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Enhancing Thermal Efficiency of Solar Water Heaters Using Internal Copper Tube Coil Collectors: Experimental and Numerical Investigation

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ABSTRACT

Solar water heater (SWH) remains a promising alternative to conventional heating methods, though traditional flat-plate systems often experience limited thermal performance. This research investigates a modified design that incorporates a copper coil within the collector unit, aiming to enhance heat transfer due to copper's superior thermal conductivity (~385 W/m·K). A hybrid arrangement combining parallel paths was constructed and evaluated both experimentally and through Computational Fluid Dynamics (CFD) modeling, using real climatic data from Najaf city, Iraq. Findings showed a notable 25% at lower flow rates and 15% at higher flows gain in thermal efficiency compared to classic designs. The system also demonstrated enhanced heat retention at lower flow rates and better peak efficiency at higher flows. These results point to a practical and eco-friendly solution tailored for domestic and light industrial use in solar-rich environments as Najaf city, Iraq.

1. INTRODUCTION

SWH is a sustainable option to conventional methods of water heating, which offer significant advantages in terms of environmental impact and energy efficiency. However, traditional configurations are plagued by thermal inefficiency and inefficient heat delivery processes. To overcome these weaknesses, the present work investigates the incorporation of a copper tube coil within the collector design. Since copper has a very high thermal conductivity of about 385 W/m·K, its use ensures improved thermal transfer efficiency and reduced energy losses.

Many studies have compared the effectiveness of various configurations of SWH systems, of which evacuated tube collectors (ETCs) and flat plate collectors (FPCs) are the leading types. In more advanced studies, researchers have focused on the optimization of efficiency outcomes by incorporating phase change materials (PCMs) and nanofluids [1]. Few have hitherto specifically examined the thermal benefits that arise from the use of copper tube coils within collectors. Given copper's high thermal conductivity compared to aluminum or stainless steel, its use within SWH systems offers much potential.

Fossil fuels, such as petroleum, natural gas, and coal, remain dominant sources for heating water despite their high costs and linked environmental impacts. Burning fossil fuels accounts for a large percentage of greenhouse gas emissions and the progression of climate change [2, 3]. Therefore, it is essential to adopt renewable energy sources.

Renewable energy, more specifically solar energy, is a clean, abundant, and sustainable source. As stressed by Chang et al. [4], Veeraboina and Ratnam [5], solar energy is a basic renewable source, especially well-suited for heating water for household, industrial, and commercial use. Utilizing heat pumps [6], the use of heat pumps has also proven to enhance the system efficiency.

Applications of solar energy include water heating for residences, healthcare facilities, and the tourism industry [7]. Solar water heaters (SWHs) are commonly used as alternatives to electrical water heating devices [8] and are recognized for their simple design, low maintenance needs, and energy-saving potential.

SWH systems are classified into two major types: active and passive systems. Active systems use electrical pumps, controllers, and valves for the transportation of water or heat-transfer fluids. Though more complex and costly, they are much more efficient. Passive systems, on the other hand, use natural buoyancy-induced flow and are best for residential use due to their low cost and simple design [9].

A traditional thermosyphon SWH system, as presented in Figure 1, consists of flat-plate collectors, water storage tanks, and piping. The system efficiency depends on several design parameters, such as the absorber plate material, selective coatings, quality of insulation, tilt angle, and the type of working fluid employed [10]. Solar radiation is absorbed by a black-chrome coated copper plate and then transferred to the water contained in the riser tubes, which achieves circulation due to the thermosyphon effect.

Despite prior advancements, limited research has examined hybrid copper coil arrangements that combine serpentine and parallel designs. The novelty of this study lies in implementing such a configuration, validated by experimental data and CFD simulation, to improve system performance throughout the day. This addresses a gap in the literature concerning efficient and economical SWH adaptations for sun-rich environments like Najaf, Iraq.

Efficiency improvements have been explored through the use of reflectors [11], which reported a 10% increase in collector efficiency when a reflector was added, elevating it from 51% to 61%. Reflectors enhance efficiency outcomes by directing both direct and diffuse solar radiation onto the collector surface.

