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Optimizing Solar Thermal and Electrical Output Through a Hybrid Fresnel Lens and TEG System

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Abstract. This study demonstrates the successful integration of a Fresnel lens into a hybrid solar cooking and thermoelectric generation system, providing both thermal energy for cooking and electrical power generation. The study analyzed various tank designs to enhance heat transfer, improve heat distribution, and optimize the cooking surface. The best-performing design, featuring an aluminium heat sink with fins, achieved the highest fluid temperature of 54.44°C, with superior heat transfer efficiency and uniform distribution. Other designs using stainless steel and copper showed promise but faced challenges, such as uneven heat spread and inefficient baffle configurations. The findings underscore the critical role of material selection and design optimization in enhancing the thermal performance of hybrid solar systems.

Keywords: Hybrid Fresnel Lens, CSP, Solar Cooking, Thermoelectric Generator, Thermal Modelling

1. Introduction

This study explores the integration of a Fresnel lens into a hybrid solar system designed for dual purposes: solar cooking and electricity generation through a thermoelectric generator (TEG). Building on the foundational work of Hussaini et al. [1], which employed a parabolic trough collector (PTC) for similar applications, this research leverages the Fresnel lens for its unique ability to concentrate sunlight onto a smaller area, providing high-intensity heat. The key advantage of Fresnel lenses lies in their lightweight and cost-effective design, making them a viable alternative to the more bulky and complex PTC systems.

The hybrid system under investigation seeks to address two major challenges especially in off-grid communities: the need for clean cooking energy and access to low-grade electricity. The system thus sought to reduce dependency on traditional fuels, thereby contributing to both environmental sustainability and public health improvements [1,2]. The inclusion of TEGs in the system allows for the conversion of excess thermal energy into electricity, providing additional value beyond cooking. The system leverages the high optical efficiency of the Fresnel lens to concentrate sunlight onto a heating spot on the cooking surface, transferring heat to both the cooking surface and the HTF for thermal storage and electricity generation.

The application of Fresnel lenses in solar energy systems has been demonstrated in several studies. For instance, Valmiki et al. introduces a novel solar cooking stove design using a large Fresnel lens for sunlight concentration. The system includes a sunlight tracking mechanism that moves the lens in both zenith and azimuth angles, ensuring reduced heat loss [3]. It maintains a stovetop temperature of up to 300°C making it suitable for cooking. Similarly, Zhao et al. utilized solar cooker fitted with a curved Fresnel lens as a concentrator, allowing for higher cooking temperatures and shorter cooking times by focusing sunlight onto an evacuated tube collector and enabling manual sun tracking [4]. Wang Hai evaluated the effect of a glass cover on a fixed-focus Fresnel lens solar concentrator with a conical cavity receiver [5]. The results show that while the glass cover reduces optical efficiency, it improves thermal efficiency at higher temperature differences. The adaptability of Fresnel lenses to various solar thermal applications underscores their potential to enhance hybrid energy systems, particularly in off-grid regions where resources are limited.

In this study, field tests and thermal modeling are conducted to optimize heat delivery into the HTF's storage tank, allowing for continued cooking and TEG use during periods of low or no solar insolation. To evaluate the effectiveness of these design modifications, thermal modeling was conducted using SolidWorks, simulating the heat transfer behavior and temperature distribution within the tank. The thermal modeling provided insights into how the system absorbs, transfers, and stores heat in the HTF, enabling a detailed comparison of the heat transfer efficiency across the different designs.

2. System Design and Optimization

The hybrid solar cooking and TEG system is designed to maximize the efficient transfer of heat into a storage tank that serves dual purposes: cooking and electricity generation. The Fresnel lens, with an active area of 1.4 m², a concentration ratio of 140 suns, and an optical efficiency of 91.9%, focuses sunlight onto a 100 mm by 100 mm heating spot on the tank's surface, made of mild steel (Figure 1). This concentrated heat is transferred into a HTF stored in the tank, allowing for continuous operation during periods of low solar insolation.

