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Design, Development and Analysis, of A Solar-Driven Air Conditioning System for Automotive Applications

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ABSTRACT

The rapid growth of the automotive sector, coupled with increasing environmental concerns and energy demand, has necessitated the development of sustainable and energy-efficient technologies. Among various vehicle subsystems, air conditioning (AC) systems account for a significant portion of total energy consumption, leading to increased fuel usage in internal combustion engine (ICE) vehicles and reduced driving range in electric vehicles (EVs). This work focuses on the design, development and analysis of a solar-driven air conditioning system for automotive applications, aiming to minimize dependence on conventional energy sources while improving system efficiency and environmental sustainability. The proposed system integrates photovoltaic (PV) panels, energy storage units (battery), a charge controller, and a vapor compression refrigeration system to achieve effective cooling using renewable solar energy. The photovoltaic system converts solar radiation into electrical energy through the photovoltaic effect, which is stored in a battery and utilized to operate the compressor and auxiliary components. The refrigeration cycle follows the conventional vapor compression process involving compression, condensation, expansion, and evaporation to produce the desired cooling effect.

Keywords: Solar Energy, Automotive Air Conditioning, Photovoltaic System, Vapor Compression Refrigeration, Energy Efficiency.

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I. Introduction

The rapid expansion of the global automotive industry, combined with increasing energy demand and environmental concerns, has driven the need for sustainable and energy-efficient technologies. In modern vehicles, energy is not only required for propulsion but also for auxiliary systems such as lighting, safety mechanisms, infotainment, and thermal comfort systems. Among these, the air conditioning (AC) system plays a critical role in ensuring passenger comfort, particularly in regions experiencing high ambient temperatures. However, conventional automotive air conditioning systems are highly energy-intensive and significantly impact overall vehicle performance. In internal combustion engine (ICE) vehicles, the air conditioning compressor is mechanically driven by the engine. This increases the engine load, leading to higher fuel consumption, reduced engine efficiency, and increased greenhouse gas emissions [1]. Studies have shown that operating an AC system can increase fuel consumption by approximately 5–20%, depending on driving conditions and climate. In electric vehicles (EVs), the situation is equally challenging, as the AC system draws power directly from the battery, thereby reducing the driving range [2]. This creates a trade-off between passenger comfort and vehicle performance, which is a major concern in modern transportation systems. With the depletion of fossil fuel resources and the growing threat of climate change, there is a global shift toward renewable energy sources. Solar energy has emerged as one of the most promising alternatives due to its abundance, sustainability, and eco-friendly nature [3]. The working of an automotive air conditioning system is based on the vapor compression refrigeration cycle, which consists of four main processes: compression, condensation, expansion, and evaporation. The compressor increases the pressure and temperature of the refrigerant, the condenser rejects heat to the surroundings, the expansion device reduces the pressure, and the evaporator absorbs heat from the cabin to produce cooling [4]. The performance of the system is evaluated using the equation (i) Coefficient of Performance (COP), which is given by:

$COP = Q_L / W$-------------------------------------(i)

Where Q_L represents the refrigeration effect and W represents the work input to the compressor. A higher COP indicates better system efficiency.

In addition to refrigeration principles, heat transfer plays a vital role in the performance of air conditioning systems. The cooling effect is governed by the heat transfer equation (ii):

$Q = mCp\Delta T$ -------------------------------------(ii)

Where Q the heat transfer rate, m is the mass of the fluid, Cp is the specific heat capacity, and ΔT is the temperature difference. Efficient heat exchange in the condenser and evaporator is essential for achieving optimal cooling performance. The increasing demand for energy-efficient and environmentally sustainable automotive systems has led to extensive research in solar-powered cooling technologies.

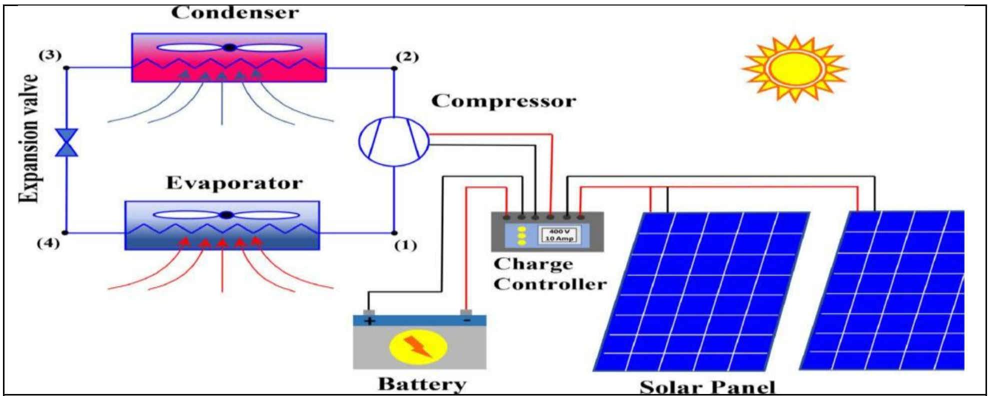


Figure:1 Conventional Automotive Air Conditioning System

Conventional automotive air conditioning systems (figure 1) consume significant energy, resulting in increased fuel consumption in internal combustion engine (ICE) vehicles and reduced driving range in electric vehicles (EVs). Researchers have investigated alternative cooling solutions using renewable energy sources, particularly solar energy, to address these challenges.

