Al-Furat Journal of Innovations in Mechanical and Sustainable Energy Engineering (FJIMSE)

Thermal efficiency Improvement Techniques in a Parabolic Solar Collector for Indirect Steam Generation

Hussein Fadhil Abdali[1] , Kadhim F. Nasir[2]

[1]Power Mechanics Engineering Department, Technical College of Al-Mussaib, Al-Furat Al-Awsat Technical University, Kufa, 54001, Iraq. E-mail: hussain.fadhil.tcm58@student.atu.edu.iq
[1]Power Mechanics Engineering Department, Technical College of Al-Mussaib, Al-Furat Al-Awsat Technical University, Kufa, 54001, Iraq. E-mail: Kad2020@atu.edu.iq (10 pt)
*Corresponding author E-mail: hussain.fadhil.tcm58@student.atu.edu.iq

Abstract.. *This review article aims to provide a complete overview of the innovations related to the thermal efficiency of parabolic trough collectors (PTCs) in the concentrated solar power (CSP) industry and will evaluate all the work that has been completed since 2020; this evaluation will evaluate four major areas of innovation, including engineering hybrid nanofluids to improve thermo-physical properties and convective heat transfer coefficients; utilizing advanced heat pipe technology for isothermal operation and effective coupling with phase change materials for thermal storage; applying geometric enhancements and passive turbulence generators to disrupt thermal boundary layers. In addition, it will evaluate the integration of artificial intelligence (AI) and machine learning (ML), including Physics-Informed Neural Networks (PINNs) and an emphasis on evolutionary algorithms that will allow for precise thermal modeling and design optimization. Finally, the article will assess the system level benefits of employing these technologies including impacts on thermodynamic performance; steam generation dynamics; and techno-economic feasibility as they relate to reducing the levelized cost of energy (LCOE) while enabling poly-generation applications such as the production of green hydrogen.*

Keywords: Parabolic Trough Collectors. Concentrated Solar Power. Hybrid Nanofluids. Heat Transfer Enhancement. Heat Pipe Technology. Passive Turbulators, Artificial Intelligence.

1. INTRODUCTION

Parabolic Trough Collectors (PTCs) are proving to be the leading technology in the Concentrated Solar Power (CSP) market and will play an even more significant role in the global clean electrical and thermal energy demand. A parabolic trough collector collects Direct Normal Irradiance (DNI) and focuses it onto a concentrated absorber tube, which will have a Heat Transfer Fluid (HTF) moved through the tube to convert radiant energy to thermal energy with performance and efficiency acceptable in comparison to other solar technologies [1]. At the same time, there are thermodynamic and structural limits on the PTC that can significantly inhibit its efficiency during the very high temperature Indirect Steam Generation used in power plants and for industrial applications [2].

The primary challenge to PTCs lies with the thermal limits of traditional HTFs such as synthetic oils and molten salts. These fluids have low thermal conductivity and limited specific heat capacities, which lead to increased thermal resistance between the inner tube wall of the absorber and the transporting fluid [3]. Further limiting the heat transfer characteristics of the tube is the non-uniform distribution of heat flux around the circumference of the tube, which creates thermal stresses and large temperature differences,

ATU- FJIMSE, Vol. 4 No. 1 (2026): volume 4,Issu 1,May 2026 , All Rights Reserved

resulting in mechanical failure of the tube and increased losses due to convection and radiation, and ultimately lower efficiency of the PTC [4].

In response to the challenges associated with the engineering design of CSP plants, the current decade (2020–2025) has seen an explosion of research dedicated to “Heat Transfer Enhancement” methods, which can be characterized as "active" and "passive”. Whereas “passive” methods are the most common and cost-effective means of improving thermal performance by altering either the properties of the working fluid or the configuration of flow around it (e.g., by increasing its density and thus reducing the size of cross-section), “active” methods provide an entirely different approach to enhancing thermal performance. For example, nanofluids have emerged as an innovative and potentially disruptive solution to CSP thermal management challenges. The use of nanofluids, which are composed of base fluids containing high thermal conductivity nanoparticles suspended in them, has a demonstrated capability for improving the convective heat transfer coefficient as well as improving the optical and thermal properties of the working fluid [5][6].

At the same time, researchers in the field of engineering have focused their attention on the development of new designs and configurations for CSP receiver tubes by using "turbulators". These include twisted tapes, internally gridded fins, or porous media that disrupt the thermal boundary layer and produce a general increase in turbulence intensity and mixing velocity within the tubes. These devices have been designed to increase the Nusselt number and improve heat transfer, but typically result in only marginal increases in pressure drop [7][8].

A relatively new and emerging technology is the combination of "Heat Pipe" technology with solar collectors, and it is one of the most innovative and effective methods to collect the sun's energy to heat water. The primary benefit of the heat pipe is its ability to transfer large amounts of heat from point A to point B, with very little temperature difference between those two points (isothermal operation), by using the phase-change properties of the internal working fluid [9, 10]. The use of a heat pipe in this manner dramatically decreases the amount of thermal resistance within the system, prevents freezing from occurring at night, and minimizes the instability created by thermal inertia during start-up, thus making it an excellent choice for steam generation. Additionally, due to the tremendous advancements in data science, there is a significant opportunity to integrate artificial intelligence (AI) and machine learning (ML) into the modelling and simulation of solar collectors into the future, providing tremendous advances in our ability to accurately predict the thermal performance of solar collectors under different environmental and operating conditions (variable and non-linear), while also assisting with the optimization of the design parameters of the collector beyond what is possible with traditional trial-and-error methods [11, 12]. This review paper aims to provide a comprehensive and critical analysis of the latest advancements in thermal efficiency improvement techniques for Parabolic Trough Collectors (PTCs) dedicated to indirect steam generation, with an exclusive focus on literature published between 2020 and 2026. This paper will discuss the integration of nanofluids, geometric engineering inserts, heat pipe technology, and the role of artificial intelligence, providing an integrated vision for the future of this technology.

2. Efficiency Enhancement using Nanofluids and Hybrid Nanofluids

Indirect steam-generation thermodynamic efficiency in PTC is primarily determined by HTF thermophysical constraints. Synthetic oils, molten salts, and other common working fluids exhibit relatively low thermal conductivity (kinetic) and therefore limit convective heat-transfer coefficient (h) at the fluid-wall interface. Consequently, there has been a recent trend in research toward using nanotechnology to alter the microstructure of these fluids. The development of hybrid nanofluids represents a significant advance in achieving the optimum balance between hydraulic-pump penalties and thermal enhancement.

The heat-transfer mechanism associated with advanced fluids involves complex particle-fluid interactions. The thermal enhancement gained through dispersion of nanoparticles by Brownian motion and formation of percolation networks. Numerical simulations performed using the Galerkin method have indicated that the dispersion of nanoparticles produces a change in effective thermal conductivity (k^ef) and effective viscosity (μ^ef) of a liquid medium. Unlike a fluid's k^ef (kinetic) increases with increasing phi, a fluid's viscosity (μ) typically increases exponentially with increasing volume fraction (phi), especially above a critical concentration range of approximately 4%. To ensure that the increase in the Nusselt number (Nu) resulting from these optimised Reynolds (Re) and Prandtl (Pr) numbers cannot be offset by an increase in the friction factor (f), it is important to carefully control the Re and Pr numbers of the hybrid nanofluid. The hybrid nanofluids are made by combining different types of nanoparticles (e.g., Cu-Fe3O4 or Cu-Au) and profiting from the synergistic effects that arise from combining dissimilar nanoparticles. As reported by computational fluid dynamics (CFD) analysis, the heterogeneous nature of hybrid nanofluid particles has been shown to create improved micro-convection within the laminar sub-layer, causing more turbulence than occurs with the single particle size fluids, as differing particle sizes/densities create a more chaotic particle motion pattern disrupting the thermal boundary layer (delta_t), thus promoting steeper temperature gradients (dT/dy) at the wall and therefore allowing for greater heat transfer capabilities due to the increase in thermal diffusivity (alpha) from the inclusion of magnetic nanoparticles such as Fe3O4 [16]. In the high-temperature environment required for steam generation, the flow behaviour of the nanofluid will not be Newtonian, so we need to use non-Newtonian constitutive equations to describe it accurately (e.g., the shear-thinning or shear-thickening behaviour of the nanofluids). The most commonly used model in the literature to describe fluids exhibiting yield stress is the Casson fluid model and is stated mathematically as follows:

$$\sqrt{\tau} = \sqrt{\tau_y} + \sqrt{\mu_{plastic} \times \gamma_{dot}}$$

The yield stress (tau_y) reduces the growth of the boundary layer over the velocity boundary layer, which in turn improves the Nusselt number in the vicinity of the yield surface. From the analysis, it is also clear that the inclusion of yield stress (tau_y) reduces the thickness of the velocity boundary layer and increases the value of Nusselt number. Also, the use of the Maxwell fluid model to study viscoelastic nanofluids has allowed researchers to consider the effect of the relaxation time of these fluids (lambda). Studies have shown that increasing the Deborah number (De = (lambda * u) / L) improves heat transfer because the elastic properties of these fluids dampen turbulence more effectively than pure viscous fluids [17-18].