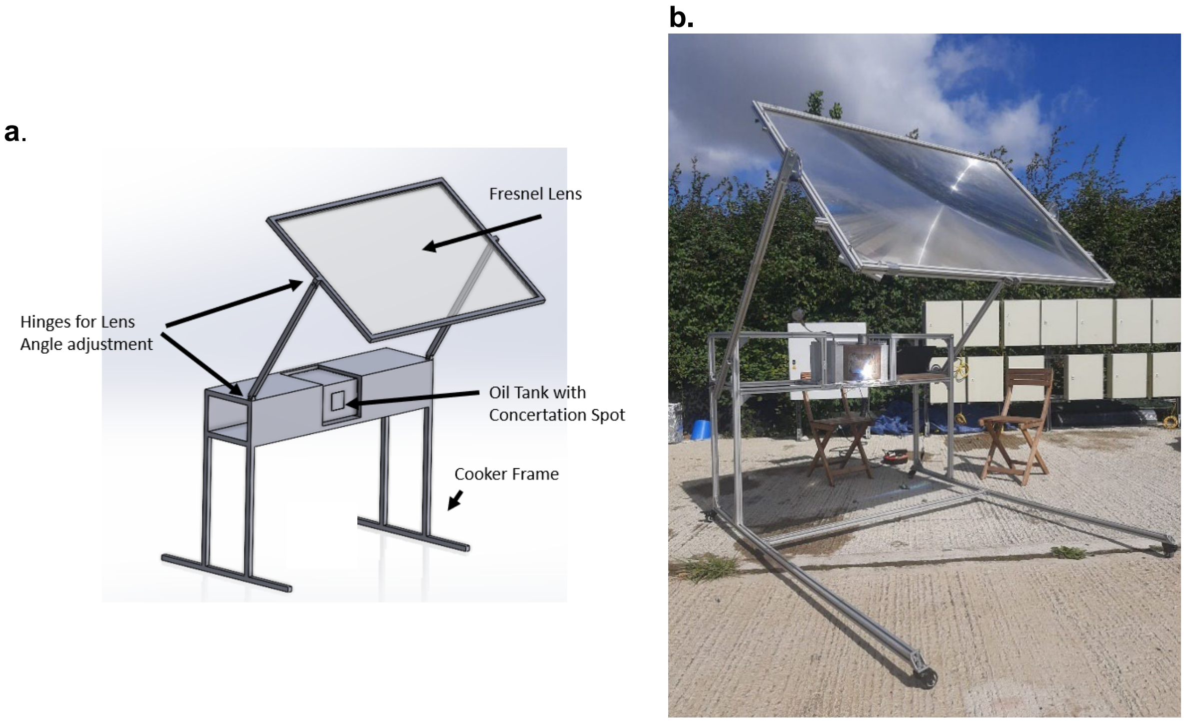


Figure 1. a. *CAD model,* ***b.*** *Built version of the Fresnel Lens System integrated with oil storage tank*

The initial design and subsequent modifications of the system focus on optimizing heat transfer into the HTF and improving the usability of the cooking surface. Thermal modelling using SolidWorks was conducted to simulate and analyse the thermal performance of each design iteration. The following sections describe the initial design, design modifications, and the modelling parameters used to evaluate performance.

2.1 Initial Design and Field Test

The initial design features an insulated mild steel tank with a total capacity of 14 litres, of which 9 litres are filled with mineral oil Shell-Thermia B heat transfer fluid. The remaining 5 litres accommodate air and allow for the thermal expansion of the HTF. This configuration ensures safe operation under varying temperatures while providing sufficient volume for energy storage.

The Fresnel lens concentrates the sun radition onto a 100 mm by 100 mm heating spot on the tank‘s surface, which transfers the absorbed heat into the HTF. The system uses the HTF to store excess thermal energy, allowing for sustained cooking and TEG operation when sunlight is insufficient or at night time.

A 12W rated TEG with specifications highlighted in Table 1 is mounted onto a copper plate placed at the focal point of the Fresnel lens, which significantly boosts heat absorption due to copper’s superior thermal conductivity. The TEG's cold side is cooled using a large aluminum heat sink sized 17.5cm by 9.8cm and with 9 fins, ensuring a consistent temperature gradient across the TEG for electricity generation.

Table 1. *Specification of TEG module*

Type	L	W	H	Rac	V	I	Power	Eff
TGM-241-1,4-1,5	55mm	55mm	4.2mm	3.80Ω	6.80V	1.80 A	12.20 W	5.1 %

Field tests conducted with this initial design showed that the system could achieve the required temperatures for cooking, while the TEG produced sufficient power, demonstrating the system's potential for off-grid use.