1.1 Solar Energy and Photovoltaic Systems

The fundamentals of solar energy utilization were extensively studied by Duffie and Beckman [1], who established that solar radiation can be effectively converted into electrical energy using photovoltaic (PV) technology. Their work highlights that PV system performance is strongly influenced by solar irradiance, temperature, and environmental conditions. Nelson [2] further explained the physics of solar cells, emphasizing the photovoltaic effect and the role of semiconductor materials in energy conversion. It was observed that the efficiency of solar panels decreases with increasing temperature, which is a critical limitation in automotive applications. Recent studies by Kalogirou [3] suggest that photovoltaic-thermal (PV/T) systems can improve overall efficiency by combining electrical and thermal energy extraction. These systems reduce panel temperature and enhance electrical output (figure 2).

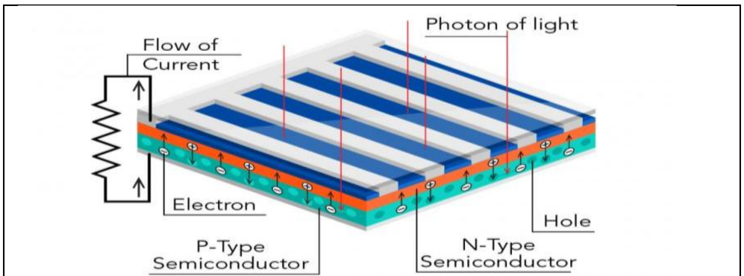


Figure:2 Working Principle of Photovoltaic Cell

1.2 Refrigeration and Air Conditioning Systems

The principles of refrigeration systems (figure 3) have been extensively discussed by Arora [4], who demonstrated that the vapor compression refrigeration cycle is the most efficient and widely used cooling method. The performance of refrigeration systems is evaluated using the coefficient of performance (COP), which depends on compressor efficiency and heat transfer effectiveness. Dossat [5] highlighted that improving heat exchanger performance and minimizing compressor work are key factors in enhancing system efficiency. His studies also emphasize the importance of proper refrigerant selection and system design.

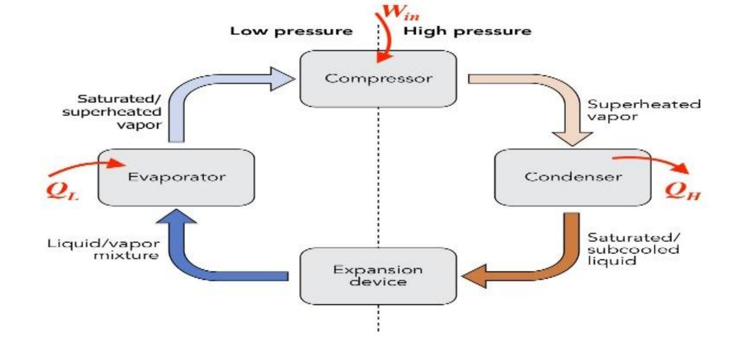


Figure:3 Vapor Compression Refrigeration Cycle

1.3 Solar-Powered Air Conditioning Systems
Solar-powered air conditioning systems have been studied as an alternative to conventional cooling systems. According to Kim and Ferreira [6], solar-assisted air conditioning can significantly reduce energy consumption and environmental impact. Henning [7] investigated solar thermal cooling systems and concluded that solar energy can effectively drive cooling systems, although system complexity and cost remain challenges. Research indicates that solar-powered AC systems are more effective in regions with high solar irradiance but require efficient energy storage systems to maintain continuous operation.

1.4 Energy Storage Systems
Energy storage is a critical component in solar-powered systems due to the intermittent nature of solar energy. Linden and Reddy [8] studied battery technologies and concluded that lithium-ion batteries offer higher efficiency and energy density compared to lead-acid batteries. Divya and Stergaard [9] analyzed battery storage systems and found that performance depends on charge-discharge cycles, temperature, and system design. Their research highlights the importance of efficient battery management systems for improving system reliability.

1.5 Thermoelectric and Hybrid Cooling Systems:
Thermoelectric cooling systems based on the Peltier effect have been studied for compact and portable cooling applications. Rowe [10] demonstrated that thermoelectric systems are suitable for small-scale applications due to their simplicity and reliability. However, studies show that thermoelectric cooling has lower efficiency compared to vapor compression systems. To overcome this limitation, Vian and Astrain [11] proposed hybrid systems combining thermoelectric and conventional cooling methods, resulting in improved performance and energy efficiency.