Figure 1. Typical thermosiphon SWH system modified design that incorporates a copper coil within the collector unit

Carried out experimental studies on ETCs using copper tubes with 7 mm internal diameters [12], achieving outlet temperatures up to 29.97°C and maximum efficiencies of 53.76%. The effectiveness of copper U-tube integration in ETCs was similarly validated by Shamsul Azha et al. [13].

Another important design advancement is the use of double glass panel covers, which help retain heat and reduce losses. Mokhlif et al. [14] demonstrated that daily thermal efficiency increased by approximately 4.6% when replacing single glass with double glass in a 140-liter storage tank setup.

Double-pass SWH designs have also shown a superior efficiency outcome [15], highlighting that increasing the mass flow rate improves efficiency, though the temperature difference between inlet and outlet water decreases. Their experiments revealed that a maximum efficiency of 50.26% was achieved at a flow rate of 0.0044 kg/s around solar noon. The double-pass design, illustrated with both upper and lower sections separated by an absorber plate, makes use of reflectors to further concentrate solar energy and enhance water heating.

As illustrated in Figure 2, the SIDOCI SWH includes several components: A single glass cover, a copper tube coil, glass wool insulation, a triplex sheet, a flat absorber plate, a sine wave plate, and a wooden collector box. These design elements were selected for their low cost and thermal efficiency, making the system viable for testing under real conditions.

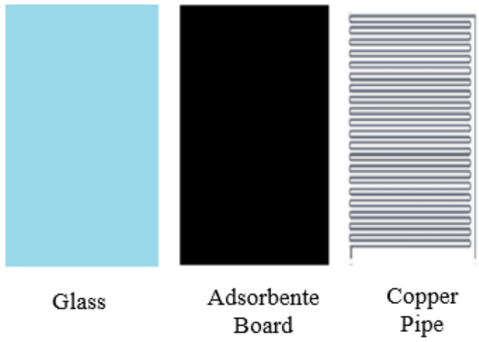

Figure 2. Disassembly of SIDOCI SWH

The performance of the solar collector was evaluated using several thermal equations:

$$\eta = Q\_u/Q\_s \times 100 \quad (1)$$

$$Q\_u = A\_c \times S \times (\tau\alpha) - U\_l \times A\_c \times (T\_i - T\_a) \quad (2a)$$

$$Q\_u = A\_c \times S \times (\tau\alpha) - U\_l \times A\_c \times (T\_o - T\_a) \quad (2b)$$

The useful gain from the rise in temperature is:

$$Q\_r = m \times C\_p \times (T\_out - T\_in) \quad (3)$$

While the direct efficiency of the SWH collector is the ratio between output and input power of the tubes arrangement, as follows:

$$\eta = (m \times C\_p \times \Delta T)/(A\_c \times G) \quad (4)$$

For each tube configuration, efficiency is as follows:

$$\eta\_serpentine = Q\_u / (A\_c \times G) \quad (4a)$$

$$\eta\_parallel = Q\_u / (A\_c \times G) \quad (4b)$$

Thus, the total efficiency of the SHW collector is:

$$\eta\_total = (\eta\_serpentine + \eta\_parallel)/2 \quad (4c)$$

These formulations allow for the comparative analysis of various tube arrangements and their thermal responses, forming the basis of the performance assessment presented in the following sections.

2. METHODOLOGY

2.1 Experimental setup

The present investigation makes use of both experimental and computational approaches to evaluate the thermal efficiency outcome of a SWH system integrated with a copper tube coil inside the collector. The experimental setup was built at the laboratories of Al-Furat Al-Awsat Technical University, Najaf Al-Ashraf Technical Institute. The collector unit consists of a wooden box measuring 150 × 85 × 10 cm, internally insulated with 3 cm thick sponge and lined with 3 mm plywood. It contains a flat plate and a sine-wave plate, both painted with black Acrylic Lacquer Black Metallic to maximize solar absorption. A 17-meter-long with a 1.27 cm diameter is arranged in a hybrid configuration combining serpentine and parallel paths to optimize heat collection across different periods of the day. The collector is covered with a single transparent glass sheet and triplex sheeting, with glass wool insulation to minimize heat loss. A 110-liter fiberglass tank is connected to store the heated water. The entire unit is mounted on a steel frame inclined at 20° facing north. Testing was carried out from 9:30 AM to 3:00 PM on clear, sunny days.