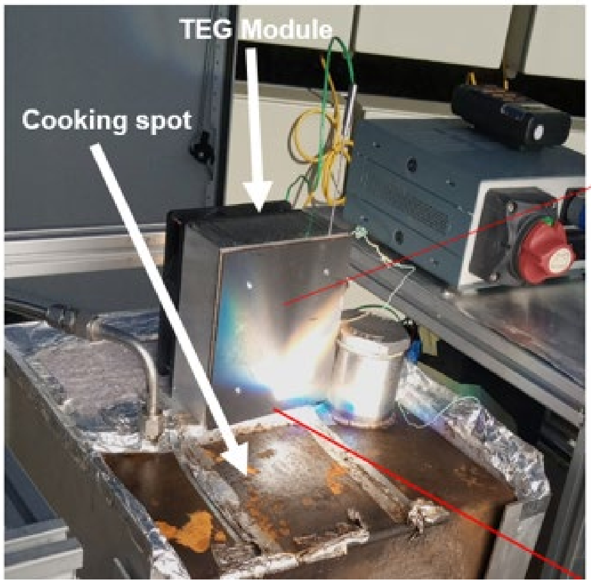


Figure 2. *Setup of rig showing the cooking spot and TEG module mounted on the oil storage tank*

2.3 Design Modification

Following the development and evaluation of the initial design, three modified tank designs were created (Figure 3) to optimize the heat transfer efficiency and improve the cooking surface. These modifications were assessed using CFD from SolidWorks Flow simulations to study heat transfer behaviour and temperature distribution.

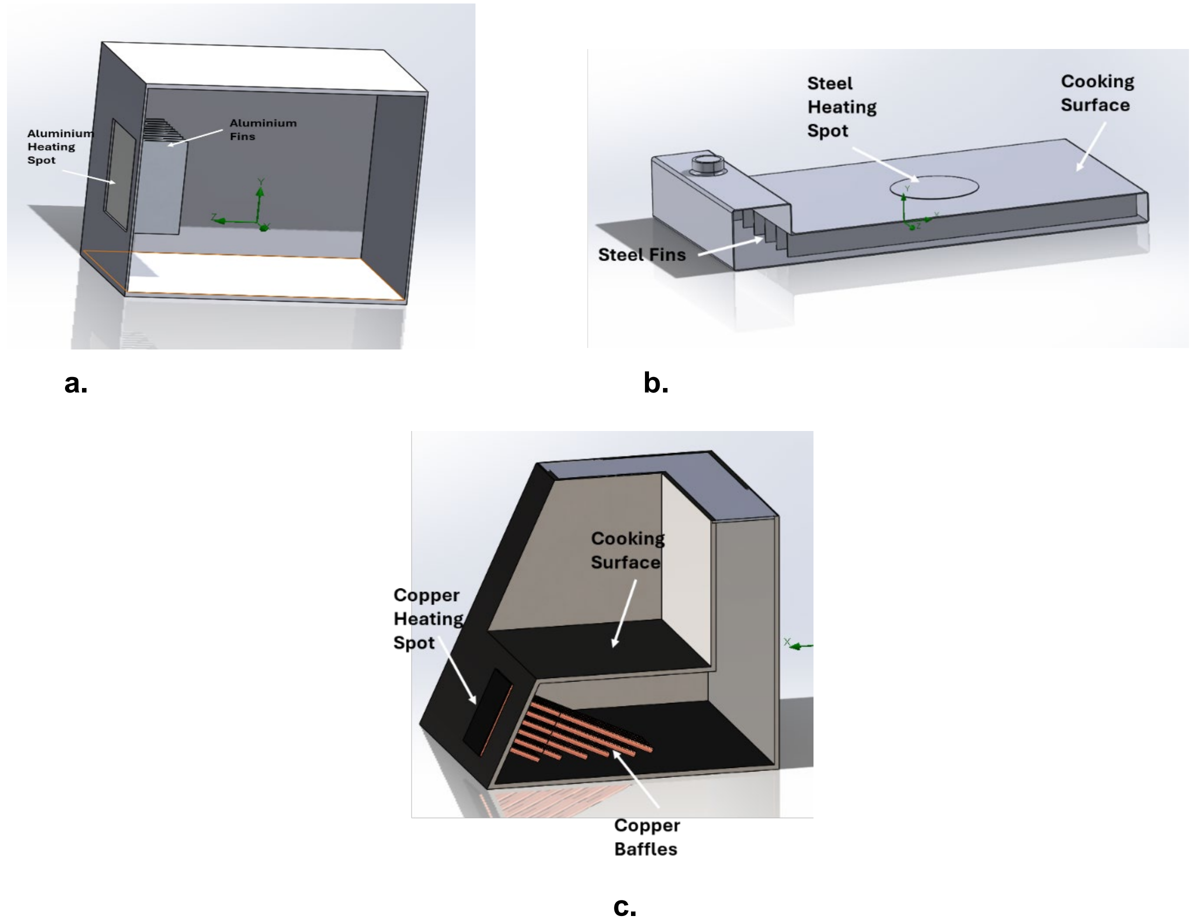


Figure 3. a. *CAD Model of 1st modified tank with aluminum finned heating spot* ***b.*** *CAD Model of 2nd modified tank with stainless steel heating spot and finns* ***c.*** *3rd CAD model with copper heating spot and baffles*