A new approach starting to gain attention from 2024 - 2025 is the development of "Compound Heat Transfer Enhancement" by combining nanofluids with passive flow enhancers (passive turbulator devices). Experimental work has been completed using twisted tape inserts in combination with hybrid nanofluids and the results have revealed a new physical mechanism for heat transfer [19]. The twisted tape creates a secondary swirl flow, and the resultant centrifugal force pushes the heavier nanoparticles outward to the outside wall of the tube, thereby forming a layer of concentrated nanoparticles at the wall and significantly increasing thermal conductivity in that area. This mechanism prevents the formation of localized hot spots that typically degrade the HTF [21]. The overall effectiveness of this technique is quantified by the Performance Evaluation Criterion (PEC), calculated as:

$$\mathrm{PEC} = \frac{\left(\frac{\mathrm{Nu}}{\mathrm{Nu}_0}\right)}{\left(\frac{\mathrm{f}}{\mathrm{f}_0}\right)^{\frac{1}{3}}}$$

The Nusselt number (Nu) and the friction factor (f) for the hybrid heat transfer system, as well as the respective values for a plain tube using a base fluid (Nu_0 and f_0), can demonstrate that the higher PEC values (> 1.35) found in the literature [21, 22] can be used to confirm that the thermal benefits of hybrid systems will be greater than the hydraulic energy consumption.

Lastly, the method of solar radiation absorption has moved away from using the surface of a material and into the absorption of radiation within the volume of a liquid. One method, referred to as Direct Absorption Solar Collectors (DASC), can employ "black" nanofluids (i.e. carbon nanotubes) that absorb radiation within their liquid suspension, as described by the Beer-Lambert

$$\mathrm{Law.\,I(x)} = \mathrm{I}_0 \times \exp(-\mathrm{K}_{\mathrm{ext}} \times \mathrm{x})$$

Where I(x) is the radiation intensity at depth x, I_0 is the incident intensity, and K_ext is the extinction coefficient of the nanofluid. By absorbing heat volumetrically, the temperature difference between the fluid and the receiver wall is minimized, which significantly reduces radiative heat losses and enhances the overall exergy efficiency of the collector [20].

Table 1: Comparative analysis of key thermophysical studies on nanofluids in PTCs.

Ref.	Fluid Composition & Model	Methodology	Key Thermodynamic Outcome	PEC / Enhancement
[13]	Hybrid Nanofluid + Turbulators	Numerical (CFD)	Micro-convection from hybrid particles alters velocity profile; significant Nu increase in turbulent core.	Nu increase > 18%
[16]	Cu-Fe3O4 / Engine Oil (Casson)	Numerical (Keller Box)	Yield stress reduces thermal boundary layer thickness; mixed convection dominated by particle concentration.	Skin friction coefficient increased by ~5%
[18]	Cu-Au / Engine Oil (Hybrid)	Numerical	Hybrid fluids show superior specific heat capacity (Cp) balance compared to mono-fluids.	Thermal efficiency +12.4%
[19]	CuO + Rotating Twisted Tape	Experimental	Centrifugal migration of particles prevents wall hot spots; enhances wall-fluid heat transfer coefficient.	PEC > 1.35
[22]	Hybrid fluid in Porous Media	Analytical	Porous matrix enhances effective surface area; Darcy number (Da) inversely proportional to pressure drop.	Optimized for low-Re flows

3. Heat Pipe Technology: The Isothermal Heat Transfer Paradigm

Heat Pipe (HP) Technology in Parabolic Trough Collectors (PTC's) typifies the collaborative integration of methods for heat transfer, i.e., Liquid-to-Liquid Phase Change (Physical phase change) vs Sensible Heat Transport (Sensible). The change in method from 'direct flowing' to heat pipe technology also remedies the primary issue of mechanical stresses and failure of the glass envelope due to axial temperature differences (dT/dX) of the 'direct flowing' type of heat collectors. By using a working fluid, heat pipes use the enthalpic energy associated with the 'Latent' Heat of the working fluid to create a quasi-isothermal fluid surface, thus eliminating internal losses (exergy destruction) and facilitating rapid response to transients that occur in solar energy collection systems.

3.1. Phase Change Storage and geometric configurations

The intermittency of solar irradiance necessitates the integration of Thermal Energy Storage (TES). Recent advanced numerical simulations [23] have modeled the thermodynamic coupling of heat pipes with Phase Change Materials (PCMs) enhanced by nanoparticles. The governing energy equation for the melting process, utilizing the enthalpy-porosity method, is expressed as:

$$\partial(\rho H)/\partial t + \nabla\cdot(\rho u H) = \nabla\cdot(k\nabla T) + S$$

Where (ρ) denotes density, (H) is enthalpy, and (S) is the source term. The findings indicate that using a Nano-PCM (a combination of paraffin and nanoparticles) in conjunction with finned heat pipes provides a direct thermal transfer (or rather a "superhighway") to the Nano-PCM, thus significantly decreasing the melting time compared to traditional fins (i.e., a decrease of approximately 24%). Consequently, this rapid charging process plays an important role in reducing output variations from indirect steam generation.

As we progress from storage to collector-type geometries, we have encountered the thermal interface resistance as being one of the limiting factors preventing the integration of these technologies. In addition, studies examining Flat Heat Pipes (FHPs) [24] that are integrated with evacuated tube collectors have demonstrated that utilizing a planar interface has resulted in substantially less contact resistance (R_c) than would be obtained from using a cylindrical type of interface. Additionally, the use of this type of geometry has been shown to increase the conductive heat transfer rate (Q) governed by Fourier's Law:

$$Q = -k\,A\,(dT/dy)$$

Where the increased contact area A provided by the flat profile directly amplifies the thermal throughput.

3.2. Wick Hydrodynamics and Capillary Limits

The operational ceiling of a heat pipe is defined by the Capillary Limit. For successful operation, the capillary pressure (ΔP_cap) generated by the meniscus curvature at the liquid-vapor interface must overcome the summation of viscous and gravitational pressure drops. This condition is rigorously defined as:

$$2\sigma\frac{\cos(\theta)}{r_{eff}} \geq \int \left(\frac{\mu_l}{(K\,A_l\rho_l)}\right)\dot{m}\,dx + \int \left(\frac{\mu_v}{K\,A_v\rho_v}\right)\dot{m}\,dx + \rho_l g\;L\sin(\varphi)$$

Currently, the surface tension (σ), Contact angle (θ), Effective Pore Radius (r_eff), Viscosity (μ), and Permeability (K) have been studied using Hydrodynamic numerical modelling [25] with respect to their Relationship to the groove aspect ratio of rectangular grooved Wicks. It has been shown that while deep grooves (K) enhance the Permeability of the wick, they also decrease the capillary pump head of the wick. Therefore, there is an optimum groove depth for the Total Pressure Drop (ΔP_total) minimisation.

To further develop these studies, the authors have also investigated the effects of the Sonic Limit on cylindrical Heat Pipes by using numerical simulations [26]. They proposed Tapered Vapor Cores that gradually enlarged the Vapour Core Cross-Sectional Area (A_v) through the evaporator. This keeps the Vapour Velocity below the Mach limit ($Ma < 1$) during rapid start-up HEAT FLUX conditions and helps prevent Choked Flow conditions from developing.

3.3. Pulsating and Loop Heat Pipe Dynamics

For long-span collectors, **Pulsating (Oscillating) Heat Pipes (PHPs)** offer a wickless alternative driven by thermally excited pressure waves. New correlations for PHPs with long evaporator sections [27] link thermal performance to the Kutateladze number (Ku):

$$\mathrm{Ku} = q / [\rho_v^{0.5} \left(\sigma g (\rho_l - \rho_v)\right)^{0.25}]$$

The switch from unstable flow to stable annular flow and subsequently to minimum thermal resistance occurs at high solar flux (high Ku). While Loop Heat Pipes (LHP) [28] overcome the entrainment limit by maintaining separate paths for vapor and liquid transport, optimizing the LHP thermodynamic cycle shows that the lowest liquid return line pressure drop provides the least total thermal resistance model (R_th) through a series of resistance networks.

$$R_{th} = R_{evap} + R_{vapor} + R_{cond} + R_{liquid}$$

This separation allows for transport distances exceeding 6 meters, making LHPs ideal for utility-scale PTC modules.

3.4. System Integration and Advanced Applications

An investigation into the use of Compound Parabolic Concentrators (CPCs) [29] coupled with gravity assisted Thermosyphons under varying operating conditions has been carried out. The results found that Thermosyphons are very sensitive to the inclination angle φ, with a dramatic drop in performance below an inclination angle of $\varphi=10°$. Additionally, the Condenser configuration downstream from the Thermosyphon has a significant impact on Thermosyphon performance. Experimental work done in [30] indicates that by increasing the surface area of a Heat Exchanger connected to a Manifold Condenser, the overall collector efficiency η of CPCs can be increased since it lowers the temperature of the Condenser Wall.

Hybrid systems combining Heat Pipes and Thermoelectric Generators (TEGs) and/or Nanofluids have also been developed as a result of these efforts [31]. In these types of hybrid systems, the Heat Pipe creates uniformity in the hot side temperature of the TEG module, which enhances the Seebeck voltage developed by the TEG module. In turn, the use of Nanofluids improves the ability of the TEG module to reject heat on the cool side.

