Design Development and Experimental Validation of a Passive Solar Tracking System Based on Pressure Driven Fluid Dynamics

Vishnu Prasad C H[1], Ashin Shaju K[2], S. Krishnanunni[3]

[1]Department of Mechanical Engineering, Jyothi Engineering College (Autonomous), Cheruthuruthy, Thrissur, Kerala – 679531, India
Corresponding Author Email: *vishnu.me22[at]jecc.ac.in*

[2]Department of Mechanical Engineering, Jyothi Engineering College (Autonomous), Cheruthuruthy, Thrissur, Kerala – 679531, India
Email: *ashin.me22[at]jecc.ac.in*

[3]Department of Mechanical Engineering, Jyothi Engineering College (Autonomous), Cheruthuruthy, Thrissur, Kerala – 679531, India
Email: *skrishnanunni[at]jecc.ac.in*

Abstract: ***The growing global demand for clean and sustainable energy has intensified interest in improving the efficiency of photovoltaic (PV) power systems. Since PV output depends strongly on alignment with the sun, fixed-panel installations can sustain optimal orientation for only a limited period each day, resulting in reduced energy capture. This paper presents the design, fabrication, and experimental validation of a passive solar tracking system driven by thermally generated pressure in a working fluid. The system operates entirely without electrical components such as motors or controllers: a sealed pressure chamber containing a low-boiling-point liquid generates internal pressure on heating, which is transmitted through a connecting tube to a pneumatic actuator that produces the mechanical motion required to adjust panel tilt. A prototype was designed using suitable structural materials and fabricated to demonstrate the underlying working principle. Experimental evaluation confirms that the generated pressure is sufficient to produce controlled, repeatable movement of the panel, and the system exhibits stable operation while converting thermal energy directly into mechanical actuation. The proposed design offers a simple, cost-effective, and energy-independent means of improving solar panel alignment, and is particularly well suited to small-scale and off-grid applications where reliability and low maintenance are essential.***

Keywords: Passive solar tracking; photovoltaic systems; thermal pressure; pneumatic actuation; renewable energy; sustainable design

Nomenclature

F	Force acting on the piston (N)
P	Pressure generated within the chamber (Pa)
A	Effective piston area (m²)
τ	Torque required to rotate the panel (N·m)
W	Weight of the solar panel (N)
d	Distance from the pivot point to the panel centre of gravity (m)
r	Effective lever arm of the actuator (m)

1. Introduction

The rising global demand for energy, along with increasing environmental concerns caused by the use of fossil fuels, has accelerated the shift toward renewable energy sources. Among these, solar energy stands out as one of the most abundant, clean, and sustainable options available today. Photovoltaic (PV) systems are widely used to convert sunlight directly into electrical energy and are increasingly applied in residential, commercial, and remote areas due to their reliability and environmental benefits. However, the efficiency of photovoltaic systems largely depends on how well the solar panel is aligned with the sun. Maximum power is generated when sunlight falls directly on the surface of the panel. Since the position of the sun changes continuously throughout the day, fixed solar panels can maintain this optimal alignment only for a short period. As a result, a significant amount of potential solar energy is not effectively captured, especially during the morning and evening hours.

To address this issue, solar tracking systems are used to adjust the position of solar panels so that they follow the movement of the sun. Most conventional tracking systems use sensors, motors, and electronic controllers to achieve accurate positioning. While these systems can improve energy output, they also increase system complexity, cost, and power consumption, making them less suitable for small-scale installations and off-grid applications. An alternative approach is offered by passive solar tracking systems, which operate without electrical components. These systems rely on natural physical effects such as thermal expansion or pressure changes in fluids to produce movement. Because of their simple design and low maintenance requirements, passive systems are more practical for rural and low-cost applications.