1.6 Automotive Air Conditioning and Energy Consumption
Studies on automotive systems indicate that air conditioning significantly impacts vehicle performance. Farrington and Rugh [12] reported that AC systems can increase fuel consumption by up to 20% in ICE vehicles. In electric vehicles, Chan [13] found that AC systems reduce battery range, making energy-efficient cooling solutions essential. These findings highlight the need for integrating renewable energy sources into automotive systems.

1.7 Control Systems and Optimization Techniques
Recent research focuses on improving system performance using advanced control techniques. Kalogirou [3] emphasized the role of artificial intelligence (AI) in optimizing solar energy systems. AI-based control systems can, Monitor system performance , Optimize energy usage ,Improve cooling efficiency.These techniques enhance system reliability and adaptability under varying operating conditions.
1.8 Research Gap Identified
Based on the literature review, the following research gaps are identified:
- Limited experimental studies on small-scale solar-driven automotive AC systems
- Lack of integrated analysis of PV systems, energy storage, and refrigeration cycles
- Insufficient focus on cost-effective and compact system design

Need for real-time performance analysis and optimization

1.9 Objectives of this work

- Reduce dependency on conventional energy sources in automotive AC systems
- Analyse the performance of a solar-powered cooling system
- Evaluate the cooling efficiency and energy consumption
- Identify key challenges and optimization opportunities
- Promote the use of renewable energy in transportation

This work contributes to the development of sustainable automotive technologies by demonstrating the feasibility of solar-powered air conditioning systems [9]. The findings of this study provide valuable insights into system design, performance optimization, and practical implementation, supporting the transition toward energy-efficient and environmentally friendly transportation solutions.

II. Material and Methods

The solar-driven automotive air conditioning system integrates photovoltaic energy conversion with a vapor compression refrigeration cycle to provide cooling using renewable energy. The system combines principles of thermodynamics, heat transfer, and electrical energy conversion. This section presents the theoretical background, system design, mathematical modeling, and experimental methodology used to evaluate system performance (figure 4).

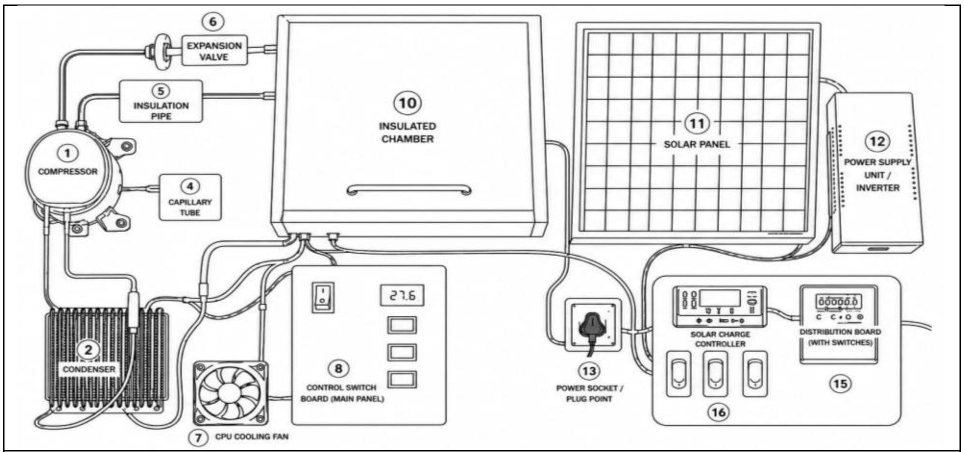


Figure:4 Block Diagram of Solar-Driven Air Conditioning System

2.1 Basic Refrigeration Principle

The system operates on the vapor compression refrigeration cycle (VCRC) figure 5, which is the most widely used refrigeration method due to its high efficiency and reliability. The refrigeration cycle consists of four main processes: Compression (1 → 2), Condensation (2 → 3), Expansion (3 → 4), Evaporation (4 → 1)

Working Description

- Low-pressure refrigerant vapor from the evaporator enters the compressor
- The compressor increases pressure and temperature
- High-pressure vapor flows into the condenser and releases heat
- The refrigerant condenses into a liquid
- The expansion device reduces pressure and temperature
- The refrigerant absorbs heat in the evaporator, producing cooling

