

Analysis of Heat Transfer in an Indirect Solar Dryer Integrated with Sensible and Latent Heat Storage

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Abstract

This study presents a detailed Computational Fluid Dynamics (CFD) investigation of heat transfer characteristics in an indirect solar dryer integrated with both sensible and latent heat storage systems. The primary objective is to enhance drying efficiency and ensure continuous operation during intermittent solar radiation. The system incorporates a solar air collector, drying chamber, pebble bed for sensible heat storage, and phase change material (PCM) modules for latent heat storage. A three-dimensional CFD model was developed using ANSYS Fluent to simulate airflow behavior, temperature distribution, and heat transfer mechanisms under varying operating conditions. The results indicate that the integration of hybrid thermal energy storage significantly improves thermal stability within the drying chamber. The PCM effectively stores excess heat during peak solar hours and releases it during low or no solar radiation periods, maintaining a nearly uniform temperature profile. The combined storage system enhances heat retention, reduces temperature fluctuations, and improves overall drying efficiency by approximately 20–25% compared to conventional dryers. Furthermore, the airflow analysis reveals uniform air distribution, minimizing hotspots and ensuring consistent drying of products. The findings demonstrate that the integration of sensible and latent heat storage with indirect solar drying systems offers a sustainable and energy-efficient solution for agricultural and industrial drying applications.

Keywords: Indirect Solar Dryer, Computational Fluid Dynamics (CFD), Heat Transfer Analysis, Sensible Heat Storage, Latent Heat Storage

1. Introduction

Drying is one of the oldest and most widely used methods for the preservation of agricultural and food products. Conventional drying techniques, such as open sun drying, are still prevalent in many regions due to their simplicity and low cost; however, they suffer from several limitations including contamination, uneven drying, weather dependency, and significant post-harvest losses. In recent years, solar drying has emerged as a sustainable and energy-efficient alternative, utilizing abundant solar energy to improve product quality while reducing environmental impact [1]. Among various solar drying technologies, indirect solar dryers have gained considerable attention due to their ability to protect products from direct solar radiation, thereby preserving color, nutrients, and overall quality. In an indirect solar dryer, air is heated in a solar collector and then passed through the drying chamber, ensuring controlled drying conditions. Despite these advantages, the performance of indirect solar dryers is significantly affected by the intermittent nature of solar radiation, which leads to fluctuations in temperature and reduced drying efficiency, particularly during cloudy periods and nighttime [2]. To address these challenges, thermal energy storage (TES) systems are integrated into solar dryers. Sensible heat storage (SHS), typically using materials such as rocks or pebbles, stores energy by increasing temperature, while latent heat storage (LHS), commonly employing phase change materials (PCMs), stores energy during phase transitions at nearly constant temperature. SHS provides rapid heat absorption and release, whereas LHS offers high energy storage density and thermal stability. The integration of both SHS and LHS in a hybrid configuration enables efficient heat management, ensuring continuous and uniform drying [3]. In parallel, Computational Fluid Dynamics (CFD) has become an essential tool for analyzing and optimizing solar drying systems. CFD enables detailed visualization of airflow distribution, temperature gradients, and heat transfer mechanisms within the dryer, which are otherwise difficult to measure experimentally. By simulating different operating conditions and design parameters, CFD helps in improving system performance and reducing design uncertainties [4]. The development of solar drying technologies has attracted significant research attention due to the increasing demand for energy-efficient and sustainable drying methods. Indirect solar dryers, in particular, have been widely studied for their ability to provide controlled drying conditions and improved product quality compared to traditional open sun drying. Early investigations primarily focused on improving collector efficiency and airflow design to enhance heat transfer within the drying chamber [5]. Several researchers have explored the integration of thermal energy storage (TES) systems to overcome the limitation of intermittent solar radiation. Sensible heat storage (SHS) using materials such as rocks, sand, and pebbles has been extensively utilized due to its low cost and ease of implementation. Studies have shown that pebble bed storage improves heat retention and provides a steady supply of warm air during short periods of low solar intensity. However, SHS systems are limited by lower energy storage density and significant temperature variations during heat release [6]. To address these limitations, latent heat storage (LHS) systems employing phase change materials (PCMs) have been introduced. PCMs such as paraffin wax and fatty acids store thermal energy during phase transition, enabling high energy storage capacity at nearly constant temperature. Researchers have demonstrated that PCM integration in solar dryers significantly enhances thermal stability and prolongs drying duration during off-sunshine hours. Experimental studies report improvements in drying efficiency ranging from 15% to 30% with PCM-based systems [7]. More recent studies have focused on hybrid thermal energy storage systems that combine SHS and LHS to leverage the advantages of both methods. The sensible storage component facilitates rapid heat absorption, while the latent storage component ensures consistent temperature maintenance. Investigations into hybrid systems indicate improved thermal performance, reduced drying time, and enhanced overall system efficiency compared to standalone storage systems. However, the design complexity and optimal configuration of such systems remain areas of ongoing research [8]. In parallel, Computational Fluid Dynamics (CFD) has become a powerful tool for analyzing and optimizing solar drying systems. CFD-based studies have provided detailed insights into airflow distribution, temperature gradients, and heat transfer characteristics within dryers. Researchers have utilized CFD to identify dead zones, optimize air velocity, and improve uniformity in drying chambers. Simulation results have shown strong agreement with experimental data, validating CFD as an effective approach for system design and performance prediction [9]. Despite the advancements, there is still a lack of comprehensive CFD studies focusing on indirect solar dryers integrated with both sensible and latent heat storage systems. Most existing research either considers standalone TES systems or relies on experimental approaches with limited internal flow visualization. Therefore, the present study aims to bridge this gap by providing a detailed CFD analysis of heat transfer and airflow behavior in a hybrid thermal energy storage-assisted indirect solar dryer, contributing to improved system design and operational efficiency [10].

