Design and Thermal Performance Analysis of a Parabolic Trough Solar Collector with Novel Inserted Fin Configurations

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doi.org/10.64643/IJIRTV12I7-187944-459

***Abstract*—The thermal performance of parabolic trough solar collectors (PTSCs) is often limited by weak convective mixing and insufficient heat-transfer area within conventional smooth absorber tubes. To address this limitation, the present study investigates the combined influence of internal fin geometry, fin dimensions, and nanofluid thermophysical enhancement on the thermo-hydraulic behaviour of a PTSC receiver. Three longitudinal fin shapes are rectangular, triangular, and trapezoidal were examined with fin heights of 5 mm and 10 mm and fin widths of 2 mm and 4 mm, selected to represent practical and thermally effective configurations. A CuO–water nanofluid with particle volume fractions of 3%, 5%, and 7% was analysed using a single-phase CFD model in ANSYS Fluent under a uniform solar-equivalent heat flux of 1000 W/m².**

The results show that both fin geometry and fin dimensions substantially enhance convective heat transfer. Increasing fin height from 5 mm to 10 mm improves the Nusselt number by 10–15%, while increasing fin width from 2 mm to 4 mm contributes an additional 6–9% enhancement. Among all configurations, rectangular fins deliver the highest performance, achieving 22–30% higher Nusselt numbers compared to the smooth tube, followed by trapezoidal fins (18–25%) and triangular fins (12–20%). Nanoparticle concentration further strengthens thermal performance, with φ = 7% resulting in 8–15% higher Nusselt numbers relative to φ = 3%. These enhancements are accompanied by expected hydraulic penalties: increasing fin height raises friction factor by 20–35%, while wider fins lead to 12–18% higher pressure drops due to greater flow obstruction. Despite this, overall thermal efficiency improves by 7–12% with optimised fin dimensions, with the best thermo-hydraulic balance achieved using the rectangular fin of 10 mm height and 4 mm width combined with CuO–water at φ = 5%. Overall, the study demonstrates that appropriate selection of fin geometry, fin size, and nanoparticle concentration can significantly enhance the heat-transfer capability and thermal efficiency of PTSC absorber tubes. The findings offer practical design guidelines for high-performance solar thermal receivers and support future experimental validation and optimisation efforts.

***Index Terms*—PTC, nanofluid, fin geometry, CFD, thermal enhancement, conjugate heat transfer**

I. INTRODUCTION

Solar thermal energy has emerged as a key solution for industrial process heating due to its ability to deliver medium-temperature heat in the range of 100–300 °C, which aligns with the requirements of sectors such as textiles, food processing, pharmaceuticals, and chemical manufacturing. Among various concentrating solar technologies, the Parabolic Trough Collector (PTC) is the most mature and widely adopted owing to its high optical efficiency, modularity, and reliable one-axis tracking, enabling concentrated solar radiation to be directed onto a receiver tube where thermal energy is transferred to a heat transfer fluid. The working principle of the PTC involves precise optical concentration, solar absorption by a selectively coated absorber tube, and convective heat transfer to the flowing fluid, typically water, thermal oils, or nanofluids. However, conventional smooth absorber tubes exhibit significant thermohydraulic limitations, including large convective resistance, thick thermal boundary layers, and constrained heat-transfer surface area, which collectively restrict thermal efficiency especially under laminar and transitional flow regimes. These shortcomings necessitate design improvements through internal modifications such as fin inserts, turbulence promoters, and advanced working fluids. While nanofluids have demonstrated enhanced thermal conductivity and improved heat-transfer performance, and internal fins have shown potential to intensify mixing and boundary-layer disruption, existing research rarely provides a systematic comparison of different fin geometries specifically rectangular, triangular, and trapezoidal configurations nor optimizes their combination with nanofluids within PTC receivers. This gap motivates the present study, which aims to enhance the overall thermal performance of PTCs by integrating novel longitudinal fin geometries with CuO–water nanofluids and evaluating their combined influence on heat transfer, frictional losses, and overall performance metrics under realistic operating conditions.

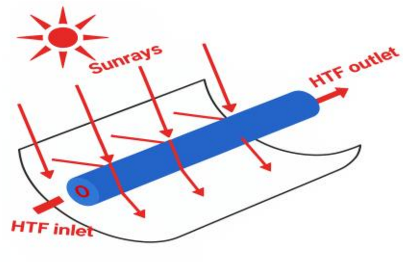
The integration of nanofluids into parabolic trough collectors (PTCs) has been widely recognized as a promising method for enhancing heat-transfer performance due to their higher thermal conductivity, improved energy absorption, and intensified convective behavior. Several review studies have shown that nanofluids such as CuO–water, Al_2O_3–water, and CNT-based suspensions significantly improve Nusselt number and useful heat gain compared to conventional fluids [1], [3], [25]. Experimental and numerical investigations further confirm that low-to-moderate nanoparticle concentrations (typically 1–7%) can increase outlet temperature and thermal efficiency while maintaining manageable viscosity levels [4], [7], [16], [18]. However, researchers also emphasize the importance of stability, dispersion quality, and temperature-dependent viscosity to avoid sedimentation and excessive pumping power requirements [3], [14]. Combined CFD–experimental studies demonstrate measurable improvements when realistic boundary conditions and conjugate heat-transfer effects are included, validating the practicality of nanofluids in operational PTC systems [20-21]. Overall, the existing body of work highlights the thermal benefits of nanofluids while stressing the need to balance enhancement with hydraulic performance.