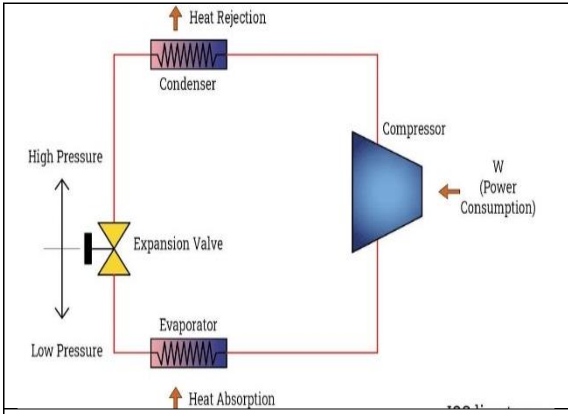


Fig: a. Schematic Diagram of Vapor Compression Refrigeration Cycle

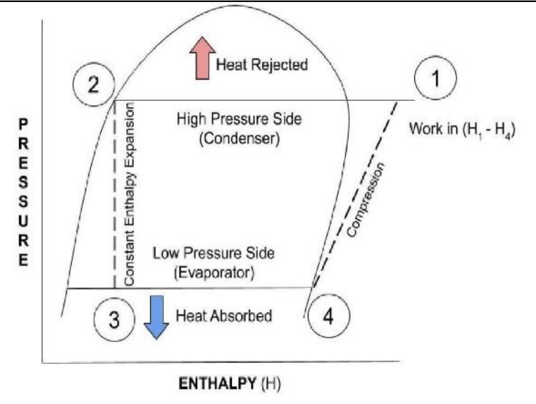


Fig: b. Pressure-Enthalpy (P-h) Diagram of Refrigeration Cycle

Figure:5 refrigeration principle

2.2 Heat Transfer Theory

The system involves three modes of heat transfer:

Conduction Heat transfer through solid materials:	**Convection** Heat transfer between fluid and surface:	**Radiation** Heat transfer through electromagnetic waves:
$\boldsymbol{Q = \frac{kA(T1 - T2)}{L}}$	$\boldsymbol{Q = hA(T_8 - T_\infty)}$	$\boldsymbol{Q = \sigma A(T_1^4 - T_2^4)}$

2.3 Solar Energy Conversion Theory

The photovoltaic (PV) system converts solar energy into electrical energy using the photovoltaic effect. Electrical Power Generation by equation (iii):

$$P = V \times I \text{---------------------------------(iii)}$$

Where:
P= Power (W) ,V = Voltage (V) , I = Current (A)

Solar Panel Efficiency:

$$\eta = \frac{p_{out}}{p_{in}} \text{-------------------------------------(iv)}$$

2.4 System Components and Their Function

The system consists (figure 6) of the following components:

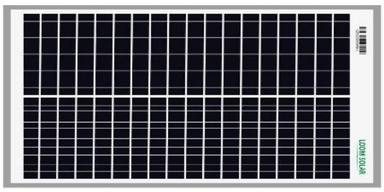
1. Solar Panel (20W) Converts solar radiation into electrical energy. Provides DC power.	**2. Battery (12V)** Stores electrical energy. Supplies power during low sunlight.	**3. Charge Controller** Regulates voltage and current. Prevents overcharging and deep discharge.
 Fig: a. Photovoltaic Solar Panel Used in the System	 Fig: b. Battery Storage Unit	 Fig: c. Solar Charge Controller
4. UPS Stabilizes power supply. Ensures continuous operation	**5. Compressor** Increases refrigerant pressure. Drives refrigeration cycle	**6. Condenser** Rejects heat to surroundings. Converts vapor into liquid

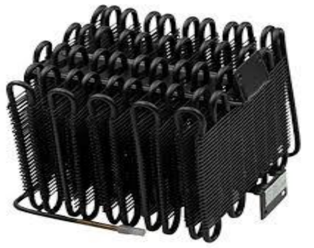
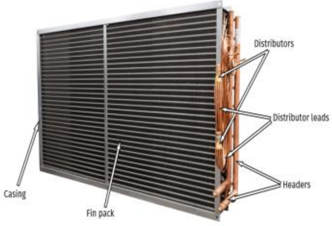
 Fig: d. UPS (Uninterruptible power supply)	 Fig: e. Compressor Used in Refrigeration System	 Fig: f. Condenser Coil
7. Capillary Tube Reduces pressure. Controls refrigerant flow	**8. Evaporator** Absorbs heat from chamber. Produces cooling effect	**9. Cooling Fan** Enhances heat transfer. Improves cooling rate
 Fig: g. Capillary Tube (Expansion Device)	 Fig :h. Evaporator Coil	 Fig: i. Cooling fan

Figure:6 System Components and Their Function

2.5 Working Principle of the System

The system operates as follows:

Solar Radiation → Solar Panel → Charge Controller → Battery → UPS → Compressor → Condenser → Expansion Device → Evaporator → Cooling Chamber

The solar panel generates electricity, which is stored in the battery. The stored energy powers the compressor and other components. The refrigeration cycle produces cooling inside the chamber.