2.3.1 First Model - Enhanced Heating Spot with Aluminium Heat Sink

The first modification maintains the overall structure of the initial design but introduces an aluminium heat sink of similar type used for TEG (17.5cm by 9.8cm and with 9 fins) directly at the heating spot. The aluminium heat sink is designed to absorb and distribute heat more effectively from the focal point of the Fresnel lens into the HTF, enhancing heat transfer and reducing the risk of localized overheating at the cooking surface. This modification is expected to improve the uniformity of heat distribution across the cooking surface while maintaining efficient heat transfer into the HTF for thermal storage.

2.3.3 Second Model – Stainless Steel Fins Heating Spot

The second modification emphasizes expanding the cooking surface for tasks requiring more space, such as grilling or cooking with multiple pots. This design features a broader cooking surface and integrates 7 units 2mm steel fins 40mm deep across the length of the tank. The fins are meant to enhance the heat transfer from the cooking surface into the HTF by increasing the contact area between the cooking surface and the fluid, ensuring that heat is distributed more evenly throughout the tank.

2.3.2 Third Model – Copper Heating Spot with Baffle Rods

The third modification focuses on improving heat absorption and transfer efficiency by replacing the mild steel heating spot with a copper plate. To enhance the optical properties of the copper heating spot, a heat-resistant black coating was applied to increase solar absorption. Once sunlight is absorbed, copper's high thermal conductivity enables more rapid and efficient heat conduction away from the focal point and into the HTF.

In addition, 9 units of 10mm diameter baffle rods with different lengths are attached to the underside of the copper plate, extending into the HTF. These rods are meant to increase the surface area for heat transfer and enhance the internal circulation of heat within the tank. The design also improves heat conduction during cooking surfaces by immersing the cooking wall in the HTF volume. The dedicated cooking surface is protected by an insulation shield, preventing heat from escaping into the environment and ensuring safer cooking operations by containing the heat from the concentrated sunlight.

Thermal Modelling Parameters

To evaluate the performance of the initial design and the three modified designs, thermal modelling was conducted with the following parameters applied consistently across all models to ensure comparable results.

- The simulation assumed a DNI of 142 W/m², resulting in an expected irradiance of 19,880 W/m² at the focal point of the Fresnel lens, with this value maintained consistently across all models. The tank material is mild steel (except where indicated) and has a total volume of 14 litres, with 9 litres filled with the mineral oil Shell Thermia B HTF.

- For each modified design, the appropriate materials (mild steel, copper, or steel) were assigned to the heat transfer surface to accurately simulate their behaviour in terms of heat absorption and distribution.

- The outer walls of the tank were simplified and modelled with adiabatic boundary conditions to simulate the insulation and prevent heat loss to the surrounding environment.

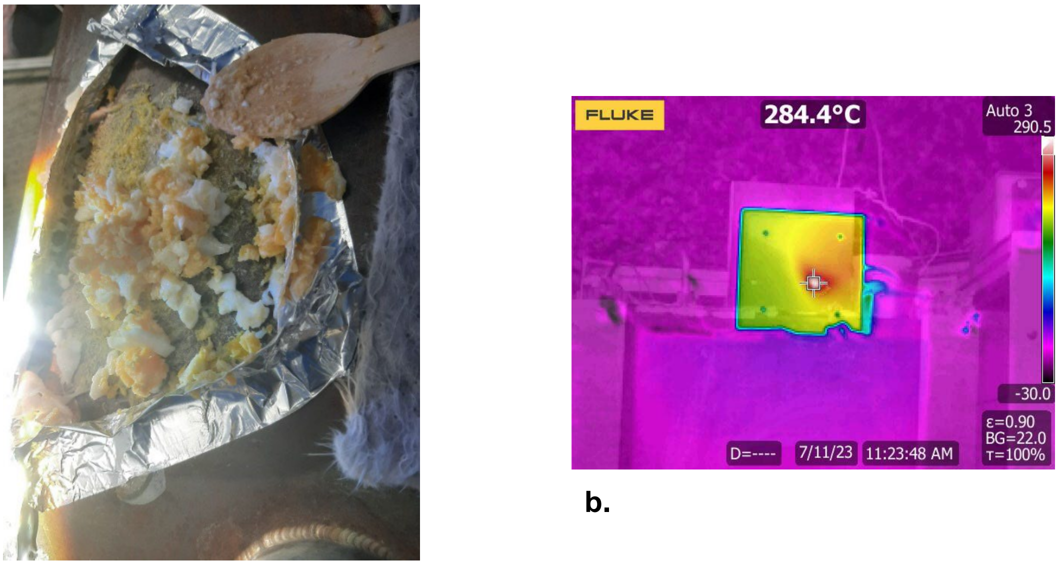
- The thermal modelling was conducted over a simulated physical time of one hour, focusing on the heat transfer from the cooking surface into the HTF and the resulting temperature distribution within the fluid.