Parallel to nanofluid research, the modification of absorber-tube geometry has emerged as an equally effective strategy for improving thermal performance in PTC receivers. Investigations on twisted-tape inserts have shown significant increases in turbulence intensity and heat-transfer rates but at the cost of substantial pressure drops and entropy generation under some conditions [5], [13], [15]. Studies involving porous media and metal-foam–filled absorber tubes also demonstrate strong enhancement due to increased surface area and improved mixing, though these designs often face practical challenges such as flow blockage and sealing issues [6]. Longitudinal fins including rectangular, triangular, and helical configurations have gained attention for offering a more balanced enhancement mechanism by increasing conductive area and inducing moderate flow disturbance, resulting in meaningful Nusselt number improvement with comparatively lower friction penalties [8-11], [19]. The literature further stresses that evaluation metrics such as friction factor, thermal performance factor (TPF), entropy generation, and pumping-power-normalized efficiency are essential for determining the true effectiveness of these enhancement techniques [22-24], [26]. Recent reviews also highlight the lack of comparative studies involving multiple fin geometries under identical conditions, indicating a clear research gap that motivates combined investigations of fin structures and nanofluids in modern PTC applications [12].

II. METHODOLOGY

2.1 Physical System Description

The study analyzes the thermo-hydraulic behavior of a parabolic trough collector (PTC) receiver equipped with internal fin structures and operating with CuO–water nanofluid. The absorber tube considered in the model has an outer diameter of 70 mm and an inner diameter of 66 mm, enclosed within a glass envelope of 115 mm outer and 109 mm inner diameter. The system includes a parabolic reflector of 5 m width, a focal length of 1.84 m, and a total aperture area of 39.2 m², representing a realistic medium-scale industrial solar collector. Heat input to the absorber is applied as a uniform outer-surface heat flux, replicating concentrated solar radiation under steady-state operating conditions. These geometric and operating configurations enable the numerical model to closely represent real-world PTC thermal environments.



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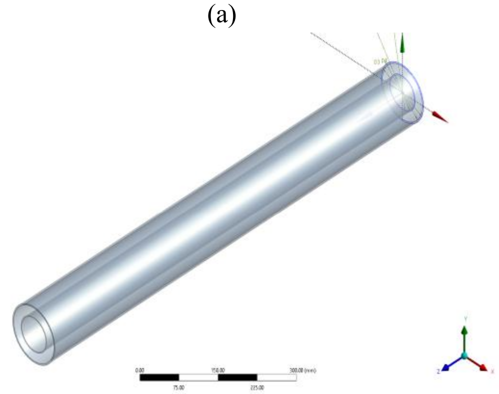

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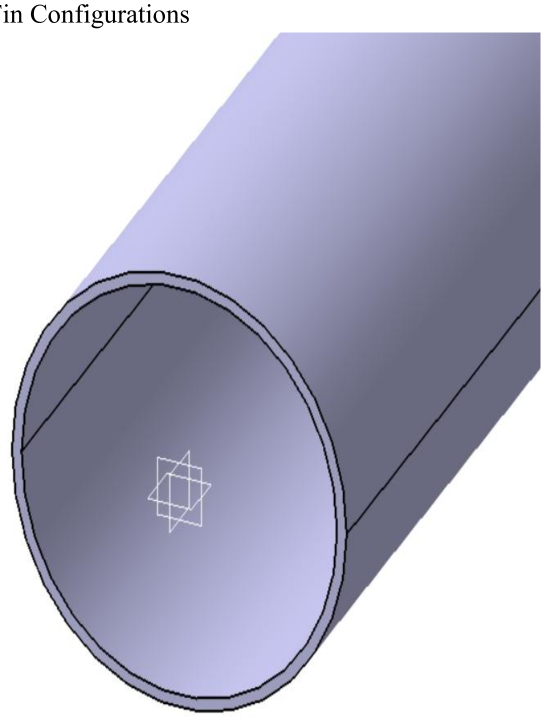
Fig 1(a) Physical System Description,(b) Geometric Model of the PTC

2.2 Fin Configurations

Three internal fin geometries are incorporated along the inner surface of the absorber tube to augment the heat-transfer process. These include rectangular, triangular, and trapezoidal fins, each extending along the full length of the tube. The rectangular fin serves as a simple extended surface with constant thickness, enhancing conduction across the fin body. The triangular fin tapers toward the tip, generating localized acceleration of the working fluid and thinning of the thermal boundary layer. The trapezoidal fin features a broader base and narrower top, offering strong conduction near the root while minimizing flow obstruction toward the core region. Fin heights of 5 mm and 10 mm and widths of 2 mm and 4 mm are considered to evaluate the influence of fin size on heat-transfer enhancement and hydraulic resistance.



