respectively, in comparison to the tubular conduit beneath identical operating circumstances.

(a)



(b)

Figure 14. Photographic view of the ribbed tube and the coned tape inserts [74]

Yan et al. [75] conducted a computational study on the phase change material (PCM), A method that reduces the response time of thermal energy storage

(TES) devices by employing a unique Y-shaped fin structure. To strengthen the phase change materials' (PCM) heat transfer efficiency, several fin designs are used. The study's numerical model is validated by comparing it to prior experimental results.

The results show that there are three main steps to the PCM melting process, and adding solid fins to the PCM drastically shortens the melting time. Under specific operating circumstances, the PCM melting time might be significantly reduced by narrowing the fin, increasing the fin angle, and elevating the HTF temperature.

Hiba et al. [76] undertook experimental and computational studies of the phase change material (PCM) melting process for the three storage system modules: (sthx), (sfthx), and (sswthx), as shown in Figure 15. With fusion durations of 1736, 2775, and 2186 seconds for (sthx), (sfthx), and (sswthx), respectively, the results showed that SFTHX and SSWTHX sped up the melting process by 21.3% and 37.5%, respectively, compared to (sthx). The helical shape of (sswthx) allowed the liquid paraffin to flow unimpededly. It increased natural convection inside the paraffin, hastening the melting process, and the use of fins to increase the surface area for heat transmission validates this. The findings demonstrated that (sswthx) altered the temperature distribution inside the paraffin more rapidly and reduced the temperature differential between the lower and upper portions of the storage, reaching the maximum temperatures compared to other designs. A high degree of agreement was obtained by combining computational and experimental data. The researchers propose further improving heat transmission in the wax of paraffin for the (sswthx) model with the use of nanoparticles.

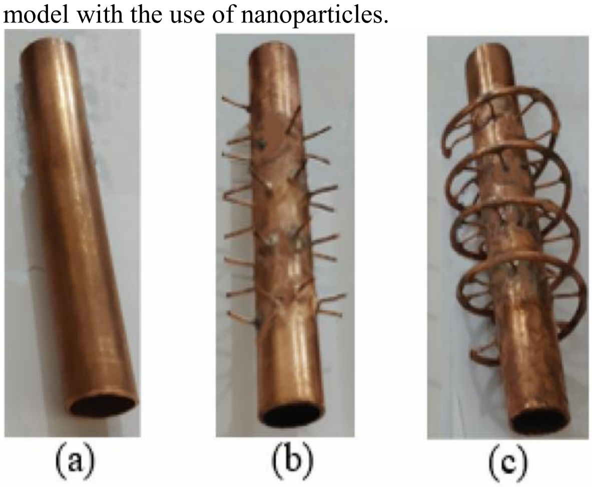


Figure 15. The Constructed Models' Tubes: (a) sthx, (b) sfthx, and (c) sswthx [76].

Elaf Mohammed et al. [77] undertook a study on heat increase strategies for parabolic trough collectors as shown in Figure 16. The initial method used a corrugated copper receiver, enhancing the tube's Area of surface and turbulence. The next method of enhancement included the use of paraffin wax phase change material (PCM) to store heat, which allowed the collector to absorb more of the energy. Using this method increases the outflow water temperature at sunset with little effect on the exit temperature during the day.

Under all volumetric flow rates tested, when a parabolic-solar trough collector is used, this method can increase the heat transfer rate by 40%. Utilizing tape with twisted turbulators within the ribbed copper tube was the third point strategy used in this investigation. Across all specified volumetric rate of flow tests, it increased the solar parabola collector's efficiency by around 35%. The overall thermal efficiency was increased to around 85% after three improvement procedures were applied to the solar trough parabolic collector.

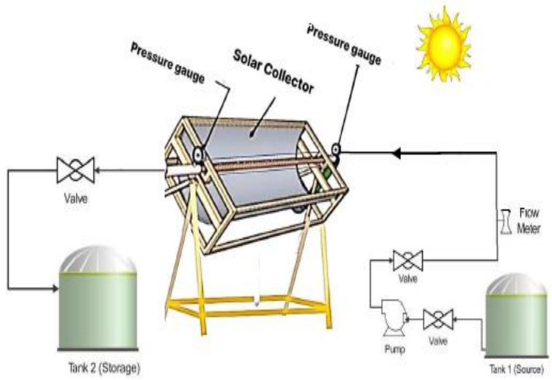


Figure 16. STPC is the water heating plant within the support structure [77]

Much theoretical and experimental work has been done to overcome the fossil fuel deficiency. Some of these important works can be illustrated in the following tables, which can be divided into two sections as follows:

6.4.1 Article Findings Based on Experimental Work

The literatures discuss many experimental work methods and findings which tried to enhance the solar energy collectors. The following Table 2 will discuss the parabolic solar collector enhancing methods experimentally.