3. Results

The results from field tests and simulations provide insight into the system's performance, particularly in terms of heat transfer from the heating spot into the oil within the tank, as well as the power generation capability of the TEG. The tests were conducted on July 11, 2023, in Cranfield, UK under normal solar irradiance averaging to 900 W/m².

3.1 Field Test Results

The field tests focused on evaluating the heat transferred into the oil from the concentrated sunlight, as well as the system's ability to generate electricity using the TEG (Figure 4).



b.

a.

Figure 4. a. *Scrambled eggs on the cooking surface atop the HTF tank* ***b.*** *Fresnel lens concetrated irradiation on the hot side of the TEG module*

The field test revealed that the oil temperature in the tank rose steadily, reaching a maximum of 164°C after approximately four hours of continuous exposure to the concentrated sunlight focused by the Fresnel lens. As seen in Figure 5, the oil temperature increased rapidly, owing to the size of the tank and volume of HTF. The rapid heat absorption indicates that the system can quickly attain the necessary temperature for cooking, even during varying solar conditions.

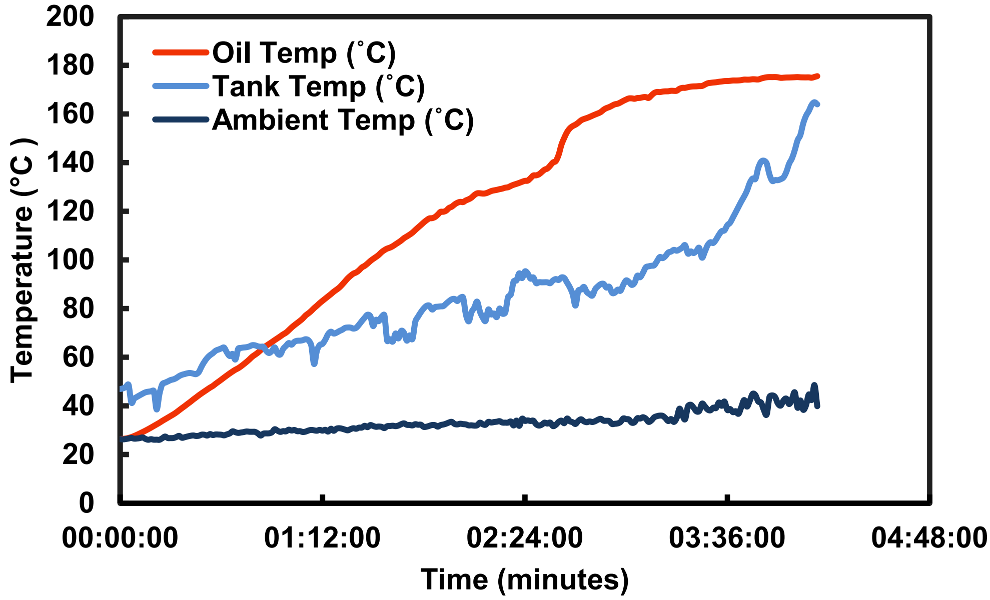


Figure 5. *Temperature of HTF in tank, tank's surface temperature and ambient tracked over time.*

An independent test on the TEG yielded a peak power output of around 8 W approximately 30 minutes into the test as shown in Figure 6. This result is attributed to the fast absorption of heat by the coated copper plate, which was placed at the focal point of the Fresnel lens. The heat sink temperature rose alongside the copper plate temperature, peaking at approximately 60°C. The significant heat absorption by the heat sink highlights the potential for further improvements to enhance heat dissipation, allowing for a greater temperature difference across the TEG potentially boosting power output.