Broadly, solar tracking technologies are classified according to their drive mechanism and degrees of freedom. Mousazadeh et al. [1] categorized tracking methods into microprocessor-based, electro-optical, and mechanical approaches, and reported that tracking can raise the collectible energy of a PV system by up to 57% relative to a fixed installation, depending on location and season. Building on this, Hafez et al. [2] classified tracker drive systems into five broad categories, namely active, passive, semi-passive, manual, and chronological tracking, and observed that single-axis and dual-axis configurations together account for the large majority of designs reported in the literature. More recently, Kazem et al. [3] reviewed advances in sensing, control, and artificial-intelligence-assisted tracking, noting that single- and dual-axis active tracking systems can improve energy yield substantially over fixed arrays, while also highlighting that the parasitic power consumption and mechanical complexity of motorized trackers remain barriers to their adoption in small-scale and remote installations. These findings collectively motivate the continued development of simple, self-actuated passive alternatives that can deliver part of the tracking benefit without the cost, complexity, and power draw associated with actively driven systems.

In this work, a passive solar tracking system based on thermally generated pressure in a working fluid is proposed. The system uses a sealed chamber containing a low boiling point liquid; when exposed to heat, the fluid produces pressure, which is transmitted through a tube to drive a pneumatic mechanism. This motion is then used to adjust the angle of the solar panel. The proposed system provides a simple and energy-independent solution for improving solar panel alignment, eliminating the need for motors and electronic control systems, and making it cost-effective and easy to maintain. This makes the design especially suitable for small-scale and off-grid solar applications where reliability and simplicity are important.

2. Literature Review

Solar tracking has been the subject of extensive review literature over the past two decades, providing a broad classification of the technologies available and a quantitative picture of the energy gains they can deliver. Mousazadeh et al. [1] surveyed sun-tracking principles and control methods and reported that, depending on geographic location and tracker type, energy gains of up to 57% can be achieved relative to fixed-tilt installations, while also cautioning that the incremental gain must be weighed against the added mechanical complexity and parasitic power draw of the tracking drive. Lee et al. [4] reviewed sensor-based tracking strategies, including light-dependent-resistor arrays, image-processing methods, and astronomical-calculation-based open-loop control, and noted that closed-loop sensor tracking generally achieves higher pointing accuracy than open-loop schemes but is more susceptible to error under diffuse or cloudy sky conditions. Hafez et al. [2], in one of the most extensively cited reviews in this field, organized tracker drive systems into five categories, active, passive, semi-passive, manual, and chronological tracking, and found that single-axis and dual-axis designs together represent the overwhelming majority of the tracking systems reported in the literature, with dual-axis systems generally outperforming single-axis systems at the cost of additional actuators and control complexity. More recently, Kazem et al. [3] extended this classification to cover emerging trends such as sensor fusion, Internet-of-Things-based monitoring, and artificial-intelligence-assisted control, concluding that while these technologies can further improve tracking precision, the underlying trade-off between energy gain, system cost, and reliability remains largely unchanged for low-cost and small-scale deployments. Taken together, these review studies establish the broader context within which passive, self-actuated tracking mechanisms, such as the one investigated in this work, are positioned as a low-complexity alternative capable of capturing part of the available tracking benefit without the power consumption and control overhead associated with actively driven systems.

Passive solar tracking systems have gained significant attention in recent years as a simpler and more efficient alternative to conventional active tracking methods. Unlike active systems that rely on motors, sensors, and electronic controllers, passive trackers operate using solar heat energy itself. This eliminates the need for external power sources and reduces system complexity as well as maintenance requirements. Studies have shown that solar tracking can improve energy output by approximately 20% to 50% compared to fixed solar panels [5], [6]. Due to their simplicity and reliability, passive systems are particularly suitable for small-scale and remote installations where maintenance and power availability are limited [7], [6]. Among various approaches, shape memory alloy (SMA)-based systems are widely explored due to their unique thermo mechanical properties. SMAs have the ability to return to their original shape when heated, enabling them to act as both sensors and actuators. Wang et al. [8] developed a system using SMA springs connected to gear mechanisms for automatic solar tracking. Similarly, Ganesh et al. [9] proposed a direct SMA-based tracker capable of achieving a tracking range of approximately 120° throughout the day. Yun et al. [10] introduced a flexible solar panel structure incorporating SMA strips that adapt to sunlight conditions, while Siebert et al. [11] demonstrated the use of Nitinol wires for precise tracking with an accuracy of ±5°. Overall, SMA-based systems have shown significant performance improvements, with reported efficiency gains of up to 75%.