2.2 Instrumentation and data collection

Temperature readings were obtained using Type-K thermocouples positioned at five key points: the collector inlet, the outlet of the serpentine section, the inlet of the parallel section, the outlet of the parallel section, and within the water storage tank. A digital thermogenic was also used for temperature verification. Solar radiation intensity was recorded at 30-minute intervals using a TENMARS Solarimeter, while ambient temperature was monitored with a mercury thermometer. Mass flow rates tested included 0.035 and 0.189 kg/s for the active system and 0.031 and 0.111 kg/s for the passive (thermosiphon) system.

2.3 Computational Fluid Dynamics (CFD) simulation

Besides the experimental trials, a CFD model was built to emulate heat transfer within the collector. It accounted for several variables: The intensity of solar radiation, the ambient temperature, the flow rates of the working fluid, and the geometry of the copper coil. It provided a look at temperature distribution and heat retention efficiency outcomes and validated our experimental data. As illustrated in Figure 3.

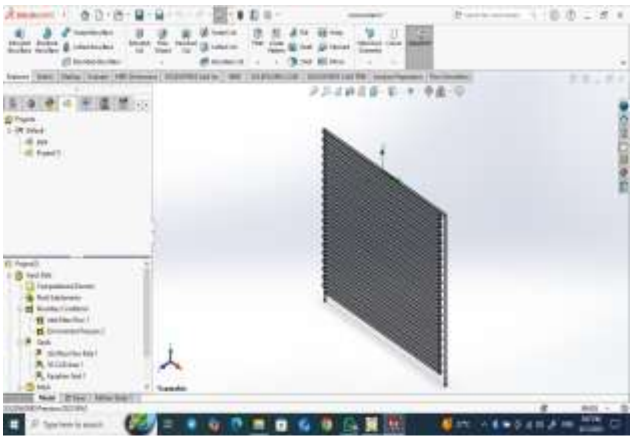

Figure 3. Simulation of a solar collector with a parallel copper tube arrangement design

2.4 Design rationale

The new copper coil design builds on previous work showing that morning-to-afternoon efficiency is best served by parallel tubes. Figure 3 was chosen based on computer simulation results, which showed this shape to be more efficient than any other design. The design was integrated into a single system that should now capture solar energy more efficiently throughout the day. We faced several challenges, including determining the tube shape, type, and thickness, and the panel design.

Therefore, the SOLIDWORK program was used to analyze the data and provide the best engineering results that can be applied to homes, hotels, and government institutions to reduce electricity consumption and rely on solar energy.

3. RESULTS AND DISCUSSION

3.1 Efficiency outcome of the passive SWH system

The efficiency of the thermosiphon system, also known as the passive SWH system, was compared using two different mass flow rates (0.035 kg/s and 0.189 kg/s). Figure 4 demonstrates that the collector efficiency is better at the lower mass flow rate of 0.035 kg/s. This improvement can be explained by the greater residence time of the water within the collector, which allows for better heat absorption. While the efficiency is still lower compared to that of the active system at similar flow rates, the passive system maintains the benefits of mechanical simplicity and low operating costs. In terms of thermal storage, Figure 5 illustrates the tank temperature profile at a flow rate of 0.189 kg/s. the temperature remained stable around 42°C during the solar heating period. This stable thermal efficiency outcome is beneficial for domestic applications requiring sustained hot water availability. Compared to the active system, the passive system maintains hot water for a longer duration, which is advantageous in periods of limited solar radiation.

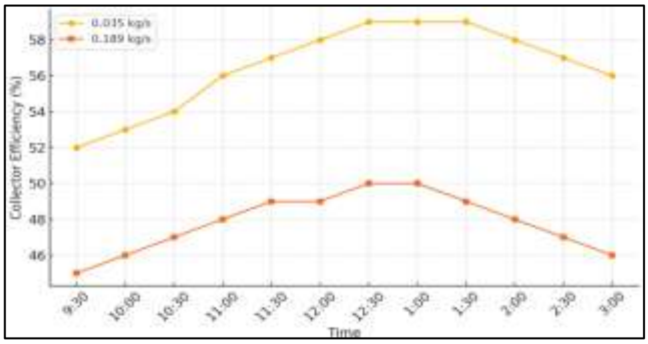

Figure 4. Comparison of the thermosiphon (passive) collector efficiency at two different flow rates