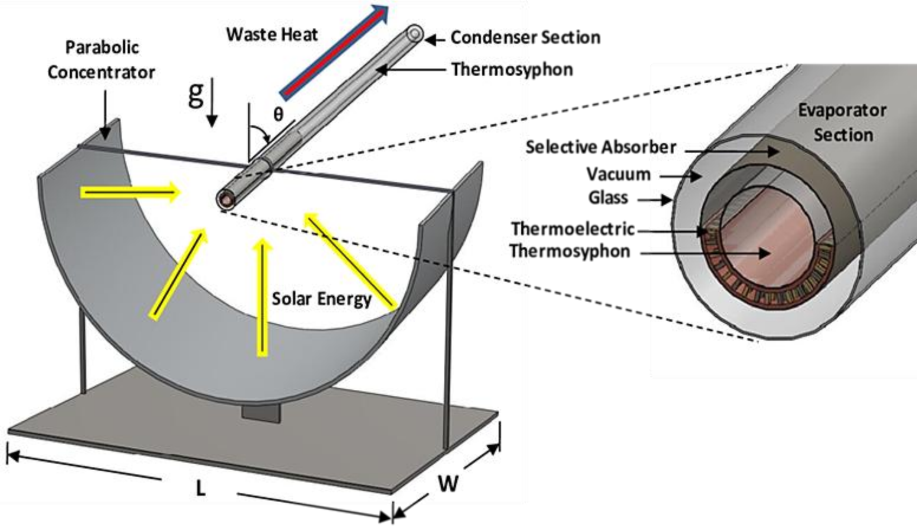

Figure 1: Schematic of a hybrid parabolic concentrator integrating a thermosyphon and thermoelectric generators (TEGs).

Figure 1 depicts how a hybrid receiver is designed. A thermosyphon relies upon gravity to evenly distribute the heat across the entire inside area of this receiver; hence all parts of this receiver will be heated evenly and therefore help maximize performance of the surrounding TEG layer, and thus facilitating production of electrical energy. The image also shows that this type of concentrator will be installed on a slope or incline (θ), which will assist in getting back the fluid that was heated inside through the thermosyphon back to the top of the receiver and eventually back into the heating source; the heat can be lost or stored using materials such as nanofluids within the condensing section.

3.5. Component Efficiency and Manufacturing Innovations

Analysing the energy efficiency of Heat Pipe Heat Exchangers (HPHE) [32] shows through the effectiveness-NTU method that HPHEs are more capable of recovering wasted heat than plate exchangers in solar applications. As such, finned-tube heat pipe systems can dramatically improve the convection of heat to an air stream in new design types of Solar Air Heaters [33]. At the micro scale, the flow conditions of Micro-channel Oscillating Heat Pipes [34] are critical in aerospace applications and high-flux solar applications. The literature suggests that controlling the transition from slug flow to annular flow is critical to avoiding dry-out when designing for these types of applications. Advances in manufacturing technology, particularly 3D-printed heat pipes [35], have made it possible to create internal geometries with complex designs that have ultra-small bending radii, which can be incorporated into non-linear receiver shapes.

Due to material advancements, wick technologies are now at a new extreme in the capabilities that they offer. Sintering methods were used with the Loop Heat Pipe wicks to help increase their porosity, and therefore their performance [36]. The most substantial development in wick technology is the creation of Biomimetic Copper Forest Wicks [37], which use a design concept based on biological transpiration. The Capillary Pressure ΔP_cap of these structures is nearly three times that of a conventional sintered wick, allowing them to operate at extremely high heat fluxes without reaching boiling limits. Thermosyphon designs that use enhanced boiling heat transfer coefficients (h_b) meet the conditions for transitioning from the liquid to vapour phases of the working fluid within the evaporator section [38]. The Schematic of Capillary Pressure Balance in a Solar Heat Pipe is illustrated in Figure 3.

Table 2: Technical specifications and outcomes of recent Heat Pipe studies.

Ref.	**HP Type**	**Critical Parameter / Model**	**Physics Mechanism**	**Outcome / Enhancement**
[23]	HP + PCM	Enthalpy H / Porosity	Latent heat diffusion	24% faster melting; stable output.
[25]	Flat HP	Permeability K / r_eff	Capillary vs. Viscous forces	Optimized groove geometry.
[26]	Cylindrical	Mach Number Ma	Compressible vapor flow	Delayed sonic limit (choking).
[27]	PHP	Kutateladze No. Ku	Self-excited oscillation	Stable operation at long lengths.
[28]	LHP	Pressure Drop ΔP	Phase separation	Eliminated entrainment limit.
[37]	Ultra-thin	Surface Tension σ	Biomimetic capillarity	3x Capillary limit increase.

4. Receiver Geometric Enhancements and Passive Turbulators

In indirect solar thermal technologies, in which an absorber tube (receiver) is used to generate heat indirectly, the heat exchanger is critical to the operation of the system. The laminar sub-layer that develops at the inner wall of a tube impedes the transfer of thermal energy from the tube wall to the bulk Heat Transfer Fluid (HTF), creating a high thermal resistance. To create flow disruption in this layer and improve the convective heat transfer coefficient (h), many researchers have conducted extensive studies of new passive inserts (turbulators) and geometric variables.

4.1. Geometric Modification of Absorber Tubes

Altering the cross-sectional shape of receiver tubes is the easiest way to increase heat transfer surface area and turbulence. Chinnappan and Raguraman (2023) performed a thermal analysis of receiver tubes modified in shape, finding that using other than circular shapes (elliptical, etc.) results in increased wetted perimeter (P_w) but relatively little change to hydraulic diameter (D_h), which increases Nusselt number

(Nu) due to fluid mixing in the area adjacent to the wall (solar flux area) where heat is concentrated. The ratio of increased Nu to original Nu was (E).:

$$E = \left(\frac{\mathrm{Nu}_{\mathrm{modified}}}{\mathrm{Nu}_{\mathrm{smooth}}}\right)\frac{n}{\left(\frac{f_{\mathrm{modified}}}{\mathrm{fsmooth}}\right)^{\frac{1}{3}}}$$

Recent research by Venkatesaperumal and others published in 2023 has investigated whether a combination of conical strip inserts and corrugated tube receivers would enable an increase in total system thermal efficiency, with specific geometries of non-circular tubes demonstrated to result in E > 1.2 [39], which indicates that the overall thermal performance of the system. In addition, as stated in the work of Venkatesaperumal and others in 2023, it has been found that the presence of the corrugation (waviness) on the corrugated tube walls provides a roughness element that continuously restarts the thermal boundary layer. The phenomenon of flow separation, created by the peaks of the corrugation, is followed by flow reattachment at the valleys of the corrugation. This cycle of separation and reattachment creates additional turbulence intensity (Tu) at these locations. In conjunction with the use of conical strip inserts, this combination can enhance the overall turbulence creating strong swirling components continuing downstream and effectively cleaning the heat transfer surfaces of the devices. [40].

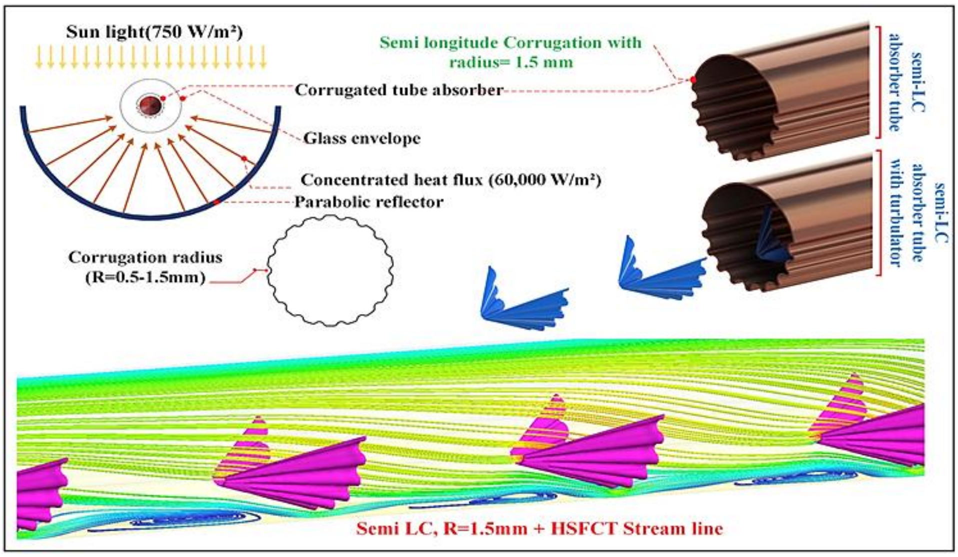

Figure 2: Geometric configuration and flow streamlines of a semi-circular corrugated absorber tube equipped with passive turbulators

Figure 2 for a representation of how the shape of a tube and its internal flow are configured in relation to passive mixing devices or turbulators. This illustration demonstrates two different strategies to enhance thermal energy transfer from a solar receiver:

1. Modification of the shape of the tube. The upper part illustrates how the wall of the tubular absorber is constructed from a series of ridges and valleys (formed by corrugations) as opposed to having a smooth surface. This increases the total surface area through which heat can be absorbed into the fluid.

2. Passive mixing devices. The 3D visualisation demonstrates how the internal flow path within the tubular absorber has been modified to create less restrictive, more turbulent flows through the absorber by inserting objects into the flow pathway.

The bottom portion of the image depicts how CFD software was used to generate flow streamlines that twist and swirl as a result of the combination of passive mixing devices and the surface of the tubular absorber. The twisting and swirling of the streamlines mix the flow and prevent the formation of thermal stagnation zones and therefore increase the value of the heat transfer coefficient (HVCO), as described in the text.