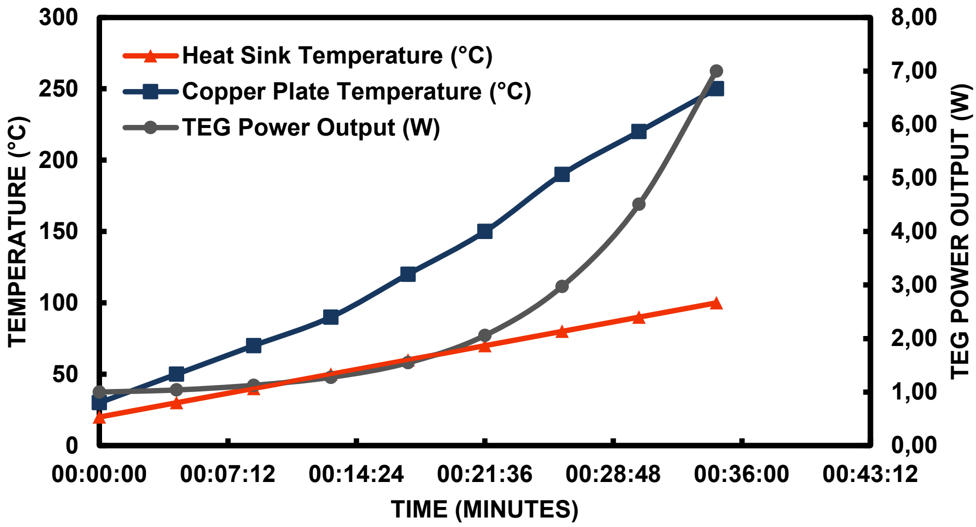


Figure 6. *TEG module power tracked over time using an MPPT tracker. Hot and cold surfaces of the TEG represneted by the heat sink's and copper plate's temperature.*

3.2 Thermal Modelling Results

Various modelled designs of the tank were implemented to enhance the absorption of heat into the oil under consistent conditions. A model of the tank used during the field test was initially modelled in order to have a consistent baseline during the comparative study. The modelling results are summarised in Figure 7.