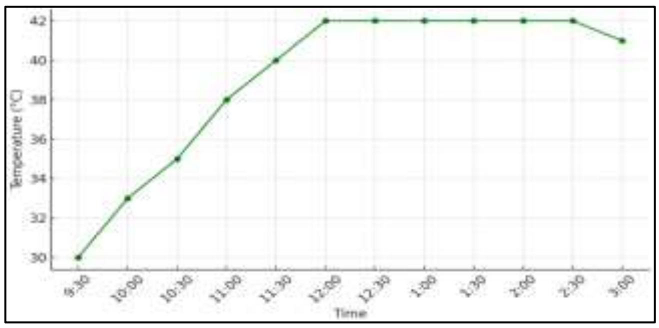

Figure 5. Water temperature in the tank for the passive system at 0.189 kg/s

3.2 Efficiency outcome of the active SWH SYSTEM

Conversely, the active SWH system demonstrated improved collector efficiency at higher flow rates. As shown in Figure 6, a mass flow rate of 0.111 kg/s yielded better efficiency than 0.031 kg/s. The system maintained relatively stable efficiency levels from noon to the late afternoon. This is particularly evident in Figure 7, which demonstrates the temporal variation in tank temperature and the temperature differential (ΔT) between the collector outlet and inlet. The ΔT peaked at around 14℃ between 12:30 PM and 3:00 PM, indicating effective solar energy conversion during peak insolation hours.

The CFD simulations aligned closely with experimental data, confirming the advantage of using a hybrid serpentine-parallel copper tube configuration in maximizing heat absorption throughout the day. These findings are consistent with the study [16], who observed enhanced efficiency in double-pass SWH systems at higher flow rates. These findings are further supported by Ghazali et al. [17], who demonstrated CFD-enhanced thermal system performance using nanofluids.

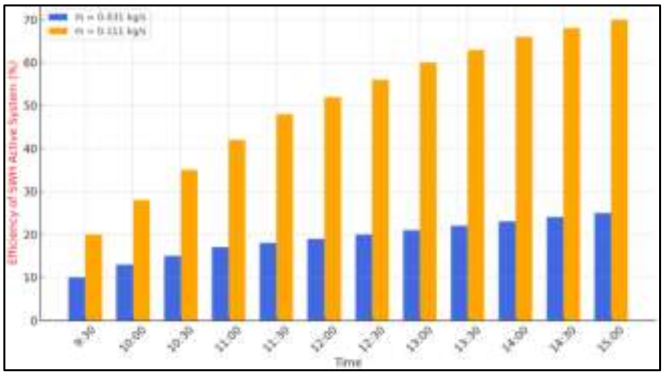

Figure 6. Efficiency of 2 mass flow rates with time heating

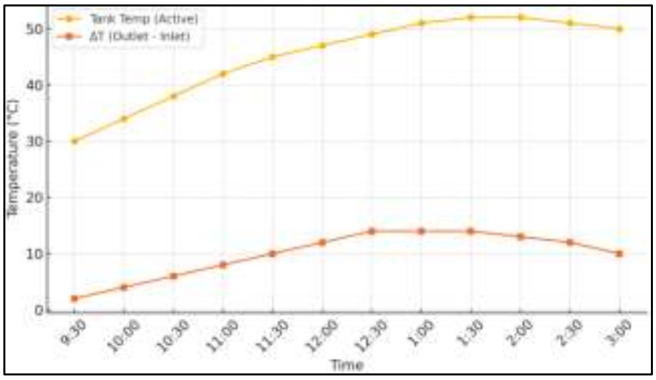

Figure 7. Variation of tank temperature and ΔT over time in the active system

3.3 Solar intensity and environmental factors

Solar radiation measurements collected in Najaf, Iraq, further support the viability of SWH systems in this region. As illustrated in Figure 8 and the accompanying dataset, solar radiation averaged 750 W/m², peaking near 800 W/m² during clear weather between 12:30 PM and 3:00 PM. Najaf receives an average global solar radiation of approximately 5.5–6.5 kWh/m²/day throughout the year. The region experiences over 300 sunny days annually. Ambient temperatures during summer often exceed 48℃, especially in July and August. Fluctuations in radiation are primarily due to environmental factors such as dust and cloud cover, which influence both scattering and absorption. Historical data also confirms Al Najaf's solar potential ranks third highest in Iraq, making it an ideal location for solar thermal applications [18].

