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Analysis of the Performance of a Solar Water Heating System Utilizing a Flat-Plate Absorber with Integrated Thermal Storage

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Abstract

Solar water heaters (SWHs) are widely used all over the world since they use solar energy to power themselves. Solar water heaters that use aluminum-alumina (AL_2O_3) thermal storage at the collector base are the focus of this experimental evaluation. To maximize the efficiency of the heat transfer process and the water heating system, it is essential to incorporate thermal storage within the collector. An investigation of the efficiency of a solar water heater with AL_2O_3 thermal storage has been conducted. Tests are conducted on two different types of absorber plates: the standard flat-plate (SFP) collector and the SFP with AL2O3 as thermal storage. The tests are carried out over the course of a period of 180 minutes and under conditions of constant solar intensity. When the SFP and SFP-TS models are compared, the results indicate that the SFP-TS type has a greater outlet temperature than the traditional SFP. The SFP-TS model delivers a thermal efficiency boost of around 6% when compared to the SFP model with the same specifications. Adding AL_2O_3 to the absorber plate as a thermal storage material improves the thermal efficiency of the plate collector, increases the duration that heat is stored in the collector, and improves the absorption of radiant heat energy.

Keywords: Solar Water Heater (SWH), Aluminum-alumina (AL_2O_3), Standard Flat Plate (SFP), Standard Flat Plate with Thermal Storage (SFP-TS)

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1. Introduction

Solar water heaters (SWHs) are devices that harness solar energy as their primary power source, widely utilized in various countries worldwide. While significant progress has been made in this field, challenges remain in improving the performance of existing solar water heaters. One notable approach to address this involves integrating solar collectors with thermal storage systems. This integrated design aims to reduce energy consumption in residential water heating systems cost-effectively [1].

Some examples of recent developments in solar water heating technology include the use of porous materials, changes to the geometries of absorber plates, and modifications to clear cover glass using fluorine-doped tin oxide nanoparticles [2]. The latest developments in Solar Water Heater Systems (SWHS) have explored enhancements to Flat-Plate Collectors (FPC). For instance, Jalaluddin et al. [3] examined the thermal efficiency of solar water heaters equipped with V-shaped absorber plates, revealing an efficiency improvement of 3.6–4.4% compared to conventional designs. Furthermore, subsequent research incorporating phase change materials (PCM) into V-shaped solar water heating systems demonstrated substantial increases in efficiency, achieving gains of 20%, 14%, and 13% at discharge rates of 0.5, 1, and 1.5 L/min, respectively [4]. Despite these advancements, challenges such as fluid leakage persist.

The elevated temperatures on the absorber plate's surface often result in significant heat loss, underscoring the need for thermal energy storage systems to enhance collector efficiency. Experimental studies, such as those conducted by Pisut Thantong et al. [5], have demonstrated that combining collectors with thermal storage improves energy efficiency under tropical conditions. The same holds true for shell-and-tube energy storage systems; experiments comparing horizontal and vertical designs [6] and integrating shell and finned-tube latent heat storage devices [7] have demonstrated daily efficiencies of up to 65%.

The utilization of porous materials to improve heat transfer is the subject of a new strategy for collector development. One promising approach involves using metal foams sandwiched between the absorber plate and the insulator. These foams can store heat for long periods of time before transferring it to the working fluid. Foam blocks made of aluminum, copper, nickel, reticulated vitreous carbon, and ceramic are among the porous materials that have been used as collectors.

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Geometry, placement, and fluid flow rate are three aspects that have been the focus of numerous simulation- and experiment-based investigations of foam's function in collectors. Thermodynamic efficiency and heat transfer area are both improved when foam is placed inside the collector channel, according to research by Gunjo et al. [8]. When comparing parabolic collector designs with and without metal foam, Valizade et al. [9] discovered that the former had better thermal efficiency. The use of aluminum foam on the top and bottom plates considerably improves efficiency when compared to designs lacking foam, according to trials conducted by Basri et al. [10].

