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Araştırma Makalesi / Research Article

Improving the Thermal Efficiency of the Parabolic Trough Solar Collector: An Overview

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Abstract

This article examines various methods to enhance the thermal efficiency of parabolic trough solar collectors (PTCs), both theoretically and experimentally. These methods include increasing the surface area of the absorber tube to increase its ability to absorb solar energy, placing a tube inserts inside the tube to induce turbulence and hence improve heat transfer. Among other methods are also minimization of reflection by using selective coatings on the surface of the absorber tube. Additionally, increasing the thermal conductivity of the working fluid, or modifying or altering the shape of the absorber tube or the reflective surface have also been shown to have improved thermal performance by minimizing energy losses due to conduction, convection, and radiation. All these and similar approaches that address and improve system parameters lead to improved efficiency and thermal performance, but they also entail a pressure drop and increase the cost of the system. In this study, the techniques that are used to improve the thermal efficiency of PTCs are addressed and presented in detail along with the findings of previous studies.

Keywords: Parabolic trough collector, Thermal efficiency, Absorber tube.

Parabolik Oluklu Solar Kolektörlerin Termal Verimliliğinin Artırılması: Genel Bakış

Öz

Bu çalışmada, parabolik oluklu güneş kolektörlerin termal verimliliğini hem teorik hem de pratik olarak artırmak için çeşitli yöntemler incelenmiştir. Bu yöntemler arasında güneş enerjisini absorbe etme yeteneğini artırmak için emici tüpün yüzey alanını artırmak, ısı transferini iyileştirmek için tüp içine turbülatör yerleştirmek yer almaktadır. Ayrıca emici tüpün yüzeyinden yansımayı azaltmak için seçici kaplamalar kullanarak yansımayı en aza indirmek gibi yöntemler de bulunmaktadır. Bunlara ek olarak, çalışma sıvısı için termal iletkenliği artırmak, emici tüpün şeklini değiştirmek ve kollektör ve yansıtıcı yüzeyin geometrisini iyileştirmek gibi diğer tekniklerin de emicinin termal performansını artırabildiği ortaya konulmuştur. Bu teknikler, parabolik oluklu güneş kollektörünün verimliliğini ve termal performansını artırmaya yol açmaktadır. Ancak aynı zamanda çalışma sıvısının basınç düşüşünü ve malzeme maliyetinde artışı da beraberinde getirmektedir. Bu çalışmada, bu teknikler önceki çalışmaların sonuçlarına bağlı olarak ayrıntılı olarak sunulmuştur.

Anahtar Kelimeler: Parabolik oluklu kollektör, Termal verim, Absorber tüp.

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1. Introduction

In recent decades, especially following the industrial revolution, the excessive and unregulated use of fossil fuels has resulted in the emission of harmful gasses and the consequent rise of their levels in the atmosphere. This has led to global warming and climate change, which have caused severe natural disasters such as hurricanes and floods in some regions, drought and desertification in others, and various other damages such as pollution from industrial waste. The use of fossil fuels also poses a direct threat to the environment as it pollutes the soil and rivers, adversely affecting living organisms and human food security. Therefore, it has become increasingly urgent to find alternative, clean, and environmentally friendly sources of energy to replace fossil fuels (Ediger et al., 1999); (Arutyunov et al., 2017); (York et al., 2019).

There have been international agreements and the establishment of organizations aimed at promoting and developing the use of renewable energy sources such as solar energy, wind energy, geothermal energy, hydropower, bioenergy, and other environmentally friendly energy sources. Among these sources, solar energy is one of the most significant due to its potential in many regions. Solar energy is utilized in various applications such as heating, cooling, drying, electricity generation, cooking, and distillation (Ozakin et al., 2020). Solar energy has a major advantage in its abundance, as the earth receives a vast amount of solar radiation each day, providing an almost limitless supply of solar energy. Furthermore, solar energy is a clean source of energy, meaning that it does not emit harmful pollutants that contribute to air pollution and climate change. Especially the increase in oil prices makes solar energy more attractive, and the number of systems that benefit from solar energy is increasing day by day (Kilic et al., 1983). However, it should be noted that the energy density per square meter of solar radiation received at the surface of the earth is low (Mao et al., 2014).

The intensity of solar energy can be increased by using Concentrated Solar Power (CSP), there are several types of solar collectors, such as the parabolic trough collector, solar dish, solar tower and others, these technologies can effectively use solar energy and increase conversion efficiency (Yesildal, 2022); (Öner, 2022); (Özakin, 2022). Among all CSP systems, the parabolic trough solar collector (PTC) stands out, it is a proven, well-developed, low cost and effective system for concentrating solar energy and is currently used for various applications (Wang, 2020).

In this study, various methods were investigated to increase the thermal efficiency of parabolic trough solar collectors both theoretically and practically in light of the studies in the literature. These methods include placing turbulators inside the tube to increase the surface area of the absorber tube, increase the system's ability to absorb solar energy, and improve heat transfer. In addition, these methods include methods such as minimizing reflection from the surface of the absorber tube, and using selective coatings to reduce direct loss. In addition, other techniques such as increasing thermal conductivity by interfering with the working fluid, changing the geometry of the absorber tube, and improving the geometry of the collector and reflective surface have also been shown to improve the thermal performance of the absorber. These techniques lead to improved efficiency and thermal performance of PTCs. However, it also brings on pressure drop and increase cost. In this study, a detailed literature review of the effects of such techniques on efficiency is presented.

2. General description of parabolic trough solar collector

As shown in Figure 1, a PTC consists of several components, including a reflective surface that reflects solar radiation towards the focus of the collector. The reflecting surface can be made of various materials, such as aluminum sheets, stainless steel, or reflective mirrors, depending on the design. Other components of the collector include the receiver tube that passes into the focal point of the parabola, support structure, connection tubes, water tank or heat exchanger, pump, control unit, measuring and control devices, and other devices or add-ons as required by the design.