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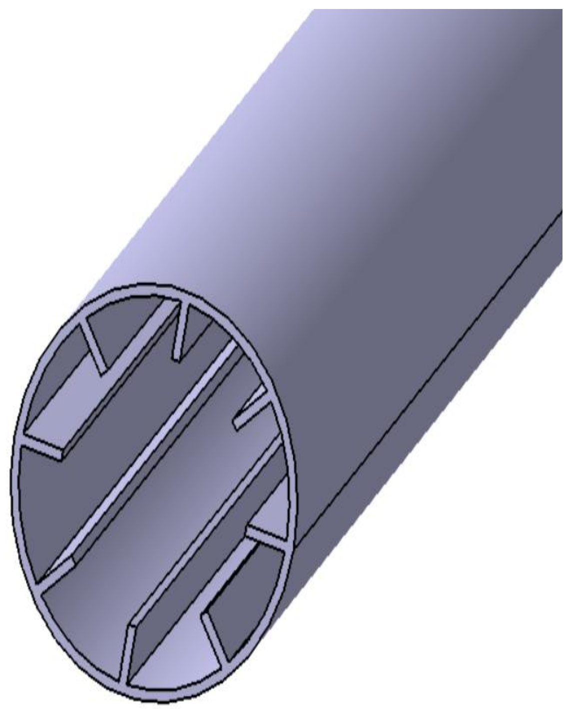

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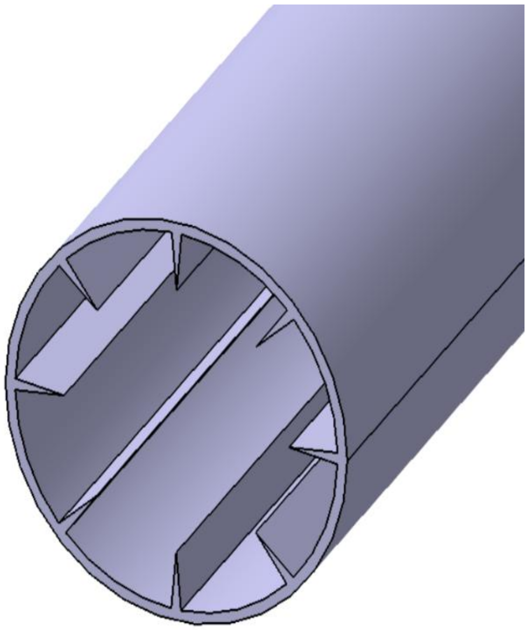

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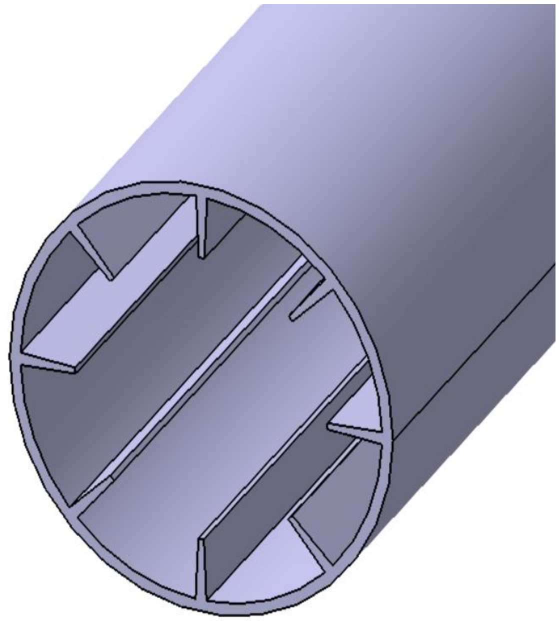

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Fig 2: Different Model Configuration of Fins used in Absorber tube in PTC

2.3 Governing Equations

A three-dimensional, steady-state, incompressible formulation is used to describe the fluid flow and heat transfer within the receiver. The continuity, momentum, and energy equations govern the fluid domain, while heat conduction is applied to the solid absorber tube and fins.

Continuity equation

$$\nabla \cdot \mathrm{V} = 0$$

Momentum equation

$$\rho(\mathrm{V} \cdot \nabla)\mathrm{V} = -\nabla p + \mu \nabla^2 \mathrm{V}$$

Energy equation (fluid)

$$\rho c_p(\mathrm{V} \cdot \nabla T) = \nabla \cdot (k \nabla T)$$

Energy equation (solid)

$$\nabla \cdot (k_s \nabla T_s) = 0$$

At the solid–fluid interface, temperature and heat-flux continuity are enforced:

$$T_{fluid} = T_{solid}$$

$$-k_s \frac{\partial T_s}{\partial n} = -k_f \frac{\partial T_f}{\partial n}$$

Key dimensionless parameters used to characterize the system include the Reynolds number (Re), Prandtl number (Pr), Nusselt number (Nu), friction factor (f), and thermal performance factor (TPF). These parameters quantify the relative contributions of momentum and thermal transport, hydraulic resistance, and overall enhancement effectiveness.

2.4 Computational Domain and Meshing

The computational domain consists of the internal fluid passage, absorber tube wall, and fin structures. A high-quality unstructured mesh is generated using tetrahedral elements with boundary-layer prism layers near all solid surfaces. Ten inflation layers are applied to accurately capture near-wall gradients, with a smooth growth ratio of 1.2 ensuring a gradual transition from fine boundary elements to coarser core elements. Curvature and proximity refinement are applied around the fin edges and tube curvature to preserve geometric fidelity, while element skewness is maintained below 0.9 to ensure numerical accuracy and stability.

A mesh-independence study is performed using several mesh densities ranging from approximately 330,000 to 1.22 million elements. The medium-density mesh (around 860,000 elements) is selected as the final grid because additional refinement leads to variations of less than 1% in key output parameters such as outlet temperature, Nusselt number, and pressure drop. This ensures that the computational model provides accurate results without incurring unnecessary computational cost.