4.2. Porous Inserts and Coatings

Another method is to change the behaviour of the inside of the outer surface. Isah et al. (2024) conducted a numerical analysis using Fiberfrax 140 porous material covered in Al2O3 in the collector pipe. The porous material acts as a volumetric heat transfer enhancer. Increasing the effective thermal conductivity of wall material surrounding the effective thermal conduction through the wall surface area of the porous insert will enable heat conduction from wall to fluid stream flowing through the porous insert. Flow through the porous insert is described by the Darcy-Forchheimer equation:

$$-(dP/dx) = (\mu/K)u + \left(\rho \frac{C_F}{\sqrt{K}}\right) u^2$$

Where K is permeability and C_F is the inertial coefficient. The study revealed that while the pressure drop increases due to the drag forces within the porous matrix, the substantial reduction in the wall temperature (T_wall) prevents thermal degradation of the HTF and enhances the overall collector efficiency [41].

4.3. Fin Inserts and Rectangular Channels

The Internal fins are a conventional means of increasing turbulence, but researchers have been working on optimizing the fins specifically for Solar receivers over the last few years. Sevim et al. (2022) conducted a laboratory experiment to determine the impact of Longitudinal and Helical fins on Solar Receiver pipes. The primary function of the fins was to provide extended conduction surfaces and additionally, induce rotation of the flow. All experimental results indicated that Helical fins produced a Centrifugal force field, limiting the development of a thermal boundary layer. The improvement in efficiency was found to be highly dependant upon both the height and pitch of the fins. A tighter pitch of fins provided better Heat Transfer, however required an increase in pumping power to achieve this added benefit [42].

The research of Vengadesan et al. (2022) shifted away from the typical tubular geometry when designing a Solar Receiver. They designed a flat rectangular channel Solar Receiver. A rectangular channel provides a flat mounting surface for solar cells in PVT applications or better optical coupling with secondary reflectors. However, the rectangular geometry creates additional flow patterns (corner vortices) in the corners of the channel that increase mixing between the core fluid and the wall. The corner vortices were shown to significantly reduce the amount of thermal stratification that can develop in large diameter circular tubes [43].

4.4. Coupled Optical-Thermal-Stress Analysis

In terms of high thermal flux, the structural integrity of the receiver needs to be carefully monitored and characterised. To assist with this task, Liu, et al. (2022) build upon their prior work in an advanced modelling tool for "coupled" optical, thermal, and stress analysis by considering extensions due to geometric changes in a combined methodology. Liu, et al. developed this through the consideration of thermal deformation (rather than only a thermal load). Thus, the governing thermo-elastic equation represents thermal deformation under load:

$$\nabla \cdot \sigma + F = 0$$
$$\sigma = C : (\varepsilon - \alpha \Delta T I)$$

Where σ = stress tensor; (C = stiffness tensor); ε = strain; α = thermal expansion coefficient; ΔT = temperature rise. Liu, et al. summarised in their conclusion that it was paramount that geometries be carefully designed to minimise the potential for high cyclic loads to create excessive stress concentrations (e.g. in regions with sharp corners of internal fins) and create low cycle fatigue failures, at the external borders, during cyclic loading of solar heat input [44].

4.5. Hybrid Turbulator-Nanofluid Systems

The combination of turbulators with advanced fluids is one of the largest areas of innovation in fluid mechanics. Mohammed et al. (2021) examined how hybrid nanofluids and conical turbulators have increased the rate of heat transfer. In order for the hybrid nanofluids to achieve this, the conical turbulators direct fluid flowing through the center of the tube through a jet impingement action toward the wall with higher heat. At the same time, the hybrid nanoparticles found in the nanofluids increase the fluid's thermal conductivity. As a result, the two effects explained above reduce the entropy generation rate (S_gen), which is expressed mathematically as:

$$S_{gen} = (Q/T^2)\,\Delta T + (m_{dot}/\rho\, T)\,\Delta P$$

The ability to reduce thermal entropy through a smaller temperature difference (lower ΔT) outweighed the increase of frictional entropy through a greater pressure drop (higher ΔP), so that this hybrid approach can be thermodynamically viable [45].

4.6. Advanced Secondary Optics and Large Apertures

Often, new optical improvements are made as well as other features such as optimizing the optical receiver geometry. Gong et al. (2020) proposed a semi-circular tube as well as external fins and a flat-plate radiation shield for large-aperture concentrators that has been designed with the asymmetry associated with the non-uniform flux distribution of parabolic troughs (where most of the concentrated light is concentrated at the bottom portion of the receiver). The addition of external fins increases the area exposed to the solar flux from the illuminated side of the receiver. The addition of a radiation shield helps to reduce the heat loss from the non-illuminated portion of the receiver to the atmosphere. All of the proposed changes significantly improve the optical-thermal efficiency of large-scale applications compared to existing designs [46]. Similarly, Sajid et al. (2023) explored what would happen if you replaced the standard conical shape of a point-focus system (dish), for example, by replacing the traditional flat disc with a conical cavity tube receiver. The main effect is that, once the radiation is trapped inside the cavity, it decreases the opportunity for reflection losses. Moreover, the conical shape of the cavity creates an accelerating flow, thus thinning the boundary layer of fluid flowing over it downstream [47].

4.7. Orientation and Small-Scale Innovations

The orientation of the absorption tube has a significant impact on the performance of an evacuated double-tube collector. Vaghasis et al. (2022) conducted an experimental investigation to assess the effects of different angles on the heat transfer capability of a double-tube evacuated collector. They demonstrated that the direction of the tube to the force of gravity can affect the natural convection currents formed in the annulus between the glass and the tubular walls. Therefore, optimizing the orientation of the tube can reduce the amount of convective heat loss [48]. Lastly, Shajan and Baiju (2022) created and tested a unique type of collector with a secondary reflector for use with small-scale systems. The secondary reflector collects and redirects solar radiation to provide a more even flux around the sides of the tube. These evenly distributed flux levels decrease the temperature variations between the sides of the tube and reduce the tendency of the tube to bow due to thermal expansion [49].

Table 3: Summary of Receiver Enhancement Techniques and Thermohydraulic Performance.

Ref.	Enhancement Technique	Physical Mechanism	Key Outcome / Performance
[39]	Non-Circular Tube Geometry	Increased wetted perimeter; wall-fluid mixing.	Compound enhancement; high turbulence intensity.
[40]	Corrugated Tube + Conical Strip	Boundary layer re-start; swirl generation.	Compound enhancement; high turbulence intensity.
[41]	Porous Insert (Fiberfrax)	Volumetric conduction; effective area increase	Significant wall temperature reduction; thermal protection.
[42]	Helical Fin Inserts	Extended surface; centrifugal flow	Suppression of thermal

		induction.	boundary layer; high Nu.
[44]	Geometric Optimization (Stress)	Thermo-elastic coupling evaluation.	Identification of stress concentration zones to prevent failure
[45]	Hybrid (Turbulator+ Nanofluid)	Flow diversion (impingement) + high k.	Minimized entropy generation; thermodynamic optimization.
[46]	Semi-Circular + Shield	Asymmetric absorption matching flux profile.	Reduced radiation loss; enhanced optical efficiency.

5. Artificial Intelligence and Advanced Optimization in Thermal Modeling

Modeling traditional methods for Parabolic Trough Collectors (PTCs) cannot take into account how the stochastic nature of solar irradiance impacts the way heat transfer fluids (HTFs) and their phase-change dynamics behave. Because of this, the work below discusses how three different approaches to optimizing PTC systems were evaluated: Neural Networks, Physics-Informed Models, and Evolutionary Algorithms.

5.1. Machine Learning for Performance Prediction

Knowing what the outlet temperature (T_out) and thermal efficiency (eta_th) of a parabolic trough collector (PTC) will be given a wide range of fluctuating meteorological variables is very important because it is the key to integrating PTCs into an electric grid and ensuring there is steam quality control for the resulting power plants. In recent research [50], machine learning algorithms were used successfully to develop a method to predict how PTCs would operate based on complex, non-linear functions between the input meteorological variables such as direct normal irradiance (DNI), ambient air temperature, flow rate, and inlet temperature and their output performance variables. Random forest (RF) and gradient boosting regression (GBR) algorithms provided the highest levels of predictive accuracy in their ability to predict the Nusselt number (Nu) of pyrolytic ceramic-corrugated receivers, achieving coefficients of determination (R^2) in excess of 0.99[51].

The general predictive function f learned by these machine learning models can be expressed as:

$$y_{pred} = f(x_1, x_2, \dots, x_n | \theta)$$

The input features (x I), the learned model parameters (θ), and the output variable (y pred) can be defined in the following way [52]. The output variable (y pred) is the target variable (e.g., efficiency), whilst the input features (x I) are the variables used in training. Learning is captured by the model parameters (weights/biases).[53] Additionally, CNNs have been developed for the analysis of heat pipe thermal fields in a novel way. When temperature contour maps from CFD simulations are processed as images by CNNs, thermal features can be extracted from spatial data that would normally be omitted from the resulting temperature profiles calculated from scalar regression methods. Utilising sparse sensor data allows the determination of the internal thermal state of a heat pipe and the health of its receiver in a real-time manner [54]. A further contribution was made in the use of ML to forecast PTC outlet temperatures. A comparison of different methodologies revealed that SVR with a radial basis function (RBF) kernel produced models with good generalisation capabilities with minimal input training data. This characteristic is especially advantageous for new power plant commissioning, where a limited operational history exists [55].

5.2. Design Optimization using Evolutionary Algorithms

In addition to forecasting (or prediction), Artificial Intelligence (AI) can also be utilized for Inverse Design and Optimization, i.e. determining the optimal geometric vector(s) (examples include: the height of a fin, twist ratio and nanoparticle concentration) which maximizes $J(X)$ (an example would be thermal efficiency) according to constraints $g(X) \leq 0$.

