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Experimental Evaluation of a Multi-Lens Solar Concentrator with Aluminum Plate Heat Storage and Copper Tube Water Heating

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Abstract

This study investigates the thermal performance of a gravity-driven concentrating solar water heating system, where the collector employing a multi-lens optical array. The proposed design incorporates forty convex lenses where these lenses are arranged to concentrate solar radiation onto an aluminum absorber plate. A copper tube attached to the absorber surface to transfer heat to a circulating water with in the system. The flow of circulating water is achieved without the use of mechanical pump, relying entirely on hydrostatic pressure generated by elevating the storage tank above the collector.

Outdoor experiments were conducted to evaluate the behavior of solar irradiance, components temperature, thermal energy gain within storage tank, and overall efficiency of the system. The experimental result shows strong correlation between solar irradiance and thermal response of the collector system. During the periods of peaks solar intensity effective, the aluminum absorber plate and copper tube exhibited rapid temperature increases, which indicates effective solar energy absorption and conductive heat transfer. Furthermore, a consistent temperature difference between the collector inlet and outlet conforming the continuous thermal energy transfer to working fluid. Meanwhile the storage tanks demonstrate a delayed thermal response due to higher thermal inertia and heat storage capacity.

The highest thermal efficiency periods close to solar noon and a similar performance pattern was recorded over operating days. Analyzing of thermal energy showed effective energy storage throughout daylight hours and expected heat losses were noticed during periods of zero irradiance. Overall, the experimental result demonstrates the practical and effectiveness of the proposed pump-free concentrating solar water heating system. The study offering a simple and energy-efficient approach for solar water heating applications, particularly in regions characterized by high solar irradiation levels.

Keywords: Convex lens, Concentrating Solar Power (CSP), Flow rate, Solar Water Heating, Useful Energy.

1. Introduction

The transition to sustainable energy paradigm is increasingly critical priority in modern societies driven by the imperatives of climate change, the expected rise is fossil fuel prices resulting consequent to the depletion of conventional energy resources, and the growing demand for energy associated with economic advancement of welfare and development. In response, significant attention has been directed for green energy for past decade, supporting by extensive academic research and industrial endeavors amid at accelerating the adoption of environmentally and renewable energy sources.

A considerable proportion of the aggregate energy consumption is associated with domestic and the generation of hot water. In this context, solar water heating emerges as a pivotal mechanism for utilizing solar energy. These systems are widely known as a cost-efficient solution and can account for substantial reduction in household reduction energy demand, approximately 20% of total residential energy consumption.[1]

Solar thermal technologies are based on the utilization of solar radiation into useful energy form. This involves the utilization of specially engineered absorbing surface. The technologies are generally divided into two systems: non-concentrating collectors, such as (FPSCs) flat plate solar collectors, require a large surface area to absorb solar radiation and are mainly used to for low-temperature application due limitation of solar energy dilution. Meanwhile concentrating solar power (CSP) incident solar radiation into a designated focal region through utilize reflective or reflective optical component, thereby significantly increasing the thermal energy, generating temperature exceeding between 1000ºC to 1500ºC. these outputs of high temperature can be directly employed for steam and power generation, and variety of thermal processes.[2]

Numerous theoretical investigation and experiments have been conducted by researches on solar collector with object of tackling the heat loss that occur during inactive period and cold nighttime condition. Although the utilization of appropriate insulation and glazing material can partially reduce these losses, while the complete elimination of heat loss remains challenging. Although researchers have explored alternative approaches to reduce heat loss. Among these approaches is one promising avenue, the integration of convex lenses into the collector cover of solar collector.

In solar collectors incorporating with convex lenses, each light ray passes the lens plays a crucial role in enhancing solar energy concertation. Ligh rays intersecting the lens center without experiencing deviation. When the rays approach the lens parallel to the optical axis of the lens, it undergoes refraction converges to orgiastic from a specific point knows as image focus (F) on lens's optical axis.

