Design, Development, and Performance Evaluation of Indirect Solar Dryer with Thermal Energy Storage for Industrial and Agricultural Applications

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Solar drying is a process that uses solar radiation energy to remove moisture from products, making it an eco-friendly and cost-efficient drying method. It is particularly significant in industries like agriculture and food processing, where it helps in preserving crops, fruits, vegetables, and other perishable goods. By reducing moisture, solar drying prevents spoilage, extends shelf life, and maintains product quality. In agriculture, it enhances food security and reduces post-harvest losses. For the food processing industry, solar drying lowers energy costs and minimizes reliance on fossil fuels, supporting sustainable and environmentally conscious production methods. One of the major challenges of the solar drying process is the sporadic character of solar radiation, as sunlight is not consistently available throughout the day or during cloudy weather. This variability in solar energy limits the continuous operation of solar drying, making it less reliable in regions with frequent low sunlight. Additionally, energy losses can occur during periods of reduced solar intensity, further affecting the efficiency of the system. To address these limitations, integrating energy storage solutions like thermal energy storage (TES) systems can help absorb excess heat for use during low sunlight periods, but this also adds complexity and cost to the system.

The thesis explores solar drying technologies, focusing on improving energy efficiency, reducing greenhouse gas emissions, and developing sustainable drying processes. The research is organized into seven chapters, each contributing to a comprehensive understanding of solar drying technologies, their industrial and agricultural applications, and economic feasibility.

Chapter 1. Introduction

This chapter provides the foundation of the thesis by presenting the background and motivation for the research. It highlights the importance of solar drying in reducing energy consumption and minimizing environmental impact. The chapter outlines the key research objectives, which include evaluating various solar drying technologies and assessing their feasibility in different regions of India. The scope of the study is also defined, with an emphasis on integrating mathematical modeling and simulation techniques for better understanding and optimization. Finally, the structure of the thesis is laid out, explaining the flow of chapters and their content.

Chapter 2. **Literature review**

This chapter covers a detailed analysis of existing solar drying technologies. Various types of solar drying systems are discussed, including **open-sun drying**, **direct solar drying** (natural and forced convection), **indirect solar drying**, and **hybrid drying systems**. The chapter delves into theoretical analyses, advances in mathematical modeling, and the simulation of solar drying systems. Environmental and energy analyses are conducted to assess the efficiency of these systems, as well as their economic impact. A critical section of this chapter addresses the importance of TES in improving the efficiency of solar drying applications, with a focus on environmental sustainability.

Chapter 3. **Feasibility Study of the Industrial Solar Dryer: A techno-economic and environmental analysis**

This chapter evaluates the feasibility of deploying industrial solar dryers across six cities in India, namely **Hanumangarh, Bangalore, New Delhi, Lucknow, Shimla**, and **Tiruchchirappalli**. Using **RETScreen Expert software**, the techno-economic viability of solar drying systems is assessed. Detailed meteorological data for each city are analyzed to understand the potential energy savings and the reduction in greenhouse gas emissions. Financial and clean development mechanism (CDM) analyses are also performed to demonstrate the economic and environmental benefits of solar drying technologies.

Chapter 4. Performance evaluation of indirect solar dryer for potato slice drying

This chapter investigates the performance of an indirect solar dryer designed for drying potato slices. The experimental setup is described in detail, and the methods for sample preparation, performance analysis, and uncertainty quantification are explained. Various parameters are analyzed, such as moisture content, drying rate, and the quality of dried potato slices. The results demonstrate the effectiveness of the solar dryer in evaporating moisture, and key findings related to temperature variations, rehydration ratios, shrinkage, color index, and water activity are discussed. The chapter provides insights into how environmental conditions and dryer efficiency affect product quality.

Chapter 5. Assessment of Phase Change Materials for Thermal Energy Storage in Solar Drying Applications

This chapter focuses on the integration of **phase change materials (PCMs)** into solar drying systems to enhance energy storage. It begins with an introduction to the role of PCMs in stabilizing temperature fluctuations in solar drying. The materials and methods section discusses the selection and properties of PCMs, followed by a detailed explanation of the simulation model and the numerical simulation methodology. The melting characteristics and enthalpy of selected PCMs are examined in the results section, where various factors, such as mesh size dependence and thermal performance, are discussed. The assessment demonstrates the potential of PCMs to increase drying efficiency.

Chapter 6. Investigation of indirect solar dryers with and without PCM for Agricultural applications

This chapter investigates the performance of indirect solar dryers with and without PCMs for the drying of potato slices, tomato slice drying, and apple slice drying. The study highlights the comparative analysis of both configurations' energy savings, drying times, and product quality. It has been demonstrated that adding PCMs improves thermal stability, which results in more effective and reliable drying operations and raises the dryer's overall performance.

Chapter 7. Summary, conclusion, and future prospects

The last chapter summarizes the key findings of the research, reiterating the significance of solar drying technologies in reducing energy consumption and environmental impact. The conclusions drawn from experimental and simulation studies indicate that integrating PCMs into solar drying systems can significantly enhance performance. This chapter also includes future prospects, suggesting further research into advanced materials and hybrid drying systems to optimize efficiency and sustainability in various climatic conditions.