Recently [51] Design of Experiments (DoE) methodology has been applied with Response Surface Methodology (RSM), using the statistical method(s) creates a surrogate model for the objective function, allowing for quick and easy studies of the design space without the need for running costly CFD for each point.

With further advancements in computational modelling, many different "meta-heuristic" algorithms have now been developed and are increasingly being adopted. For example, the development of a hybrid Random Vector Functional Link (RVFL) Network (RVFLN) and the Chimp Optimization Algorithm (ChOA) were employed to predict and solve for the performance of Solar Dish Stirling Systems [56]. The ChOA algorithm emulates the hunting behaviours of Chimpanzees in order to traverse through the multidimensional, complex landscape (search space) of parameters associated with solar collector design so as to avoid getting trapped in local optima as seen in traditional methods based on gradients. Consequently, design configurations were found that improved both energetic and exergetic efficiencies by over 15% when compared to baseline designs.

5.3. Physics-Informed Neural Networks (PINNs)

A paradigm shift in thermal modeling is the emergence of **Physics-Informed Neural Networks (PINNs).** Standard neural networks are "black boxes" that ignore physical laws. PINNs, however, embed the governing partial differential equations (PDEs)—Continuity, Momentum, and Energy—directly into the loss function of the neural network.

$$\mathrm{Loss} = \mathrm{Loss}_{\mathrm{data}} + \mathrm{lambda}_{\mathrm{PDE}} * \mathrm{Loss}_{\mathrm{physics}}$$
$$\mathrm{Loss}_{\mathrm{physics}} = \frac{\partial u}{\partial t} + u \cdot \nabla u + \nabla P - \left(\frac{1}{\mathrm{Re}}\right)\nabla^2 u \ ||\text{^}2$$

The loss function defined as Loss_data measures the difference between the outputs of the neural network (i.e. predicted velocities and temperatures) and the experimental data that was collected; however, in order to accurately reproduce actual experimental data with a set of training data, physical laws must be incorporated into the network using techniques called "PINN" (Physics-informed Neural Networks).

Game-changing work [57] utilizing PINNs to perform inverse problems in heat transfer has shown that by imposing the physical laws of heat transfer onto the prediction models, the predictive performance of a PINN is superior to that of classic approaches (which rely solely on data). As this technology matures and becomes easier to implement, the applicability of PINNs has increased dramatically for modeling fluid flow through porous media (such as soils) or complex heat exchangers, where data are difficult and expensive to collect.

Since its inception, this technology has found additional applications in the study of heat transfer through porous structures for the purposes of improving thermal management ([58]). Using a custom-built Python application, PINNs were used to solve the coupled equations of fluid movement in porous media (Darcy-Brinkman-Forchheimer). The resulting mesh-less simulation approach is many orders of magnitude faster than traditional mesh-based approaches (Finite Volume Method - FVM).

5.4. Extrapolation and Generalization in Heat Pipe Modeling

Extrapolation is a key risk associated with data-driven based modeling, particularly data-driven based model performance outside of the training range used to generate the model. A recent study [52] examined the extrapolation capabilities of ANNS with respect to finned heat pipe thermal performance. The research demonstrated that standard ANNS, when subjected to test input data representing heat fluxes that exceed the training data, do not accurately predict the thermal performance of the finned heat pipes, but ANNS that incorporate domain knowledge through the imposition of monotonic constraints and/or the implementation of physics-guided initialization yield significant improvements regarding extrapolation robustness, thereby providing confidence when extrapolating to extreme solar flux events not included in the training data.

Correlations for hybrid nano-fluids were developed [54] using GEP. GEP generates mathematical correlations instead of adjusting the weights of standard NEURAL NETWORKS. As a result, the explicit equations generated for Nusselt number Nu = f(Re, Pr, phi) are more beneficial to engineers than THE NEURAL NETWORK MODELS, as they facilitate direct integration into the system simulation software TRNSYS or SAM.

Table 4: Classification of AI/ML Techniques in Solar Thermal Engineering.

Ref.	Algorithm / Method	Application Domain	Key Advantage / Outcome
[50]	Random Forest (RF), GBR	Corrugated Receiver Efficiency	High prediction accuracy (R^2 > 0.99); captures non-linear geometric effects.
[53]	SVR (RBF Kernel)	Outlet Temperature Prediction	Robust generalization with sparse datasets; ideal for new plant startup.
[55]	CNN (Deep Learning)	Heat Pipe Thermal Field	extracts spatial thermal features (hot spots) from CFD images; enables real-time monitoring.
[56]	Chimp Optimization (ChOA)	System Design Optimization	Avoids local optima in high-dimensional search spaces; >15% efficiency gain.
[57]	PINNs (Physics-Informed)	Heat Transfer PDEs	Embeds Navier-Stokes equations into learning; mesh-free, data-efficient simulation.
[58]	PINNs (Python Framework)	Porous Media Flow	Solves coupled Darcy-Brinkman equations faster than FVM.

6. System-Level Thermal Performance and Steam Generation Dynamics

Through improving local efficiencies via individual enhancements (via nanofluids, heat pipes, and/or turbulators) - it is clear that improvements to the overall system-level performance of Parabolic Trough Collectors (PTC's) are critical to their long-term prospects. Thus, one must consider the complex interactions of all elements (collector field, steam cycle, various storage subsystems, variations in environmental loads) when assessing a PTC's performance.

6.1. Thermodynamic Analysis of Steam Generation Cycles

The integration of advanced PTCs into steam cycles requires a rigorous energetic and exergetic assessment. Singh and Kaur (2024) conducted a detailed performance analysis of a PTC-based steam generation system [59]. Their study utilized the First and Second Laws of Thermodynamics to map the exergy destruction across components. The exergy efficiency (eta_ex) of the collector field is defined as:

$$\mathrm{eta_{ex}} = \frac{\left(\mathrm{Q_u} * \left(1 - \frac{\mathrm{T_{amb}}}{\mathrm{T_{fm}}}\right) - \mathrm{W_{pump}}\right)}{\left(\mathrm{A_{ap}} * \mathrm{DNI} * \left(1 - \frac{\mathrm{T_{amb}}}{\mathrm{T_{sun}}}\right)\right)}$$

The terms used in this section include Q_u for useful heat gain, T_fm for mean fluid temperature (T_fm), W_pump for the power of the pumping process, and T_sun for the effective temperature (of the sun at ~5777 K). The results of this study indicated that most of the exergy destruction in a receiver tube was due to the difference in temperature between the sun and absorber surface and accounted for ~45% of total exergy destruction. This could be reduced significantly if both the concentration ratio (C_R) and the optical errors are optimized [59].

The study by Mahran (2023) also highlighted the effect geometric shape has on the performance of the tube. Increasing the rim angle (phi_rim) past 90° allowed for more capturing of reflected rays, but this also resulted in more shadowing at the receiver. The geometric parameter of the optimal rim angle was found to be approximately 80°-85°, producing the maximum intercept factor (gamma) and, therefore, the most thermal power produced by the steam generator [64].

6.2. Hydrogen and Poly-generation Integration

Recent advances in energy generation have led to "poly-generation," which consists of multiple products from one concentrating solar thermal (CST) technology or parts of CSTs. For example, Dou and co-workers (2024) developed a new system using parabolic trough collectors (PTCs) for the production of solar-derived hydrogen via steam electrolysis, incorporating a Solid Oxide Electrolyzer Cell (SOEC) using superheated steam generated from a high-temperature CST collector at an operating temperature greater than 350 °C, or by adding to a Solar-thermal Coal Gasification process to generate steam for gasification of coal and produce hydrogen. Additionally, the research team created a "partially rotatable tracked tracking strategy" to maximize energy collection through all seasons, resulting in an annual hydrogen yield of 6.8% more than standard track-based tracking strategy and demonstrated that PTCs could play a significant role in the green hydrogen economy. [60] Similarly, Alhawsawi and colleagues (2023) modelled the connection between a solar power dish- a Stirling engine coupled with a single-effect desalination unit; although the study focuses on dishes, it could be applied to trough-based cogeneration systems; through this connection the waste heat from the Stirling engine's cooling loop was converted to an energy source to drive the desalination process, ultimately resulting in EUF exceeding 75%. The research illustrates the importance of cascading heat utilization in modern solar thermal plants. [67].

6.3. Wind Loads and Structural Dynamics

Large aperture troughs used for generating energy through utility-scale steam must maintain aerodynamic stability. Egerer et al. (2024) researched the effects of turbulent winds on parabolic trough collectors (PTC) in the field. Their research shows that a parabolic trough collector's optical defocusing occurs when the reflected beam of sunlight moves off the receiver target due to wind-induced vibrations. While this dynamic optical loss is normally not considered in static thermal models, it may result in an annual energy yield reduction of 5-10% in areas with frequent windy weather. To address this problem, stiffening the torquebox structure and implementing an active vibration damping control system were suggested to promote the maintenance of the optical alignment of the parabolic trough collectors [62].

6.4. Advanced Optical and Thermal Modeling

Enhancing optical efficiency (ηopt) is critical for achieving optimal thermal performance. Chen et al. (2024) presented a new approach using a coupled simulation technique that integrates Monte Carlo Ray Tracing (MCRT) with Finite Volume Method (FVM). Through this coupling process, the non-uniform radiative flux distribution q (θ) on the absorber tube can be calculated with precision and directly inputted into the thermal fluid simulation, which allows for detailed investigation of the “direct absorption” solar receiver system where the working fluid serves as the radiation absorber eliminating the conductive resistance of the wall tube; thereby, yielding a more homogenous temperature profile while reducing thermal stresses [61, 65]. In terms of thermal storage, Praveen and Chandra Mouli (2022) explored how thermal energy storage (TES) has been incorporated into PTC power plants. The authors emphasised the idea of "solar multiple" (SM), which indicates the solar field size with respect to the power block size. Higher values of SM allows for additional energy to be stored for subsequent account after sunset. The authors concluded that at a SM range of 2.0 to 2.5 in combination with storing molten salt for a time duration of 6 to 10 hours, the lowest LCOE for steam generation on a continuous basis can be achieved [68].