Convex lenses known as economical and lightweight optical elements, this making them suitable for numerous solar energy applications. In their design, the amount of non-optical interface material is normally minimized since the optical performance is mainly governed by refractive interface itself. A fundamental characteristic of convex lenses is their ability to converge incident rays lights. When infinite set of parallel ryas aligned with the principle axis strike the lens surface, the lens refracted the rays and concentrated them at a single focal point. The principal axis is defined as the line perpendicular to the lens plane. The point which refracted rays converge after passing through the lens known as the focal point, while the distance from the focal point to the lens plan is referred to as focal length. [3]

2. Literature Review

Kale et al. investigated the thermal performance of convex lens-based concentrated solar power (CSP) system, this system were designed for hot water and steam production. The experimental setup contained six convex lenses, each with an aperture area of 0.0417 m^2, which to concentrate solar radiation onto a copper receiver tube with inner and outer diameter of 5 mm and 10 mm, respectively. The experimental results showed that the system achieved a maximum temperature of 810ºC at a water mass flow rate of 1 kg/h. under these operating conditions, the thermal efficiency was between 63% to 64%. [4]

Vinod kumar verma et al. carried out experimental study to evaluate the heat transfer performance of convex lens-based solar concentration system. Their experimental setup employed of six convex lenses that concentrated solar radiation onto a copper receiver tube. To ensure continues alignment solar energy throughout the day, the system was employed with a manually operated dual-axis solar tracking mechanism. The experimental finding demonstrated the use convex lenses into a concentrated solar power (CSP) system can significantly improve heat transfer performance, highlighting its suitable for solar thermal applications, particularly solar water heating. [5]

In 2023, Abdul Samim, Narjis and Abdul Rafay Khatri explored the application of convex lenses in solar-powered water heating systems, using their concentrating to influence on thermal behavior and heat transfer. In their system they use convex lenses to concentrate incident solar radiation onto a small region of the water, allowing more solar energy to be absorbed. This design helped to improve the water heating process more efficiently by concentrating the effective use of the available solar energy. The study focused on developing a water heating system power entirely by solar energy, as a sustainable alternative to conventional electric and gas fired water heaters. [6]

Ammaralifarhan et al. carried out an experimental study of three solar collectors to evaluate the thermal performance with different designs of absorber plate. The first configuration employed a conventional perforated absorber plate, whereas the other two collectors used perforated plates with different size holes of 3 mm and 6 mm, respectively. The experimental showed that the collector equipped with the 3 mm holes achieved higher energy gain. [7]

Li et al. examined the heat transfer performance of a triangular perforated fin through a combination of computing fluid dynamics (CFD) simulations and experimental testing. The numerical results and the experimental measurements, confirming the reliability of the simulation approach. The finding demonstrated that the use of triangular perforated fin significantly improved heat transfer performance.[8]

Thulasi et al. experimentally compared the thermal performance of a convectional solar collector with modified designs incorporating concentric twisted plate tape (CTPT) and concentric solid plate tape (CSPT) inserts. The finding showed that combining convex lenses with these inserts enhanced the collector's thermal performance. Among the tested configurations, the CTPT insert with a twist ratio of 3 showed the best performance, with efficiency around 1.9 times higher efficiency than the corresponding CSPT configuration. Also, the integration of convex lenses and CTPT insert increased the overall collector efficiency by up to 9% compared with conventional collector. [9]

The development of solar water heating systems has contributed an important role in expanding the use of renewable energy for both residential and commercial applications. The solar collector is the main component of these systems, as it absorbs incoming solar radiation and transfers the captured thermal energy to the working fluid, typically water. While many considerable efforts have focused on improving the overall design of collectors, recent studies have considered to emphasized optimizing the collector tube geometry to enhance heat transfer and system performance.