Phase change material (PCM)-based systems represent another approach, in which materials expand during phase transition (typically from solid to liquid) to generate mechanical motion. Mendecka et al. [12] investigated paraffin-based PCMs integrated with thermal energy storage systems, enabling dual functionality of energy storage and solar tracking. Zagolla et al. [13] developed a self-tracking solar concentrator using localized PCM heating to create a dynamic optical effect, allowing sunlight acceptance over a wide range of angles. These systems are particularly beneficial in applications involving solar concentration and thermal storage.

Bimetallic-based tracking systems provide a cost-effective and simpler alternative. These systems operate on the principle of differential thermal expansion between two metals, resulting in bending motion. Alemayehu et al. [14] proposed a system capable of automatic daytime tracking and nighttime resetting. Similarly, Sanchez [15] developed a dual-axis tracker using bimetallic strips, demonstrating its suitability for remote applications. Brito et al. [16] introduced a vertical strip design achieving approximately 28% improvement in energy output. Although less precise than SMA systems, bimetallic trackers offer advantages in simplicity and cost. Performance comparisons indicate that SMA-based systems generally achieve the highest efficiency improvements, typically ranging from 55% to 75% [9], [6]. Bimetallic systems provide moderate gains of around 28% [16], while PCM-based systems are more suitable for solar concentration applications [13]. However, system performance is highly dependent on environmental conditions; for instance, SMA systems are sensitive to ambient temperature, which can affect their activation and cooling cycles [5]. From a practical perspective, passive solar tracking systems offer several advantages. The absence of motors and electronic components results in lower cost, reduced weight, and minimal maintenance requirements. Some studies report system costs as low as €0.04/W for SMA-based designs [6]. Additionally, these systems are self-regulating and automatically adapt to environmental conditions, and experimental studies confirm that SMA components exhibit reliable long-term performance with minimal fatigue [11].

A further category of passive trackers, closely related to the mechanism investigated in this work, relies on the vapor pressure of a low boiling point working fluid rather than on solid-state material transformation. In these systems, differential heating of a sealed fluid reservoir generates a pressure or density imbalance that is used to displace a piston or shift the position of the tracker without any external power input. Such vapor-pressure-driven trackers are noted in the broader tracking-technology reviews [1], [2] as a distinct sub-class of passive tracking, valued for their mechanical simplicity and use of readily available components, though they are generally reported to be slower to respond and less angularly precise than SMA-based or sensor-driven active systems. This trade-off between simplicity and precision motivates the present study, which investigates a pneumatically actuated, pressure-driven tracking mechanism as a practical middle ground between fully passive thermal trackers and complex active tracking systems.

Despite these advantages, several challenges remain. Sensitivity to ambient temperature, particularly in hot climates, can affect system reset behaviour after sunset [9]. Many passive systems primarily track the sun in the east-west direction and do not account for seasonal elevation changes [16]. Long-term durability is not well documented and further field studies are required to evaluate system lifespan [11]. Additionally, variations in solar radiation due to cloud cover can introduce tracking inaccuracies [9]. Addressing these limitations is essential for improving the reliability and widespread adoption of passive solar tracking systems.

3. Proposed System

3.1 System Overview

The proposed system is a passive solar tracking mechanism designed to enhance the energy capture of photovoltaic panels by maintaining improved alignment with solar radiation throughout the day. Unlike conventional active tracking systems that rely on electrical components such as motors, sensors, and control circuits, the proposed approach utilizes thermally induced pressure in a working fluid to generate mechanical actuation. This eliminates the need for external power input for tracking, thereby improving overall system efficiency and reliability.