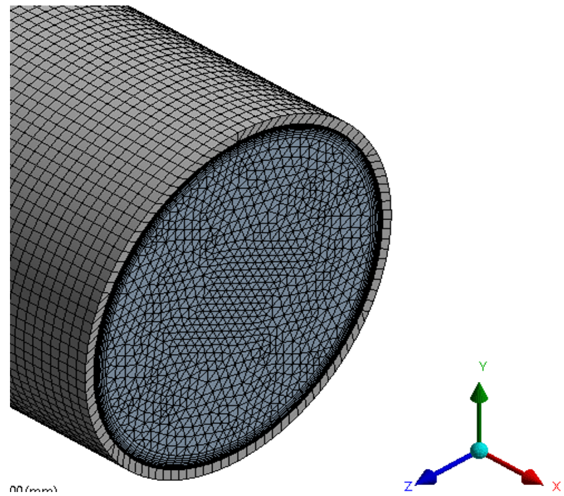


Fig 3**:** A mesh visualization showing the inflation layers and refinement

Table 1: Mesh Independence Test Results

Cells (approximately)	Outlet temperature T_out (K)	Pressure drop ΔP (Pa)	Average Nu	Friction factor f
330,000	305.10	46.00	11.20	0.0360
450,000	305.32	46.40	11.30	0.0362
600,000	305.50	46.65	11.38	0.0364
720,000	305.60	46.80	11.42	0.0365
860,000	305.65	46.90	11.45	0.0366
950,000	305.72	46.94	11.46	0.03665
1,050,000	305.78	46.97	11.47	0.03670
1,150,000	305.83	46.98	11.475	0.03675
1,220,000	305.86	47.00	11.48	0.0368

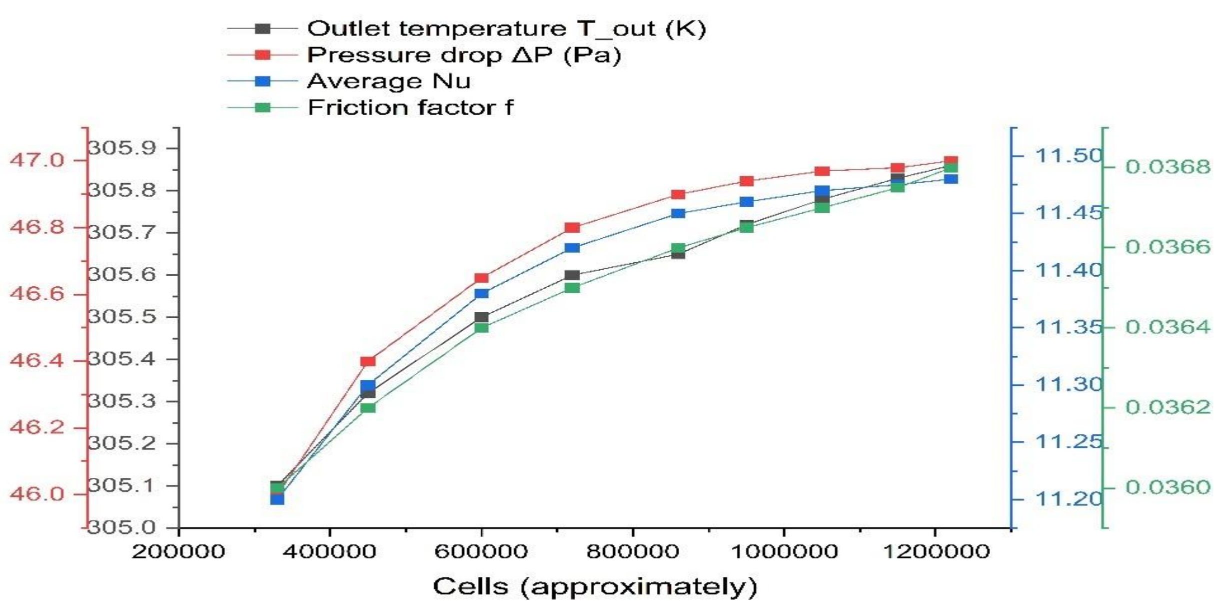


Fig 4: Mesh Independence of different parameters

2.5 Boundary Conditions

The numerical model is subjected to steady-state operating conditions representing typical thermal loads encountered in parabolic trough collector applications. Four different mass flow rates are imposed at the inlet to cover a wide range of Reynolds numbers and to evaluate how changes in flow rate influence heat-transfer augmentation and frictional losses. The inlet temperature is specified uniformly for all cases to maintain consistent thermal entry conditions and enable direct comparison among nanofluid concentrations and fin geometries. At the outer surface of the absorber tube, a constant heat flux of 1000 W/m^2 is applied to represent the absorbed portion of concentrated solar radiation after optical conversion. This approach ensures uniform heating of the receiver in the numerical domain and avoids the need for complex solar ray-tracing models.All internal walls, including the fin surfaces, are treated as no-slip boundaries for momentum transport and participate in conjugate heat transfer for energy exchange. The outlet boundary is assigned a zero-gauge static pressure condition, allowing fully developed flow to exit the domain naturally. Material properties for the working fluid are assigned dynamically through a User-Defined Function (UDF) that computes density, viscosity, thermal conductivity, and specific heat as functions of both temperature and nanoparticle volume fraction. This ensures that the nanofluid physics including viscosity increase, thermal conductivity enhancement, and temperature-dependent behaviors are accurately represented throughout the computational domain.