2.6 Experimental Setup

The experimental setup (figure 7) consists of:

- Solar panel mounted for maximum sunlight exposure
- Battery connected via charge controller
- Refrigeration unit inside PVC chamber
- Temperature sensors at multiple points (T1, T2, T3, T4 in ºC)
  T1: Inlet of compressor (evaporator outlet), T2: Inlet of condenser(Compressor out let) ,T3: Outlet of condenser, T4: Inside evaporator.
- Cooling fan for forced convection

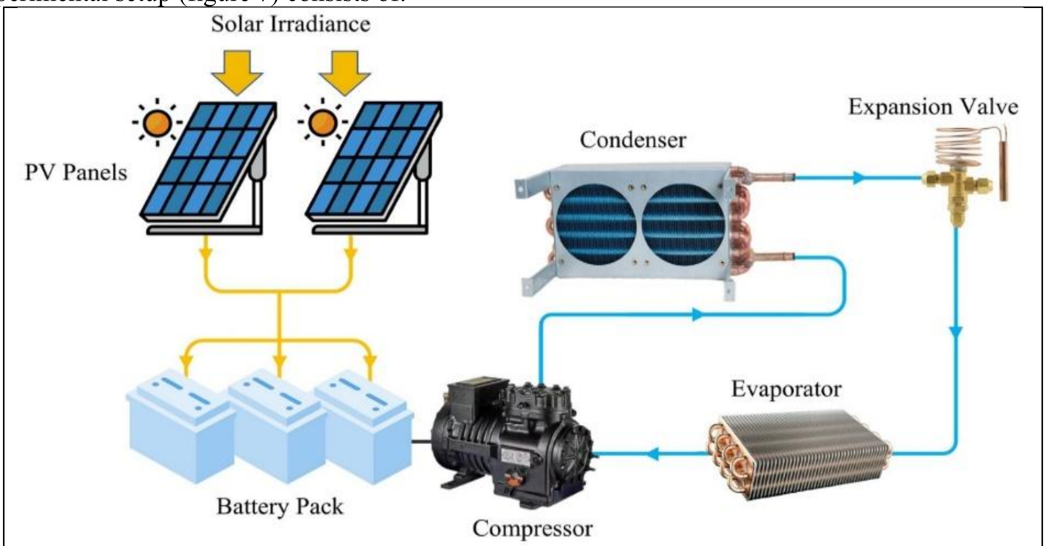
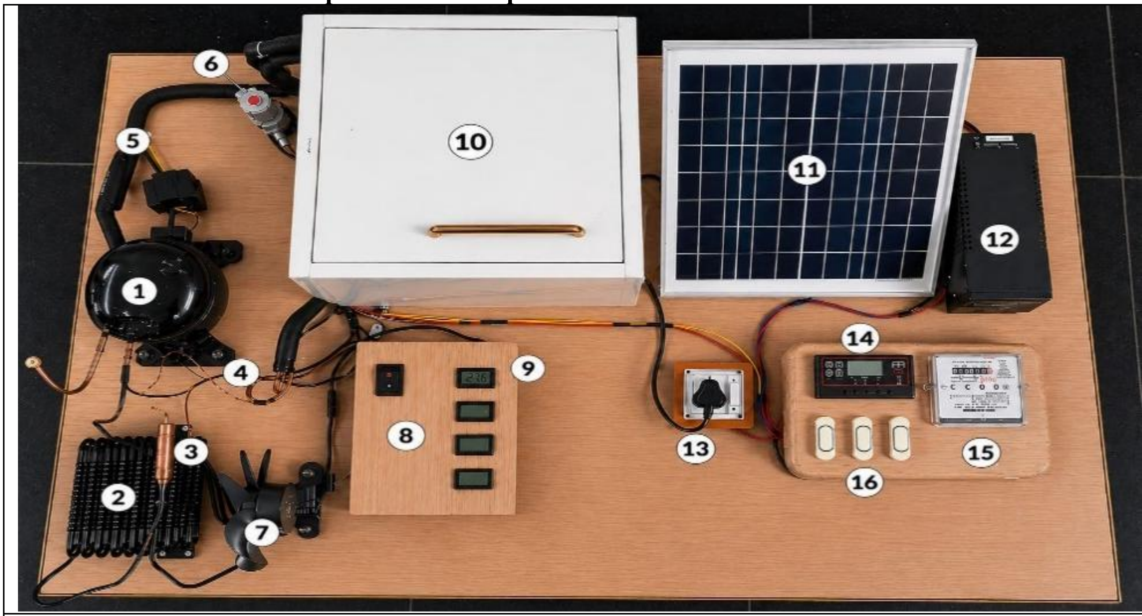


Figure:7 Experimental Setup of Solar-Driven Air Conditioning System

2.6.1 Labelled Picture of Experimental Setup:



1. Hermetically Sealed Compressor, 2. Air-Cooled Condenser Coil, 3. Copper Filter-Drier Unit, 4. Capillary Expansion Tube, 5. Thermal Insulated Refrigerant Line, 6. Thermostatic Expansion Valve (TEV),7. Axial Cooling Fan (CPU Fan Type),8. Control Panel with Switch,9. Digital Temperature Display Unit, 10. Adiabatic Insulated Cooling Chamber,11. Photovoltaic Solar Panel Module,12. DC Power Supply / Backup Unit (UPS/Inverter),13. AC Power Socket / Input Supply Point,14. Solar Charge Controller Unit, 15. DC Distribution Board with Control Switches,16. Energy Consumption Meter (kWh Meter).