In this context, Aruan Munsamy and Debabrate Brarik investigated the thermal performance of a parabolic plate solar water heater equipped with copper dimpled tube and aluminum-coated channels. The experiments evaluated at mass flow rates ranging from 1.0 to 3.0 kg/min, with increments of 0.5 Kg/min. between each test, the result showed the best thermal performance was achieved at a mass flow rate of 2.5 Kg/min, while overall collector efficiency of 31.85%. this value represented an improvement of around 11% compared with a conventional smooth-tube configuration employing the same base fluid. [10]

Flat plate collector (FPC) solar water heating systems widely adopted solar water heating technologies for residential and commercial applications due of their simple design and reliable operation. The important factor that influences in the collector performance systems is the selection of the absorber plate material, which directly influence the thermal conductivity, heat absorption, and the ability to retain thermal energy during periods of reduced solar irradiance.

In this regard, Billy Anak Sup experimentally compared the performance of (FPC) solar water heaters using copper and aluminum absorber plates. The tests were conducted under solar irradiance levels exceeding 800 W/m^2, and the thermal performance of each material was evaluated by examining the resulting water temperature increment and heat transfer characteristics. The result showed that the aluminum plate achieved a heat gain of 1100.69 W, while the copper plate obtained 1025.36 W. Similarly, the water heating efficiency reached 0.97 for aluminum, and 0.93 for copper. Based on these findings, the aluminum offers better thermal performance than copper as absorber plate material in flat plate collectors.[11]

Another study aimed at showcasing the viability of convex lenses as an innovative approach in solar water heating systems.

Fadhl Mustafa Alanabi, Abdelhafid A. Almrid, investigated the performance of solar water heating using Convex Lens Solar Water Heating System. The design consist set of convex lenses are strategically positioned at the top of the collector to capture sunlight and direct it onto the ascending thermally insulated copper tube, thereby optimizing solar radiation absorption and rapidly heating the water within. The Experiments were conducted at different flow rates of 4, 6, and 10 g/s to examine the system performance. The results showed a progressive increase in useful heat gained, ranging from 46.3 to 238.6 watts, while the highest output temperature recorded at

41.5°C at a flow rate of 4 g/s. However, this temperature decreased with higher mass flow rates and reduced solar intensity. These findings showed the potential of convex lenses to improve solar water heating efficiency.[12]

After review of previous researches that aimed at enhancing the efficiency of solar water heaters, it became evident that existing approaches of utilization of a Convex Lens Solar Water Heating System (CLSWHS) has been largely neglected. Addressing this gap, the present study propose a new design aimed at reducing in heat loss during both operating and inactive periods, this achieved through limiting the surface area exposed to the surrounding environment and increase the contact area between absorber plate and copper tube carrying the transport fluid tube.

3. Methodology

- ***Experimental Setup***

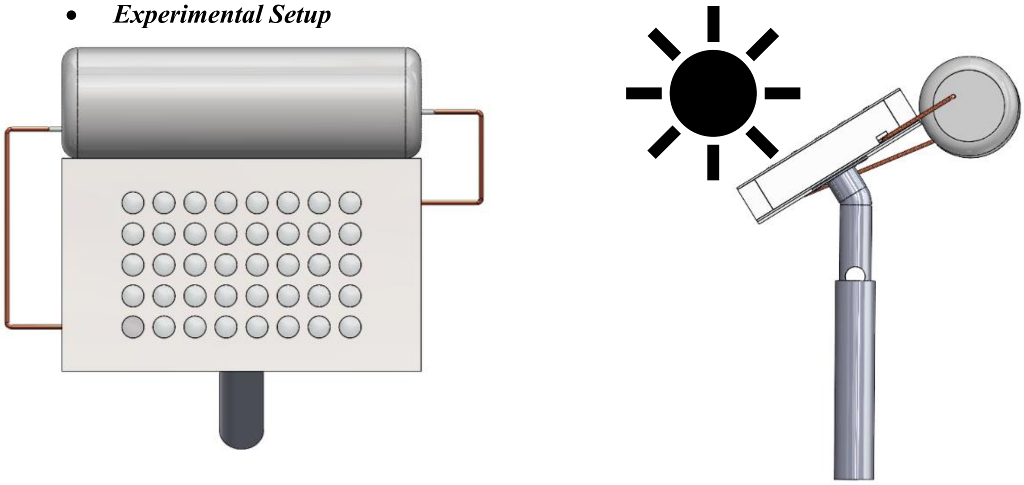


Figure (1) Schematic diagram of the experimental setup.