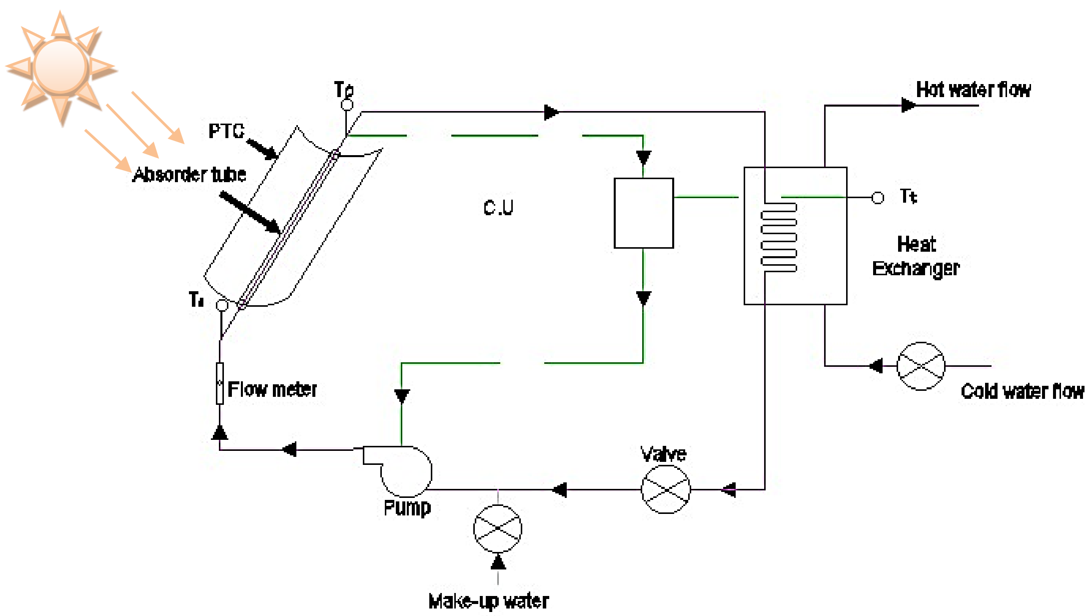


Figure 1. Schematic diagram of the components for a parabolic trough solar collector.

Prior to initiating the device's operation, the working fluid is loaded into the tank and pumped to the solar collector using a pump. As it flows through the absorber tube, the working fluid absorbs heat and exits the solar collector at a high temperature.

The temperature and pressure of the water at the inlet and outlet, as well as the water flow rate, are measured by special sensors, which are connected with a central control unit (CU) that regulates the operation of the device.

2.1. Enhancement of thermal efficiency

Numerous studies have been conducted to improve the thermal efficiency of parabolic trough solar collectors (PTC). The research on improving the thermal efficiency of PTC has been divided into six categories.

2.1.1. By placing turbulators inside the absorber tube

In order to improve the heat transfer rate from the absorber tube to the working fluid, the best of thermal enhancement techniques use turbulators in the flow zone. More specifically, the use of turbulators aims to increase the fluid mixing and working fluid's effective thermal conductivity in order to increase turbulence intensity.

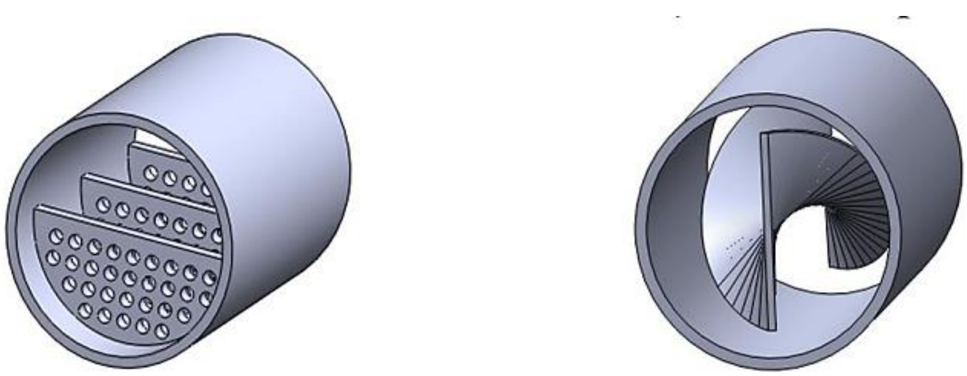
Table 1. Previous researches using inserts inside the receiver tube in PTC

Author	Type of insert	Working fluid	Method	Increase (%)		
				η_{th}	h	Δp
(Jaramillo et al., 2016)	Twisted tape	Water	Thermodynamic model frame work	10	400	2000
(Diwan et al., 2015)	Wire coil	Water	Model	-	330	2200
(Benito et al., 2015)	Wire coil and twisted tape	Compressed air	Model	-	100-300	200-1000
(Sahin et al., 2015)	Wire coil	Water	CFD+ Experimental	-	240	2000
(Jamal-Abad et al., 2017)	Metal foams	water	Experimental	3	-	2000
(Ghasemi et al., 2017)	Porous rings	Syltherm 800	CFD	-	50	1000
(Reddy et al., 2015)	Porous discs	Water	Experimental	6	-	-
(Abed et al., 2021)	Conical strip inserts	SiO2	CFD	14.62	-	258.42

As presented in Table 1, the twisted tape insert is the most common insert type used inside the absorber tubes. (Jaramillo et al., 2016) carried out an experimental study about the twisted tape insert and reported a significant thermal enhancement but along with a large increase (by 2000%) in the pressure drop.

The use of wire coil inserts has been investigated by (Diwan etal., 2015); (Sahin et al., 2015); (Benito et al., 2015) contrasted these using two different techniques; they discovered that the addition of twisted tape inserts increased h (330,300,240) % respectively. All of the previous studies made an effort to rotate the flow and enhance the fluid mixing.

Other options that have been examined include the use of metal foams (Jamal-Abad et al., 2017). The study found that the use of copper foam as a filler in the absorber improved the efficiency of the collector. Additionally, filling the absorber with metal foam resulted in a 45% reduction in the overall loss coefficient (UL), thereby increasing efficiency by minimizing energy loss. Similarly, both porous rings (Ghasemi et al., 2017) and porous discs (Reddy et al., 2015) have been employed to increase the surface area for heat exchange and improve the heat transfer from the receiver to the working fluid (see Figure 2). However, the use of turbulators also increase pressure drop, which results in higher pumping power. Thus, it is important to carefully evaluate the impact of pressure drops in such techniques.



(a) (b)

Figure 2.a. porous discs (Reddy, Ravi Kumar, & Ajay, 2015) , **b.** twisted tape (Jaramillo, Borunda, Velazquez-Lucho, & Robles, 2016)

(Abed et al., 2021) conducted a numerical study to examine the impact of swirl inserts on the performance of a parabolic trough solar collector. The results indicated that using straight conical strips alone increased the Nusselt number by 47.13%. However, incorporating swirl generators reduced thermal losses by 22.3%. The investigation of various swirl generator designs revealed that different configurations led to varying levels of improvement in overall thermal and thermal exergy efficiency.

The largest swirl generator (H=30 mm, θ=30°, N=4) with 6% SiO_2 nanofluids was identified as the optimal configuration, resulting in a 14.62% increase in overall collector efficiency and a 14.47% increase in thermal exergy, but the pressure drop increased by 258.42% (see Figure 3).