Based on these findings, incorporating thermal storage into collectors significantly improves heat transfer processes and water heating system performance. The porous structure of metal foams provides excellent thermal conductivity and heat retention capabilities. However, their metallic properties also facilitate rapid heat dissipation, limiting their efficiency as heat storage materials. Ceramics, on the other hand, are less efficient overall but absorb heat better and retain it for longer. Composite constructions made of these materials show potential for improving collector efficiency, heat transfer, and retention. Two absorber plate types are examined in this study: the Standard Flat-Plate (SFP) collector and the SFP-TS, which combines the SFP with AL_2O_3 thermal storage.

2. Methodology

Chemical energy, sensible heat, and latent heat are the three main forms of energy storage. Both heating and cooling fluids, as well as keeping a constant temperature, are possible with the help of these sources of stored energy. The main areas of concentration in the field of thermal storage materials research at the moment are sensible and latent heat [11]. Latent heat storage involves substances undergoing phase changes, such as melting, boiling, or solid-to-crystal structure transformations, where heat is absorbed or released without changing the temperature. Phase change material (PCM) or heat of transformation describes the amount of energy needed for this shift. The equation for the heat required during phase change is expressed as [12]:

$$Q = m\mathrm{Le} \qquad (1)$$

Where is the heat required for phase change (J), m is the mass of the substance (kg), and Le is the specific latent heat capacity (J/kg). The schematic representation of a solar water heater with composite thermal storage is shown in Fig. 1.

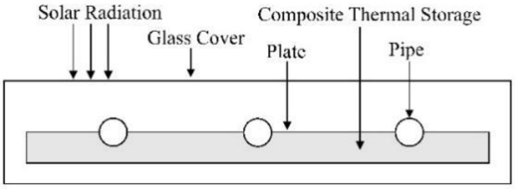


Figure 1. SWH integrated composite thermal storage

Composite materials combine two or more distinct constituents to achieve enhanced mechanical, thermal, and physical properties. These composites contain reinforcement materials and a binder (matrix), such as metals, ceramics, or polymers. Factors like geometric configuration, phase morphology, concentration distribution, matrix alignment, and volume percentage influence the properties of composites [13].

A steady-state energy balance describes the performance of a solar collector by dividing incident solar energy into thermal losses, optical losses, and usable energy gain. The net usable energy produced by a given collector area is the sum of its solar energy absorption and thermal losses A_c [14]:

$$Q_u = A_c[s - U_L\,(T_{pm} - T_a)] \qquad (2)$$

Q_u, Useful energy can also be determined from the temperature measurements of inlet and outlet water in the collector using the equation [14].

$$Q_u = \int Q_u dt = \dot{m}C_p\,(T_o - T_i) \qquad (3)$$

where $\dot{m}$ is the mass flow rate (kg/s), C_p is the specific heat capacity (kJ/kg·K), T_o is the outlet fluid temperature (°C), and T_i is the inlet fluid temperature (°C).

Collector efficiency is defined as the ratio of useful output to the incident solar energy over a specific time period [15]:

$$\eta = \frac{\int \mathrm{Q_u} dt}{A_c \int \mathrm{I_T} dt} \qquad (4)$$

$\mathrm{I_T}$ where represents solar intensity (W/m²) and A_c is the collector surface area (m²).

The Hasanuddin University Department of Mechanical Engineering's Renewable Energy Laboratory was the site of the research. A solid insulator, a collector, and a lighting unit serving as the heat source made comprised the experimental setup's ET-202 solar thermal energy unit. Several sensors were installed to monitor the water temperature at the intake and outflow, as well as the surrounding air temperature, the amount of solar radiation, the flow rate, and the water pump's ability to circulate air within the storage reservoir.