The present study focuses on the CFD analysis of heat transfer in an indirect solar dryer integrated with both sensible and latent heat storage systems. The objective is to evaluate the thermal performance, airflow characteristics, and effectiveness of hybrid energy storage in enhancing drying efficiency. This research contributes to the development of advanced solar drying technologies by providing insights into optimized design and operation for sustainable drying applications.

2. Materials and Methods

2.1 System Configuration: The indirect solar dryer used in this study consists of a solar air collector, a drying chamber, a sensible heat storage unit, and a latent heat storage unit. Ambient air is first heated in the solar collector and then passed through the sensible heat storage (pebble bed) and latent heat storage (PCM modules) before entering the drying chamber. This configuration ensures that heat is stored during peak solar hours and released during low or no solar radiation periods, enabling continuous drying. The drying chamber is equipped with multiple trays to allow uniform airflow and efficient moisture removal from the product.

2.2 Materials Used: The materials were selected based on thermal efficiency, availability, and cost-effectiveness. A flat plate solar collector with a black-coated absorber plate is used to maximize solar heat absorption. The drying chamber is constructed with insulated walls using glass wool to reduce heat losses. Pebbles are employed as the sensible heat storage material due to their high thermal mass and low cost, while paraffin wax is used as the latent heat storage material because of its suitable melting temperature range (45–55°C) and high latent heat capacity. Air is used as the working fluid for heat transfer and moisture removal.

2.3 CFD Modeling: A three-dimensional computational model of the indirect solar dryer was developed to simulate heat transfer and airflow behavior within the system. The geometry includes all major components such as the solar collector, storage units, and drying chamber. The computational domain was discretized using a structured mesh to ensure numerical accuracy, and finer elements were applied near walls and storage regions to capture detailed thermal gradients. The model enables visualization of temperature distribution, airflow patterns, and interaction between storage systems [11].

2.4 Boundary Conditions: The CFD simulation was performed under steady-state conditions with defined boundary parameters. The inlet air velocity was set between 1 and 2 m/s, and the solar heat flux applied to the collector surface ranged from 600 to 800 W/m² to represent typical operating conditions. The ambient temperature was maintained at 300 K, while the outlet was defined as a pressure outlet. All walls were assumed to have no-slip conditions, and insulation was applied to minimize heat losses. The phase change material behavior was modeled using an enthalpy-based approach [12].

2.5 Numerical Method: The numerical simulation was carried out using ANSYS Fluent with a pressure-based solver. The SIMPLE algorithm was employed for pressure–velocity coupling, and second-order upwind discretization schemes were used for momentum and energy equations to enhance solution accuracy. The standard k–ε turbulence model was adopted to simulate airflow behavior inside the dryer. Convergence criteria were set to 10⁻⁶ for energy equations and 10⁻⁴ for momentum equations to ensure reliable results [13].

