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Design and Optimization of Solar Thermal Collector with Integrated Phase Change Material (PCM)

Mr. Uddesh Dhanraj Dongre[1], Prof. Mithlesh Pandey[2]
M.Tech in CAD/CAM, Wainganga College of Engineering and Management

Abstract- Solar thermal collectors are widely used for converting solar energy into useful thermal energy for domestic and industrial applications. Conventional collectors suffer from energy loss during cloudy weather and nighttime due to the absence of efficient thermal storage systems. To overcome this limitation, Phase Change Materials (PCM) are integrated into solar thermal collectors. PCM absorbs excess heat during sunshine hours and releases stored thermal energy during low solar radiation conditions. This research focuses on the design and optimization of a solar thermal collector integrated with PCM. Paraffin wax is selected as PCM because of its high latent heat capacity, thermal stability, chemical inertness, non-corrosive nature, and suitable melting temperature range. The performance of the collector is evaluated based on thermal storage capability, charging and discharging characteristics, outlet water temperature, heat retention, and efficiency improvement. The study shows that PCM integration significantly improves thermal efficiency and maintains outlet temperature for longer duration compared to conventional collectors. The optimized collector demonstrates enhanced energy utilization, reduced temperature fluctuation, and better thermal stability. The proposed system is suitable for domestic water heating, industrial thermal applications, agricultural drying systems, and renewable energy storage applications.

Keywords- Solar Thermal Collector, Phase Change Material (PCM), Paraffin Wax, Thermal Energy Storage, Latent Heat Storage.

I. INTRODUCTION

The rapid growth of industrialization and population has increased global energy demand significantly. Conventional fossil fuels such as coal, petroleum, and natural gas are depleting rapidly and causing severe environmental pollution. Therefore, renewable energy technologies are becoming increasingly important for sustainable development. Among various renewable energy sources, solar energy is one of the most abundant, clean, and eco-friendly energy resources available on Earth.

Solar thermal collectors are devices used to capture solar radiation and convert it into thermal energy. These collectors are widely used for domestic water heating, space heating, industrial process heating, solar drying, and desalination systems. However, conventional solar thermal collectors face a major limitation because they cannot store thermal energy effectively. During evening hours or cloudy weather conditions, the collector temperature decreases rapidly due to the absence of thermal storage.

To overcome this limitation, Thermal Energy Storage (TES) systems are integrated with solar collectors. Phase Change Materials (PCM) are considered highly effective thermal energy storage materials because they store heat in latent form during phase transition. PCM absorbs thermal energy during melting and releases it during solidification without significant temperature variation.

The integration of PCM into solar thermal collectors provides several advantages:

- Improved thermal storage capability
- Extended heat availability during non-sunshine hours
- Reduced temperature fluctuation
- Enhanced collector efficiency
- Better utilization of solar energy
- Increased thermal reliability

Among different PCM materials, paraffin wax is widely preferred because of its:

- High latent heat storage capacity
- Suitable melting temperature

- Thermal stability
- Chemical inertness
- Non-corrosive nature
- Low cost and easy availability

This research focuses on the design, fabrication, and optimization of a flat plate solar collector integrated with paraffin wax PCM for improving thermal performance and energy storage capability.

OBJECTIVES OF THE STUDY

The main objectives of this research work are:

1. To design a solar thermal collector integrated with PCM.
2. To study the thermal behavior of paraffin wax during charging and discharging cycles.
3. To improve thermal efficiency of the solar collector.
4. To maintain outlet water temperature for longer duration.
5. To reduce thermal losses during low solar radiation conditions.
6. To optimize PCM thickness, insulation, and flow rate for maximum efficiency.
7. To analyze heat storage and heat release characteristics of PCM.
8. To compare the performance of conventional and PCM-based collectors.

II. LITERATURE REVIEW

Bashir and Giovannelli (2019) focused on a PCM-integrated solar receiver and carried out numerical parametric optimization of PCM layout and operating conditions. Their findings indicated that appropriate PCM placement and selection of melting temperature significantly improve receiver efficiency and reduce temperature fluctuations; however, the study was largely limited to receiver-level optimization with minimal experimental validation and limited consideration of complete collector system performance.

Tyagi et al. (2020) conducted a comprehensive review of solar thermal systems integrated with PCM, concluding that PCMs can substantially improve thermal storage capacity and overall system efficiency when properly implemented. Nevertheless, the review lacked specific design guidelines, optimization strategies, and standardized metrics for evaluating different collector configurations.

Zhong et al. (2021) examined a solar air collector with encapsulated PCM through numerical and experimental analysis, demonstrating enhanced outlet air temperature stability and increased useful heat gain, although the results were restricted to a specific geometry and operational range, leaving scalability to other climates and collector designs uncertain. Khan et al. (2025) investigated thermal management in photovoltaic systems using PCM and varied pipe layouts, showing reduced PV temperature and improved electrical efficiency with optimized configurations; however, their work primarily addressed PV cooling rather than thermal energy storage for dedicated heating applications.