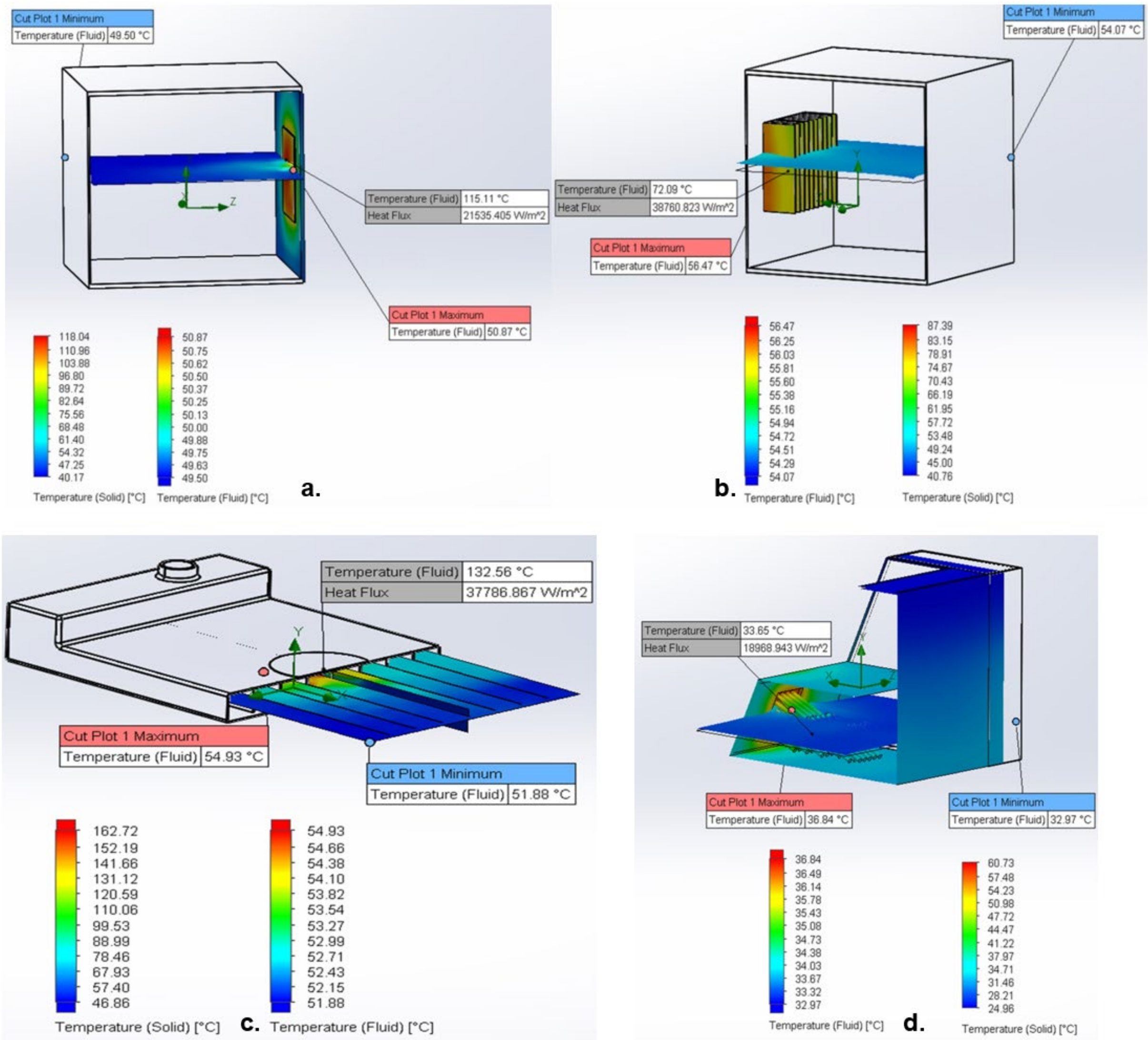


Figure 7. *Thermal modelling results of* ***a.*** *Initial field test tank model* ***b.*** *aluminum finned tank model* ***c.*** *Steel finned tank model* ***d.*** *copper tank with baffles model*

In the field test tank, which used a mild steel heating spot, the simulation revealed that the oil reached an average temperature of 49.58°C after one hour. The average heat flux from the heating spot was 18,572.26 W/m², reflecting mild steel's moderate thermal conductivity, which resulted in a total heat transfer of 185.72 W. Convective heat transfer was measured at 134.87 W, indicating a limited transfer of heat into the oil due to mild steel's lower conductivity. The overall performance of the tank, while consistent, demonstrated the limitations of mild steel in efficiently transferring and distributing heat, serving as a solid baseline but showing room for improvement.

The 1st modified tank, which introduced an aluminium heat sink with fins, showed significant improvement. Aluminium's higher thermal conductivity enabled more efficient heat transfer, resulting in an average fluid temperature of 54.44°C. The average heat flux reached 25,636.95 W/m², with a total heat transfer of 256.37 W. Despite a lower convective heat flux per unit area (2,186.02 W/m²), the fins increased the total surface area for heat transfer, leading to a total convective heat transfer of 233.03 W. This design proved particularly effective at distributing heat more uniformly throughout the fluid, enhancing both total heat transfer and convective efficiency.

The 2nd modified tank exhibited a different thermal profile compared to other models. Stainless steel's lower thermal conductivity caused heat to build up at the surface, resulting in the highest total heat transfer among all the models, reaching 366.09 W. Despite this, the oil reached an average temperature of 52.72°C, which is lower than expected given the high total convective heat transfer of 254.13 W. The heat distribution from the modeling shows that the fins, which run along the entire length of the tank, are not directly connected to the heating spot, which is isolated to the middle. This design limits the efficiency of heat spreading and results in uneven heating across the fluid.

In the final modified tank the results were unexpectedly low. Despite copper's high thermal conductivity, the oil only reached an average temperature of 32.04°C, suggesting poor absorption of the concentrated light at the focal point. The total heat transfer in the solid/fluid domain was 189.68 W, similar to the baseline mild steel tank. This resulted in a lower convective heat transfer, measured at 169.00 W. One potential factor contributing to the reduced performance could be the size and diameter of the baffles, which slowed heat transfer to the fluid as the modelling results show. Thinner or optimized baffle designs should be assessed to improve heat conduction. The unexpectedly low total heat flux suggests that this model and desing requires further investigation into the absorption of the concentrated light s well as a reassessment of the baffle design to enhance thermal performance. Figure 8 shows the buildup of fluid temperatures over the modeling time for each tank.

