Journal of Solid and Fluid Mechanics (JSFM), 16(3): 1-4, 2026

Shahrood University of Technology

Journal of Solid and Fluid Mechanics (JSFM)

DOI: 10.22044/jsfm.2026.17508.4049

Manufacturing Engineering of Iran

Experimental investigation of concurrent utilization of photovoltaic cells with thermal systems in hybrid solar collectors

Amin Samimi Behbahan[1,*], Hossein Hosseinipour[2]

[1]Assist. Prof., Mech. Eng., Behbahan Khatam Alanbia University of Technology, Behbahan, Iran.
[2]M.Sc. Mech. Eng., Behbahan Khatam Alanbia University of Technology, Behbahan, Iran.

*Corresponding author: Samimi.scu@gmail.com

Received: 02/17/2026 Revised: 03/31/2026 Accepted: 06/25/2026

Abstract

Solar energy, as one of the most sustainable energy resources, plays a pivotal role in addressing the growing global energy demand. However, the rise in photovoltaic (PV) cell temperature directly leads to a reduction in electrical efficiency; therefore, effective thermal management is essential for performance enhancement. In this study, a tri-generation solar collector integrating simultaneous electricity generation with thermal energy recovery for water and air heating is experimentally investigated. Furthermore, the effects of incorporating reflectors and enhancing heat transfer mechanisms on the overall system performance are systematically evaluated. The results indicate that increasing the fluid flow rate leads to a reduction in thermal efficiency, while liquid working fluids exhibit superior heat transfer performance compared to gaseous media. Additionally, reducing the operating temperature of PV cells improves electrical efficiency; specifically, during peak solar irradiance periods, an enhancement in electrical efficiency ranging from 3% to 5.7% is observed across different experimental conditions.

Keywords: Photovoltaic cell, solar collector, solar energy, solar cell, hybrid collector

1. Introduction

The continuous rise in global energy demand has rendered the heavy reliance on fossil fuels unsustainable, primarily due to rapid resource depletion and adverse environmental impacts [1]. Solar energy has emerged as a prominent alternative, finding applications in water heating, space conditioning, and electricity generation. Flat-plate collectors are particularly favored for their structural simplicity and low maintenance requirements [2, 3]. Photovoltaic (PV) cells represent another major solar technology, directly converting sunlight into electricity. They are highly reliable, operate without moving parts, and are well-suited for off-grid applications [4]. However, a significant operational challenge persists: as PV cells absorb solar radiation, their temperature rises, leading to a marked decline in electrical efficiency.

These systems extract excess heat from the panel using a coolant—typically air or water—which can subsequently be utilized for domestic or industrial heating applications [5, 6]. Over the years, various methods have been explored to enhance heat transfer in these systems, such as integrating aluminum cans into air channels [7], employing Al_2O_3 nanofluids [8], or adding internal fins [9]. Expanding upon these concepts, the present study investigates a tri-generation PVT system designed to produce electricity, hot water, and hot air simultaneously.

Additionally, the impact of external reflectors on the overall system performance is evaluated.

2. Setup and Methodology

The experimental phase involved designing and installing a hybrid PVT system in Bandar Ganaveh, Iran (Figure 1). A 200W monocrystalline panel (open-circuit voltage of 22.2V; dimensions: 1390×1000×28 mm) served as the base module. This specific type was selected over polycrystalline alternatives because of its superior efficiency and reduced power degradation at elevated temperatures. Mounted on the rear of the panel, a custom aluminum heat exchanger featuring bent tubes (2.5 cm inner and 3 cm outer diameter) facilitated the circulation of water as the primary cooling fluid.

An aluminum profile plate was incorporated to maximize the thermal contact surface. Proper thermal coupling between the exchanger and the panel was achieved using a high-conductivity thermal paste (Ultracool MAP10003). Airflow behind the panel was driven by a 250W centrifugal fan, while a custom MDF damper regulated the inlet air and mitigated turbulence. Radiation capture was further enhanced by positioning four aluminum reflectors around the collector at a 45° angle. By reflecting sunlight from two directions onto the active cell surface, this configuration significantly boosted output power.