2.6 Nanofluid Property Models

The CuO–water nanofluid used in the simulations is modeled through a dedicated User-Defined Function (UDF) that updates its thermophysical properties at each iteration. Instead of using fixed or default Fluent correlations, the UDF computes effective density, viscosity, specific heat, and thermal conductivity based on established mixture formulations tailored to the nanoparticle concentration. Density is calculated using a mass-weighted formulation, while specific heat uses a capacity-weighted model that accounts for the differing thermal masses of CuO nanoparticles and water. The viscosity relation incorporates the influence of particle loading on momentum diffusion, capturing the increase in apparent viscosity at higher nanoparticle fractions. Thermal conductivity is modeled using enhancement correlations that reflect improved conductive pathways and micro-convection around suspended particles. All properties are treated as temperature-dependent within the UDF, ensuring that the nanofluid behavior changes realistically as the fluid experiences temperature rise along the absorber tube. This dynamic evaluation is essential for representing accurate flow physics because nanofluids typically undergo viscosity reduction and conductivity enhancement with temperature. Implementing the UDF allows the numerical model to account for these variations without relying on simplified or constant-property assumptions, thereby improving the fidelity of the heat-transfer and pressure-drop predictions.

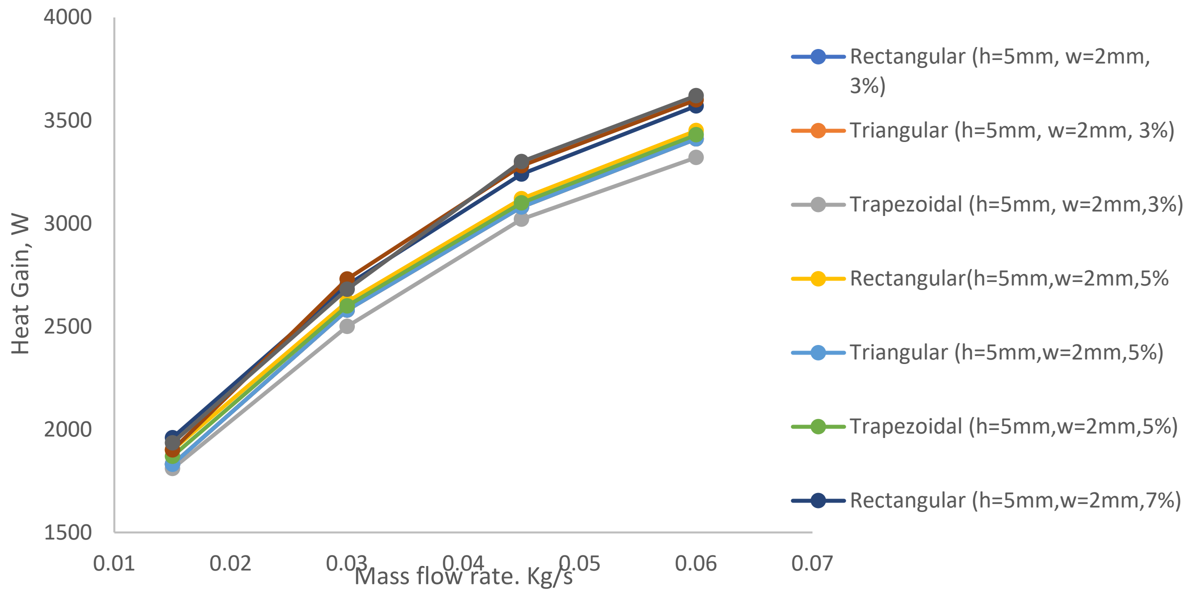
2.7 Solver Setup

The computational analysis is performed using a pressure-based solver appropriate for incompressible internal flows. Momentum–pressure coupling is handled through the SIMPLE algorithm, which provides robust convergence characteristics for steady-state simulations. Second-order upwind discretization is applied to both momentum and energy equations to minimize numerical diffusion and accurately capture gradients near fin surfaces, where velocity and temperature fields vary sharply. Spatial gradients are evaluated using a least-squares cell-based scheme to maintain consistency on the unstructured tetrahedral mesh.

Under-relaxation factors are progressively adjusted during the solution procedure to ensure numerical stability in early iterations and accelerated convergence during later stages. Convergence is judged using a combination of residual thresholds 10^{-6} for the energy equation and 10^{-4} for continuity and momentum and steady values of key global quantities such as outlet temperature, pressure drop, and heat-transfer rate. This strategy ensures that the final solution is both numerically stable and physically meaningful, providing reliable data for subsequent thermal–hydraulic performance comparisons.