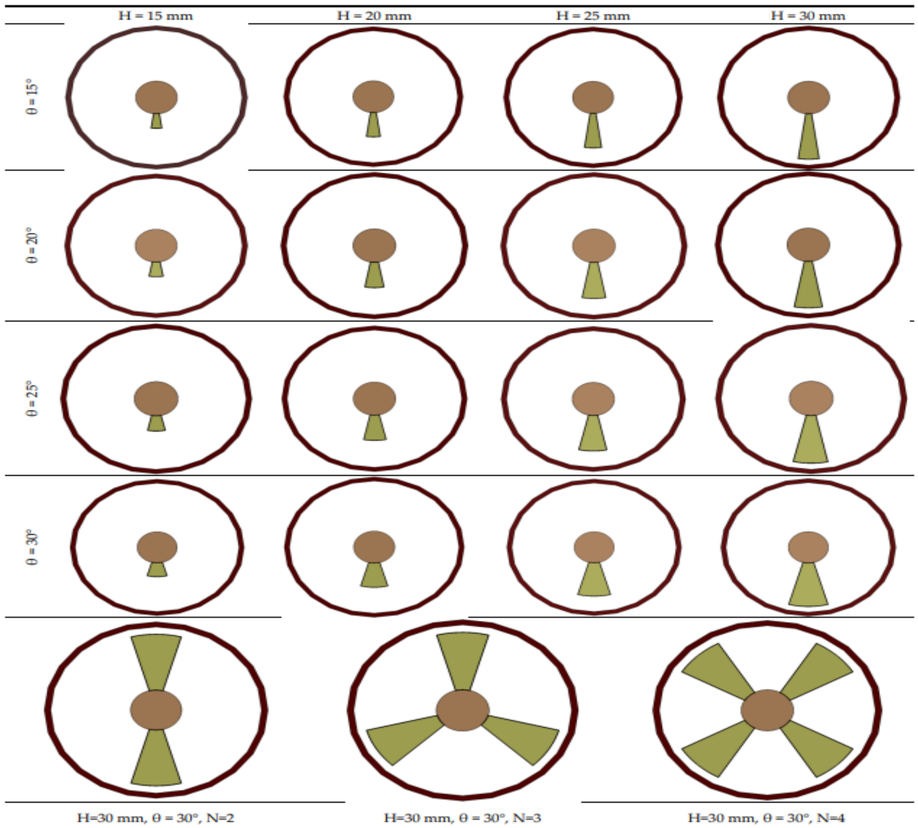


Figure 3. Different configurations of the examined straight conical strips (Abed, Afgan, Iacovides, Cioncolini, Khurshid, & Nasser, 2021)

2.1.2. By increasing surface area of absorber tube

Raising the convective contact area inside the absorber tube or the heat transfer rate within the absorber tube will enhance the useful heat rate. A lot of research has focused on improving geometric designs of absorber tubes to increase their heat transfer surface area.

Because the heat flux is focused in the lower half of the absorber, (Benabderrahmane et al., 2016) have attempted to change this section, they examined the usage of small two fins rectangular or triangular by numerical methods as shown in Figure 4. The results show that when a fin was employed in the low part in absorber, the heat transfer coefficient increased dramatically when compared to a smooth tube model, it increased by 68%. It is observed that cases 1 and 2 have larger Nu, with augmentations ranging from

1.3 to 1.8 times more than with a smooth tube. The scholars ultimately showed that the geometric parameters of the fins have a remarkable effect on improving heat transfer.

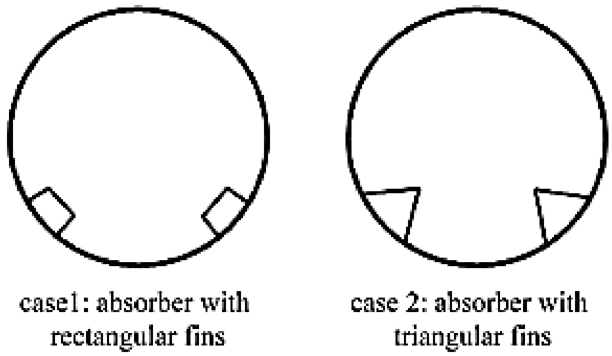


Figure 4. Physical model of absorber with longitudinal fins inserts. (Benabderrahmane et al., 2016)

Utilizing numerical techniques, the efficiency of the collector is improved by 3%, according to Munoz and Abanades's investigation (Muñoz et al., 2011) by using helical fins. However, the parasitic losses related to the pressure losses in the tube would rise with the number of fins and its helix angle (see Figure 5).

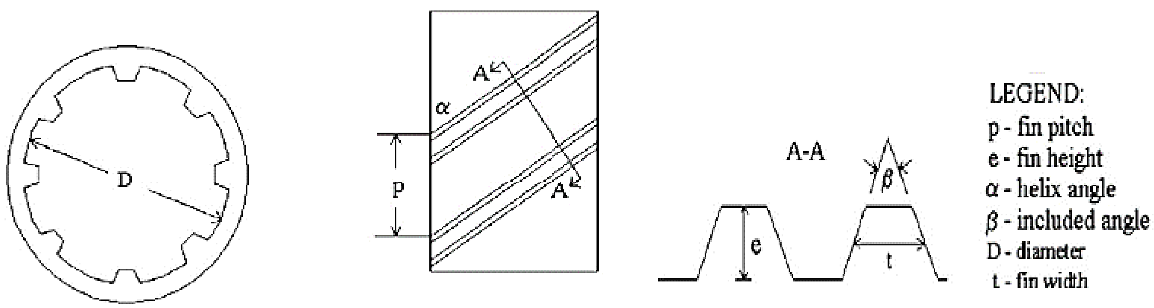


Figure 5. Geometrical parameters for the helical fin. (Muñoz & Abánades, 2011)

(Saedodin et al., 2021) utilized numerical analysis to examine the fluid flow and heat transfer in a parabolic trough solar collector equipped with turbulence-inducing elements on the absorber tube wall. The elements were helically profiled throughout the pipe. The findings indicated that the model with elements having a rectangular cross-section exhibited the highest thermal performance compared to all other cross-sections considered. At an inlet velocity of 0.2 m/s, the models with rectangular and triangular cross-sections had the highest and lowest thermal efficiency enhancements, respectively, with enhancements of 29% and 21.8%. This trend was observed across all the inlet velocities studied. Additionally, they have analyzed five different models, which included two, four, six, and eight turbulence-inducing elements, and the model with eight elements demonstrated the highest thermal performance at different inlet velocities (see Figure 6).