Table 2. Previous experimental enhancing methods on a parabolic solar collector

Author (Year)	Dimension	Type of Enhancement	Location	Efficiency / Key Result
Chafie et al. (2016) [63]	Focal length: 0.835 m; Width: 2.7 m; Length: 4 m; Absorber: 4 m long, 120 mm ID glass cover	Selective coating on steel absorber tube; heat transfer oil	Tunisia (Research and Technological Center)	Sunny: 41.09%, Rainy: 20.91%, Overall: 55.1%
Zou et al. (2016) [64]	Width: 1 m; Absorber tube: di = 0.023 m, do = 0.026 m	Double-glazed evacuated tubes (coated & uncoated)	China	Coated: 30%, Uncoated: 33%
Jaramillo et al. (2016) [68]	Aperture area: 5.187 m², Receiver area: 0.389 m², Aperture width: 1.063 m, Length: 4.88 m, Focal length: 0.266 m, Rim angle: 90°, External diameter: 2.54 cm, Internal diameter: 2.32 cm	Twisted tape inserts with twist ratio ≈ 1	Mexico (Te-mixco, Morelos)	Improved heat transfer at low Reynolds numbers
Gong et al. (2017) [69]	PFAI-PTR Length: 4.06 m Absorber Tube Diameter: 0.07 m (thickness 0.003m) Glass Envelope Diameter: 0.12 m PTC Aperture: 0.525 m Absorptivity: 0.95 Reflectivity: 0.90 Rim Angle: 15° Non-parallelism Angle: 16°	Pin fin arrays inside absorber tube	Spain (validation site)	Nusselt number ↑ 9%, heat transfer coefficient ↑ 12%
Jamal-Abad et al. (2017) [70]	Reflector: 1.28 m long, 1 m aperture; Copper foam: 90% porosity, 30% density; steel mirror 1 mm	Copper foam (porous medium) inside absorber tube	Iran	Total loss coefficient ↓ 45%, efficiency ↑ with higher flow and foam insert

Olubunmi et al. (2017) [73]	Copper tubing with 45°C paraffin wax; solar heater setup	PCM (paraffin wax) in copper tubing; siphon transfer using water -based heat	Nigeria	PCM case produced more hot water; next-day temps: 57.6 °C (PCM) vs. 46.5 °C (water-only); charging temps: 65 °C (PCM) vs. 54.5 °C (water-only)
Moravej & Soozanyar (2017) [81]	Diameter: 0.6 m (conical body), Area: 1 m²	Helical stationary solar collector	Iran (Ahwaz)	Avg. thermal efficiency ≈ 53%; ↑ efficiency with ↑ mass flow rate
Nasir et al. (2018) [71]	80-liter tank, vacuum tube collector, 12 kg paraffin wax	Solar-powered water heater, varying water flow (200, 300, 500 L/h)	Iraq	Complete melting: 3–4 h (summer), 14–16 h (winter); faster with higher flow rate; slower with lower solar radiation
Esmaeilinasab et al. [78] (2020)	PVT panel: 0.42 m² area; 60W PV module; 12 copper tubes; glass cover; closed-loop system	1–3 wt% SiO_2 /water nanofluid (11–14 nm and 60–70 nm)	Iran	Max thermal: 54.18%, electrical: 8.57%, overall: 62.76%; 3 wt% SiO_2 nanofluid outperformed water
Maryam Ibrahim et al. [65] (2021)	Curve width: 20 cm; Focus length: 5 cm; Curve length: 1 m; Area: 1 m²; Weight: 48.4 kg	Chromium-coated ferrous mirror panel	Iraq	Fixed: 65%, Dual-axis tracker: 74%
Moravej [79] (2021)	Triangular flat plate collector; base: 80 cm, height: 125 cm; Absorber area: 0.5 m²; glass: 6 mm	Zigzag, non-riser U-shaped copper tubes (no riser)	Iran	Efficiency: 32%–58.9%; pressure drop < 0.1 bar in all flow rates; higher flow → higher efficiency
Venkatesaperumal et al. [74] (2022)	Ribbed tube receiver: 8 mm pitch (PC), 2 mm height (HC); Coned tape inserts with 20, 30, 50 mm pitch	Hybrid enhancement: ribbed tube + coned tape inserts	India	Max Nu ↑ 177%, friction ↑ 38%, instantaneous effectiveness ↑ 26.92%, thermal efficiency ↑ 9% (vs. straight tube)
Hiba et al. [76] (2023)	Storage systems: STHX, SFTHX, SSWTHX	Helical tubes, fins, experimental + simulation	Iraq	Melting duration ↓ by 21.3% (SFTHX) and 37.5% (SSWTHX); better thermal uniformity and convection in SSWTHX