III. RESULTS AND DISCUSSION

3.1 Effect of Mass Flow Rate



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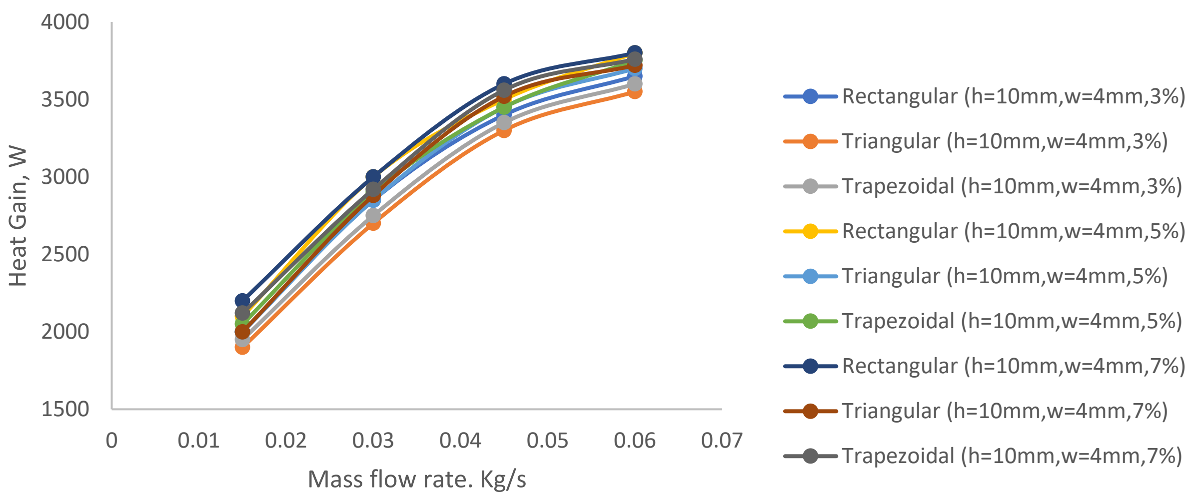

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Fig 5(a)(b): Heat Gain results of results of PTC with all different Fins

The mass flow rate has a strong influence on both thermal and hydraulic characteristics of the absorber tube. As the mass flow increases from 0.015 to 0.060 kg/s, the outlet temperature shows a gradual decrease for all working fluids. This behavior is expected, as higher flow rates reduce fluid residence time inside the heated absorber, thereby limiting the temperature rise despite the same applied heat flux. However, the useful heat gain (Q_u) exhibits a clear increasing trend with flow rate, indicating that a larger quantity of fluid absorbs more total energy even though the temperature rise per unit mass is reduced.

The Nusselt number increases significantly with mass flow rate, reflecting stronger forced convection and thinner thermal boundary layers at higher Reynolds numbers. This trend is consistent across smooth tubes and all fin geometries. Conversely, the friction factor decreases as the flow rate increases, which is characteristic of internal turbulent flow where frictional resistance reduces with increasing Reynolds number. The pressure drop (ΔP) shows the opposite behavior, increasing almost linearly with mass flow rate due to higher momentum requirements. Overall, increasing the flow rate improves convective transport and useful heat extraction, but at the cost of larger pumping power.

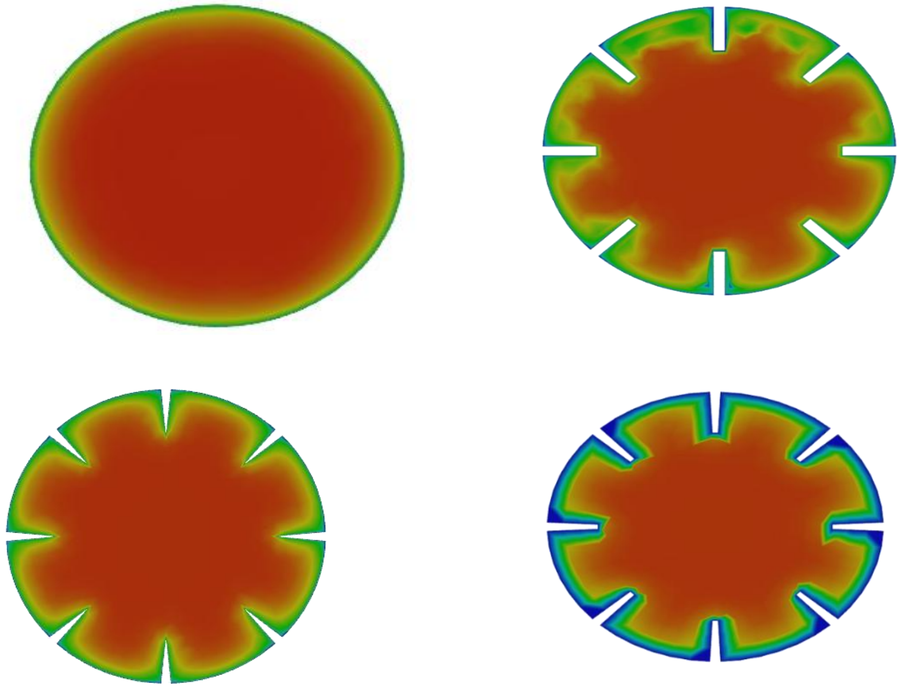
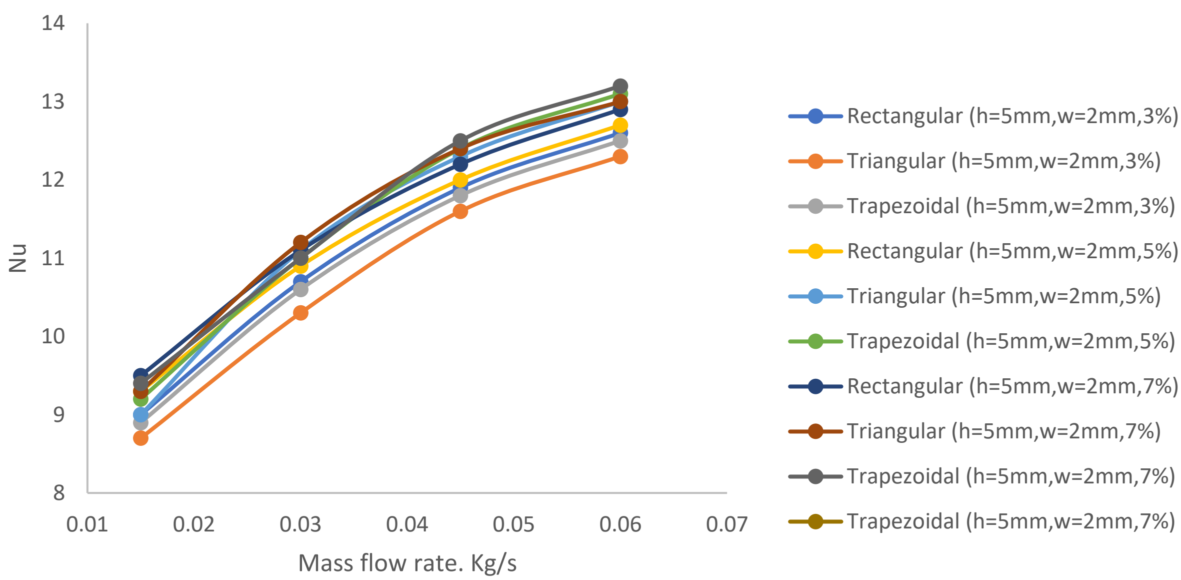