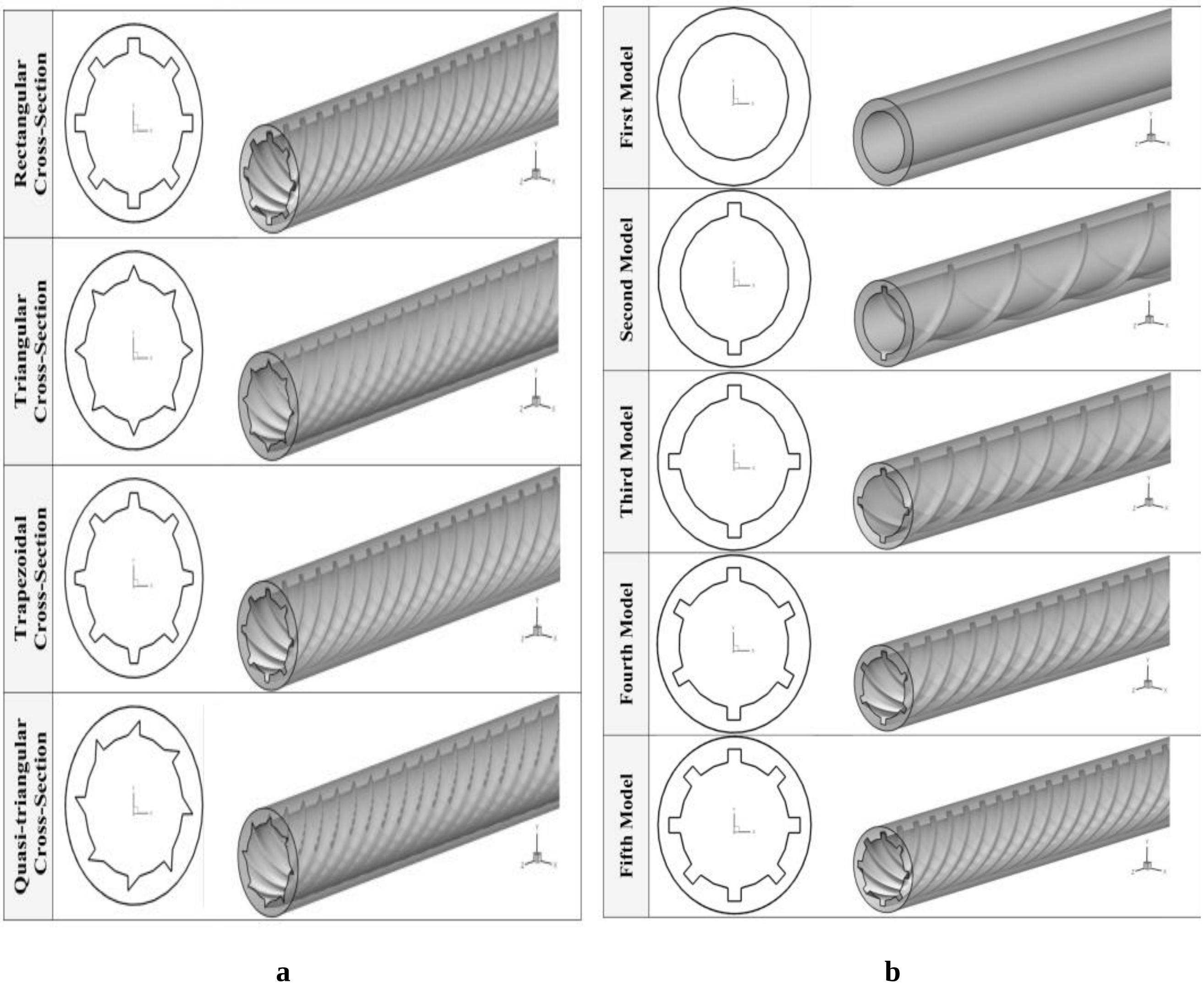


Figure 6. a. various cross-section geometries of the turbulator element.
b. Five models of the same shape turbulator elements. (Saedodin, Zaboli, & Ajarostaghi, 2021)

In an article it is studied twelve rectangular longitudinal fins with lengths that ranged up to 20 mm and thicknesses that ranged up to 6 mm (Bellos et al., 2017). It was determined that larger lengths and thicker walls lead to greater pressure losses and thermal enhancement, Nu increases 65.8%, and η_{th} is improved by about 0.82%.

(Sanaz, 2020) analyzed the effectiveness of nine different corrugated absorber tubes with varying pitch lengths and roughness heights in a parabolic trough collector (PTC). The results indicated that the PTC's thermal efficiency increased with an increase in roughness height to diameter ratio and a decrease in pitch to diameter ratio of the absorber tube. The corrugated tube's wall generated a region of adverse pressure gradient, leading to recirculation and more turbulence, which improved the mixing fluid near the wall and the core, thereby enhancing the PTC's efficiency. The PTC with a helically corrugated absorber tube with a pitch length of P=3 mm and roughness height of e=1.5 mm had the highest thermal efficiency of 65.8%, but the friction factor was 1.84 times higher than the plain tube. The study confirmed that the pressure drop did not significantly affect entropy generation, as demonstrated by the variation in the Bejan number (see Figure 7).

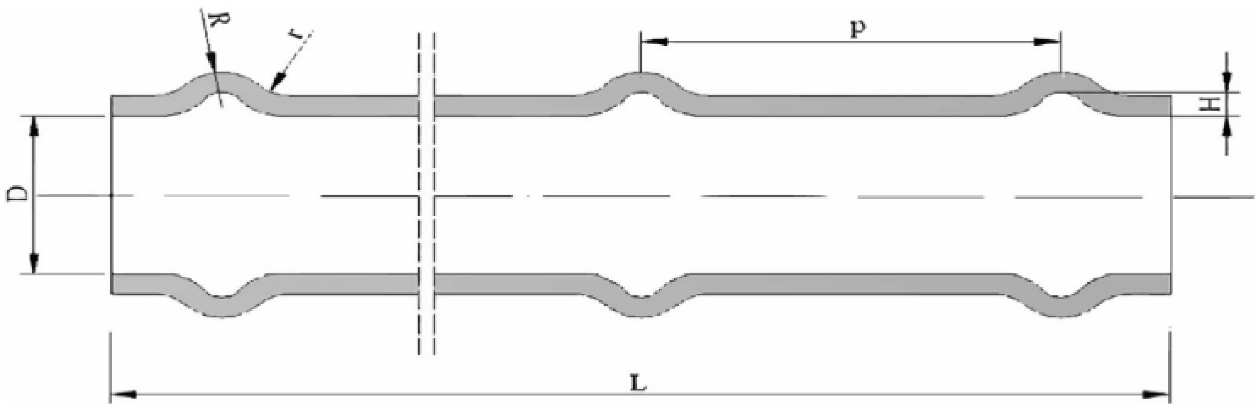


Figure 7. The outlined design of the corrugated tube. (Sanaz, 2020)