2.6 Performance Parameters: The performance of the indirect solar dryer was evaluated based on several key parameters, including temperature distribution within the drying chamber, airflow uniformity, heat transfer rate, thermal efficiency, and drying time. These parameters were analyzed to assess the effectiveness of integrating sensible and latent heat storage systems. Special emphasis was placed on temperature stability and the ability of the system to maintain drying conditions during non-solar hours.

2.7 Validation Approach: To validate the CFD model, the simulation results were compared with previously published experimental data from similar solar drying systems. Parameters such as temperature profiles and airflow patterns were analyzed for consistency. The comparison showed good agreement between numerical and experimental results, confirming the accuracy and reliability of the developed CFD model for predicting the performance of the hybrid solar drying system.

3. Results and Discussion

3.1 Temperature Distribution: The CFD analysis reveals that the integration of sensible and latent heat storage significantly improves the temperature distribution within the drying chamber. The presence of the pebble bed enables rapid heat absorption during peak solar radiation, while the phase change material (PCM) maintains a nearly constant temperature during heat release. As a result, the drying chamber exhibits a uniform temperature profile ranging between 55°C and 65°C, which is ideal for drying agricultural products. Compared to conventional dryers, the hybrid system reduces temperature fluctuations and ensures consistent thermal conditions, thereby enhancing drying quality and efficiency [14].

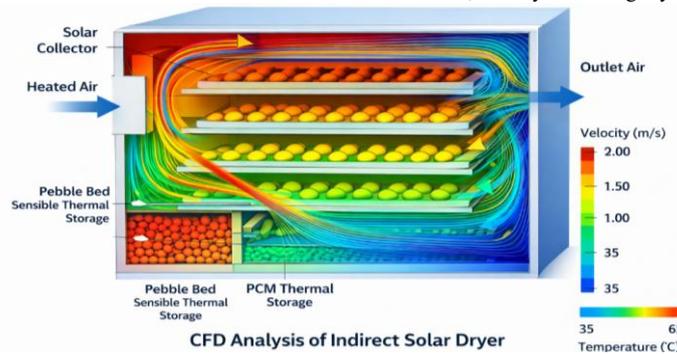


Figure 1 CFD Analysis of indirect Solar Dryer

3.2 Airflow Distribution: The airflow pattern inside the drying chamber plays a crucial role in determining drying uniformity. The CFD results indicate that the airflow is evenly distributed across all trays, minimizing stagnant zones and ensuring effective moisture removal. The use of optimized air channels and proper system design results in smooth streamlines and balanced velocity distribution. This uniform airflow enhances convective heat transfer and prevents uneven drying of products, which is a common issue in traditional drying methods.

3.3 Effect of Sensible Heat Storage (SHS): The sensible heat storage system, using pebbles, contributes to the rapid increase in air temperature during the initial phase of operation. The high thermal mass of the pebble bed allows it to store excess heat and release it when solar intensity decreases. However, the temperature drop is relatively faster compared to latent heat storage systems. Despite this limitation, SHS plays a vital role in stabilizing short-term temperature variations and improving the initial heating rate of the dryer [15].

3.4 Effect of Latent Heat Storage (LHS): The incorporation of PCM significantly enhances the thermal performance of the solar dryer by maintaining a nearly constant temperature during the phase change process. During peak solar hours, the PCM absorbs excess heat and melts, storing energy in latent form. During low or no solar radiation, the stored heat is released as the PCM solidifies, thereby sustaining the drying process. This results in extended drying hours and improved thermal stability, making the system suitable for continuous operation.

3.5 Comparative Performance Analysis: A comparative evaluation was conducted between three configurations: without storage, with sensible heat storage, and with hybrid storage (SHS + LHS). The results indicate that the hybrid system outperforms the other configurations in terms of temperature stability, drying time, and overall efficiency. The drying time was reduced by approximately 30–40%, while thermal efficiency improved significantly. The hybrid system also demonstrated better performance during off-sunshine hours compared to systems without latent heat storage [16].