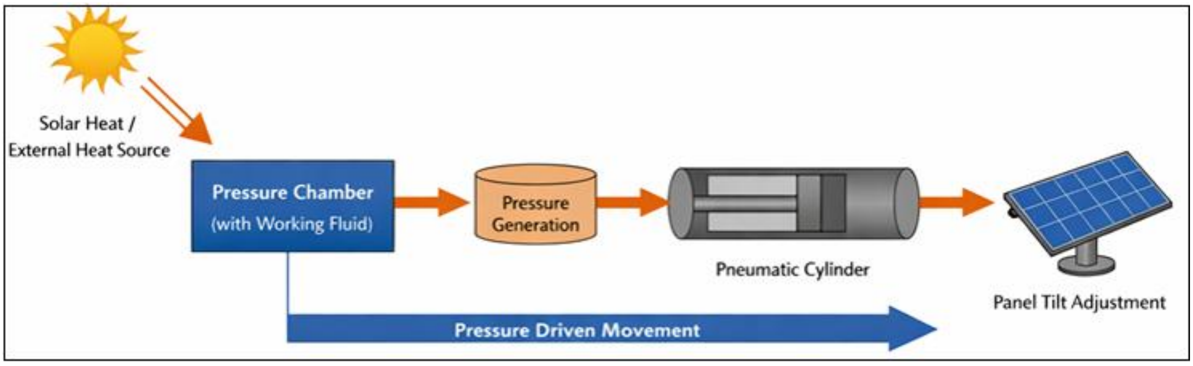

Figure 1: Overall structure and working of the proposed passive solar tracking system

The system is developed as a mechanically simple and energy-independent solution, particularly suitable for small-scale and off-grid solar applications. By directly converting thermal energy into mechanical motion, the design reduces system complexity, operational cost, and maintenance requirements while ensuring effective tracking performance under varying environmental conditions. The overall structure and working of the proposed system are illustrated in Fig. 1.

3.2 Working Principle

The operation of the system is based on thermally induced phase change and pressure generation within a sealed chamber. When the pressure chamber is exposed to solar radiation or an external heat source, the temperature of the working fluid increases, resulting in partial vaporization. This phase change leads to a rise in internal pressure within the chamber. The generated pressure is transmitted through copper tubing to a pneumatic cylinder, where it acts on the piston to produce linear displacement. The magnitude of this displacement depends on the pressure developed within the chamber and the effective area of the piston. The linear motion of the piston is then converted into controlled angular displacement through a pivot mechanism connected to the solar panel mounting structure.

As the panel tilts toward the direction of maximum solar radiation, improved alignment is achieved. When the temperature decreases, the pressure inside the chamber reduces, allowing the system to return toward its initial position. This cyclic process enables passive tracking of the sun without the need for electronic control.

3.3 System Components

The proposed system consists of a set of mechanically integrated components designed to facilitate efficient pressure generation and motion transfer. The primary component is a sealed cylindrical mild steel pressure chamber, as shown in Fig. 2 (a), capable of withstanding the internal pressure generated by vaporization of the working fluid. A low boiling point fluid, such as ethanol or acetone, is utilized to ensure effective pressure generation under moderate thermal conditions.

Copper tubing, illustrated in Fig. 2 (c), is employed to connect the pressure chamber to the pneumatic cylinder due to its high thermal conductivity, corrosion resistance, and compatibility with the working fluid. The generated pressure is transmitted through the tubing to the pneumatic cylinder, shown in Fig. 2 (d), which acts as the primary actuator by converting pressure energy into linear mechanical motion through piston displacement. The solar panel is mounted on a pivot-based support structure, as depicted in Fig. 2 (b), enabling controlled angular movement. A mechanical linkage mechanism is incorporated to efficiently convert the linear motion of the piston into rotational displacement of the panel. The coordinated interaction of these components ensures smooth operation, reliable actuation, and effective solar tracking performance.

(a) (b)

(c) (d)

Figure 2: (a) Mild steel pressure chamber, (b) Solar panel mounted on the pivot frame, (c) Copper tubing connecting the chamber and actuator, (d) Pneumatic cylinder used for linear actuation

3.4 Design and Fabrication

The system is designed with emphasis on structural integrity, mechanical efficiency, and ease of fabrication. Mild steel is selected as the primary structural material due to its high strength, durability, and cost-effectiveness. The frame is designed to provide stable support for the solar panel and associated components while accommodating dynamic loading during operation.
Computer-aided design is performed using SolidWorks to develop a three-dimensional model of the system, as shown in Fig. 3. The CAD model illustrates the complete structural layout, including the supporting frame, solar panel mounting arrangement, pressure chamber placement, and actuator alignment. The modelling process is used to determine appropriate dimensions, verify component alignment, and evaluate mechanical feasibility. Design considerations include torque requirements for panel rotation, piston stroke length, and optimal positioning of the pressure chamber and actuator.

