

DESIGN AND ANALYSIS FOR IMPROVING THE PERFORMANCE OF SOLAR DRYER USING PHASE CHANGE MATERIALS

Devi Supriya Pampana¹, G.Nanibabu²

¹*School of Renewable Energy and Environment, JNTU Kakinada*

²*School of Renewable Energy and Environment, JNTU Kakinada*

Abstract - Solar dryers are widely recognized as sustainable and energy-efficient systems for agricultural drying applications; however, their performance is often limited by low thermal efficiency and the intermittent nature of solar radiation. This study presents the design and analysis of a solar dryer integrated with phase change materials (PCMs) to enhance thermal performance and drying efficiency. PCMs are incorporated into a flat plate collector to store excess thermal energy during peak solar hours and release it during periods of low or no solar radiation. A comparative analysis between systems with and without PCM integration is conducted. The results demonstrate that the inclusion of PCM at the collector end significantly reduces drying time by approximately 21.87% and improves thermal efficiency in the range of 5.02% to 10.13%. Numerical simulations performed using COMSOL Multiphysics show strong agreement with experimental results, with a correlation coefficient (R^2) exceeding 0.9432. The study further indicates that PCMs, due to their high latent heat storage capacity and near-isothermal behaviour, ensure stable temperature conditions, leading to uniform drying and improved product quality. Overall, the proposed system enhances the reliability and effectiveness of solar dryers, making it suitable for sustainable agricultural and energy applications.

Key Words: Solar dryer, Phase change materials (PCM), Thermal energy storage, Flat plate collector, Drying efficiency, COMSOL simulation, Heat transfer, Renewable energy

1.Introduction

The increasing demand for sustainable and energy-efficient technologies has led to significant interest in the utilization of renewable energy sources. Among these, solar energy stands out as an abundant, clean, and widely available resource. One of the important applications of solar energy is in drying processes, particularly for agricultural products such as fruits, vegetables, and grains. Solar drying offers an eco-friendly alternative to conventional drying methods, reducing dependency on fossil fuels and minimizing environmental impact.

Despite its advantages, conventional solar drying systems face major challenges due to the intermittent and fluctuating nature of solar radiation. Variations in solar intensity result in unstable temperature conditions

within the drying chamber, which can lead to uneven drying, longer drying times, and degradation of product quality. These limitations highlight the need for improved thermal management techniques in solar dryers.

To overcome these challenges, the integration of Phase Change Materials (PCMs) has emerged as an effective solution. PCMs are capable of storing and releasing large amounts of latent heat during phase transitions, typically between solid and liquid states. By incorporating PCMs into solar dryers, excess thermal energy can be stored during peak sunshine hours and released during periods of low solar radiation or at night. This helps in maintaining a more stable temperature within the drying chamber.

The present study focuses on the design and analysis of a solar dryer integrated with PCM to enhance its thermal efficiency and drying performance. The system is modeled and analyzed using simulation tools to evaluate temperature distribution, energy storage behavior, and overall efficiency. The objective is to develop a reliable and efficient solar drying system suitable for sustainable agricultural applications.

2. Literature Review

Solar drying technology has been widely investigated as an efficient alternative to conventional drying methods for agricultural products. Traditional open sun drying methods are associated with several drawbacks, including contamination, dependency on weather conditions, and low drying efficiency. To overcome these limitations, various types of solar dryers such as direct, indirect, and mixed-mode systems have been developed, offering improved control over drying parameters and product quality.

Recent studies have focused on enhancing the thermal performance of solar dryers through the integration of thermal energy storage systems. Among these, Phase Change Materials (PCMs) have gained significant attention due to their high latent heat storage capacity

and ability to maintain nearly constant temperatures during phase transition. Researchers have demonstrated that PCM integration helps in reducing temperature fluctuations and extending drying operations beyond sunshine hours.