The experimental was carried out under outdoor conditions concentrating solar thermal collector designed to heat water by transferring concentrated solar radiation to a metal absorber and then to a circulating working fluid. The system consisted forty convex lenses arranged in an array to concentrate incident solar radiation onto a flat aluminum absorber plate. A copper tube is attached to the rear side of the aluminum plate to improve heat conduction from the absorber to the circulating water. The collector operates in a closed-loop circulation: water is passed through the copper tube, then exits the collector, enters a storage tank, and then returns from the tank back to the collector inlet, forming a continuous cycle.

Table 1 below shows the specifications of the FPC for this project which locally found.

Table 1: Specifications of flat plate collector

Component	unit
Length of collector	810 mm
Wide of collector	480 mm
Thickness of collector	180 mm
Copper tube (diameter)	10 mm
Copper tube thickness	1 mm
Tube spacing	59 mm
Tube overall length	4000 mm
Lens diameter	50 mm
Focal length	80 mm
Number of lenses	40
Lens spacing	65 mm
Thickness of the center	9 mm
Thickness of the edge	2mm
Material of absorber	aluminum
Absorber plate thickness	1 mm
Absorber plate length	380 mm
Absorber plate wide	550 mm
Insulator material	Fiper glass
Insulation thickness	25 mm

Tank diameter	250 mm
Tank length	550 mm
Tank volume	25 L

This testing was conducted at location coordinate:32°36'27.08"N, 12°30'08'.96"E, Surman.

- ***Optical–thermal receiver (collector) assembly***

Each convex lens concentrates sunlight onto the absorber surface, increasing the local heat flux on the aluminum plate. The aluminum plate served as the primary absorbing element due to its high thermal conductivity, while the copper tube provides an efficient heat transfer path from the plate to the water. The absorber and tube were insulated to limit parasitic heat losses to the surrounding (state the insulation type/thickness here if available).

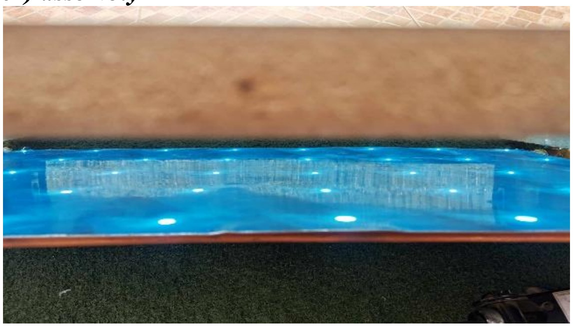


Figure (2) Solar Radiation Focused on the Absorber Plate by Convex Lenses

- ***Hydraulic loop and storage tank***

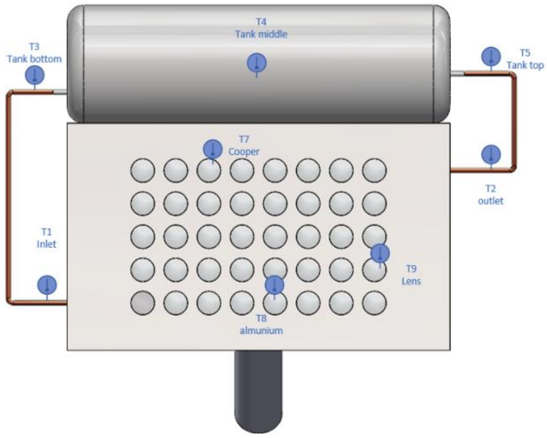
A water circulation loop connects the collector to the storage tank. This design operated without a pump relying on natural circulation by placing the storage tank above the collector. Water is drawn from the tank to the collector inlet, flows through the copper tube where it absorbs heat, and returns to the tank.

The tank holds 20kg of water and serves as both a thermal storage and a mixing volume, limits the temperature fluctuations. The loop was purged of air before testing to avoid flow instability.