Fig 6 Velocity Contour of Different Geometric fins in Absorber tube at 0.05 kg/sec mass flow rate

3.2 Effect of Fin Geometry



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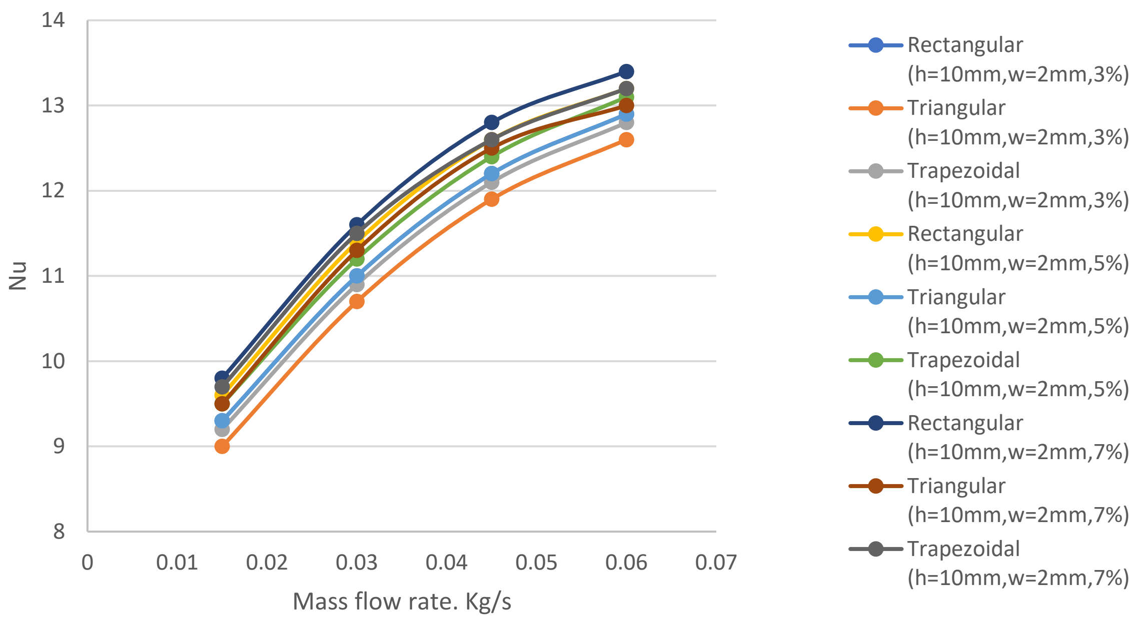