Elaf Mohammed et al. [77] (2023)	Collector aperture width: 62 cm, Length: 100 cm, Parabolic curvature: 82.97 cm, Aperture area: 6200 cm², Rim angle: 105°, Focal distance: 9.61 cm, Glass envelope diameter: 8 cm, Copper tube diameter:	Corrugated copper tube, PCM (paraffin wax), twisted tape inserts	Iraq	Heat transfer ↑ 40% with PCM; twisted tape ↑ efficiency by ~35%; overall efficiency ↑ to ~85%
Kolahkaj et al. [80] (2024)	Flat plate collector; External size: 10×70×140 mm; Absorber: 0.5 mm Al (Sun strip); Glass: 6 mm; Area: 51.1 m²	Elliptical copper risers; 1% wt. MgO/water nanofluid	Iran (South)	Max efficiency: Water 62.7%, MgO nanofluid ~82.3%; Higher flow rates led to improved efficiency

6.4.2 Articles Findings Based on Theoretical Work

Different search articles investigate the enhancement techniques on solar parabolic collectors theoretically. Some of these studies will illustrated in Table 3 as shown below:

Table 3. Previous theoretical studies on parabolic solar collectors.

Author (Year)	Dimension	Type of Enhancement	Locatio n	Efficiency / Key Result
Diwan & Soni (2015)[67]	Absorber tube: Di = 19.5 mm, do = 26.5 mm; wire coil: d = 1.2 mm, length = 250 mm	Wire-coil inserts (varied pitch 6–20 mm)	India	Nusselt number ↑ by 104–330%; optimal pitch 6–8 mm; friction factor ↑ ~12.6%; enhanced turbulence and heat transfer
Bellos e t al (2017). [66]	Eurotrough ET-150 PTC; Aperture width: 5.8 m; Length: 12 m; Absorber diameter: 66–70 mm	Working fluid investigation: water, Therminol VP-1, molten salt, sodium, air, CO_2 , helium	Greece	Max exergetic efficiency: 47.48% with sodium at 800 K; water best under 550 K; CO_2 /He best >1100 K
Esapour et al. (2018) [72]	Multi-tube heat exchanger (1 m long); copper foam porosity 0.7–0.9, 20 PPI	Porous copper foam with PCM (RT35); tube arrangements	Iran	Melting time reduced by 14–55%; solidification faster with foam; 4 tubes & ε=0.7 gave best performance

Yan et al. (2022) [75]	TES system with Y-shaped fins; validated numerically	Y-shaped fins to enhance PCM melting	United Kingdom	Melting time ↓ significantly with narrow fins, higher angles, and elevated HTF temp

7. Limitations of Parabolic Trough Collectors (PTCs)

Solar collectors are the most widely used techniques for energy generation. By reviewing many theoretical and experimental works on solar parabolic trough collectors, many factors affect their performance. By applying this technology, many factors arise in its application range, for example:

- Non-Uniform Heat Flux Distribution: Uneven solar flux distribution around the absorber tube causes temperature gradients, leading to thermal stresses and efficiency loss [82].
- The change of the optical centre of the receiver and thermal storage along the day and night.
- Structural vulnerability to wind loads: Wind loads affect mirror alignment, tracking accuracy, and structural integrity, reducing efficiency [83].
- High Operation and Maintenance Costs: The flat plate collector requires high, difficult, and expensive maintenance to replace the glass sheet because it needs to turn off all the systems. Compared with the (EFC), which has an easy method to replace the glass tubes, the tubes can be replaced individually without stopping the entire system. So, it has low maintenance [84].
- Dependence on Direct Sunlight (DNI): PTSCs require high direct normal irradiance (DNI) to function efficiently and are ineffective in cloudy or diffuse conditions [85].
- Thermal Fluid Limitations: Heat transfer fluids like molten salts have high freezing points, requiring heating to prevent solidification and avoid operational downtime [86].
- Large Land Requirement: PTSC fields require vast areas for installation due to spacing needs for tracking and avoiding shadowing, which increases costs [87].
- Cleaning the accumulating dust particles on solar collectors: Dust accumulation on the glass plate of solar collectors is one of the biggest problems because it obscures solar radiation, which reduces their efficiency, especially in countries with hard climates. Dust accumulation mostly depends on weather conditions and geographical locations [88].
- Some of the reflected rays dissipated out of the receiver tube collector [89].

The knowledge of the parabolic solar collector trough limitations and short back points will help in developing a strategy for new search articles.