2.1.3. By increasing thermal conductivity

One of the most important components of solar conductors that significantly contribute to enhancing heat transfer in PTC is the working fluid. Since the beginning of the use of solar energy, there have been several efforts to improve the performance of thermal conductivity of the working fluid. They are produced by distributing metallic nanoparticles in the primary fluid (water or oils)

Established an empirical model, investigated the effect of two diverse nanofluids CuO/water (0.05vol.%) and Al_2O_3/water (0.01vol.%) compared with water as a base heat transfer fluid (HTF), they discovered that at a maximum $\dot{m}$, utilizing 0.05 vol. % of CuO and Al_2O_3 has the highest total thermal efficiency of 15.25% for CuO/water, 12.39% for the Al_2O_3/water and 10.58% for the water. This indicates that compared to water, using CuO/water nanofluid increased efficiency by about 44% (Sharma et al., 2014).

(Rehan, et al., 2018) led an examination to determine the impact of Al_2O_3 and Fe_2O_3 nanoparticles distributed in water at different flow rates (1-2 L/min) and weight fractions ranging from 0.2% to 0.3% on η_{th} of PTC in winter season. The results showed that adding Al_2O_3/water nanofluids increased thermal efficiency by 13% and it is increased 11% when they used Fe_2O_3/water, respectively, at 2 L/min flow rate and 0.3wt.% (see Figure 8).

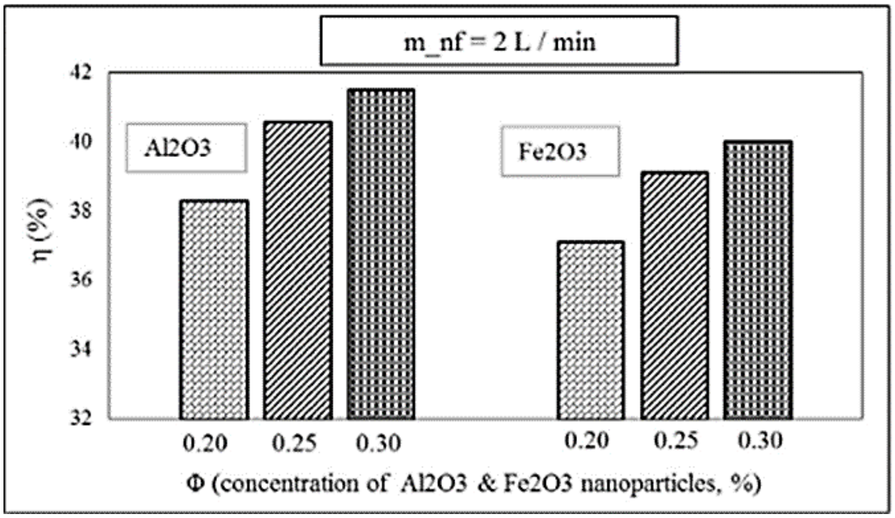


Figure 8. Average variations in PTC Efficiency using Al_2O_3 and Fe_2O_3 nanoparticles. (Rehan, et al., 2018)

At four separate sites in Iran, (Marefati et al., 2018) conducted an experimental investigation into the influence of Al_2O_3, CuO, and SiC mixed with water at a concentration of 1 to 5 vol.% on the thermal performance of the PTC (Tehran, Yazd, Tabriz and Shiraz). The PTC in Shiraz was maximum efficiency it was 37.2%. The results showed that CuO nanofluid increased conduction of heat more than Al_2O_3 nanofluid, and Al_2O_3 nanofluid increased heat transmission more than SiC nanofluid. They added that the use of a CuO/water nanofluid enhanced convective heat transfer by about 33% as compared to water alone. As a result, CuO/water nanofluid is the greatest choice for increasing thermal efficiency.

The Nickel Ferrite nanofluid was prepared using a two-step procedure and its effectiveness in enhancing the efficiency of the parabolic trough solar collector (PTC) was experimentally investigated. The study involved testing the nanofluid at two different volume fractions of 0.01% and 0.05%, as well as using deionized water as a working fluid. The experiments were conducted at three different volume flow rates, ranging from 0.5 to 3 l/min. The analysis showed that the application of the Nickel Ferrite nanofluid at high flow rates was more effective and suitable in the PTC. The highest efficiency recorded was 40%, achieved using Nickel Ferrite nanofluid with a volume fraction of 0.05% at a flow rate of 3 l/min. This is significantly higher than the 28% efficiency recorded using pure water. The findings suggest that the thermal efficiency of the parabolic trough solar collector improves with increasing flow rate and volume fraction of the nanofluid (Mohammad, 2021). Table 2 shows the results of study using water as working fluids using absorber with and without U-tube.

Table 2. Results of study using water and nanofluid at two different volume fractions as working fluids.

Working fluid	Flow rate (L/min)	T_{inlet} (°C)	T_{outlet} (°C)	ΔT (°C)	Efficiency %
water	0.5	50	56.5	6.5	16
	1.5	50	53.8	3.8	27
	3	50	52	2	28
Nanofluid 0.01%	0.5	50	59.1	9.1	21
	1.5	50	54.8	4.8	33
	3	50	52.7	2.7	38
Nanofluid 0.05%	0.5	50	63.9	13.9	27
	1.5	50	56.1	6.1	36
	3	50	53.4	3.4	40

2.1.4. By decreasing heat losses

In order to reduce convection and radiation heat losses even in hot environments a tube made of high transmittance and antireflective glass can be used around the absorber tube and the air evacuate between the tubes. Since evacuated receivers have a high vacuum (i.e., 10-5 mbar) between the absorber and the glass tube, they are widely applied for temperatures up 300 °C. This reduces thermal losses and boosts the PTC's overall efficiency, it also preferable to improve the transmittance of solar radiation using glass tube formed from low-iron borosilicate glass. To increase solar transmittance and improve performance, the glass tube is usually coated with an anti-reflective coating.

(Premjit, 2011) numerically compared the heat loss for three configuration of absorber tube with glass shell, evacuated tube, non-evacuated and vacuum shell (see Figure 9), for an operating temperature 250°C, in comparison to the other configurations at the test temperature, the heat loss from the non-evacuated tube is more sensitive to outside weather conditions. The results of the study are shown in Table 3.