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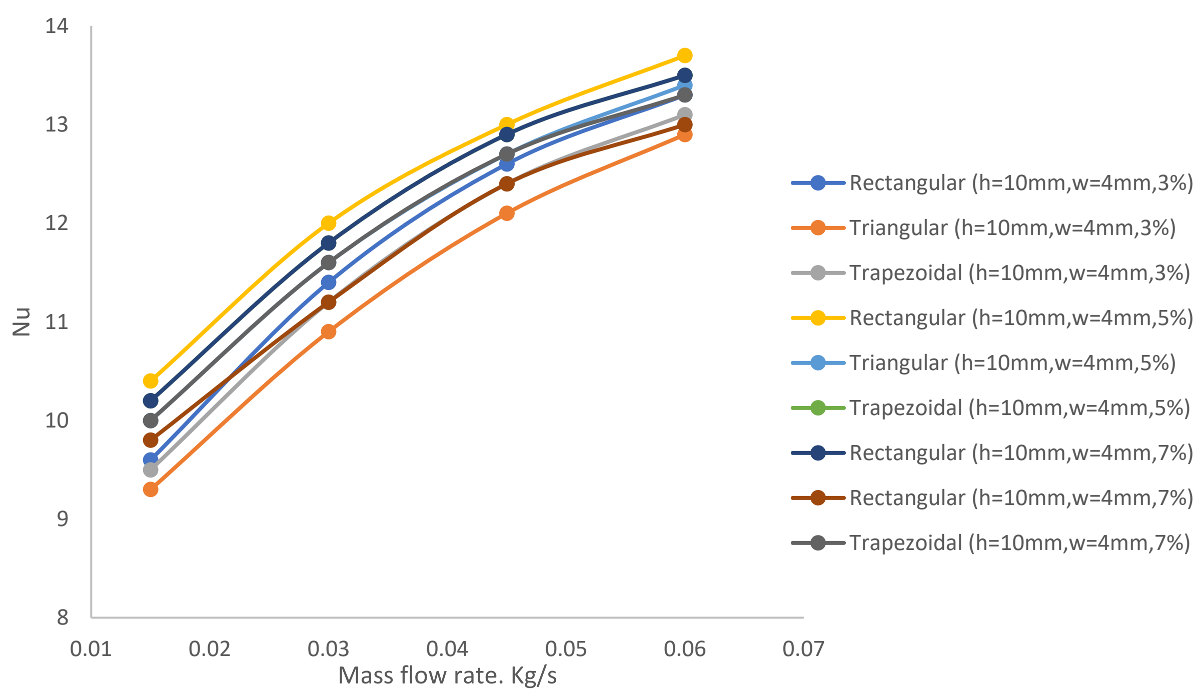

(c)

Fig 7 (a)(b)(c): Nusselt Number Variations for Different Reynolds number for all geometric fins

The introduction of internal fins significantly enhances heat-transfer performance compared to smooth tubes, with the magnitude of improvement strongly dependent on the fin geometry. Rectangular fins consistently deliver the highest Nusselt numbers, primarily due to their larger surface area and strong conductive heat-transfer pathway from the tube wall to the fluid. Trapezoidal fins show the next-best performance, offering a balance between conduction at the wider base and reduced flow obstruction at the top. Triangular fins, while still effective, provide slightly lower enhancement because their tapering shape results in reduced heat-transfer area near the fluid core.

This hierarchy is observed across all mass flow rates and nanoparticle concentrations, with rectangular fins offering approximately 12–20% higher Nusselt numbers than triangular fins and 5–10% higher compared to trapezoidal fins. However, fins also introduce additional flow resistance. Rectangular fins cause the largest friction factor and pressure drop, followed by trapezoidal and then triangular fins. The increased hydraulic penalty of rectangular fins must therefore be evaluated alongside their superior heat-transfer capability.

3.3 Effect of Nanoparticle Concentration (3%, 5%, 7%)

Increasing the nanoparticle volume fraction enhances overall heat-transfer performance due to improved thermal conductivity and stronger energy transport. Moving from 3% to 5% concentration results in a noticeable rise in Nusselt number and useful heat gain, typically in the range of 8–12%. However, further increasing the concentration to 7% produces diminishing returns, with heat-transfer enhancement reducing to around 3–5% compared to 5%.

The pressure drop (ΔP) increases with concentration because the effective viscosity of the nanofluid also increases. The growth in hydraulic resistance becomes more pronounced at higher flow rates, where viscous effects compound with inertial forces. While higher nanoparticle loading improves thermal performance, the corresponding increase in viscosity introduces additional pumping requirements, especially at the 7% level.

IV. CONCLUSION

This study conducted a comprehensive numerical investigation of the thermo-hydraulic performance of a parabolic trough collector receiver equipped with three internal fin geometries rectangular, triangular, and trapezoidal and operating with CuO–water nanofluids at different concentrations. The results demonstrate that integrating fin structures significantly enhances convective heat transfer by increasing surface area and promoting flow interaction, while the use of nanofluids further strengthens thermal transport through improved thermal conductivity. Among the geometries evaluated, rectangular fins consistently provided the highest heat-transfer enhancement due to their larger conductive pathway and stronger interaction with the flowing fluid. Trapezoidal and triangular fins also improved performance relative to the smooth tube, though with slightly lower thermal gains and reduced hydraulic penalties.

Nanofluid concentration played a notable role in determining system behavior. Increasing the CuO content from 3% to 5% resulted in substantial increases in Nusselt number and useful heat gain, while further increasing to 7% delivered diminishing benefits due to viscosity-driven pressure losses. The thermal performance factor confirmed that 3% and 5% concentrations provide a favorable balance between enhancement and flow resistance, whereas the hydraulic penalty at 7% begins to offset thermal gains, especially at higher flow rates.

Overall, the analysis identifies the rectangular fin with 10 mm height and 4 mm width used with a 5% CuO–water nanofluid as the optimal configuration, offering the highest heat-transfer performance with acceptable pressure-drop characteristics. This combination delivers consistently strong thermal enhancement while maintaining a thermal performance factor greater than unity across operating conditions. The results highlight the potential of fin–nanofluid integration as a practical and effective approach for improving PTC receiver efficiency, particularly in applications requiring compact design, high thermal output, and stable hydraulic behavior.

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