The variation in water temperature for two different mass flow rates (ṁ = 0.035 kg/s and ṁ = 0.189 kg/s) in the passive SWH system is illustrated in Figure 9. The findings indicate that while the lower flow rate maintains more stable temperatures over time, the higher flow rate results in initially higher water temperatures due to faster heat absorption. However, the system with lower mass flow retains the heat for a longer duration, aligning with the thermosiphon mechanism and reducing thermal losses.

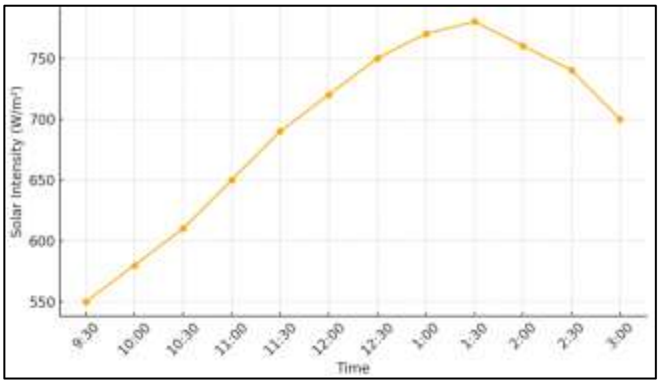

Figure 8. Solar radiation intensity throughout the observation period

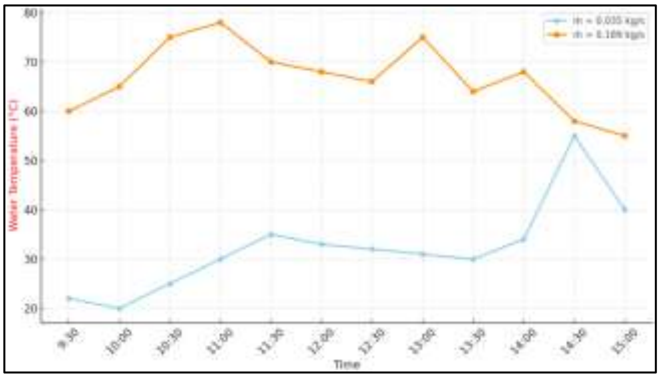

Figure 9. Water temperature in passive SWH system at two flow rates (ṁ = 0.035 kg/s and ṁ = 0.189 kg/s)

3.4 Comparative and economic analysis

The comparative analysis between the active and passive systems revealed that while the active system offers superior thermal efficiency, the passive system excels in thermal retention. The copper tube coil demonstrated an improvement in thermal efficiency ranging from 15% to 25% compared to conventional straight-tube designs. Additionally, the more uniform temperature distribution within the collector contributes to reduced thermal losses. Despite a higher initial installation cost, the use of copper results in a faster return on investment—approximately 3 to 5 years due to higher system efficiency and reduced dependency on auxiliary heating sources. This finding aligns with the conclusions drawn by the previous studies [19-21], who emphasized copper's superior thermal conductivity (385 W/m·K) and its effect on system efficiency outcome.

3.5 Analysis of weather factors affecting solar energy systems in Najaf City, Iraq

Najaf city, located in central Iraq, lies within an arid hot climatic zone. Although it has a very high level of solar radiation, several weather-related factors—particularly solar radiation intensity and dust accumulation—strongly influence the performance.

This analysis explains exactly how this factor affects system performance and proposes effective mitigation strategies.

3.5.1 Solar radiation characteristics in Najaf

Climatic profile: Najaf receives an average global solar radiation of approximately 5.5–6.5 kWh/m²/day throughout the year.

The region experiences over 300 sunny days annually.

Ambient temperatures during summer often exceed 48℃, especially in July and August.

3.5.2 Effect of dust and airborne particles

(1) Dust conditions in Najaf

Najaf is surrounded by desert areas such as the Najaf and Karbala city deserts. Consequently, it is frequently exposed to dust storms and suspended particulate matter, particularly during the spring and summer seasons.