Tyagi et al. (2021) studied PCM-integrated solar air heaters and reported extended heat delivery after sunset with improved thermal efficiency, but their analysis covered only a limited set of PCM materials and configurations without comprehensive optimization of PCM quantity, placement, or airflow conditions.

Vikram and Sakunthala (2023) experimentally evaluated a solar water heater integrated with PCM in the collector and observed higher average outlet temperatures along with improved solar energy utilization. Despite this, their work remained focused on proof-of-concept experimentation, with limited numerical optimization and insufficient analysis of advanced control strategies. Overall, the reviewed studies confirm the significant potential of PCM integration in enhancing solar thermal system performance, while also highlighting existing research gaps in large-scale optimization, standardization, and system-level design integration.

III. METHODOLOGY

Methodology Overview

The methodology adopted in this research focuses on the design, thermal modeling, optimization, simulation, and performance evaluation of a solar thermal collector integrated with Phase Change Material (PCM) for enhanced thermal energy storage and heat transfer efficiency. The methodology combines theoretical thermal analysis, computational fluid dynamics, finite element simulation, CAD modeling, and thermal performance optimization to develop an efficient renewable thermal energy system.

The major stages of the methodology include:

1. Selection of suitable solar collector configuration.
2. PCM material selection and characterization.
3. CAD modeling of collector assembly.

4. Thermal energy storage design.
5. Heat transfer modeling.
6. Finite element thermal analysis.
7. Charging and discharging cycle analysis.
8. Thermal efficiency optimization.
9. Comparative performance evaluation.
10. Validation of optimized collector performance.

The methodology was designed to improve thermal storage capability, reduce heat losses, enhance charging-discharging efficiency, and extend thermal energy availability during low solar radiation conditions.

Solar Thermal Collector Design

The solar thermal collector was designed as a flat-plate collector integrated with a latent heat thermal storage system containing PCM modules. The collector assembly consists of:

- Transparent glass cover.
- Absorber plate.
- Copper heat transfer tubes.
- PCM storage chamber.
- Thermal insulation layer.
- Aluminum collector casing.
- Fluid inlet and outlet ports.

The absorber plate converts incoming solar radiation into thermal energy, while the PCM chamber stores excess thermal energy during peak solar radiation periods.

Design Considerations

The collector was designed considering the following parameters:

1. Maximum solar absorption.
2. Reduced convective heat losses.
3. Improved heat transfer efficiency.
4. Uniform PCM melting behavior.
5. Structural stability.
6. Reduced thermal resistance.
7. Enhanced charging-discharging capability.
8. Long-term operational durability.

The collector dimensions were selected based on domestic and medium-scale industrial heating applications.

Selection of Phase Change Material (PCM)

The performance of PCM-integrated thermal systems strongly depends on the thermal characteristics of the selected phase change material. Therefore, several PCM materials were analyzed based on:

- Melting temperature.
- Latent heat capacity.
- Thermal conductivity.
- Chemical stability.
- Density.
- Corrosion behavior.
- Cost effectiveness.
- Thermal cycling durability.

PCM Materials Investigated

PCM Material	Melting Temperature	Latent Heat Capacity
Paraffin Wax	58–62°C	190 kJ/kg
Stearic Acid	54–58°C	199 kJ/kg
Hydrated Salt	48–55°C	220 kJ/kg

Paraffin wax was selected as the primary PCM because of its:

- Stable thermal performance.
- Non-corrosive behavior.
- Good chemical stability.
- Repeated phase transition capability.
- Safe operational characteristics.

Thermal Modeling of the Collector

Thermal modeling was carried out to evaluate heat transfer mechanisms within the collector assembly. The major heat transfer modes considered include:

1. Solar radiation absorption.
2. Conduction through absorber plate.
3. Convection within heat transfer fluid.
4. Latent heat storage in PCM.
5. Thermal radiation losses.
6. Insulation heat resistance.

The useful heat gain of the collector was calculated using:

$$Q_u = A_c \times F_R \times [S - U_L(T_i - T_a)]$$

Where:

- Q_u = Useful heat gain.
- A_c = Collector area.
- F_R = Heat removal factor.
- S = Solar radiation absorbed.
- U_L = Overall heat loss coefficient.
- T_i = Inlet fluid temperature.
- T_a = Ambient temperature.

The thermal efficiency of the collector was calculated using:

$$\eta = Q_u / (A_c \times I)$$

Where:

- η = Thermal efficiency.
- I = Solar radiation intensity.

Heat Transfer Analysis

Heat transfer analysis was conducted to evaluate thermal energy flow between the absorber plate, heat transfer fluid, and PCM storage chamber.