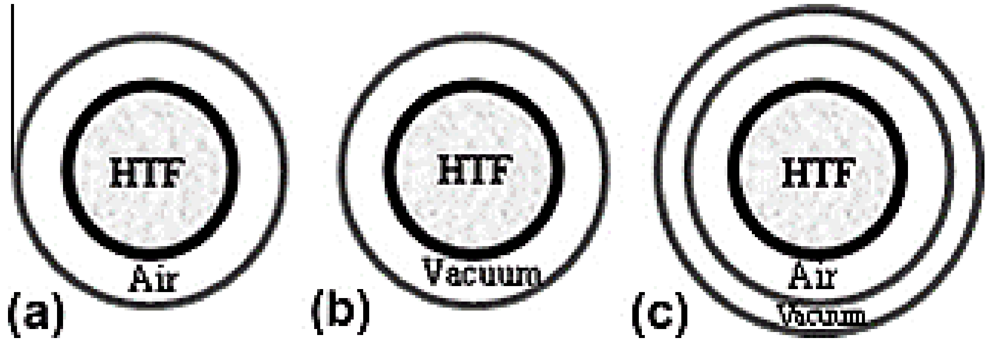


Figure 9. Absorber tube with three different shells. (Premjit, 2011)

Table 3. Comparison of heat loss for different receiver configurations (at 250 °C). (Premjit, 2011)

Velocity (m/s)	Heat loss (W)		
	(a) Non evacuated	(c) Vacuum shell	(b) Evacuated
1	456	282.5	102.5
2	494	290.4	103.2
3	517	294.4	103.7
4	533	296.9	103.7
5	545	298.5	103.8

Other study was done by (Soudani et al., 2017) to analyze the non-evacuated tube using both experimental and theoretical methods. Copper was used to make the receiver, which had diameters of (do = 0.051m, di = 0.028 m) and (do = 0.053m, di = 0.051 m) for the glass cover, respectively. The results showed that at 11.30 am, the efficiency reached 77% with the reflector dimensions were (1.8 x 1.6 m), the output temperature was 90 °C, and with different was 9% bigger than efficiency obtained from reflector without cover as shown in fig.10.

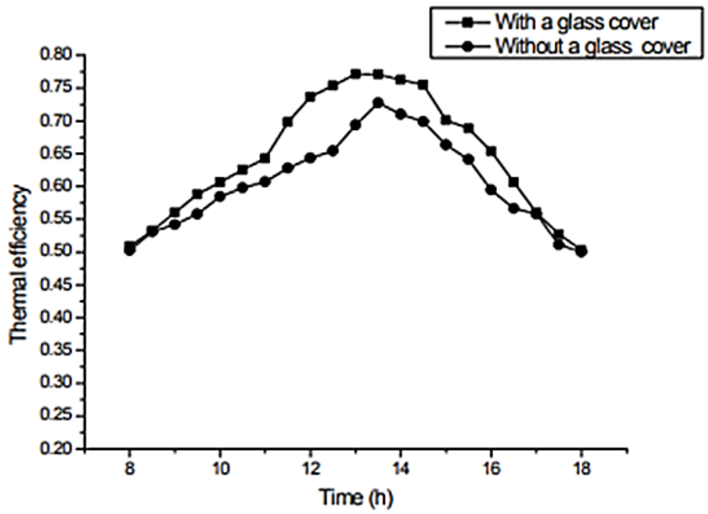


Figure 10. Experimental thermal efficiency during the day (water flow rate: 0.009 kg /s). (Soudani et al., 2017)

(Al-Ansary et al., 2011) propose an alternative method for improving the thermal performance of parabolic trough collectors by incorporating heat-resistant thermal insulation material into the receiver annulus that does not receive concentrated sunlight. This approach is compared to the conventional use of receivers with air-filled annuli, which are currently used mainly for process heat applications and have lower thermal performance than evacuated receivers. Numerical modeling is utilized to calculate conduction and convection heat losses from the proposed receiver, and its performance is compared to that of a conventional receiver with an air-filled annulus. The findings indicate that using fiberglass insulation in the proposed receiver can decrease the combined conduction and convection heat loss by up to 25%. However, the proposed approach's benefit diminishes at high temperatures due to the insulation material's increasing thermal conductivity.

2.1.5. By increasing emissivity and decreasing reflectivity

Black coating can be used to on absorber tubes to decrease the losses that occur when operation temperature is high. In order to improve heat transfer, the absorber must to be coated. PTC uses a variety of coatings, such TiAlN/TiAlON/SiO_2, Au-MgO, HfMoN/HfON/Al_2O_3, Mo-SiO_2, and Ni-25, Al2O_3, $NiCo_2O_4$, Ni-5Al, Mo-Al_2O_3,TiAlN/TiAlON/Si_3N_4, $CuCoO_4$(NiFe)Co_2O_5, W-Al_2O_3,AlNi-Al_2O_3, Ni-SiO_2,

As an ideal absorbance the coating may absorb the most solar radiation as possible ($\alpha \geq 0,95$), which minimizes solar radiation reflection. Additionally, there should be little heat loss through convection or conduction (including emission ε ≤ 0.050) onto the surroundings, having thermal stability (TS) of up to the working temperature of the receiver (Chen, 2011) (see Figure 11).

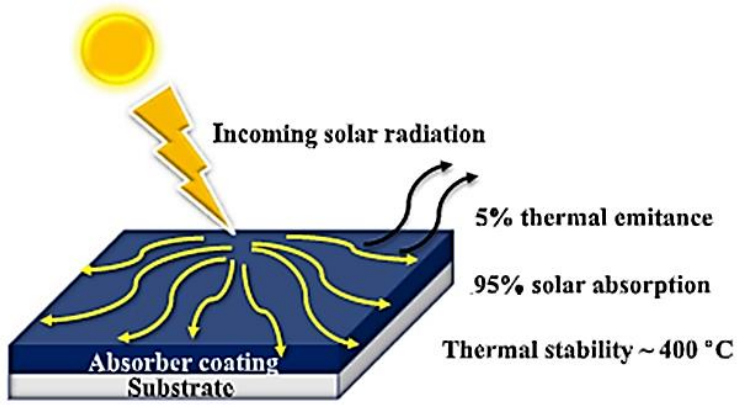


Figure 11. Solar selective absorber. (Chen, 2011)

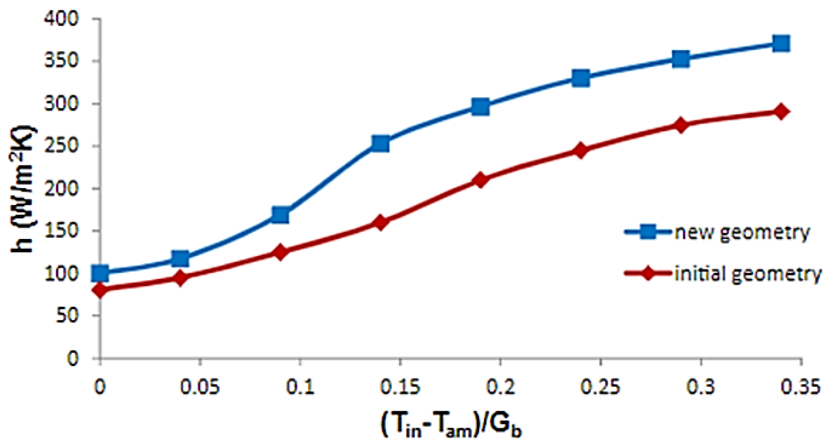
(Asaad, 2022) reviewed several types of selective coating materials and their properties for various solar power concentrator designs. By reducing thermal losses, the coating used in the absorber tube of PTSC demonstrated an impressive improvement in thermal efficiency. On the other hand, to achieve higher properties, various coatings must be combined with other materials providing better properties.