The region may experience 10–20 dust storm events per year.

(2) Mechanisms of dust impact

Dust affects SWH system performance in multiple ways:

• Optical losses

A thin layer of dust blocks and scatters sunlight, reducing the solar irradiance reaching the SWH surface by 5–40%, depending on dust density.

Thermal Effects: Dust layers trap heat, increasing module surface temperature and further lowering efficiency.

• Material DEGRADATION

When mixed with humidity, dust can chemically or mechanically damage the glass surface, forming hard-to-remove stains. Overall, uncleaned systems may experience performance losses of 25–40% in heavily dusty environments.

(3) Minimizing dust accumulation

• Optimal tilt angle

In Najaf, the recommended tilt angle is 30–33° facing south, which allows partial self-cleaning by gravity. Automated Cleaning Systems, such as robotic brushes or low-pressure water sprinklers (especially useful for utility-scale plants). Anti-Soiling Coatings Nano-coatings can reduce dust adhesion by 50–70%.

• Regular maintenance schedule

Cleaning every 1–2 weeks during summer, depending on dust intensity.

• Performance monitoring systems (IoT sensors)

Detect real-time performance drops due to soiling and trigger cleaning alerts.

4. STUDY LIMITATIONS

The present investigation demonstrates improved thermal efficiency in a SWH system using a copper tube coil, but a number of limitations need to be addressed. The experiments were first carried out at specific meteorological conditions of the area of Najaf, Iraq, which include fairly steady solar radiation. The result may not represent the full functionality of the system for varying or extreme conditions, including the existence of rain, dust, or clouds, which are more commonly experienced at other sites. The study was also limited to a small mass flow rate and used a specific collector angle of 20° that may not adequately represent the best configuration for transition seasonal periods. Additionally, the prototype design was constructed using wood and basic insulation materials, which might not be as durable or effective as commercially available systems over extended use. Long-term durability tests, material degradation effects, and maintenance requirements were beyond the scope of this research. Lastly, while CFD simulations were used to validate heat transfer behaviors, real-time dynamic modeling with transient boundary conditions was not implemented, which could provide deeper insight into system behavior during varying solar intensity.

5. CONCLUSION

The present investigation confirms that integrating a copper tube coil within an SWH collector significantly enhances the system's thermal efficiency outcome. The experimental findings indicate that the hybrid serpentine-parallel copper tube configuration improves heat transfer efficiency by 15–25% compared to conventional straight-tube collectors. The passive SWH system, especially at a lower mass flow rate (0.035 kg/s), demonstrated excellent thermal retention, maintaining tank temperatures around 42℃ for extended periods. In contrast, the active system, operating at 0.111 kg/s, achieved higher peak efficiencies due to more aggressive water circulation and rapid heat extraction. Moreover, the temperature distribution remained more uniform in the copper coil-based design, reducing thermal losses and ensuring better energy utilization. Solar intensity measurements in Najaf, which peaked at around 800 W/m², validate the regional suitability for solar thermal applications. Although the initial cost of copper-based systems is higher, the projected payback period of 3–5 years, combined with minimal operational costs, positions this design as a sustainable and economically viable solution for domestic and small-scale industrial water heating. Future studies should explore optimization of coil geometry, incorporation of nanofluids, and broader climatic testing to support commercialization. This system can be implemented on residential rooftops as well as in hotels, using a thermally insulated hot water tank to provide hot water after sunset and for use when needed.

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NOMENCLATURE

$\dot{m}$	air mass flow rate, kg/s
A_c	area
η	efficiency
ρ	density, kg/m^3
H_{ch}	depth of airflow channel, m
μ	dynamic viscosity, kg/m·s
μ_t	eddy viscosity, kg/m·s
$u_i^{'}$	fluctuation velocity components, m/s
in	inlet temperature, °C
L	length of the collector, m
Γ	molecular thermal diffusivity, m^2/s
u	mean velocity, m/s
out	outlet temperature, °C
PCM	phase change material
SAH	solar air heater
T	temperature, °C
k	thermal conductivity, W/m·K
η_{th}	thermal efficiency, %
C_μ	turbulence model constant
ε	turbulent dissipation rate, m^2/s^3
Γ_t	turbulent thermal diffusivity, m^2/s
W	width of the collector, m