- ***Instrumentation and measured variables***

To characterize system performance, the following variables were measured as a function of time:

- ✓ Solar irradiance (I, W/m^2): measured using a calibrated pyranometer mounted in the plane of the collector (or horizontal plane; specify your mounting plane).
- ✓ Collector inlet temperature (T_1, °C): water temperature at the collector inlet line.
- ✓ Collector outlet temperature (T_2, °C): water temperature at the collector outlet line (bottom outlet).
- ✓ Storage tank temperature (T_4, °C): temperature at the middle height of the tank (representative bulk temperature).
- ✓ Copper tube temperature (T_7, °C): surface temperature of the copper tube in contact with/adjacent to the absorber.
- ✓ Aluminum plate temperature (T_8, °C): surface temperature at the absorber plate near the focal region (or representative location).



Temperature measurements were recorded using thermocouples (e.g., K-type) and others temperature sensors were attached to the measurement points using thermal paste and insulation over the junction to limit contact resistance and ambient influence. All sensors were connected to a recording device. measurements were collected throughout the daytime heating period and extended into evening/night to capture thermal storage and cooling behavior.

Figure (3) Temperature Sensor Locations in the Experimental Solar Thermal System

- ***Test procedure***

Experiments were carried out under outdoor conditions. before each run, the system was filled and stabilized at ambient conditions, and the initial temperatures for the collector and tank were recorded. The lens array and collector were positioned to receive direct sunlight. Solar irradiance and all measurements temperature points were then recorded at each time step for the duration of the test. Periods of irradiance disturbance (e.g., cloud passages) were naturally captured and later reflected in the transient thermal response of the collector and tank.

- ***Material Specifications***

  -Absorber material

The absorber plate plays a crucial role in thermal performance of solar collectors: it's main function is to maximize the absorption of coming radiation limiting radiation losses reflected upward to the atmosphere and downward through the back of the collector, and subsequently transferring the retained heat to the circulating working fluid.

Typically constructed from materials such as copper, aluminum, or stainless steel in Flat Plate Collectors (FPCs), the heat absorber plate in this study comprises aluminum sheet and copper tube, each with a thickness of 1mm, chosen for their high thermal conductivity. Selection criteria for these materials include thermal conductivity, durability, ease of fabrication, cost, and availability. Additionally, the heat absorber plate is often coated with a dark-colored surface coating to enhance solar radiation absorption. Table 2 provides absorbance values for various colors used in plate coatings. [13]

Table 2: Absorbance value for several commonly used colors.

Material colors	Absorbance (α)
White	0.07
Green paint	0.5
Grey paint	0.75
Black tar	0.93
Flat black	0.98
Granite	0.55
Blue paint	0.7

Blue paint color is used in this project because it has a good radiation absorbance as shown in Table 2.

- ***Data reduction and performance indicators***

The thermal energy gained by the water over each measurement interval was evaluated based on the measured temperature rise and the water mass flow rate:

$$Q_u = m\,Cp\,(T_{out} - T_{in})$$

where (m) is the mass (kg), (cp) is the specific heat of water (J/kg·K), and (T_{out}) and (T_{in}) correspond to the collector outlet and inlet temperatures, respectively. The heat gain in the storage tank over a time interval was determined from the measured change in tank temperature and tank water mass:[14]

$$Q_{tank} = m_{tank} Cp\,(T_{tank,t} - T_{tank,t-1})$$

The instantaneous (or interval-averaged) system efficiency was computed by comparing useful thermal energy to the incident solar energy over the effective optical aperture area of the lens array:

$$\eta = \frac{Q_u}{I\,A_{eff}}$$

where (I) is solar irradiance in (J) and (A_{eff}) is the effective collecting area (sum of lens apertures or equivalent projected area). These indicators were plotted versus time together with irradiance to assess the transient behavior, thermal lag between components, storage performance, and overall conversion efficiency.[15]