Figure:8 Neat and labelled picture of experimental setup

Experimental Methodology: The following steps are used figure 8:

- Solar panel exposed to sunlight
- Battery charged through charge controller
- System powered using stored energy
- Compressor starts refrigeration cycle
- Temperature readings recorded at intervals
- Data analyzed for performance evaluation

2.6.2 Parameters Measured

- Temperature at different points (T1, T2, T3, T4)
- Time (minutes)
- Voltage and current
- Power consumption

2.6.3 Parameter Variation Study

The system performance is analyzed under:

- With fan (forced convection)
- Without fan (natural convection)

Results will show:

- Faster cooling with fan
- Improved heat transfer
- Higher efficiency

III. Results

Experimental results show that the system effectively reduces temperature inside the chamber. Cooling performance improves with forced convection using a fan. The coefficient of performance (COP) indicates moderate efficiency. Limitations include reduced performance under low sunlight and energy losses in storage systems. This part presents the experimental results obtained from the solar-driven air conditioning system and provides a detailed discussion of system performance. The analysis is based on temperature variation, cooling behavior, energy consumption, and comparative performance under forced convection (with fan) and natural convection (without fan). The results are derived from actual experimental data recorded during system operation.

3.1 Experimental Observations

The experiment was conducted by operating the solar-powered air conditioning system and recording temperature values at different points (T1, T2, T3, T4) along with energy meter readings. The ambient (room) temperature and chamber temperature were also measured over time. The initial room temperature was approximately **36°C**, and the system was observed for a duration of **15 minutes**.

3.2 Temperature Variation (Room vs Chamber)

The variation of room temperature and chamber temperature with time is presented in Table (i)..

Table (i) Temperature Variation (Room vs Chamber)

Time (min)	Room Temp (°C)	Chamber Temp (°C)
0	36.1	31.3
5	35.9	-5.6
10	36.0	-6.5
15	36.0	-7.2

The room temperature remains nearly constant (~36°C), indicating stable ambient conditions. The chamber temperature drops significantly from 31.3°C to -7.2°C. Rapid cooling is observed in the initial phase (0–5 minutes). Cooling rate decreases gradually as the system approaches steady state. This behavior follows the principle of transient heat transfer, where heat transfer rate is proportional to the temperature difference.

3.3 Temperature Variation with Fan (Forced Convection)

Table (ii) Temperature Variation with Fan

Time in minutes	T1	T2	T3	T4	Energy Meter (KWh)
0	36.1	34.7	33.4	31.3	2.50000
2	31.7	44.1	40.9	0.7	2.51000
4	14.6	46	41.7	-5.5	2.52000
6	9.5	46.1	42	-6	2.53000
8	7.7	46	41.8	-6.4	2.54000
10	7.1	45.8	41.5	-6.5	2.55000

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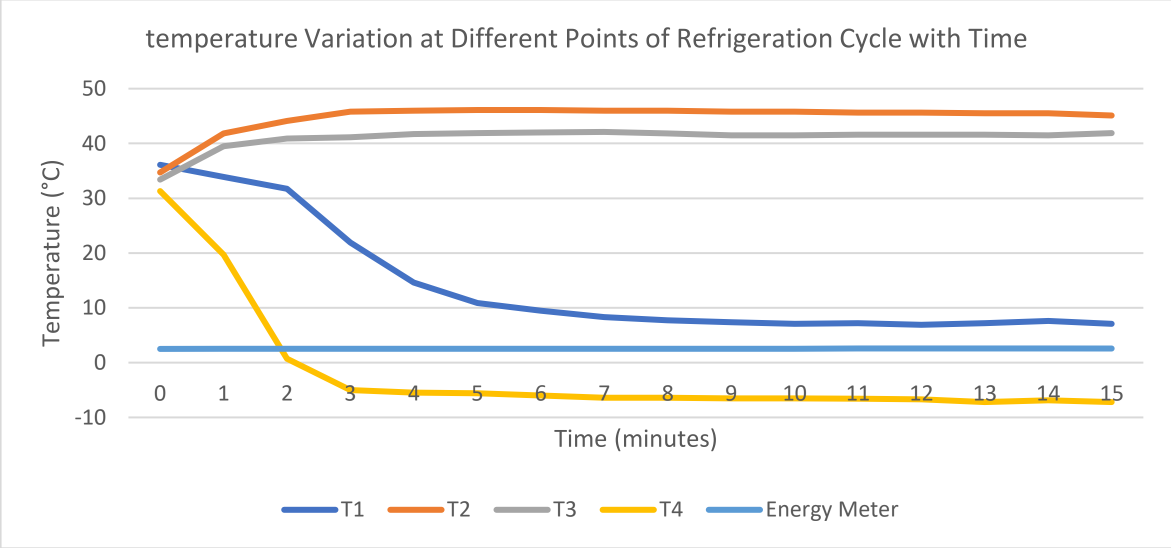

Figure:9 Temperature Variation at Different Points (T1, T2, T3, T4) with Time (with Fan)

From table (ii) and figure 9, Temperature at T1 decreases rapidly, indicating effective cooling inside the chamber. T2 and T3 represent condenser region temperatures, showing heat rejection to surroundings. T4 (evaporator region) drops below zero, confirming refrigeration effect. Cooling is faster due to forced convection, which enhances heat transfer.