Sandia National Laboratories (Ambrosini et al., 2015) is investigating solar selective coatings on CSP to improve physical and chemical properties. A thermal spraying coating with using a laser had improved properties for 480 hours and had an absorptivity of more than 90% at 600 and 700 °C.

2.1.6. By changing shape of absorber tube

The receiver tube (absorber) is in charge of transmitting heat to the HTF of the PTC system and the major section to influence the thermal proprieties of the system. Several studies have suggested changes shape of the absorber tube to enhance its thermal performance by expanding the local quantity and the overall inner tube surface.

The results shown in Figure 12 (Bellos et al., 2016), a new design of the tube taking a converging-diverging form was recommended to increase the heat transfer performance of a solar PTC. Their numerical results indicated a mean efficiency improvement up to 4.55% than smooth tube geometry because converging tube pushes the flow to be mixed better and gives a more uniform temperature distribution inside the tube.



h	heat transfer coefficient.
T_{in}	inlet temperature.
T_{am}	ambient temperature.
G_b	specific thermal capacity.

Figure 12. Heat transfer coefficient comparison for the two examined geometry with thermal oil as working fluid. (Bellos et al., 2016)

(Chakraborty, 2021) by simulation the thermal performance of the parabolic trough collector with a helical absorber tube; three models (0 (smooth), 75, 85, and 95 turns) are proposed also they used two mass flow rate of water (0.15 and 0.6 kg/s). The output of the tube with higher number (95) of turns using water as working fluid was the highest thermal efficiency and the exergy efficiency; it was 10% and 5%. As compared to an absorber tube that is smooth. Additionally, the Nusselt number of PTC with a helical absorber tube has boosted in value by up to 25% (See Figure 13, 14).

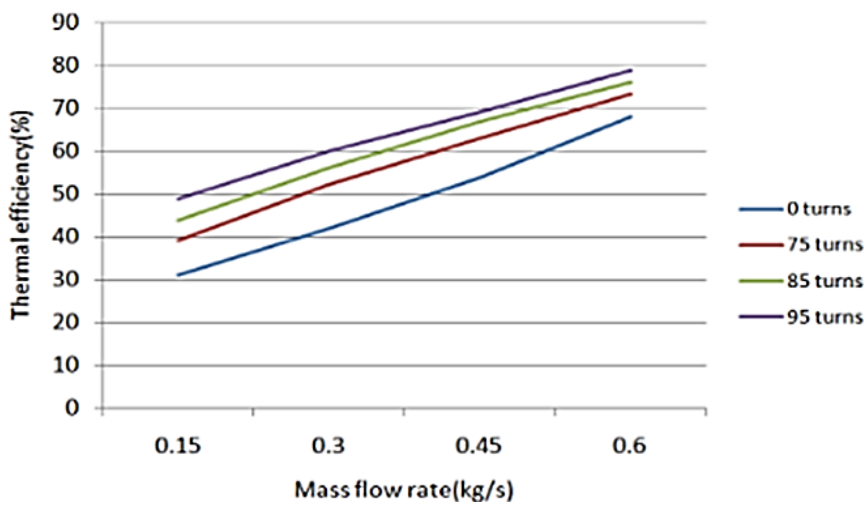


Figure 13. Thermal efficiency of the PTC collector with helical absorber tube. (Chakraborty, 2021)

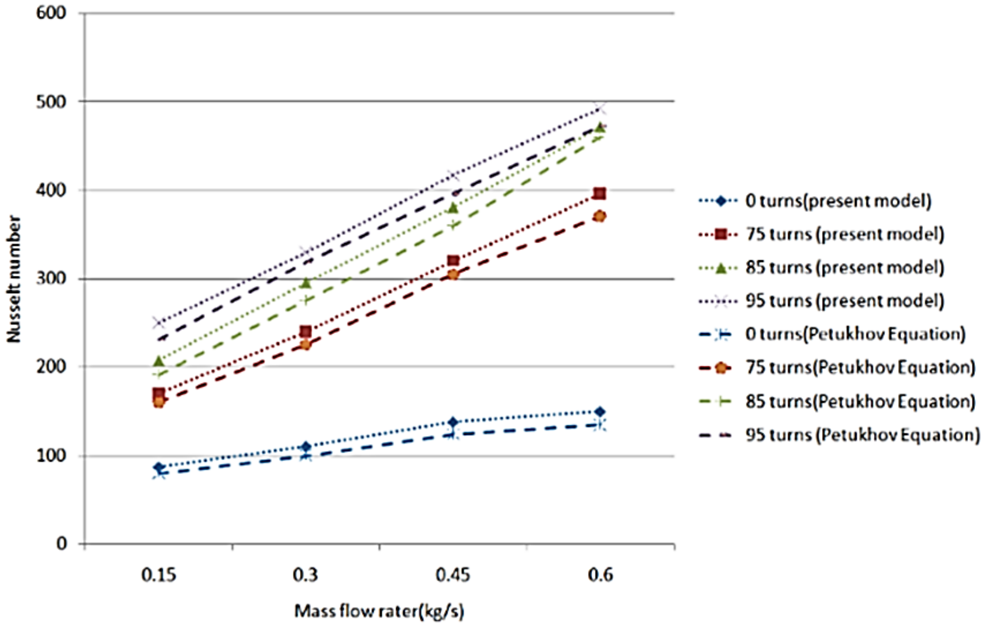
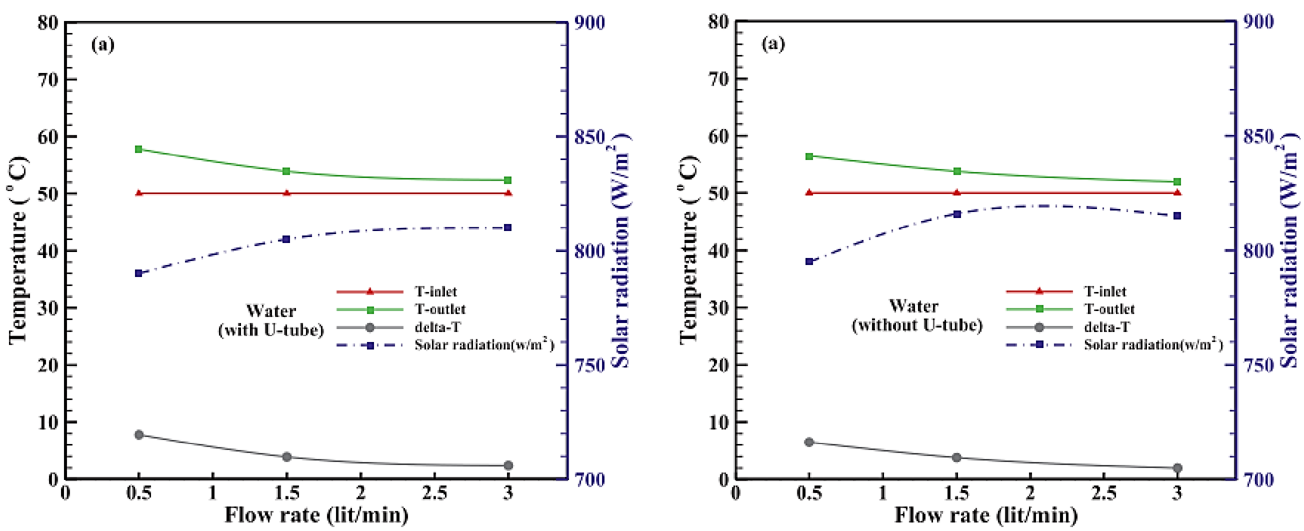