4. Experimental Results

1. Solar Irradiance and Thermal Response of the Concentrating Collector over Time.

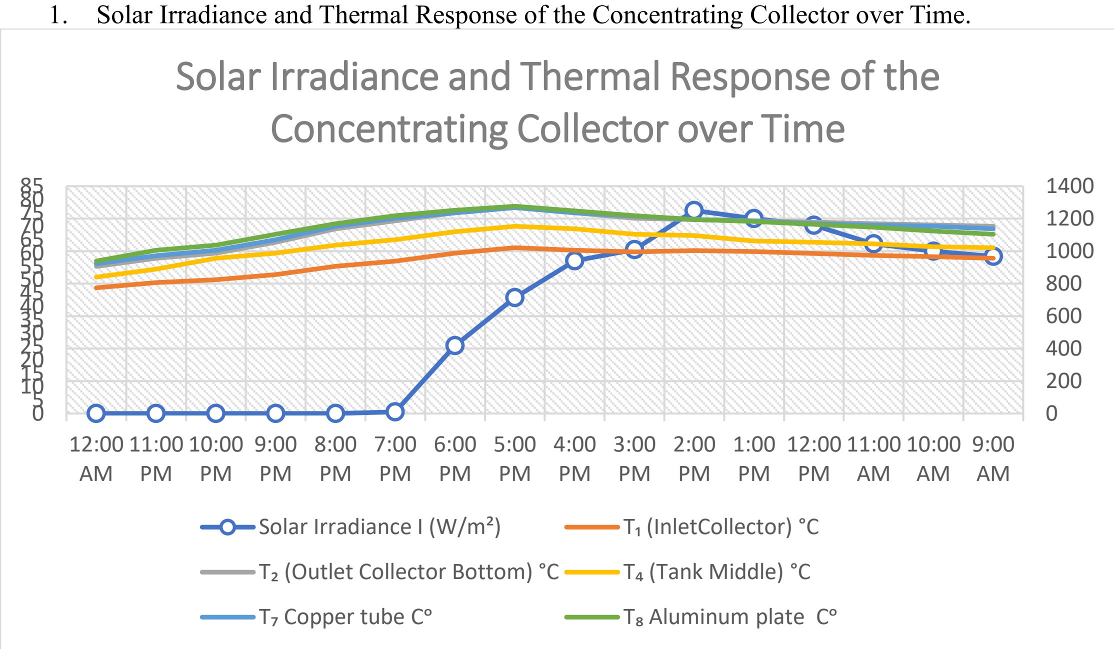


Figure (4) Solar Irradiance and Thermal Response of the Concentrating Collector over Time

The figure (4) shows the time-dependent variation of solar irradiance and the corresponding temperature response of main components of concentrating solar thermal system. With increasing of irradiance after sunrise, a significant rise in the temperature of the aluminum absorber plate and copper tube is noticed. This behavior indicates their direct exposure to concentrated solar radiation as well as their high thermal conductivity. Among all components, the aluminum absorber consistently reaches the highest temperature values, thereby demonstrating its effectiveness as the main solar energy absorbing surface within the system.

The temperature profile of the copper tube follows the same bath of the aluminum absorber plate, demonstrating effective conductive heat transfer between the aluminum absorber surface and the working fluid. In comparison, the inlet and the outlet water temperature changed more gradually due to thermal inertia of circulating fluid. The sustained temperature difference between the collector outlet and inlet confirms the continuous heat gain by the water during periods of elevated solar irradiance.

The storage tank temperature changed more slowly and showed delayed response compared to the collector components, due to its larger thermal mass. This behavior highlights the system's ability to store thermal energy and effect short-term fluctuations in solar irradiance. As irradiance decreases, all component temperatures decline accordingly, with solid components cooling faster than the stored water.

Overall, the observed thermal behavior is consistent with heat transfer and confirms the effective operation of the gravity-driven concentrating solar system in converting solar irradiance into useful thermal energy.