8. Conclusion

List and number all bibliographical references at the end of the paper. The references can be numbered in alphabetical order or in order of appearance in the document. When referring to them in the text, type the corresponding reference number in square brackets as shown at the end of this sentence [1].

This review concentrated on the energy problem that enhanced creative research, especially regarding energy from renewable supplies. Solar power is the optimal solution to address the current growing power demand, which is expected to rise more. Multiple types of solar parabolic-trough arrays, as well as methods for improving heat transmission, are the focus of this investigation. The initial section of this study identified the categories of solar collectors concerning their design, construction, and achieved efficiency. The second part covered the passive methods of improving heat transport, which include using coiled and corrugated tubes, Phase Changing Materials for heating storage (used when sunlight isn't available), and twisted tape inside the system. The third section disclosed the dual improvement strategies applied to SPTC, utilizing an expanded surface with phase change materials (PCM) and corrugated conical strip inserts for better thermal transfer efficacy. The most important conclusions obtained at the end of the experiments are:

➢ First part: smooth receiver tube collector

- The initial technique employed a single-stage parabolic trough collector with a steel receiver and an extensive capture area, revealing that the collector's efficiency is lower relative to its cost.
- The second technique employed the multi-stage solar PTC with a copper receiver, small area capture, and a sun tracker, exhibiting

greater efficiency relative to the single-stage.
- Experimental studies demonstrated that the copper tube receiver enhanced the effectiveness of the solar heater.
- There are many limitations that were discussed in section 6 that must be taken into consideration in the design of SPTC

➢ Second part: Passive enhancement techniques

The first promising method showed that using twisted tape improves SPTC performance and heat transmission. The previous work concerning passive enhancement techniques proves the following:
- Using a receiver tube that has scratches or corrugations can improve the system's thermal efficiency.
- Sealing the PTC receiver tube's inside can increase the system's thermal efficiency.
- Adding thermal storage paraffins will extend the system's efficient working time after sunset and improve the system's efficiency.

➢ Third part: hybrid enhancement techniques.

Employing more than one enhancement technique on the system will produce multiple effects on the system, as proved by the previous studies.
- By employing corrugated tubes and conical strip inserts within them, which raises the transference of heat and improves efficiency.
- When applying extended surfaces (fins) of various shapes reduces the melting time and enhances efficiency, hence improving heat transfer performance.
- Also, utilizing a corrugated copper tube in conjunction with paraffin wax (PCM) and twisted tape exhibited great efficiency in SPTC.

Finally, using a sun tracker will enhance the solar collector efficiency throughout the day especially if a 3-D collector type is used. Also, the modification of the receiver geometry through the use of corrugated tubes significantly enhances the thermal performance of solar thermal parabolic collectors (STPCs), owing to an increased heat transfer surface area and improved solar energy absorption. Variations in volumetric flow rate, relative to the receiver tube diameter, influence thermal efficiency and heat gain, highlighting the importance of flow dynamics in system performance. An enlarged aperture area of the concentrator facilitates greater solar irradiance capture, thereby increasing the thermal input to the collector. The incorporation of paraffinic wax as a phase change material (PCM) contributes to thermal energy storage by stabilizing the collector's heat gain and prolonging heat delivery during off-sunshine hours, particularly at night, through latent heat release. The use of twisted tape inserts within the receiver tube enhances convective heat transfer by generating turbulence and secondary flow structures, leading to improved thermohydraulic performance. A copper receiver tube further improves heat transfer efficiency due to copper's superior thermal conductivity, optimizing the interaction between the tube wall and the working fluid. Additionally, internal fins increase the effective heat transfer area, resulting in higher collector efficiency and thermal output.

These strategies can substantially improve the efficacy of the parabola trough collector, producing enhanced efficiency and efficacy in solar energy acquisition technologies.

Nomenclature

A	Area (m)
CPC	Concentrated Power Collector
CSP	Concentrated Solar Power
di	inner diameter(cm)
do	Outer diameter(cm)
DNI	Direct Normal Irradiance
EES	Electrical Energy Storage
ETC	Evacuated Tube Collectors
F	focal distance (m)
FPC	Flat Plate Collector
FCP	Full Cell Panel
h	heat-transfer coefficient ($w/m^2.^oC$)
HC	High Corrugated
HFC	Heliostat Field Collector
L	length (m)
LFR	Linear Fresnel Reflector
MCRT	Monte Carlo Ray Tracing
P	Pressure (bar)
PC	Pitch Corrugated
PCM	Phase Change Material
PDR	Parabolic Dish Reflector
PI	Pitch Insert
SPTC	Solar Parabolic Trough Collector
PTC	Parabolic Trough Collector
PTCs	Parabolic Trough Collector System
PV	Photovoltaic

W	width (m)

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