Based on the finalized CAD design, a prototype is fabricated using standard manufacturing processes. Care is taken to ensure proper alignment, secure mounting, and leak-proof connections, particularly in the pressure transmission pathway. The fabricated system is configured to allow smooth conversion of pressure energy into mechanical motion, consistent with the design represented in Fig. 3.

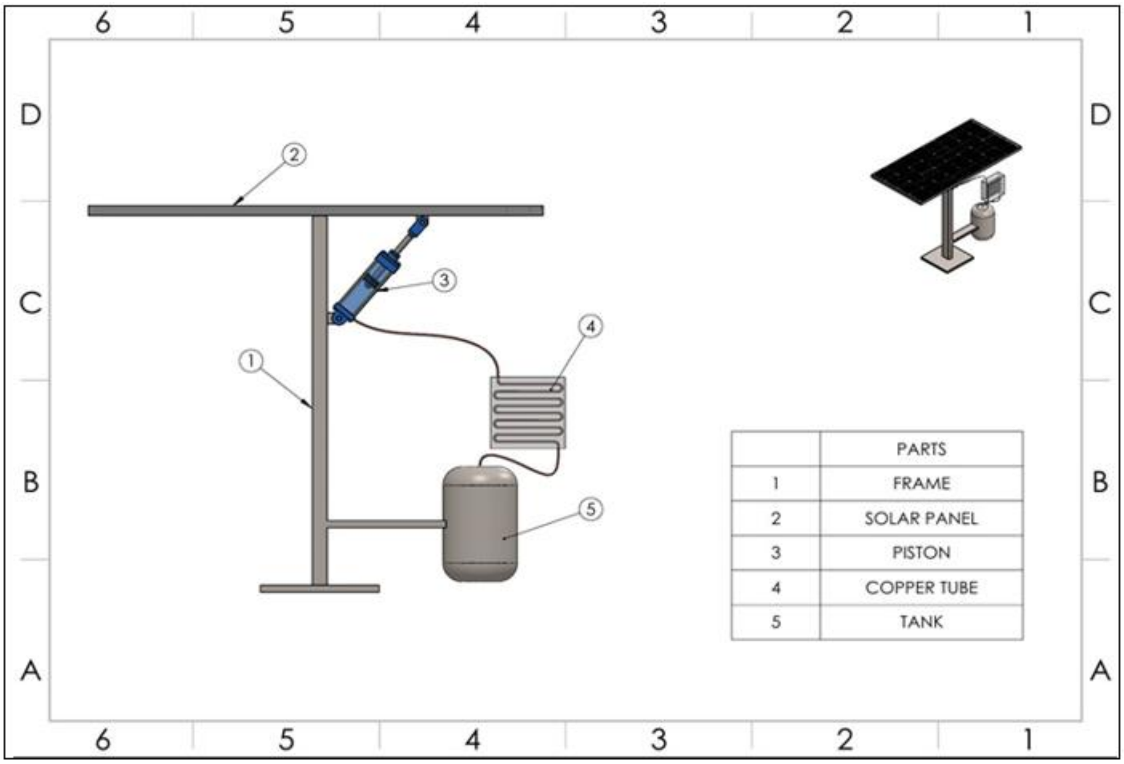

Figure 3: CAD model of the proposed system developed in SolidWorks.

3.5 Experimental Setup

Experimental validation of the proposed system was carried out under controlled conditions to evaluate the feasibility of pressure-driven actuation. Due to limitations in natural solar heating during testing, a hot air gun was used as an external heat source to simulate thermal input. The pressure chamber was subjected to controlled heating, resulting in a temperature rise and subsequent vapor pressure generation. The complete experimental setup used for testing is shown in Fig. 4.