Figure 14. Validation of the model in terms of Nusselt number for helical absorber tube. (Chakraborty, 2021)

The main aim of studies by (Mohammad, 2021) was to evaluate the efficacy of the U-tube as an absorbent in a parabolic trough solar collector. The experiments were conducted at varying volume flow rates, ranging from 0.5 to 3 L/min. The results indicated that using a U-tube as an absorbent was more effective than pipe without the U-tube. In particular, at a flow rate of 3 L/min, the efficiency and the outlet temperature of the pipe with the U-tube was 34% 52.4 °C respectively, while the efficiency and the outlet temperature of the pipe without the U-tube and at the same flow rate was 28% 52 °C (see Figure 15).



a. **b.**

Figure 15. Changes in outlet temperature, solar radiation, and temperature difference between inlet and outlet at different water flow rates; **a.** U-tube **b.** without U-tube. (Mohammad S. D., 2021)

Researchers (Kulahli et al., 2019) present a novel parabolic reflector for the axial focal length variable Parabolic Trough Collector (PTC). The reflector contains a focal length that changes in the longitudinal direction while maintaining a fixed focal line. They showed that because of this geometry, the heat flux around the absorber changes not only circumferentially but also axially. Scholars defined a new geometric design parameter, the ratio of the focal length at the ends, and numerically examined its effects on thermal behavior using a custom code to create the new reflector in SolTrace (a ray tracing software). As a result, they performed flow optimization analysis as well as geometric factor analysis. As a result of parametric analysis, they showed that thermal efficiency increased by 0.21%, and as a result of flow optimization, an increase of 0.63% was achieved in net energy gain.

(Taher et al., 2023) by proposed a new optical design for a PTC that uses the Monte Carlo Ray-Trace (MCRT) method to estimate the solar flux distribution on the absorber tube surface. They applied Taguchi and ANOVA analysis methods to simultaneously investigate multiple control parameters and determine their contribution rates. In addition, multi-objective optimization of optical efficiency and solar flux uniformity was obtained using the Gray Relational Analysis (GRA) method. The proposed design achieved an optical efficiency of 83.01% and a heat flow uniformity of 92.24%, demonstrating its effectiveness in balancing optical efficiency and heat flow uniformity.

3. Conclusions and Recommendations

Due to the importance of the receiver tube in the parabolic trough solar collector since it is the part that absorbs the focused solar rays from the reflecting surface, so this paper collects some results from previous studies to improve heat transfer and obtain higher thermal performance. The following are the list of the outcomes:

- After testing several inputs to change the working fluid stream and increase the Reynolds number and making the flow turbulent, the conical strip inserts was the highest increase ratio in thermal efficiency, which was 14.62%.
- Several shapes of fins were used to expand the inner surface of the receiver tube, and the results showed an increase in the conductivity, Nusselt number and efficiency, in addition as the length and number of the fins rise, thermal enhancement also rises accompanied by a rise in pressure drop. The results from the study involving elements with a helically profiled design throughout the pipe showed that the model with elements featuring a rectangular cross-section

demonstrated the most superior thermal performance. The increase in thermal efficiency of this model was found to be 29%.

- The vacuum glass tube has the lowest heat losses after comparing it with absorber without glass tube and non-evacuated class tube, because it was not affected by the weather unlike with the others, this is also preferable to use glass tubes made of low-iron borosilicate glass to increase the transmittance of solar radiation.
- Previous researchers have noted the benefit of using coating in reducing heat losses by boosting permeability and minimizing reflection from the absorber tube furthermore a thermal spraying coating with using a laser was the best method.
- Changing the shape of the absorber tube that contains the working fluid and the use of a tube with a spiral shape or undulating internal area led to an increase in heat conduction and convection due to the presence of secondary vortices inside the fluid. Despite the increase in thermal efficiency with the increase in the number of turns of the spiral tube, the pressure drop has increased. Moreover, the absorber with a U-tube demonstrated the highest increase in thermal efficiency, reaching 21%.
- The use of nanofluid was efficient in improving the thermal conductivity of the liquid and a significant improvement in the output temperatures, use of CuO nanoparticles was the better and highest thermal efficiency, with Al_2O_3 came in second place. Where, the application of nanofluids as the working fluid yielded the greatest improvement in thermal efficiency compared to all other studies. To be specific, the utilization of CuO nanofluids resulted in a 44% increase
- Based on the results of previous studies, we recommend integrating more than one method to improve the thermal performance of the parabolic trough solar collector, such as using a helical or straight absorber tube with vortex generators (turbulators), coating it with a selective coating, and using a vacuum glass tube, at the same time. Nanofluids can be mixed with the working fluid, taking into account costs, as well as the amount of pressure drop of the working fluid.

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Authors' Contributions

All authors contributed equally to the article.

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There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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