2. The Evolution of Thermal Efficiency over multiple days.

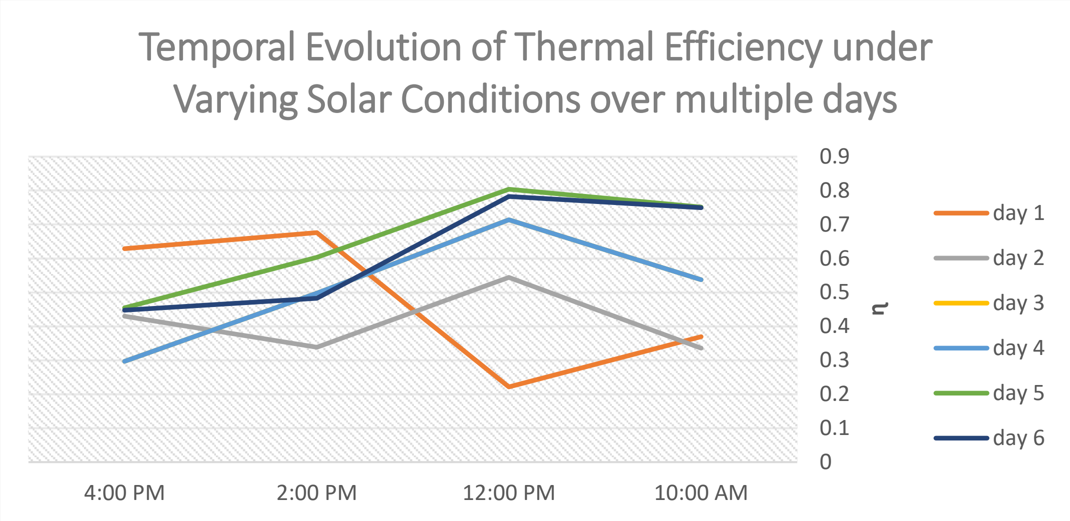


Figure (5) Temporal Evolution of Thermal Efficiency under Varying Solar Conditions over multiple days

The figure (5) shows the temporal variation of the system thermal efficiency (η) over six different operating days; a similar daily pattern can be seen across most of tests highlighting the influence of time of day and solar conditions on system performance. For all days, the efficiency generally increases during the morning toward midday, reaching its highest values around 12:00 PM, and then gradually decreases during the afternoon. Where higher solar irradiance and improved optical alignment near solar noon enhance energy conversion efficiency.

Differences in efficiency levels among the days indicate the effect of varying atmospheric and operational conditions, such as fluctuations in solar irradiance, ambient temperature, and possible optical misalignment of the concentrating lenses. Days exhibiting higher peak efficiencies show a more stable increase toward midday, suggesting more favorable and consistent solar input. In contrast, days with lower efficiency values or irregular profiles may reflect transient cloud cover or reduced heat transfer effectiveness during those periods.

After midday, a gradual decline in efficiency is observed for all days, which can be attributed to the reduction in solar irradiance and increased thermal losses from the collector and storage components as temperature differences between the system and the surroundings increase. Overall, the results demonstrate that the system achieves its highest performance under strong and stable solar conditions, while maintaining reasonable efficiency levels across multiple days, confirming the repeatability and reliability of the gravity-driven concentrating solar thermal system.

5. Conclusion

This work demonstrates the effective operation of a gravity-driven concentrating solar thermal system based on a multi-lens optical collector and a metal absorber–tube assembly. Experimental results show a strong correlation between solar irradiance and system thermal response, with rapid temperature increases in the aluminum absorber and copper tube, confirming efficient solar energy absorption and heat transfer to the working fluid.

The measured inlet–outlet temperature difference and the heat gain trends validate the system's ability to deliver useful thermal energy during peak solar periods, while the storage tank provides short-term thermal buffering due to its inherent thermal inertia. System efficiency peaks near solar noon and exhibits consistent behavior across multiple operating days, indicating reliable and repeatable performance under varying conditions.

Overall, the findings confirm the technical feasibility of a pump-free, gravity-driven concentrating solar water heating system, offering a simple and energy-efficient solution for solar thermal applications. Further performance gains may be achieved through improved thermal insulation and optical optimization.

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