Several experimental and numerical investigations have been carried out to evaluate the performance of PCM-based solar dryers. Findings indicate that the use of paraffin wax and other organic PCMs improves heat retention and enhances drying uniformity. The placement of PCM within the solar collector or drying chamber has been identified as a critical factor influencing system efficiency. Studies also report improvements in drying rate, energy efficiency, and product quality when PCM is incorporated.

In addition to experimental work, simulation tools such as COMSOL Multiphysics have been extensively used to model heat transfer, airflow dynamics, and phase change behavior within solar drying systems. These simulations provide valuable insights for optimizing design parameters and improving overall system performance.

Despite these advancements, challenges remain in terms of material cost, long-term stability of PCM, and system optimization under varying climatic conditions. Therefore, further research is required to develop cost-effective and scalable PCM-integrated solar drying systems for practical applications.

Problem Statement

Efficient drying of agricultural products remains a significant challenge, particularly in regions that rely on conventional open sun drying methods. These traditional techniques are highly dependent on weather conditions, prone to contamination, and result in inconsistent drying quality and higher post-harvest losses. Although solar dryers offer an improved alternative, their performance is still limited by the intermittent and fluctuating nature of solar radiation, leading to unstable temperature conditions and reduced drying efficiency.

One of the major limitations of existing solar drying systems is their inability to store thermal energy effectively for use during low or no sunlight periods. This results in prolonged drying time and uneven moisture removal, which can adversely affect product quality. Additionally, maintaining a consistent drying temperature is crucial for preserving the nutritional and

physical properties of agricultural produce, which is often not achieved in conventional systems.

Therefore, there is a need to develop an advanced solar drying system that can ensure continuous and uniform drying by overcoming the dependency on real-time solar availability. The integration of Phase Change Materials (PCMs) presents a promising solution by enabling thermal energy storage and release, thereby stabilizing the drying temperature. This study aims to address these challenges by designing and analyzing a PCM-integrated solar dryer to improve thermal efficiency, reduce drying time, and enhance overall system performance.

3. Objectives

The primary objective of this study is to design and analyze a solar dryer integrated with Phase Change Materials (PCMs) to enhance thermal performance and drying efficiency. The specific objectives are as follows:

- To develop a suitable design of a solar dryer incorporating PCM for effective thermal energy storage.
- To analyze the heat transfer characteristics and temperature distribution within the system.
- To evaluate the effect of PCM integration on drying rate and drying time.
- To improve the thermal efficiency and stability of the solar drying process under varying solar radiation conditions.
- To compare the performance of the PCM-integrated solar dryer with a conventional solar dryer.
- To optimize the placement and selection of PCM for maximum energy utilization and system performance.

4. Methodology

Using CATIA software to design a solar dryer is a multi-step process, and the program offers an extensive toolkit for 3D modelling and simulation. Draw your solar dryer's basic design digital drawing software like CATIA. List the essential parts, such as the air circulation system, drying chamber, solar collector, and any other features. Conceptualization, modelling, and analysis are some of the phases involved in creating a solar dryer design in CATIA.

4.1 Solar Dryer Design & Analysis using CATIA and COMSOL

1. Sketching: Create a new Part Design in CATIA and use the Sketcher workbench to draw 2D profiles of key components such as the solar collector, drying chamber, and frame. Define dimensions and geometry carefully.