6.5. Dynamic Simulation and Control Strategies

Transient conditions, such as cloud cover and the start-up and shut-down operations, have been a part of real-world operations. Chaouch et al. (2024) conducted a long-duration non-linear simulation of a roll-bonded PVT collector, using a methodology applicable to PTCs. A differential algebraic equation (DAE) approach was used to represent the system's thermal inertia in the study, which determined that daily energy output estimates produced with steady-state methods were overstated by excluding the "warm-up" time at the beginning of the day. A large improvement in overall energy output from predictive control algorithms that identify cloudy weather based on predicted data [63]. Kanniyan and Neeraj (2022) looked at various controlled operating conditions with different heat transfer fluids. Their results show that, for variable DNI situations, controlling mass flow (m_dot) to keep outlet temperature constant is more effective than using a constant flow operating method. This "matched-flow" technique protects the turbine from a high-temperature thermal shock and keeps the steam quality within the superheated area [69].

6.6. Techno-Economic Feasibility

Economic viability is the ultimate decision-making component of a project. The results of et al. (2021) conclude that the ability to implement PTCs for industrial process heating can be determined through techno-economic analysis using NPV and IRR indicators. The results demonstrated that for facilities with an annual average DNI of greater than 1800 kWh/m²/year, it is financially competitive to replace traditional fossil-fuel boilers with PTCs. The evolution of receiver efficiencies and lower manufacturing costs have contributed to the reduced payback periods of PTC systems to 5-7 years; due to these factors the economic feasibility of implementing these technologies continues to improve. [71-72].

A novel, yet low-cost, design of a PTC for water heating has been proposed by Upadhyay and Patel (2021). Their PTC design is characterized by the use of lightweight materials and a simpler tracking technique. Their analysis demonstrates that low-cost "appropriate technology" designs could allow for entry into the residential and small industry markets, offering a significantly lower cost-per-thermal-watt than complex utility-scale troughs [70]. The System-Level Studies and associated Key Performance Indicators are detailed in Table 5.

Table 5: System-Level Studies and Key Performance Indicators.

Ref.	System Application	Methodology	Key Thermodynamic / Economic Outcome
[59]	Steam Generation Cycle	Exergy Analysis	Receiver is main exergy destruction site (45%); C_R optimization is key.
[60]	Solar-to-Hydrogen (SOEC)	Integrated Process Sim.	Partially rotatable tracking increases H2 yield by 6.8%.
[61]	Direct Absorption PTC	MCRT + FVM Coupling	Eliminated wall resistance; improved flux uniformity.
[62]	Structural/Optical	Field Measurements	Wind-induced vibration causes 5-10% optical loss; requires stiffening.
[68]	Power Plant + TES	Solar Multiple Optimization	SM = 2.5 with storage minimizes LCOE for dispatchable power.
[71]	Industrial Process Heat	Techno-Economic (NPV)	Feasible for DNI > 1800; Payback period reduced to < 7 years.

7. Conclusions

This review article critically summarises and synthesises technological advancements in the use of parabolic trough collectors (PTCs) for indirect steam generation, based on relevant literature published between 2020-2026. It has demonstrated that the future of PTC system performance can be achieved through the combined use of advanced heat transfer fluids, innovative geometric configurations and advanced computational models.

The shift from traditional working fluids to hybrid nano-fluids provides an opportunity to decouple thermal conductivity from viscosity limitations, and by taking advantage of the synergetic properties of dissimilar nanoparticles, incremental improvements were made to Nusselt number and convective heat transfer coefficients that minimise the trade-off between thermal enhancement and increased hydraulic pumping penalties. The transition to Heat Pipe technology has moved towards an isothermal heat transfer model. The incorporation of heat pipes with Phase Change Materials (PCMs) and bio-inspired wick structures eliminates much of the thermal inertia associated with start-up operations, while reducing the likelihood of mechanical failure due to non-uniform heat flux and axial temperature differences.

In addition to this, the use of enhanced methods for passive heat transfer, such as twisted tape turbulators, porous inserts, and corrugated tubes, have all been proven effective in reducing the effects of the thermal boundary layer. However, the findings from this review indicate that, while these types of modifications are effective, they must also be considered in conjunction with other concerns regarding structural integrity. As a result of the growing need to protect against low cycle fatigue failures caused by the cyclic thermal loads that occur on complicated geometric configurations, it has become essential to employ a combination of optical-thermal-stress numerical analysis during the analysis phase of design. Among the trends that will change everything in solar thermal engineering is the combination of artificial intelligence (AI) and machine learning (ML) with traditional methods of solar thermal engineering. The advent of physics-informed neural networks (PINNs) represents a shift from traditional empirical "black-box" methods of modeling to the use of robust physics-compliant predictive tools. The combination of AI and ML provides capability to conduct inverse design of collector geometries and accurately model collector performance under stochastic meteorological conditions; these capabilities were previously unattainable using trial-and-error techniques.

In summary, the convergence of these technologies (nanofluids, heat pipes, passive turbulence augmentation techniques, and AI optimization) is leading to increasingly higher exergetic efficiencies and lower LCOE for PTC technology. As this industry shifts toward poly-generating applications, particularly for green hydrogen production and desalination, these technologies are establishing parabolic trough collectors as a key technology leading to a global shift toward sustainable, dispatchable forms of renewable energy.

References:

[1] Upadhyay, B. H., Patel, A. J., & Ramana, P. V. (2022). A detailed review on solar parabolic trough collector. International Journal of Ambient Energy, 43(1), 176-196. https://doi.org/10.1080/01430750.2019.1636869

[2] Ajbar, W., Parrales, A., Huicochea, A., & Hernández, J. A. (2022). Different ways to improve parabolic trough solar collectors' performance over the last four decades and their applications: A comprehensive review. Renewable and Sustainable Energy Reviews, 156, 111947. https://doi.org/10.1016/j.rser.2021.111947

[3] Pal, R. K., & Kumar, R. (2021). Investigations of thermo-hydrodynamics, structural stability, and thermal energy storage for direct steam generation in parabolic trough solar collector: a comprehensive review. Journal of Cleaner Production, 311, 127550. https://doi.org/10.1016/j.jclepro.2021.127550

[4] Malan, A., & Kumar, K. R. (2021). A comprehensive review on optical analysis of parabolic trough solar collector. Sustainable Energy Technologies and Assessments, 46, 101305. https://doi.org/10.1016/j.seta.2021.101305

[5] Panduro, E. A. C., Finotti, F., Largiller, G., & Lervåg, K. Y. (2022). A review of the use of nanofluids as heat-transfer fluids in parabolic-trough collectors. Applied Thermal Engineering, 211, 118346. https://doi.org/10.1016/j.applthermaleng.2022.118346

[6] Rubbi, F., Das, L., Habib, K., Aslfattahi, N., Saidur, R., & Rahman, M. T. (2021). State-of-the-art review on water-based nanofluids for low temperature solar thermal collector application. Solar Energy Materials and Solar Cells, 230, 111220. https://doi.org/10.1016/j.solmat.2021.111220

[7] Raval, P., & Ramani, B. (2024). Heat transfer enhancement techniques using different inserts in absorber tube of parabolic trough solar collector: A review. Journal of Thermal Engineering, 10(4), 1068-1091. https://doi.org/10.14744/thermal.0000847

[8] Nazir, M. S., Shahsavar, A., Afrand, M., Arıcı, M., Nižetić, S., Ma, Z., & Öztop, H. F. (2021). A comprehensive review of parabolic trough solar collectors equipped with

turbulators and numerical evaluation of hydrothermal performance of a novel model. Sustainable energy technologies and assessments, 45, 101103. https://doi.org/10.1016/j.seta.2021.101103

[9] Gomupandian, T., Pandian, R., Vivek, C. M., & Tuncer, A. D. (2026). Solar parabolic trough collectors with heat pipe technology: a review of efficiency enhancement and machine learning-based optimization. Multiscale and Multidisciplinary Modeling, Experiments and Design, 9(1), 46. https://doi.org/10.1007/s41939-025-01115-4

[10] Chen, L. P., Yu, L. P., Hao, M. C., Li, Y. S., & Wang, Q. W. (2021). Advances and prospects in heat pipe: A critical eview. In E3S Web of Conferences (Vol. 252, p. 03023). EDP Sciences. https://doi.org/10.1051/e3sconf/202125203023

[11] Venkatesaperumal, R., & JAFAR, K. S. (2024). Machine learning predictions for enhancing solar parabolic trough collector efficiency with corrugated tube receivers. Sādhanā, 49(2), 130. https://doi.org/10.1007/s12046-024-02493-0

[12] Cai, S., Wang, Z., Wang, S., Perdikaris, P., & Karniadakis, G. E. (2021). Physics-informed neural networks for heat transfer problems. Journal of Heat Transfer, 143(6), 060801. https://doi.org/10.1115/1.4050542