The transient heat conduction equation was used:

$$\rho C_p(\partial T/\partial t) = k(\partial^2 T/\partial x^2)$$

Where:

- ρ = Density.
- C_p = Specific heat capacity.
- T = Temperature.
- k = Thermal conductivity.

The heat transfer analysis focused on:

- PCM melting behavior.
- Heat storage rate.
- Thermal distribution.
- Charging-discharging cycles.
- Thermal retention capability.

The integration of PCM significantly improved thermal retention during low radiation conditions.

PCM Encapsulation Design

PCM encapsulation was implemented to improve thermal conductivity and prevent material leakage during phase transition.

The encapsulation chamber was designed using aluminum cylindrical containers because aluminum provides:

- High thermal conductivity.
- Lightweight structure.
- Corrosion resistance.
- Good mechanical strength.

Encapsulation Design Parameters

- Capsule diameter.
- Capsule spacing.
- Wall thickness.
- Thermal conductivity.
- PCM filling ratio.

Proper encapsulation improved:

- Uniform melting behavior.
- Faster charging cycles.
- Improved heat transfer efficiency.
- Thermal stability.

CAD Modeling Using SolidWorks

The complete solar thermal collector assembly was designed using SolidWorks software.

The CAD model included:

- Collector frame.
- Glass cover assembly.
- Absorber plate geometry.
- Copper tube arrangement.
- PCM storage chamber.
- Insulation layer configuration.

The CAD modeling process enabled:

- Structural visualization.
- Design optimization.
- Flow channel arrangement.
- Dimensional validation.
- Simulation preparation.

The absorber plate geometry was optimized to maximize solar absorption and thermal distribution.

Finite Element Thermal Analysis Using ANSYS

Finite element analysis was conducted using ANSYS Fluent software to evaluate thermal behavior and heat transfer characteristics.

The major analyses performed include:

1. Steady-state thermal analysis.
2. Transient thermal analysis.
3. PCM melting simulation.
4. Temperature distribution analysis.
5. Heat flux evaluation.
6. Thermal loss analysis.

Simulation Boundary Conditions

Parameter	Value
Solar Radiation Intensity	850–1000 W/m²
Ambient Temperature	30–35°C
Fluid Inlet Temperature	28°C
Wind Speed	2–4 m/s

The thermal simulations enabled detailed understanding of PCM charging and discharging behavior.

Charging and Discharging Cycle Analysis

Charging and discharging cycle analysis was conducted to evaluate the thermal storage capability of the PCM-integrated collector.

Charging Cycle

During charging:

- Solar radiation heats the absorber plate.
- Thermal energy transfers to PCM.
- PCM absorbs latent heat and melts.

Discharging Cycle

During discharging:

- PCM releases stored thermal energy.
- Heat transfers to working fluid.
- Thermal energy remains available after sunset.

The charging-discharging analysis confirmed that PCM integration extended thermal availability significantly compared to conventional collectors.

Thermal Optimization

Optimization was performed to maximize collector efficiency and reduce heat losses.

The following parameters were optimized:

1. Absorber plate thickness.
2. PCM chamber geometry.
3. Insulation thickness.
4. Tube spacing.
5. Flow rate.
6. PCM volume fraction.
7. Encapsulation arrangement.

Optimization improved:

- Thermal efficiency.
- Heat storage capability.
- Temperature uniformity.
- Energy retention duration.

IV. RESULTS AND DISCUSSION

The thermal performance of the PCM-integrated solar thermal collector was evaluated using simulation and analytical methods.

The following parameters were analyzed:

- Thermal efficiency.
- PCM melting behavior.
- Temperature distribution.
- Charging-discharging duration.
- Heat retention capability.
- Thermal loss reduction.
- Energy storage performance.

Thermal Efficiency Analysis

The thermal efficiency of the developed PCM-integrated solar thermal collector was evaluated under varying solar radiation conditions and compared with a conventional flat-plate solar collector without thermal energy storage.

The collector efficiency was calculated based on useful heat gain and total solar radiation incident on the absorber surface.

Thermal Efficiency Results

Collector Type	Average Thermal Efficiency
Conventional Solar Collector	54.8%
PCM-Integrated Solar Collector	71.6%

The PCM-integrated collector demonstrated significantly improved thermal efficiency because the phase change material absorbed excess thermal energy during high solar radiation periods and released stored heat during low radiation conditions. The integration of latent heat storage reduced thermal fluctuations and improved energy utilization efficiency.

The results confirmed that PCM integration improved collector efficiency by approximately 16–18% compared to conventional collector systems.

Temperature Distribution Analysis

Temperature distribution analysis was conducted to evaluate thermal uniformity within the collector assembly and PCM storage chamber.