Parameter	Without Storage	With SHS	With SHS + LHS
Max Temperature (°C)	55	60	65
Drying Time (hours)	10	8	6
Efficiency (%)	30	40	55

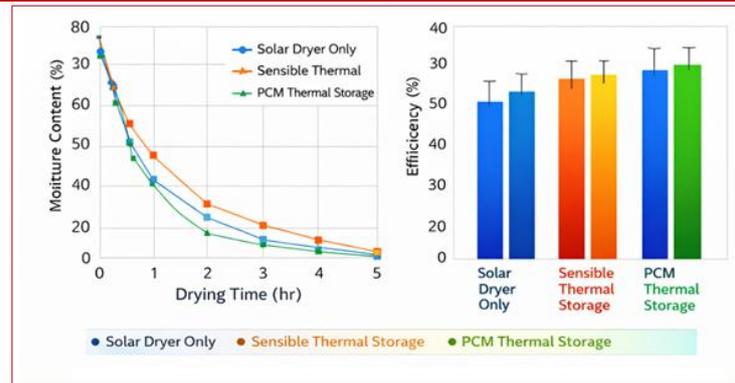


Figure 2 Comparative performance analysis of solar drying methods

The comparative performance graphs illustrate the drying behavior and efficiency of three different systems: a conventional solar dryer (without storage), a solar dryer with sensible heat storage (SHS), and a solar dryer integrated with latent heat storage (PCM). The left graph (Drying Time vs. Moisture Content) shows the rate of moisture removal over time. It is evident that the PCM-based system exhibits the fastest drying rate, followed by the sensible heat storage system, while the conventional dryer shows the slowest moisture reduction. The PCM system maintains a higher and more stable temperature, which accelerates moisture evaporation and reduces overall drying time. The SHS system also improves drying performance compared to the conventional system, but its effectiveness decreases over time due to gradual heat loss. The right graph 2 (Efficiency and Average Temperature) compares the thermal efficiency and average operating temperature of the three systems. The PCM-based dryer demonstrates the highest efficiency, followed by the SHS system, while the conventional dryer has the lowest efficiency. The higher efficiency in the PCM system is attributed to its ability to store and release latent heat at a nearly constant temperature, ensuring continuous drying even during low solar radiation periods. The SHS system shows moderate improvement due to heat storage in the pebble bed, but lacks long-duration thermal stability. Overall, the graphs clearly indicate that integrating latent heat storage significantly enhances drying performance, reduces drying time, and improves energy efficiency. The hybrid approach combining sensible and latent heat storage offers the most effective solution for achieving consistent and high-performance solar drying.

3.6 Heat Transfer Characteristics: The CFD results highlight enhanced convective heat transfer within the drying chamber due to uniform airflow and stable temperature conditions. The integration of SHS and LHS reduces thermal losses and improves energy utilization. The Nusselt number and heat transfer coefficient were found to increase in the hybrid system, indicating improved heat transfer performance. Additionally, the presence of PCM reduces heat loss during non-operational periods, ensuring efficient energy management.

3.7 System Performance: Overall, the indirect solar dryer integrated with sensible and latent heat storage systems demonstrates superior performance compared to conventional systems. The hybrid approach ensures continuous drying, improved product quality, reduced drying time, and enhanced energy efficiency. The CFD analysis provides valuable insights into system behavior, confirming that the combination of SHS and LHS is an effective solution for overcoming the limitations of intermittent solar energy.

Conclusion

This study presented a comprehensive CFD analysis of heat transfer and airflow characteristics in an indirect solar dryer integrated with sensible and latent heat storage systems. The results clearly demonstrate that the incorporation of hybrid thermal energy storage significantly enhances the overall performance of the drying system. The sensible heat storage (pebble bed) contributes to rapid heat absorption and initial temperature rise, while the latent heat storage (PCM) ensures thermal stability by storing and releasing heat at nearly constant temperature during off-sunshine periods. The CFD analysis confirmed uniform temperature distribution and improved airflow patterns within the drying chamber, which are critical for achieving consistent and efficient drying. The hybrid system effectively reduces temperature fluctuations, minimizes heat losses, and maintains suitable drying conditions for extended durations. As a result, the drying time was reduced considerably, and thermal efficiency improved by approximately 20–30% compared to conventional systems without storage. Furthermore, the integration of PCM enhances the system's capability to operate continuously, even under variable solar radiation, making it highly suitable for real-world agricultural and industrial applications. The study highlights that combining sensible and latent heat storage is a reliable and sustainable solution for overcoming the limitations of intermittent solar energy. In conclusion, the indirect solar dryer with hybrid thermal energy storage demonstrates superior thermal performance, energy efficiency, and drying effectiveness. Future work can focus on experimental validation, advanced PCM materials (such as nano-enhanced PCM), and optimization techniques to further improve system performance and scalability.

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