The response of the system was analysed by measuring the displacement of the piston and the corresponding angular movement of the solar panel. Temperature values were recorded at the surface of the pressure chamber, and their relationship with panel tilt was examined. The experimental arrangement enabled evaluation of system responsiveness, stability, and the effectiveness of thermal-to-mechanical energy conversion. The results indicate that the generated pressure was sufficient to overcome mechanical resistance and produce controlled panel movement, thereby validating the proposed passive solar tracking mechanism.

Figure 4: Experimental setup used for testing of the prototype.

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3.6 Design Considerations

The design of the proposed system is governed by the relationship between pressure, force, and torque required to rotate the solar panel. The pressure generated inside the chamber produces a force on the piston, which can be expressed as:

$$F = P \times A \quad (1)$$

where F is the force acting on the piston, P is the generated pressure, and A is the piston area.

The force generated must be sufficient to overcome the gravitational force acting on the panel and the mechanical resistance of the system. The torque required to rotate the panel is given by:

$$\tau = W \times d \quad (2)$$

where W is the weight of the panel and d is the distance from the pivot point. For effective operation, the generated torque must satisfy:

$$F \times r \geq W \times d \quad (3)$$

where r is the effective lever arm of the actuator. Based on these considerations, the dimensions of the pressure chamber, piston, and linkage mechanism were selected to ensure sufficient actuation under thermal input conditions.

4. Results and Discussion

The performance of the proposed passive solar tracking system was evaluated through experimental testing of the pressure-driven actuation mechanism under controlled conditions. Since natural solar radiation was not sufficient to produce the required pressure during testing, a controlled heat source was used to simulate thermal input to the pressure chamber.

At the initial stage, the electrical performance of the photovoltaic panel in a fixed position was analysed. The variation of output voltage with respect to time is presented in Fig. 5, which shows a gradual decrease in voltage due to changes in solar intensity and angle of incidence. Similarly, the variation of output current under load and no-load conditions is illustrated in Fig. 6, confirming that panel performance is influenced by operating conditions and loading effects.

During thermal testing, the temperature of the pressure chamber was increased using an external heat source, resulting in vaporization of the working fluid and subsequent pressure generation. This pressure was transmitted through the copper tubing to the pneumatic cylinder, causing the piston to move outward. The resulting linear displacement was effectively converted into angular motion of the solar panel.

The relationship between temperature and panel tilt angle was further analysed using two different working fluids, namely ethanol and acetone. The variation of tilt angle with temperature for ethanol is shown in Fig. 7, while the corresponding behaviour for acetone is presented in Fig. 8. It is observed

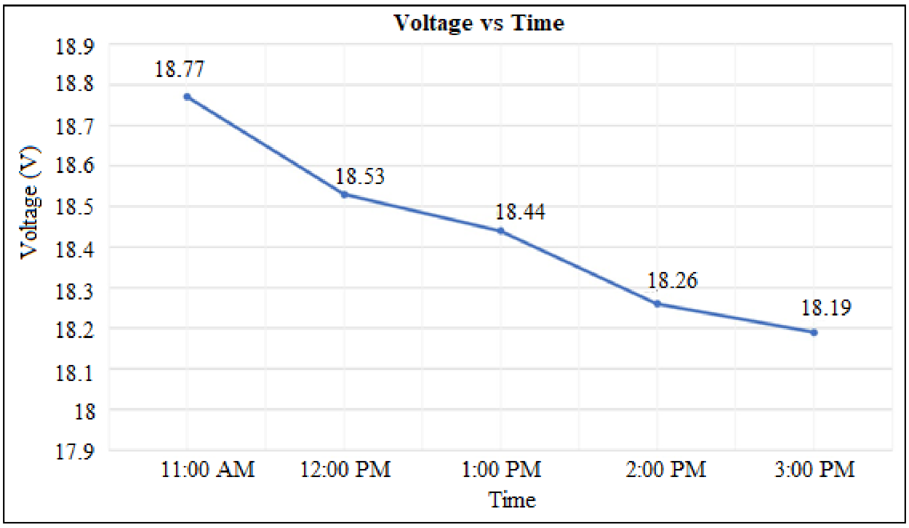

Figure 5: Variation of output voltage of the solar panel with time under fixed-panel conditions.