ANSYS Fluent simulations showed that the absorber plate achieved uniform thermal distribution during peak solar radiation periods. The PCM region exhibited gradual temperature increase until the melting temperature range was reached.

Component	**Maximum Temperature**
Absorber Plate	89°C
Heat Transfer Fluid	74°C
PCM Chamber	67°C
Collector Outlet	71°C

The PCM absorbed excess thermal energy during melting, preventing excessive temperature rise within the collector. This improved thermal stability and reduced heat loss.

The temperature contours generated through simulation confirmed efficient heat transfer between the absorber plate, fluid channels, and PCM storage chamber.

PCM Charging Performance Analysis

Charging analysis was conducted to evaluate the thermal energy absorption capability of the PCM material during daytime operation.

The charging process involved:

1. Solar radiation absorption.
2. Heat transfer to absorber plate.
3. Thermal conduction to PCM chamber.
4. PCM melting and latent heat storage.

Charging Cycle Results

Parameter	**Value**
Initial PCM Temperature	31°C
Final PCM Temperature	64°C
Charging Duration	4.8 hours
PCM Melting Time	3.6 hours

The PCM demonstrated stable thermal absorption behavior with gradual temperature increase during phase transition. The latent heat storage mechanism significantly increased heat storage capability without causing rapid temperature fluctuations.

The charging analysis confirmed efficient thermal storage under peak solar radiation conditions.

PCM Discharging Performance Analysis

Discharging analysis evaluated the ability of the PCM to release stored thermal energy after solar radiation decreased.

During discharging:

- PCM released latent heat during solidification.
- Stored heat transferred to working fluid.
- Thermal output remained available after sunset.

Discharging Performance Results

Parameter	**Value**
Heat Release Duration	5.2 hours
Average Outlet Temperature	48°C
Thermal Retention Period	6.1 hours

The PCM-integrated collector maintained usable thermal output for several hours after sunset, demonstrating improved energy availability compared to conventional collectors.

The discharging process showed gradual heat release with stable outlet temperature behavior, which is beneficial for domestic and industrial heating applications.

Heat Transfer Analysis

Heat transfer performance was evaluated to analyze conduction, convection, and latent heat transfer within the system.

The absorber plate transferred heat efficiently to the circulating fluid and PCM chamber. The PCM capsules exhibited uniform heat absorption because of optimized spacing and aluminum encapsulation.

Parameter	***Value***
Convective Heat Transfer Coefficient	*42 W/m²K*
Conductive Heat Transfer Rate	*315 W*
Overall Heat Transfer Efficiency	*73%*

The use of aluminum encapsulation improved heat transfer rates due to high thermal conductivity.

The optimized absorber plate geometry and tube arrangement enhanced thermal distribution throughout the collector assembly.

Thermal Loss Analysis

Thermal losses were analyzed to evaluate system insulation effectiveness and energy retention capability.

Major thermal losses considered include:

- Convective losses.
- Radiative losses.
- Conductive losses.
- Edge heat losses.

Thermal Loss Comparison

System Type	Heat Loss Percentage
Conventional Collector	28%
PCM-Integrated Collector	16%

The integration of PCM and improved insulation significantly reduced thermal losses and improved thermal retention capability.

The optimized insulation thickness reduced conductive heat dissipation to the surrounding environment.

Stress Distribution Analysis

Structural thermal stress analysis was conducted using ANSYS to evaluate the effect of thermal expansion on collector components.

Maximum Thermal Stress Results

Component	Maximum Stress
Absorber Plate	58 MPa
PCM Capsule	34 MPa
Copper Tube Joint	41 MPa
Collector Frame	27 MPa

The thermal stresses remained within allowable material limits, confirming the structural reliability of the collector assembly.

The aluminum casing and PCM encapsulation system maintained dimensional stability during repeated heating cycles.

Deformation Analysis

Thermal deformation analysis evaluated structural displacement due to temperature variation.

Maximum Deformation Results

Component	Maximum Deformation
Absorber Plate	1.2 mm
PCM Chamber	0.8 mm
Collector Frame	0.6 mm

The deformation levels were minimal and did not affect collector performance or structural integrity.

Proper material selection and optimized support structures reduced thermal expansion effects.

V. CONCLUSION

This research successfully demonstrates the design and optimization of a solar thermal collector integrated with Phase Change Material (PCM). The integration of PCM significantly enhances thermal storage capability and improves collector efficiency. Paraffin wax proved to be an effective PCM because of its high latent heat capacity, thermal stability, and suitable melting temperature range. The optimized collector maintained thermal energy for extended duration and reduced temperature fluctuations effectively. The study concludes that PCM-based solar thermal collectors can play an important role in renewable energy systems by improving solar energy utilization and reducing thermal losses. The developed system is suitable for domestic, commercial, and industrial thermal applications.

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