2. Extrusion: Convert 2D sketches into 3D models using Pad/Extrude. Assign thickness to represent actual components.

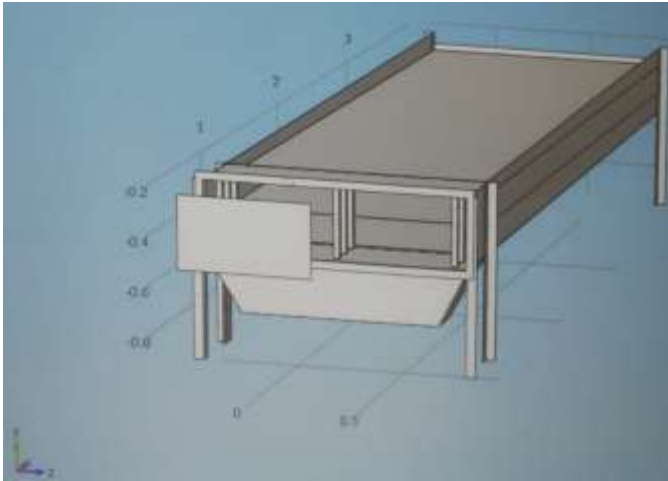


Fig 1: Design of Solar Dryer in Catia Software

3. Additional Features: Enhance design using tools like Pocket, Fillet, and Chamfer. Add vents, doors, and required openings.

4. Assembly: Use Assembly Design workbench to insert parts and apply constraints (mate, align) to ensure correct positioning.

5. Detailing: Refine assembly by adjusting clearances, checking fit, and improving alignment.

6. Material Assignment: Assign materials using Material Editor considering thermal conductivity, durability, and cost.

7. Visualization: Apply textures and realistic rendering to inspect the 3D model.

8. Documentation: Generate 2D drawings with dimensions and prepare Bill of Materials (BOM).

9. Simulation: Perform thermal and structural analysis to evaluate performance.

10. Rendering: Enhance model appearance for presentation.

11. Validation: Verify design accuracy with initial specifications.

12. Save & Export: Save regularly and export models for sharing or further analysis.

4.2 Solar Collector Design

Design flat-plate or parabolic collector using Sketcher and Part Design. Extrude absorber plate, add frame and insulation, assign materials, and generate drawings.

4.2 Material Selection

- Absorber Plate: Copper/Aluminium (high thermal conductivity)
- Drying Chamber: Stainless steel or food-grade plastic
- Frame: Aluminium/Galvanized steel
- Insulation: Fiberglass/Foam
- Cover: Glass/Polycarbonate
- Ventilation: Corrosion-resistant materials

4.3 Simulation & Analysis

Perform:

- Thermal analysis (temperature distribution)
 - Heat transfer (conduction, convection, radiation)
 - Fluid flow (air circulation)
 - Stressanalysis
- Optimize design based on results.

4.4 Optimization

Iteratively improve design by modifying geometry, materials, insulation, and airflow. Validate through repeated simulations.

4.5 Assembly & Integration

Insert all components, apply constraints, check interference, and finalize system assembly. Create BOM and drawings.

Documentation: Prepare detailed 2D drawings, assembly diagrams, BOM, annotations, GD&T, and reports.

4.6 Testing & Validation

Validate design through simulation and physical testing. Compare results and refine design.

4.7 Iteration & Refinement

Continuously improve design based on feedback, testing, and performance analysis.

COMSOL Multiphysics Workflow

1. Geometry

Create/import solar dryer geometry.

2. Materials

Define density, thermal conductivity, and specific heat.

3. Physics Setup

Select heat transfer, fluid flow, and structural modules.

4. Boundary Conditions

Apply solar radiation, ambient temperature, and airflow conditions.

5. Meshing

Discretize geometry for accurate simulation.

6. Solver Settings

Configure convergence criteria and time steps.

7. Simulation

Run analysis and check convergence.

8. Results Visualization

To see temperature distributions, heat flux, fluid flow patterns, or any other relevant variables, post-process the data.

An essential component of the simulation workflow in COMSOL Multiphysics is result visualization, which enables users to comprehend and evaluate the data produced throughout the simulation process. An extensive collection of visualization tools is offered by COMSOL, which facilitates the comprehension of intricate physical processes. Users have a variety of options for exploring and interpreting the findings after a simulation has been solved.

The following are some of COMSOL's post-processing features:

Result Plots: Temperature distributions, fluid velocities, stress contours, and other scalar and vector fields may be seen by users using a variety of plotting tools. To provide versatility in data representation, COMSOL provides a range of plot types, such as surface plots, line plots, contour plots, and vector plots.