Rectangular containers with absorber plates and heat storage medium made up the test components. We put the Standard Flat Plate (SFP) and the Standard Flat Plate with AL2O3 Thermal Storage (SFP-TS) absorber plate designs to the test. Both prototypes were tested experimentally for 180 minutes under the same conditions. Data such as flow rates, water temperatures at the intake and outflow, and solar intensity were recorded. Followed the steps outlined in the ET-202 manual for performance analysis and measurement [16].

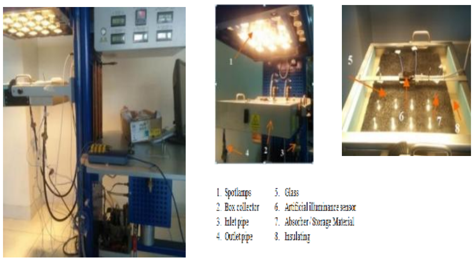
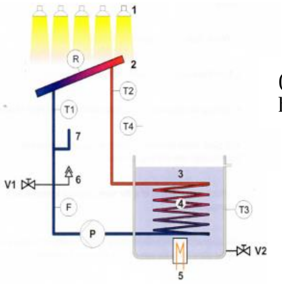


Figure 2. Solar thermal energy unit



(a) Absorber plate flat shape without heat storage material (SFP)

(b) Absorber plate flat shape with the addition of heat storage material (SFP-TS)

Figure 3. Experimental set-up

Table 1. Solar thermal energy unit specifications

Description	Dimension	Unit
ET 202 FPC		
Absorbing surface	0.32 x 0.34	m
Angle adjustment	0	deg
Height adjustment	0.5	m
Lighting unit		
Illuminance	1	kW/m^2
Peristaltic Pump		
Flow rate	10	L/h

Figure 4. Composite Thermal Storage

Table 2. Specifications Composite Thermal Storage

	Alumina 65%	Aluminum 35%
Density (kg/m^3)	3720	2700
Melting point (^{o}C)	2049	660
Thermal Conductivity (W/m.K)	38	220

3. Results and Discussion

AL_2O_3 composite integrated absorber plates were the subject of this experimental investigation. Two models were teste with SFP and SFP-TS. To ensure accuracy, data collection for each model was repeated three times.

3.1. *Solar intensity*

The intensity of solar radiation during testing was provided by a lighting unit and measured using an artificial solarimeter. Both SFP and SFP-TS models were subjected to a consistent solar intensity of 1 kW/m² for 180 minutes. After 60 minutes, the lighting unit was turned off, rendering the solar intensity unreadable. Figure 5 shows the solar intensity during testing.

3.2. *Temperature of absorber plate*

Figure 6 illustrates the temperature profiles of the SFP and SFP-TS models throughout the test. The absorber plates' copper substance has a strong heat absorption capability, therefore the temperatures increased gradually from an initial reading of around 40°C. That the absorber plate gets even hotter thanks to the AL_2O_3 thermal storage is evident from this. After 180 minutes, the SFP-TS model reached a maximum temperature of around 63°C, while the SFP model peaked at 60°C, indicating a 3°C difference. The SFP-TS model retained heat more effectively, cooling at a slower rate after the lighting was turned off. This behavior highlights the advantage of thermal storage in heat retention.