Thermal losses were minimized by applying polystyrene (plywood foam) insulation around and behind the collector assembly. Electrical load simulation was achieved by wiring two 100W resistors in parallel, yielding an equivalent resistance of 50 ohms and a total power consumption of roughly 202W. Data acquisition relied on a TES-1333 solar power meter, a GM8901 anemometer, a flowmeter, DS18B20 digital temperature sensors (±0.5°C accuracy), and ACS712 current/voltage sensors. Measurement reliability was verified through a general empirical uncertainty analysis, which confirmed an overall error margin of less than 5% [10].

a

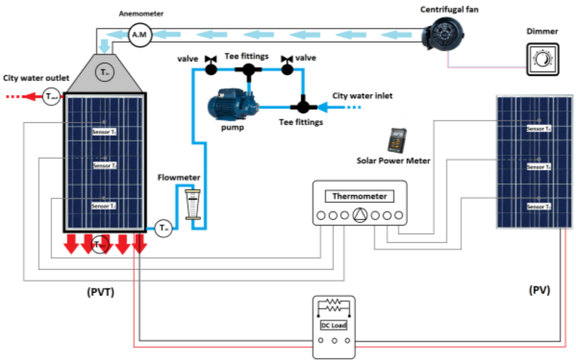

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Figure 1. a) Installed collector and reference panel, and b) Schematic of the experimental setup

The experiments were conducted over 18 daily cycles from 9:00 AM to 3:00 PM. Data were recorded at 30-minute intervals. The variable parameters in these experiments were the cooling air velocity and the water flow rate, which were applied in 6 different states, as shown in the table below:

Table 1. Control parameters

Experiments	Air Velocity (m/s)	Water Flow Rate (l/h)
1	2	80
2	4	80
3	6	80
4	2	120
5	4	120
6	6	120

An uncooled PV panel was installed adjacent to the prototype to serve as a baseline for comparison.

3. Results and Discussion

A critical first step in evaluating the PVT system's performance involves analyzing the total solar energy input received during the experimental periods. Fluctuations in environmental conditions and solar irradiance directly dictate the total energy entering the system, thereby influencing the overall efficiency.

Figure 2 illustrates the solar energy profiles for the six test runs. Due to natural weather variations, the irradiance curves exhibit slight fluctuations. However, evaluating the data specifically within the peak irradiance zone—where solar radiation falls between 785 and 800 W/m²—reveals a tight clustering of data points. This concentration indicates that the tests were conducted under highly comparable solar conditions.

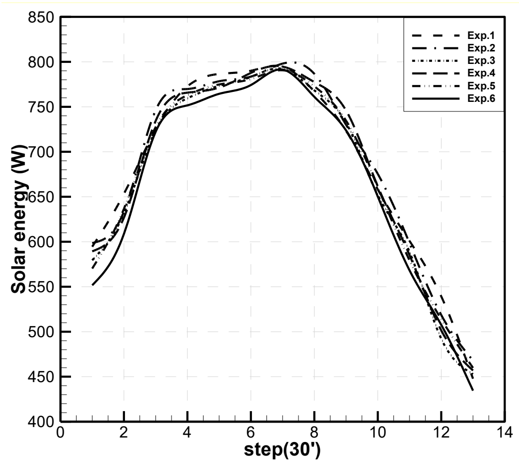

Figure 2. Solar energy received during the experiment period

The low scattering of data in this peak zone is crucial; it confirms that any subsequent performance differences between the experimental runs are attributable to the controlled variables (air and water flow rates) rather than anomalies in solar input. A minor deviation of roughly ±15W was observed during the peak hours, which gradually increased later in the afternoon as solar intensity naturally declined. This confirms the environmental consistency and repeatability of the experimental phase.

The primary metric for evaluating the success of the cooling mechanism is the electrical efficiency difference between the actively cooled PVT panel and the passive reference panel. Maintaining a lower operating temperature directly mitigates the increase in internal cell resistance, thereby stabilizing the open-circuit voltage and power output.

As depicted in Figure 3, the efficiency gap remains relatively stable during the lower-irradiance morning hours but expands significantly as the system approaches midday peak conditions. Analysis of the peak irradiance window (time steps 6 to 8) provides the most telling data. During this period, the uncooled reference panel experiences maximum thermal stress, causing its efficiency to drop. Conversely, the PVT system's active cooling suppresses this thermal degradation.