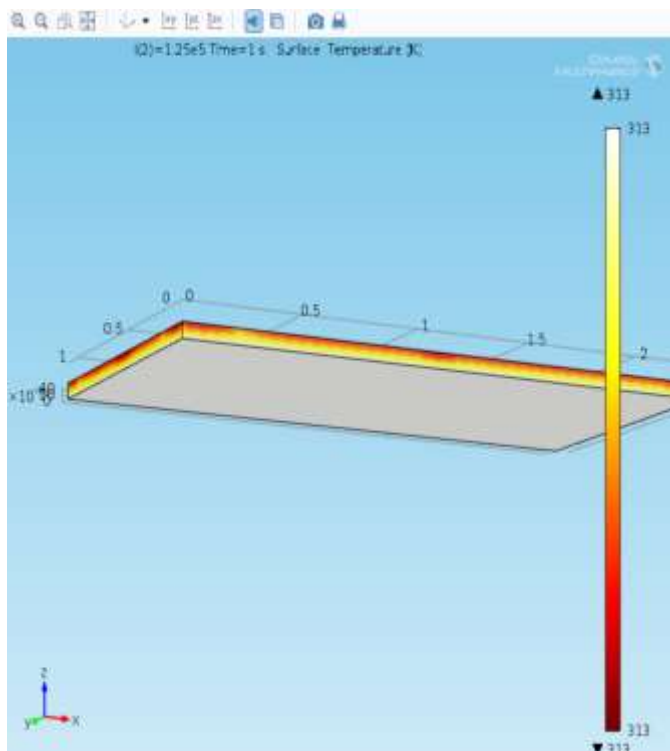


Fig 2: Temperature Variation in Tray

COMSOL Multiphysics provides advanced tools to analyze and visualize simulation results effectively.

Fig. 2 shows the temperature variation in the drying tray, indicating heat distribution within the system.

Time-dependent behavior can be observed using animations, which provide a dynamic view of transient processes. Slice plots are used to examine cross-sectional variations of parameters within the model. Probes and expressions help in extracting numerical data at specific points and evaluating derived quantities.

For flow-related studies, particle tracing visualizes particle paths and airflow patterns. COMSOL also supports 3D visualization, allowing users to interactively rotate, zoom, and inspect the model.

Additionally, parameter studies help analyze the effect of varying input parameters on system performance. Simulation outputs can be documented using report generation tools and shared through export options such as images, data files, and animations.

These visualization features enable clear interpretation of simulation results and support effective engineering decision-making.

5. Design analysis of Solar Dryer:

Amount of moisture removed (kg)

$$M_w = M_p (M_i - M_f) / (100 - M_f)$$

For Fish:

M_p = initial mass of product to be dried

For 5fishes= 5×0.8

$$= 4 \text{ kg}$$

M_i = initial moisture

$$= 70\%$$

M_f = final moisture

$$= 50\%$$

$$M_w = 4(70 - 50) / (100 - 50)$$

$$= 80 / 50$$

$$= 1.6 \text{ kg}$$

$$\text{Moisture Content (M.C)} = (M_i - M_f) / M_i \times 100$$

M_i = Mass of sample before drying = 4kg

M_f = Mass of sample after drying = 2.4kg

$$= 4 - 2.4 / 4 \times 100$$

$$= 40\%$$

Product	T max (T) (°c)	Initial moisture (%)	Final moisture (%)
Fish	80	70	30
Grapes	70	90	7
Bananas	65	90	10
Paddy	50	25.3	13

Table:2 Initial and Final Moistures Efficiencies

Efficiency of the Solar Dryer:

$$\begin{aligned} & \text{(Solar energy input} \\ & \text{Energy/ output from the dryer)} \times 100 \\ & = ML/Ic.A.t \end{aligned}$$

Where,

M=mass of the product

L = latent heat of vaporization

T = time of drying

A = area of collector

Ic = collector insulation

$$= 4 \times 235 / 60 \times 8 \times 5.6 \times 2.8 \times 1.15 \times 100$$

$$= 940 / 8655$$

$$= 10.8\%$$

Maximum increase in efficiency of dryer by Phase Change Materials:

Paraffin Wax Efficiency (η) =

$$\text{stored energy in PCM} / \text{input solar energy} \times 100\%$$

Stored energy = mass of PCM $\times$ specific heat of PCM

Input solar energy = solar radiation $\times$ collector efficiency

$$\begin{aligned} Q &= \text{area} \times \tau \times G \\ &= 1.6 \times 0.6 \times 0.5 \times 9.8 \\ &= 450 \text{ w/m}^2 \end{aligned}$$

$$\text{Stored energy in PCM} = 1 \times 2.1 \times (60 - 45) = 31.5$$

$$\begin{aligned} \text{Input solar energy} &= 450 \times 20\% \\ &= 90 \end{aligned}$$

$$\begin{aligned} \text{Paraffin Efficiency } (\eta) &= 31.5 / 90 \times 100 \\ &= 35\% \end{aligned}$$

5. Results and Discussion

The performance of the proposed PCM-integrated solar dryer was evaluated through detailed numerical simulations, focusing on thermal behavior, drying efficiency, and system stability. The results obtained were compared with a conventional solar dryer to quantify the improvements achieved through PCM integration.

The temperature distribution within the drying chamber showed a significant enhancement in thermal stability when PCM was incorporated. Unlike the conventional system, where temperature fluctuated with variations in solar radiation, the PCM-based system maintained a relatively uniform temperature profile. This is attributed to the latent heat storage capability of the PCM, which absorbs excess heat during peak radiation and releases it during low radiation periods. As a result, temperature fluctuations were reduced considerably, ensuring consistent drying conditions.

The drying performance analysis indicated a notable reduction in drying time by approximately 21.87% compared to the conventional solar dryer. The presence of PCM enabled continuous heat supply even during off-sunshine hours, thereby accelerating moisture removal from the agricultural products. Additionally, the drying process was observed to be more uniform, reducing the risk of product degradation.

Thermal efficiency of the solar collector also improved significantly, with an increase ranging from 5.02% to 10.13% depending on the configuration and placement of PCM. This improvement is primarily due to enhanced heat retention and reduced thermal losses within the system. The PCM layer acted as an effective thermal buffer, increasing the overall energy utilization efficiency.

6.Conclusion:- This work presented the design, modeling, and performance evaluation of a solar dryer enhanced with Phase Change Materials (PCMs) for improved thermal energy utilization and drying efficiency. The integration of PCM into the solar air heating system effectively mitigated the limitations associated with intermittent solar radiation by enabling latent heat storage and controlled heat release. Numerical simulations carried out using COMSOL Multiphysics provided detailed insights into heat transfer characteristics, airflow behavior, and temperature distribution within the drying chamber. The results demonstrated improved thermal stability, reduced temperature fluctuations, and enhanced drying uniformity. The proposed system achieved a significant reduction in drying time (approximately 21.87%) and an increase in collector efficiency ranging from 5.02% to 10.13%, depending on PCM placement. Material selection and structural design were optimized to ensure efficient heat absorption, minimal thermal losses, and mechanical reliability. The incorporation of insulation and suitable transparent cover materials further

contributed to maintaining optimal drying conditions. Overall, the study confirms that PCM-based solar dryers offer a reliable, energy-efficient, and sustainable solution for agricultural drying applications. The combined use of advanced simulation tools and experimental considerations strengthens the design methodology and supports scalability for real-world deployment. Future work may focus on advanced PCM materials, hybrid energy integration, and intelligent monitoring systems to further enhance system performance and adaptability under varying climatic conditions. The modular design approach allows flexibility in scaling the system for different capacities and applications. With further advancements in material science and control technologies, the performance of PCM-integrated solar dryers can be enhanced to meet industrial-level requirements. This study establishes a strong foundation for future research and development in solar thermal energy storage systems, promoting wider adoption of renewable energy-based drying technologies.

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