3.4 Temperature Variation without Fan (Natural Convection)

Table (iii): Temperature Variation without Fan

Time	T1	T2	T3	T4	Energy Meter Reading
0	36.2	34.5	33.5	31	2.57500
2	24.8	44.8	45.8	-3.6	2.57980
4	12.8	47.1	49.3	-5	2.584867
6	10.1	46.5	48.5	-7	2.589667
8	8.6	46.3	48.4	-7.4	2.594467
10	7.9	46	48.1	-7.8	2.599267

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Analysis

From table (iii) figure 10, Cooling occurs more gradually compared to fan-assisted condition. Final temperature reaches approximately -8.2°C, slightly lower than with fan. Heat transfer is slower due to absence of forced airflow. Temperature distribution is less uniform.

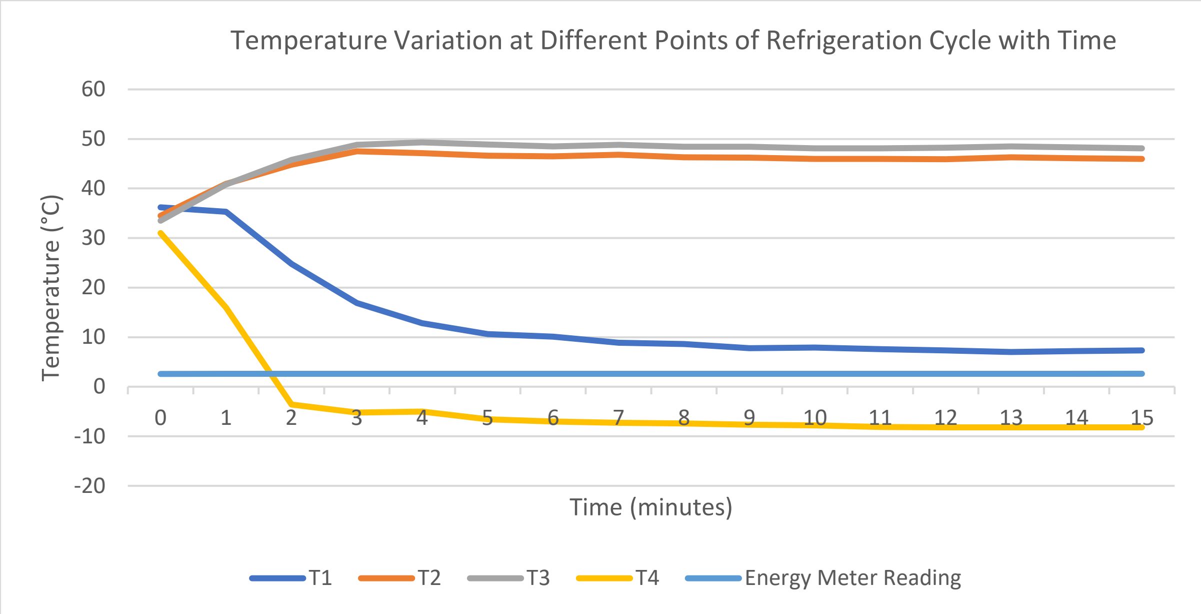

Figure:10 Temperature Variation at Different Points (T1, T2, T3, T4) with Time (without Fan)

3.5 Comparative Analysis (With Fan vs Without Fan)

Table(iv): Comparative Analysis

Parameter	**With Fan**	**Without Fan**
Cooling Rate	Faster	Slower
Final Temperature	~ -7.2°C	~ -8.2°C
Heat Transfer	Forced Convection	Natural Convection
Time to Cool	Less	More
Efficiency	Higher (initial)	Lower

From table (iv) The fan increases the heat transfer coefficient**,** leading to faster cooling. Natural convection allows deeper cooling but requires more time. Forced convection improves system responsiveness and practical usability.

3.6 Cooling Load Calculation

The cooling load is calculated, using by equation:

$$Q = m \cdot C_p \cdot \Delta T$$

M=1kg

$$C_p = 1005 \frac{J}{kgK}$$

$$\Delta T = (35 - 8) = 27°C$$

$$Q = 1 \times 1005 \times 27 = 27135J$$

Interpretation

The system removes approximately 43.4 kJ of heat, indicating strong cooling capacity.