[13] Allauddin, U., Ikhlaq, M., Jamil, T., Alvi, F., Hussain, H. A., Mustafa, H., & Azeem, M. H. (2023). Heat-transfer enhancement of a solar parabolic trough collector using turbulators and nanoparticles: a numerical study. Journal of Enhanced Heat Transfer, 30(3). DOI: 10.1615/JEnhHeatTransf.2022045462

[14] Alkathiri, A. A., Jamshed, W., Eid, M. R., & Bouazizi, M. L. (2022). Galerkin finite element inspection of thermal distribution of renewable solar energy in presence of binary nanofluid in parabolic trough solar collector. Alexandria Engineering Journal, 61(12), 11063-11076. https://doi.org/10.1016/j.aej.2022.04.036

[15] Shahzad, F., Jamshed, W., Safdar, R., Hussain, S. M., Nasir, N. A. A. M., Dhange, M., ... & Elfasakhany, A. (2022). Thermal analysis characterisation of solar-powered ship using Oldroyd hybrid nanofluids in parabolic trough solar collector: An optimal thermal application. Nanotechnology Reviews, 11(1), 2015-2037. https://doi.org/10.1515/ntrev-2022-0108

[16] Jamshed, W., Uma Devi S, S., Safdar, R., Redouane, F., Nisar, K. S., & Eid, M. R. (2021). Comprehensive analysis on copper-iron (II, III)/oxide-engine oil Casson nanofluid flowing and thermal features in parabolic trough solar collector. Journal of Taibah University for Science, 15(1), 619-636. https://doi.org/10.1080/16583655.2021.1996114

[17] Jamshed, W., Eid, M. R., Nasir, N. A. A. M., Nisar, K. S., Aziz, A., Shahzad, F., ... & Shukla, A. (2021). Thermal examination of renewable solar energy in parabolic trough solar collector utilizing Maxwell nanofluid: A noble case study. Case Studies in Thermal Engineering, 27, 101258. https://doi.org/10.1016/j.csite.2021.101258

[18] Jafer Kutbudeen, S., Logesh, K., Mahalingam, A., & Vinoth Kanna, I. (2024). Performance enhancement of solar collector using strip inserts and with water based Al2O3/DI water nanofluids. Energy sources, part A: Recovery, utilization, and Environmental Effects, 46(1), 14768-14778. https://doi.org/10.1080/15567036.2021.1872745

[19] Pavan, K. N., Kapilan, N., & Madhusudana, C. K. (2024). Rotating Twisted Tape Turbulators and CuO Nanofluid Synergy: Investigating Heat Transfer Characteristics in Tubular Systems. https://doi.org/10.21203/rs.3.rs-4869596/v1

[20] Mashhadian, A., & Heyhat, M. M. (2022). Energy, exergy, and environmental assessments of a direct absorption parabolic trough collector based on nanofluid volume absorption approach. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 44(2), 4230-4255. https://doi.org/10.1080/15567036.2022.2072022

[21] Abdullatif, Y. M., Okonkwo, E. C., & Al-Ansari, T. (2021). Thermal performance optimization of a parabolic trough collector operating with various working fluids using copper nanoparticles. Journal of Thermal Science and Engineering Applications, 13(5), 051011. https://doi.org/10.1115/1.4049872

[22] Shahzad, F., Jamshed, W., Sathyanarayanan, S. U. D., Aissa, A., Madheshwaran, P., & Mourad, A. (2021). Thermal analysis on Darcy-Forchheimer swirling Casson hybrid nanofluid flow inside parallel plates in parabolic trough solar collector: An application

to solar aircraft. International Journal of Energy Research, 45(15), 20812-20834. https://doi.org/10.1002/er.7140

[23] Sheikholeslami, M., & Mousavi, S. M. (2024). Numerical simulation of heat pipe solar system combined with finned thermal storage unit incorporating mixture of nanoparticles and paraffin. International Communications in Heat and Mass Transfer, 155, 107468. https://doi.org/10.1016/j.icheatmasstransfer.2024.107468

[24] Zhang, D., Diao, Y., Wang, Z., Pan, Y., Sun, M., Wang, X., ... & Zhao, Y. (2024). Thermal performance of two evacuated tube solar collectors with flat heat pipes. Applied Thermal Engineering, 241, 122366. https://doi.org/10.1016/j.applthermaleng.2024.122366

[25] Chhokar, C., Ashouri, M., & Bahrami, M. (2024). Modeling the thermal and hydrodynamic performance of grooved wick flat heat pipes. Applied Thermal Engineering, 257, 124281. https://doi.org/10.1016/j.applthermaleng.2024.124281

[26] Roy, P. S. D., Das, K., & Kalita, H. M. (2024). Numerical analysis of tapered wick configurations in cylindrical heat pipes. International Journal of Thermal Sciences, 206, 109333. https://doi.org/10.1016/j.ijthermalsci.2024.109333

[27] Sakulchangsatjatai, P., Siritan, M., Wanison, R., Kammuang-Lue, N., & Terdtoon, P. (2024). Correlation to predict thermal characteristics of pulsating heat pipes with long evaporator section. Applied Thermal Engineering, 254, 123868. https://doi.org/10.1016/j.applthermaleng.2024.123868

[28] Zhao, Y., Wei, M., & Dan, D. (2024). Modeling, design, and optimization of loop heat pipes. Energies, 17(16), 3971. https://doi.org/10.3390/en17163971

[29] Govindasamy, K., Palanivel, V., Meena, R. S., Muthusamy, S., Panchal, H., Shah, M. A., & Siddiqui, M. I. H. (2024). Performance analysis of evacuated tubes with thermosyphon heat pipe solar collector integrated with compound parabolic concentrator under different operating conditions. Energy Exploration & Exploitation, 42(1), 231-249. https://doi.org/10.1177/01445987231202618

[30] Nithyanandhan, K., Suganeswaran, K., & Murugan, P. C. (2024). Experimental study on heat pipe evacuated tube solar collector for residential use with various condenser configurations. Energy Conversion and Management, 312, 118583. https://doi.org/10.1016/j.enconman.2024.118583

[31] Köysal, Y., Yakut, Y., Özbektaş, S., Bülbül, H., Atalay, T., & Şahin, F. (2024). Evaluation of energy efficiency of thermoelectric energy generator system with heat pipes, solar tracker, Fresnel lens and nano-particle fluids. Applied Thermal Engineering, 246, 123027. https://doi.org/10.1016/j.applthermaleng.2024.123027

[32] Yike, B., Yi, Y., & Shouqing, Z. (2023). Design and analysis of heat pipe heat exchanger efficiency. Бюллетень науки и практики, 9(6), 373-380. https://doi.org/10.33619/2414-2948/91/44

[33] Sachdeva, A., Chandrashekara, M., & Yadav, A. (2023). Experimental investigation of a novel solar air heater based on heat pipe vacuum tube collector integrated with finned-tube heat exchanger. Journal of Thermal Analysis and Calorimetry, 148(20), 10917-10936. https://doi.org/10.1007/s10973-023-12413-9

[34] Zhao, X., Su, L., Jiang, J., Deng, W., & Zhao, D. (2023). A review of working fluids and flow state effects on thermal performance of micro-channel oscillating heat pipe for aerospace heat dissipation. Aerospace, 10(2), 179. https://doi.org/10.3390/aerospace10020179

[35] Zhao, K. X., Duan, Y., Dai, S. L., Pang, L., Wang, M. J., Tong, J. F., ... & Zhu, S. L. (2022). Experimental investigation of the performance of a 3D printed heat pipe with ultra-small bending radius for space applications. Microgravity Science and Technology, 34(3), 49. https://doi.org/10.1007/s12217-022-09955-2

[36] Htoo, K. Z., Huynh, P. H., Kariya, K., & Miyara, A. (2021). Experimental study on thermal performance of a loop heat pipe with different working wick materials. Energies, 14(9), 2453. https://doi.org/10.3390/en14092453

[37] Luo, J. L., Mo, D. C., Wang, Y. Q., & Lyu, S. S. (2021). Biomimetic copper forest wick enables high thermal conductivity ultrathin heat pipe. ACS nano, 15(4), 6614-6621. https://doi.org/10.1021/acsnano.0c09961

[38] Gürtürk, M., Kale, C., & Kok, B. (2021). Investigation of the performance of a new thermosyphon heat pipe design for applications heat transfer from liquid to gas. Applied Thermal Engineering, 186, 116520. https://doi.org/10.1016/j.applthermaleng.2020.116520

[39] Chinnappan, T., & Raguraman, C. M. (2024). Enhancing thermal efficiency of a parabolic trough collector through geometric modification of absorber tubes: a performance analysis. International Journal of Ambient Energy, 45(1), 2269161. https://doi.org/10.1080/01430750.2023.2269161

[40] Venkatesaperumal, R., Syed Jafar, K., Elumalai, P. V., Abbas, M., Cuce, E., Shaik, S., & Saleel, C. A. (2022). Heat transfer studies on solar parabolic trough collector using corrugated tube receiver with conical strip inserts. Sustainability, 15(1), 378. https://doi.org/10.3390/su15010378

[41] Isah, M. Z., Abioye, A. M., & Fachway, A. A. (2024). NUMERICAL HEAT TRANSFER ENHANCEMENT OF SOLAR RECEIVER TUBE OF PARABOLIC TROUGH COLLECTOR USING FIBERFRAX 140 COATED WITH AL 2 O 3. Nigerian Journal of Tropical Engineering, 18(1), 30-48. DOI: 10.59081/njte.18.1.004