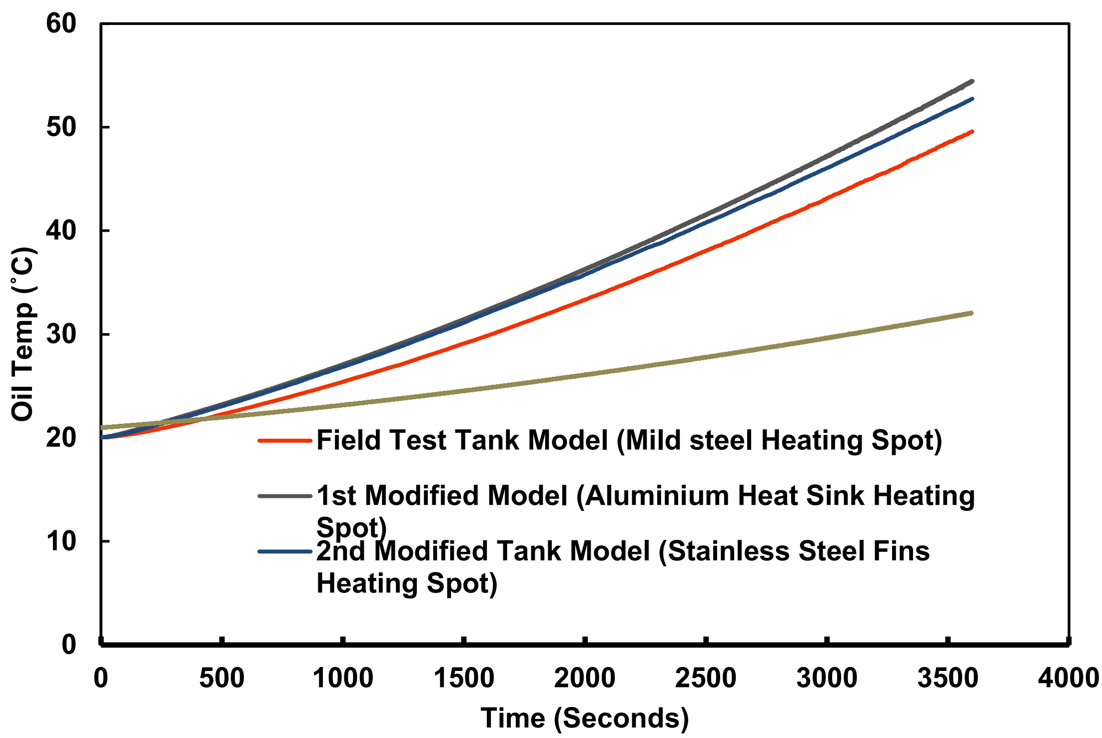


Figure 8. *Fluid Tempreture change profile with time accross the different models*

4. Conclusion

This study demonstrates the successful integration of a Fresnel lens into a hybrid solar cooking and thermoelectric generation system, providing both thermal energy for cooking and electrical power generation. The study analyzed various tank designs to enhance heat transfer, improve heat distribution, and optimize the cooking surface.

The initial design, featuring a mild steel tank with a concentrated heating spot, served as a baseline. Thermal modelling and field testing identified limitations in heat transfer efficiency due to material properties and design constraints. Subsequent modifications focused on enhancing heat transfer into the HTF, improving the cooking surface by submerging it in the fluid level, and addressing safety and heat loss concerns.

The first modified design incorporated an aluminium heat sink with fins at the heating spot. This design demonstrated the best performance, achieving efficient heat transfer and a higher average fluid temperature of 54.44°C. The second modified tank which features a broader cooking surface achieved the highest total heat transfer but suffered from uneven heat distribution due to the isolated heating spot. The average fluid temperature of 52.72° and heat distribution pointed out the need for better integration between the heating spot and the fins to improve uniform heat spread across the tank. The third modification utilized a copper heating spot with submerged baffle rods, aiming to improve the cooking surface and internal heat distribution. Despite copper's thermal conductivity, the average fluid temperature reached only 32.04°C. This is likely due to the limited initial absorption of the concentrated light and a suboptimal baffle design. However, submerging the cooking surface in the fluid showed potential for better heat conduction during cooking TEG use. The findings underscore the critical role of material selection and design optimization in enhancing the thermal performance of hybrid solar system.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article. Additional information on data can be made available upon reasonable request from the corresponding author.

Author contributions

Khalifa Aliyu Ibrahim: Conceptualization; resources; investigation; formal analysis; writing – review and editing. Zaharaddeen Ali Hussaini: Conceptualization; writing – original draft; formal analysis; investigation; resources. Fergus Crawley: Conceptualization; resources; investigation. Mounia Karim: Writing – review and editing. Zhenhua Luo: Resources; supervision; project administration; writing – review and editing. Abdullah Ayed Alrwili: Investigation; writing – review and editing. Christopher Sansom: Supervision; project administration; writing – review and editing. Jonathan Siviter: Resources.

Competing interests

The authors declare that they have no competing interests.

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