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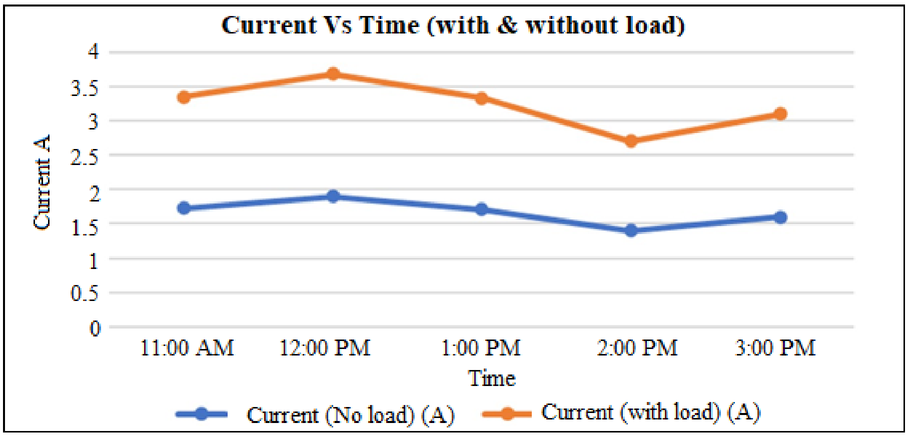

Figure 6: Variation of output current of the solar panel with time under load and no-load conditions.

That the tilt angle increases progressively with temperature, indicating efficient conversion of thermal energy into mechanical motion.

The experimental data summarized in Table 1 and Table 2 further support these observations. Ethanol exhibits a gradual and stable increase in tilt angle with temperature, whereas acetone demonstrates a relatively faster response due to its higher vapor pressure characteristics. However, both fluids require relatively high temperatures to initiate significant movement, which may limit performance under natural environmental conditions.

Table 1: Temperature and corresponding panel tilt angle variation using ethanol.

Stage	Temperature (°C)	Angle (°)	ΔTemp (°C)	ΔAngle (°)
Start	36	53	–	–
Temp 1	44	55	8	2
Temp 2	49	58	5	3
Temp 3	54	62	5	4
Temp 4	59	66	5	4
Temp 5	63	69	4	3
Temp 6	68	73	5	4
Final	73	77	5	4

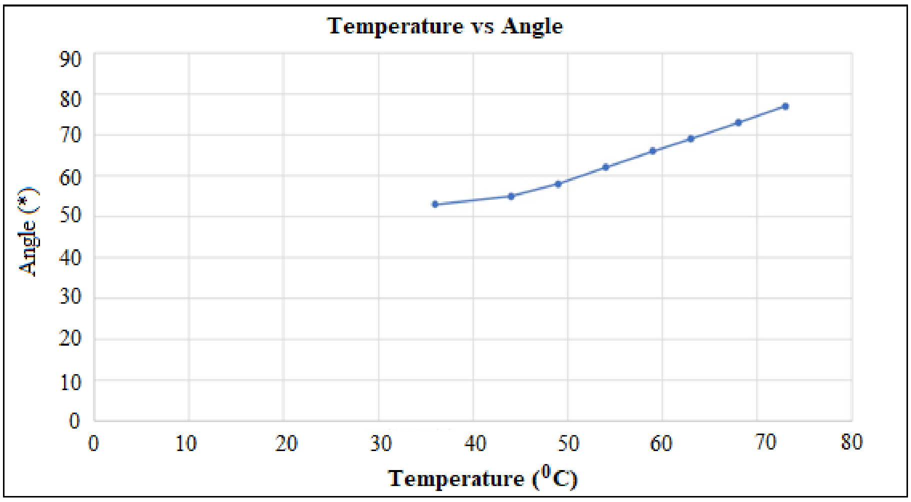

Figure 7: Variation of panel tilt angle with temperature using ethanol.

Table 2: Temperature and corresponding panel tilt angle variation using acetone.