[42] Sevim, S., Bektas, A., & Ilbas, M. (2022). Enhancement of parabolic trough solar collector heat transfer properties by insert fins to the receiver pipe. Osmaniye Korkut Ata University Journal of Science and Technology, 5(2), 1022–1040. https://doi.org/10.47495/okufbed.1129853

[43] Vengadesan, E., Thameenansari, S., Manikandan, E. J., & Senthil, R. (2022). Experimental study on heat transfer enhancement of parabolic trough solar collector using a rectangular channel receiver. Journal of the Taiwan Institute of Chemical Engineers, 135, 104361. https://doi.org/10.1016/j.jtice.2022.104361

[44] Liu, S., Yang, B., Hou, Y., & Yu, X. (2022). Effects of geometric configurations on the thermal-mechanical properties of parabolic trough receivers based on coupled optical-thermal-stress model. Renewable Energy, 199, 929-942. https://doi.org/10.1016/j.renene.2022.09.055

[45] Mohammed, H. A., Vuthaluru, H. B., & Liu, S. (2021). Heat transfer augmentation of parabolic trough solar collector receiver's tube using hybrid nanofluids and conical turbulators. Journal of the Taiwan Institute of Chemical Engineers, 125, 215-242. https://doi.org/10.1016/j.jtice.2021.06.032

[46] Gong, J. H., Wang, J., Lund, P. D., Zhao, D. D., Hu, E. Y., & Jin, W. (2020). Improving the performance of large-aperture parabolic trough solar concentrator using semi-circular absorber tube with external fin and flat-plate radiation shield. Renewable Energy, 159, 1215-1223. https://doi.org/10.1016/j.renene.2020.06.059

[47] Abbas, S., Yuan, Y., Hassan, A., Zhou, J., Ahmed, A., Yang, L., & Bisengimana, E. (2023). Effect of the concentration ratio on the thermal performance of a conical cavity tube receiver for a solar parabolic dish concentrator system. Applied Thermal Engineering, 227, 120403. https://doi.org/10.1016/j.applthermaleng.2023.120403

[48] Vaghasia, J. G., Ratnadhariya, J. K., Panchal, H., Sadasivuni, K. K., Ponnamma, D., Elkelawy, M., & Bastawissi, H. A. E. (2022). Experimental performance investigations on various orientations of evacuated double absorber tube for solar parabolic trough concentrator. International Journal of Ambient Energy, 43(1), 492-499. https://doi.org/10.1080/01430750.2019.1653980

[49] Shajan, S., & Baiju, V. (2022). Designing a novel small-scale parabolic trough solar thermal collector with secondary reflector for uniform heat flux distribution. Applied Thermal Engineering, 213, 118660. https://doi.org/10.1016/j.applthermaleng.2022.118660

[50] Venkatesaperumal, R., & Syed Jafar, K. (2024). Machine learning predictions for enhancing solar parabolic trough collector efficiency with corrugated tube receivers. Sādhanā, 49, 130. https://doi.org/10.1007/s12046-024-02493-0

[51] Sivalingam, A., Ravivarman, G., Kalaiyarasan, A., et al. (2024). Optimizing thermal performance in parabolic trough solar power systems: An experimental design and analysis. E3S Web of Conferences, 529, 02005. https://doi.org/10.1051/e3sconf/202452902005

[52] Seo, Y. M., Choi, H. Y., Ko, R. K., et al. (2024). Evaluation of extrapolation ability of artificial neural network modeling on the heat transfer performance of a finned heat pipe. Journal of Mechanical Science and Technology, 38, 6657–6671. https://doi.org/10.1007/s12206-024-1122-9

[53] Ahmed, S., Nadim Mahmud, M., Bashar Bhuiyan, K., et al. (2023). Outlet temperature assessment of parabolic trough collector: A machine learning approach. Heliyon. 9. https://dx.doi.org/10.2139/ssrn.4631115

[54] Kani, G. T., & Ghahremani, A. (2023). Predicting the thermal performance of heat pipes applying various machine learning methods and a proposed correlation. International Communications in Heat and Mass Transfer, 142, 106671. https://doi.org/10.1016/j.icheatmasstransfer.2023.106671

[55] Kumararaja, K., Khiran Kumar, C. S., & Sivaraman, B. (2021). A convolutional neural network analysis of a heat pipe with hybrid nanofluids. International Journal of Ambient Energy, 43(1), 6284–6296. https://doi.org/10.1080/01430750.2021.2014959

[56] Zayed, M. E., Zhao, J., Li, W., Elsheikh, A. H., Abd Elaziz, M., Yousri, D., ... & Mingxi, Z. (2021). Predicting the performance of solar dish Stirling power plant using a hybrid random vector functional link/chimp optimization model. Solar Energy, 222, 1-17. https://doi.org/10.1016/j.solener.2021.03.087

[57] Zhang, Q., Guo, X., Chen, X., Xu, C., & Liu, J. (2022). PINN-FFHT: A physics-informed neural network for solving fluid flow and heat transfer problems without simulation data. International Journal of Modern Physics C, 33(12), 2250166. https://doi.org/10.1142/S0129183122501662

[58] Ganji, D. D., Mahboobtosi, M., & Chari, F. N. (2025). Investigating fluid flow and heat transfer in porous media: a python-based approach for medical applications and thermal regulation. Multiscale and Multidisciplinary Modeling, Experiments and Design, 8(8), 343. https://doi.org/10.1007/s41939-025-00930-z

[59] Singh, H., & Channi, H. K. (2023, June). Performance Analysis of a Parabolic Trough Collector. In International Conference on Intelligent Manufacturing and

Energy Sustainability (pp. 471-482). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-99-6774-2_42

[60] Dou, L., Liu, T., Jiao, F., & Liu, Q. (2024). Characteristics of solar to hydrogen-rich fuel production integrating parabolic trough collectors with partially rotatable tracking strategies. International Journal of Hydrogen Energy, 84, 491-501. https://doi.org/10.1016/j.ijhydene.2024.08.154

[61] Chen, Z., Han, X., & Ma, Y. (2024). Performance analysis of a novel direct absorption parabolic trough solar collector with combined absorption using MCRT and FVM coupled method. Renewable Energy, 220, 119727. https://doi.org/10.1016/j.renene.2023.119727

[62] Egerer, U., Dana, S., Jager, D., Stanislawski, B. J., Xia, G., & Yellapantula, S. (2024). Field measurements reveal insights into the impact of turbulent wind on loads experienced by parabolic trough solar collectors. Solar Energy, 280, 112860. https://doi.org/10.1016/j.solener.2024.112860

[63] Chaouch, A., Brahim, T., Abdelati, R., & Jemni, A. (2024). Energy and exergy analysis of a long-term nonlinear dynamic roll bond PVT solar collector model under Tunisian (North Africa) climatic conditions. Thermal Science and Engineering Progress, 53, 102727. https://doi.org/10.1016/j.tsep.2024.102727

[64] Kasem, M. A. M. (2023). Detailed performance analysis of parabolic trough collectors including geometric effect. Journal of Mechanical Engineering and Sciences, 9552-9563. https://doi.org/10.15282/jmes.17.3.2023.2.0756

[65] Riza, R. I., Chekifi, T., & Boukraa, M. (2023). Thermal efficiency enhancement of parabolic trough concentrators: A review. PROCEEDING OF INTERNATIONAL SUMMIT ON EDUCATION, TECHNOLOGY, AND HUMANITY 2021, 2727(1), 030019. https://doi.org/10.1063/5.0153800

[66] Ahmad, A., Prakash, O., Kausher, R., Kumar, G., Pandey, S., & Hasnain, S. M. (2024). Parabolic trough solar collectors: A sustainable and efficient energy source. Materials Science for Energy Technologies, 7, 99-106. https://doi.org/10.1016/j.mset.2023.08.002

[67] Alhawsawi, A., Zayed, M. E., Moustafa, E., Banoqitah, E., & Elsheikh, A. H. (2023). Hybridizing solar dish Stirling power system with single-effect desalination for sustainable electricity and freshwater co-generation: Mathematical modeling and performance evaluation. Case Studies in Thermal Engineering, 45, 102997. https://doi.org/10.1016/j.csite.2023.102997

[68] Praveen, R. P., & Mouli, K. V. C. (2022). Performance enhancement of parabolic trough collector solar thermal power plants with thermal energy storage capability. Ain Shams Engineering Journal, 13(5), 101716. https://doi.org/10.1016/j.asej.2022.101716

[69] Kannaiyan, S., & Bokde, N. D. (2022). Performance of parabolic trough collector with different heat transfer fluids and control operation. Energies, 15(20), 7572. https://doi.org/10.3390/en15207572

[70] Upadhyay, B. H., Patel, A. J., Sadasivuni, K. K., Mistry, J. M., Ramana, P. V., Panchal, H., ... & Essa, F. A. (2021). Design, development and techno economic analysis of novel parabolic trough collector for low-temperature water heating applications. Case Studies in Thermal Engineering, 26, 100978. https://doi.org/10.1016/j.csite.2021.100978

[71] Mohammadi, K., Khanmohammadi, S., Immonen, J., & Powell, K. (2021). Techno-economic analysis and environmental benefits of solar industrial process heating based on parabolic trough collectors. Sustainable Energy Technologies and Assessments, 47, 101412. https://doi.org/10.1016/j.seta.2021.101412

[72] Alshukri, M. J., Eidan, A. A., & Najim, S. I. (2021). Thermal performance of heat pipe evacuated tube solar collector integrated with different types of phase change materials at various location. Renewable Energy, 171, 635-646. https://doi.org/10.1016/j.renene.2021.02.143