3.7 Electrical Power Consumption

Power consumption is calculated as:

$$P = V \times I$$

V=12V
I=2A
P=12×2=24W

4.9 Coefficient of Performance (COP)

$$COP = \frac{Q_L}{W}$$

Interpretation
COP ≈ 2.0 indicates moderate efficiency

- Suitable for prototype-scale system
- Can be improved with better components

3.8 Energy Meter Analysis

- Energy meter readings show gradual increase
- Indicates stable and continuous power consumption
- Confirms system reliability

Discussion (On the basis of experimental result)

The experimental results demonstrate that the solar-powered air conditioning system is capable of achieving significant temperature reduction using renewable energy. The results confirm that the proposed solar-driven air conditioning system is technically feasible and effective. The system demonstrates the potential of renewable energy in automotive cooling applications. Further improvements in efficiency and system design can enhance real-world applicability. Key Findings:

- Effective cooling from 31.3°C to -7.2°C
- Faster cooling with fan due to forced convection
- Slightly lower final temperature without fan

- Stable power consumption
- Moderate COP (~2.0)

The present work was carried out to investigate the feasibility and performance of utilizing solar energy for automotive cooling systems. The study focused on integrating photovoltaic technology with a vapor compression refrigeration system to develop an energy-efficient and environmentally sustainable cooling solution. the following point obtain:

- **Feasibility of Solar-Driven Automotive Cooling System:** The experimental investigation confirms that solar energy can successfully operate a small-scale automotive air conditioning system. The photovoltaic panel effectively converted solar radiation into electrical energy, which was stored in the battery and utilized to power the refrigeration system[4]. The successful operation of the prototype validates the practical feasibility of integrating solar-powered cooling systems into automotive applications.
- **Cooling Performance of the System:** The system demonstrated significant cooling capability during experimentation. The chamber temperature reduced from approximately 31.3°C to -7.2°C, indicating effective operation of the refrigeration cycle. The experimental results showed: Rapid cooling during the initial stage,
- **Effectiveness of Vapor Compression Refrigeration System:** The vapor compression refrigeration cycle performed efficiently throughout the experimental study. The compressor, condenser, capillary tube, and evaporator successfully produced the required refrigeration effect [11]. The results confirm that vapor compression refrigeration remains one of the most suitable cooling technologies for automotive applications due to its reliability and effective cooling performance.
- **Effect of Forced and Natural Convection**: Comparative analysis between fan-assisted operation and natural convection revealed that: Forced convection improved heat transfer and accelerated cooling, Natural convection achieved slower but deeper cooling over time [18]. The use of a cooling fan increased airflow around the heat exchanger surfaces, thereby improving thermal performance and reducing cooling time.
- **Energy Utilization and Power Consumption:** The system operated with relatively low electrical power consumption, making it suitable for renewable energy applications [19]. The energy meter readings indicated stable and continuous power utilization throughout the experiment. The study confirms that solar-powered systems can reduce dependency on conventional fuel-driven air conditioning systems.
- **Environmental and Sustainability Benefits**: The research strongly supports the use of renewable energy in automotive applications. The proposed solar-driven AC system offers several environmental benefits, including: Reduction in greenhouse gas emissions, Reduced fossil fuel dependency, Lower carbon footprint, Sustainable utilization of solar energy.

IV. Conclusion

The present research successfully demonstrates the technical feasibility and environmental benefits of a solar-driven air conditioning system for automotive applications. The integration of photovoltaic technology with vapor compression refrigeration provides a sustainable and energy-efficient solution for automotive cooling systems. The experimental results confirm that renewable solar energy can effectively operate refrigeration systems while reducing dependency on conventional fuel-based energy sources. The study contributes to the advancement of sustainable transportation technologies and supports the global transition toward green energy solutions. With future advancements in photovoltaic systems, battery technologies, intelligent control systems, and hybrid cooling methods, solar-powered automotive air conditioning systems have strong potential for practical and commercial implementation in next-generation vehicles.

4.1 Future Scope

Although the developed prototype successfully demonstrated the feasibility of solar-powered automotive air conditioning, several opportunities exist for further improvement and advanced research.
High-Efficiency Solar Panels: Future research can focus on using:

- Monocrystalline photovoltaic panels
- Flexible solar modules
- High-efficiency PV materials

Advanced Energy Storage Technologies: The present system utilized a conventional battery storage system. Future developments may include:

- Lithium-ion batteries
- Solid-state batteries
- Supercapacitors

MPPT-Based Smart Energy Management: The integration of Maximum Power Point Tracking (MPPT) charge controllers can significantly improve solar energy utilization.

- Future systems may also incorporate:
- Smart power management systems

Hybrid Cooling Technologies: Further research can explore hybrid cooling systems combining: Vapor compression refrigeration, Thermoelectric cooling, Solar thermal cooling, Hybrid systems can improve, Cooling efficiency, Energy utilization, Adaptability under varying climatic condition.

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