Stage	Temperature (°C)	Angle (°)	ΔTemp (°C)	ΔAngle (°)
Start	34	53	–	–
Temp 1	39	56	5	3
Temp 2	42	63	3	7
Temp 3	45	67	3	4
Temp 4	48	73	3	6
Temp 5	50	75	2	2
Temp 6	54	80	4	5
Final	56	84	2	4

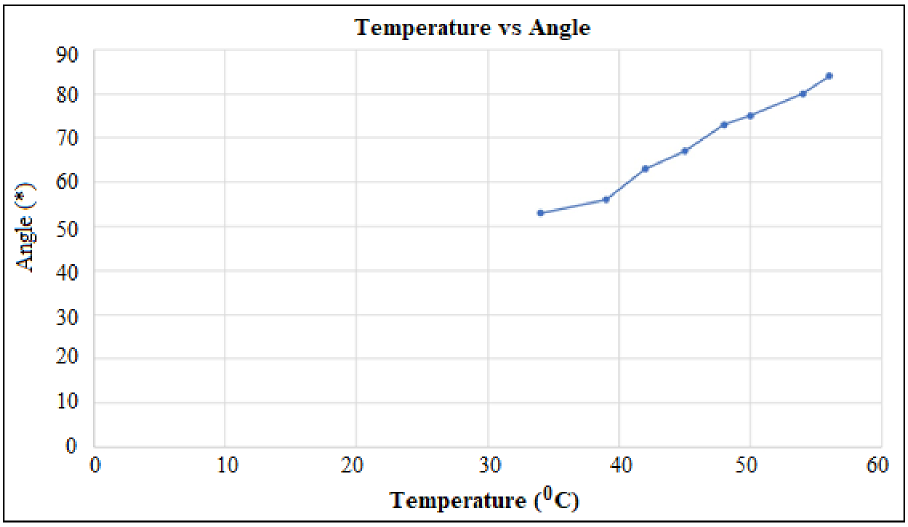

Figure 8: Variation of panel tilt angle with temperature using acetone.

Overall, the system demonstrates stable operation and reliable actuation, validating the feasibility of pressure-driven passive solar tracking. The results confirm that the proposed mechanism is capable of improving panel alignment without the use of electrical components, making it a practical solution for low-cost and small-scale solar applications. It should be noted that ethanol and acetone were used as working fluids in this study due to the unavailability of refrigerants such as R134a in liquid form under the given experimental conditions. Although these fluids enabled successful demonstration of the pressure-driven actuation mechanism, their thermal properties differ from those of standard low boiling point refrigerants.

The experimental results indicate that the proposed system is capable of achieving effective panel movement through thermally induced pressure generation. This suggests that the performance of the system can be further enhanced by employing suitable refrigerants such as R134a, which possess more favourable thermodynamic characteristics. Therefore, the study validates that the proposed passive solar tracking mechanism can operate effectively in real-world conditions when an appropriate low boiling point working fluid is utilized.

5. Conclusion

The present study successfully demonstrates the design and implementation of a passive solar tracking system based on pressure-driven fluid dynamics. The proposed mechanism effectively converts thermal energy into mechanical motion, enabling automatic adjustment of the solar panel without the use of electrical components such as motors or controllers. Experimental results confirm that the system is capable of generating sufficient pressure to actuate the pneumatic cylinder and produce controlled panel movement. The analysis of voltage and current characteristics highlights the limitations of fixed solar panels, while the temperature-based actuation results validate the effectiveness of the proposed tracking approach.

Although ethanol and acetone were used as working fluids due to the unavailability of refrigerants such as R134a in liquid form, the system demonstrated stable and reliable performance. The findings indicate that the use of appropriate low boiling point refrigerants can further enhance system efficiency and responsiveness under real environmental conditions.

Overall, the proposed system offers a simple, cost-effective, and energy-independent solution for improving solar panel alignment. The study confirms the feasibility of pressure-driven passive solar tracking and its potential application in small-scale and off-grid renewable energy systems.

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Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability
The experimental data generated and analysed during this study are available from the corresponding author upon reasonable request.

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