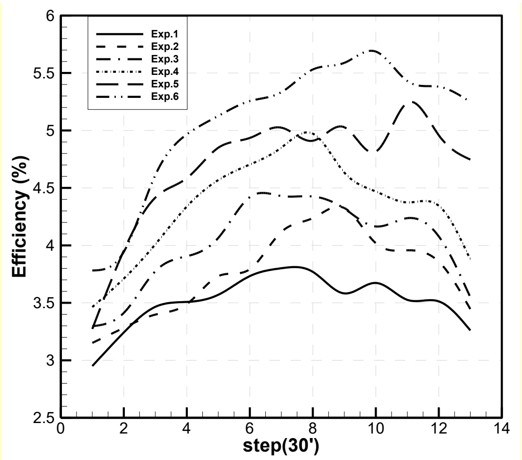

Figure 3. Difference in electrical efficiency between the tested panel and reference panel

Averaging the data across all six experiments within this peak window yields an electrical efficiency improvement of approximately 4.6% in favor of the PVT panel. The standard deviation across these measurements was a mere 0.6%, highlighting a highly consistent and repeatable performance trend. While liquid coolant (water) handles the bulk of the thermal load due to its superior thermodynamic properties, the forced air convection plays a vital supporting role. The maximum efficiency improvement recorded reached 5.7%, specifically under the parameters of Run 6 (air velocity of 6 m/s and water flow rate of 120 L/h). This proves the direct correlation between aggressive thermal management and electrical output preservation during peak solar exposure.

Beyond electrical preservation, the system's viability depends on its ability to recover usable thermal energy. The total thermal efficiency is a composite metric, representing the combined heat absorbed by both the circulating water and the forced air.

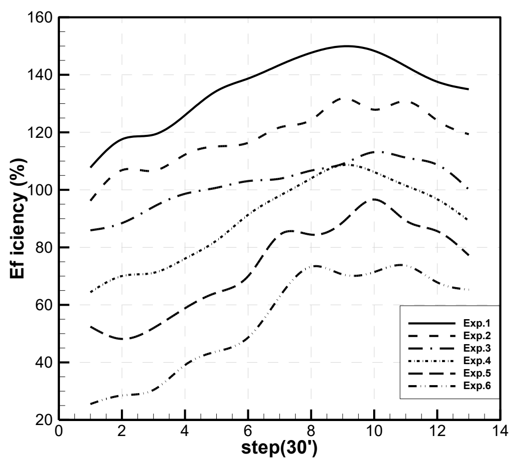

Figure 4. Total thermal efficiency

Figure 4 tracks the thermal efficiency over the duration of the daily tests. An initial observation is the dynamic nature of the efficiency curves, which respond to both the incoming solar radiation and the specific flow parameters of each run. Focusing again on the peak irradiance window (time steps 6 to 8), the extracted values show an average total thermal efficiency of approximately 103.5%.

The standard deviation in this peak zone was calculated at 2.5%. While slightly higher than the electrical efficiency deviation, this remains statistically acceptable given the complex fluid dynamics at play. The variations are directly linked to the inverse relationship between fluid velocity and thermal residence time. In runs where higher air and water velocities were applied (such as Runs 3 and 6), the fluids had less contact time with the hot absorber plate, leading to a slight dip in thermal capture efficiency. However, this trade-off was intentional, as the priority shifted toward maximizing electrical output through rapid heat removal.

Furthermore, the data demonstrates the dominant role of water in the thermal absorption process. The energy captured by the air stream remained relatively minor compared to the water circuit, owing to water's significantly higher specific heat capacity and direct contact with the aluminum exchanger. The system's behavior in the peak zone confirms that it operates as a unified thermal-electrical mechanism, where adjusting the fluid parameters allows for a tunable balance between heat recovery and electrical generation.

4. Conclusions

The present study demonstrated that the utilization of tri-generation hybrid Photovoltaic-Thermal (PVT) collector systems is a highly efficient strategy for increasing solar energy utilization. The key findings obtained are as follows:

- The simultaneous water and air cooling system significantly reduces the temperature of solar cells during peak sunlight hours.
- The reduction in panel temperature leads to an increase in power output and improves electrical efficiency by 3% to 5.7% compared to standard panels.
- Water plays a dominant role in heat transfer and panel cooling due to its superior thermodynamic properties compared to air.
- Increasing the velocity of the cooling fluid, while decreasing thermal efficiency (due to reduced contact time), leads to an increase in electrical efficiency through faster heat removal.
- The optimal system performance was observed at an air velocity of 6 m/s and a water flow rate of 120 L/h. The use of aluminum reflectors and proper thermal insulation played a crucial role in increasing effective irradiance and minimizing thermal losses.

Ultimately, the development of these hybrid systems is not only economically viable but also serves as an effective step toward sustainable development, reducing dependence on fossil fuels, and optimizing the use of solar energy in residential and industrial sectors.

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