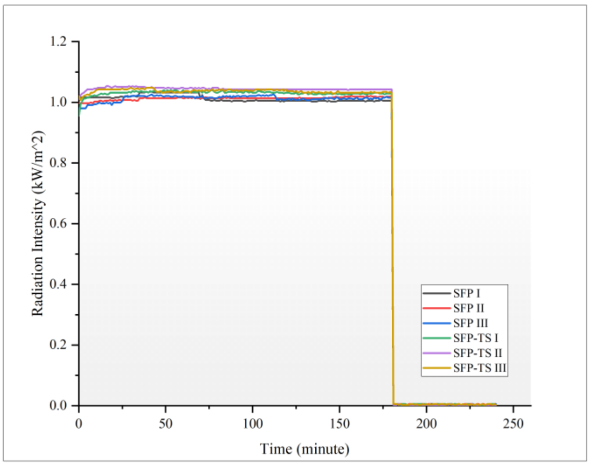


Figure 5. Radiation intensity

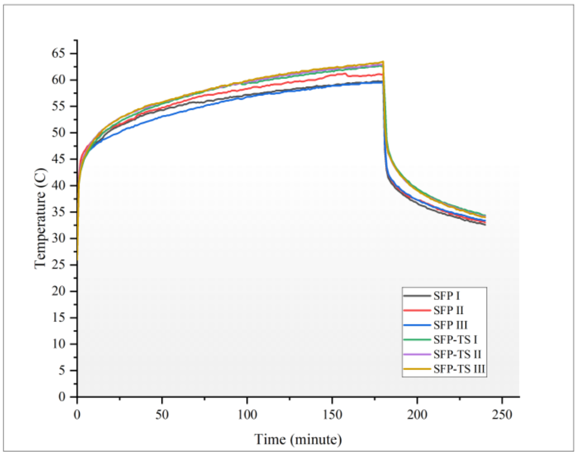


Figure 6. Absorber plate temperature

3.3. *Temperature of inlet and outlet water*

Figure 7 shows a graph with constant flow rate of 10 L/h comparing entrance and exit temperatures for every data collecting point. Every model's inlet temperature runs from 27°C in the early minutes to 38°C around 180 minutes before the lights go out. The output temperature of the SFP-TS variation shows higher than that of the SFP model. During 180 minutes of illumination, the SFP-TS type's maximum outlet temperature is about 48°C. The input and output temperatures seem to be exactly same at a given point when the illumination is turned off. Still, the SFP-TS model's temperature drop seems to be more gradual than that in the SFP. Thermal storage in the SFP-TS model helps it to retain heat for around thirty minutes after lights deactivation. Heat retention is improved by including AL_2O_3 thermal storage at the base of the absorber plate. Measuring an artificial solarimeter, the lighting unit determines the strength of solar radiation on the test equipment. Figure 5 shows the two SFP models' received solar intensity. SFP-TS models For 180 minutes, both models were tested under a fixed solar intensity of 1 kW/m². The lighting unit is turned off sixty minutes later, hence the measurement instrument cannot read the solar intensity.

Figure 7 shows the water temperatures for the outlets and inlets for both models. Beginning at 27°C and rising to 38°C over 180 minutes, the inlet temperature was 10 L/h constant flow rate. Reaching a maximum of 48°C, the SFP- TS model routinely attained greater outlet temperatures than the SFP model. The SFP-TS model showed a sustained heat retention capacity once the lighting unit was turned off, preserving higher temperatures for an extra thirty minutes.

3.4. *Energy Absorption*

Figure 8 contrasts the energy absorbed by the SFP and SFP-TS absorber plates throughout the 240-minute test. The energy rises over the first 30 minutes and subsequently stabilizes until the 180th minute. The SFP-TS model can absorb up to 103 watts of energy, however the SFP model can only absorb approximately 93 watts, indicating a notable difference between the two types. This demonstrates that AL_2O_3 thermal storage is highly effective in energy absorption up to a differential of 10 watts.

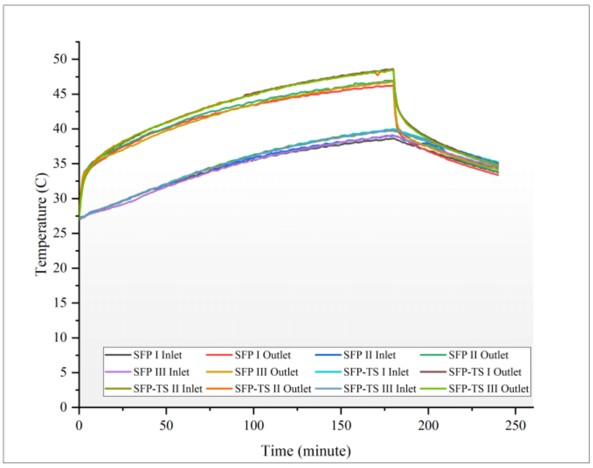


Figure 7. Inlet and outlet water temperature

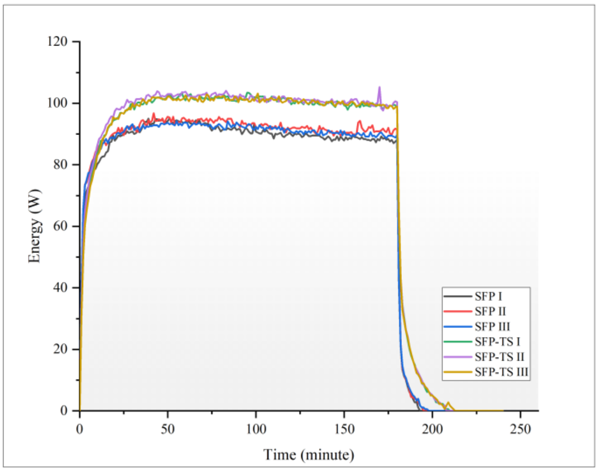


Figure 8. Energy absorption

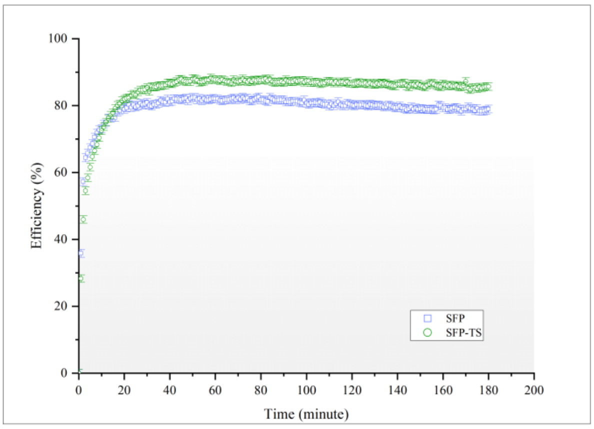


Figure 9. Efficiency

3.5. *Collector Efficiency*

Figure 9 shows the comparison of operational lifetime with thermal efficiency. Over the first three hours, the thermal efficiency of the SFP model stabilises after around 20 minutes of operation at an efficiency of about 80%. Concurrently, the SFP-TS type requires around sixty minutes to attain a continuous thermal efficiency of about 85%. The stop of radiation intensity causes the collector's thermal efficiency to zero after 180 minutes of running. Nevertheless, as Figures 6 and 7 show, the thermal energy in the SFP-TS stays kept in thermal storage for about 30 minutes even with the reduction of radiation intensity. The SFP-TS model shows an efficiency value somewhat higher than that of the SFP model—about 6%. Underlying the collecting plate with thermal storage greatly improves heat absorption, storage, andretention.

Alumina thermal storage combined with the absorber plate improves heat absorption, storage, and retention. Acting both as a heat absorber and reservoir, the thermal storage medium enhances the general performance of the system.

4. Conclusions

A solar water heater and AL_2O_3 thermal storage have been studied for their potential effectiveness. Experimental evaluations were conducted for two kinds of absorber plates under continuous solar intensity for 180 minutes. One model was the standard flat-plate (SFP) collector, and the other was the SFP with AL_2O_3 thermal storage (SFP-TS). The SFP-TS model's water temperature outlet is higher than the SFP model's. Additionally, compared to the SFP model, the SFP-TS model's thermal efficiency rises by about 6%. By adding AL_2O_3 to the absorber plate's base for thermal storage, radiant heat energy is better absorbed, the collector's heat storage time is extended, and the plate collector's thermal efficiency is raised.

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