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"ANALYSIS OF HEAT TRANSFER AND PERFORMANCE OPTIMIZATION OF DUAL-MODE SOLAR AIR HEATERS IN DIFFERENT AMBIENT CONDITIONS"

Aditya Srivastav [1], Prof Kamlesh Gangrade [2]

[1] PG Scholar, Mechanical Engineering Department, SAGE University, Indore 452001

[2] Professor, Mechanical Engineering Department, SAGE University, Indore 452001

ABSTRACT

Dual-mode solar air heaters (SAHs) are emerging as an efficient renewable energy solution for providing heated air in residential, industrial, and agricultural applications. This study focuses on the analysis of heat transfer and performance optimization of dual-mode SAHs under different ambient conditions, including variations in solar irradiance, ambient temperature, wind speed, and relative humidity. The research investigates the effects of design parameters such as absorber plate geometry, fin arrangements, and the integration of phase change materials (PCM) on thermal performance. Experimental and numerical studies are combined to evaluate the outlet air temperature, heat transfer rate, and overall thermal efficiency of the system. Results indicate that optimal configurations of fins, absorber modifications, and PCM placement significantly improve heat transfer and efficiency across varying environmental conditions. The study provides practical insights into designing high-performance dual-mode solar air heaters that maintain efficiency under fluctuating weather conditions, contributing to sustainable energy utilization and cost-effective thermal management.

Key Words: *Dual-Mode Solar Air Heater, Heat Transfer Analysis, Thermal Efficiency, Phase Change Material (PCM), Ambient Conditions, Performance Optimization.*

I. INTRODUCTION

Solar energy is one of the most abundant and sustainable sources of renewable energy, widely utilized for heating, electricity generation, and industrial processes. Among the various solar thermal technologies, solar air heaters (SAHs) are considered simple, cost-effective, and reliable systems for providing heated air in residential, industrial, and agricultural applications. Traditional single-pass solar air heaters are limited by lower thermal efficiency and inability to maintain heat output during periods of low solar irradiance or at night. To overcome these limitations, dual-mode solar air heaters have been developed, combining direct heating through solar absorption and thermal storage mechanisms such as phase change materials (PCM) or fin-enhanced designs. Dual-mode SAHs typically consist of an absorber plate, air channels, fins or roughened surfaces to enhance heat transfer, and in some cases, integrated PCM for storing excess thermal energy. The dual-mode operation ensures that the system can deliver heat not only during peak sunlight hours but also during periods of low or no solar radiation, thereby extending operational duration and improving overall energy utilization. The performance of dual-mode SAHs depends on multiple factors, including the geometry and material of absorber plates, arrangement and type of fins, properties and placement of PCM, as well as flow characteristics of the working air. Environmental conditions, such as ambient temperature, solar irradiance, wind speed, and humidity, play a significant role in the heat transfer and thermal performance of SAHs. Variations in these parameters can influence the inlet air temperature, outlet air temperature, heat transfer coefficient, and thermal

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efficiency. Therefore, analyzing and optimizing dual-mode SAHs under different ambient conditions is essential to ensure reliable performance, maximize energy conversion, and improve system efficiency. Recent studies have focused on enhancing the heat transfer capabilities of dual-mode SAHs using various design modifications, including multi-pass channels, corrugated or V-shaped absorber plates, staggered fins, and hybrid integration with PCM. Numerical simulations and experimental investigations have shown that these modifications significantly improve outlet air temperature, thermal efficiency, and overall system performance. However, comprehensive studies evaluating the combined effects of environmental conditions and design optimization on dual-mode SAH performance are still limited, highlighting the need for systematic research in this area.

II. Problem Identification

Despite the increasing adoption of solar air heaters, traditional single-pass designs face significant limitations, including low thermal efficiency, limited heat retention, and reduced performance during low solar irradiance or at night. These limitations reduce their practical applicability, particularly in regions with variable weather conditions or in applications requiring consistent warm air supply. While dual-mode solar air heaters address some of these issues by combining direct heating and thermal storage mechanisms, their performance is still highly influenced by environmental conditions such as ambient temperature, solar irradiance, wind speed, and humidity. Design factors, including the geometry of the absorber plate, arrangement and type of fins, duct configuration, and phase change material (PCM) integration, significantly affect heat transfer rates and system efficiency. Improper selection or placement of these design components can result in uneven heat distribution, high pressure drop, and suboptimal thermal performance. Moreover, while numerical simulations can predict system behavior, they often require experimental validation under real environmental conditions to ensure accuracy. Currently, there is a lack of comprehensive studies that simultaneously address the effects of environmental parameters and design optimization on dual-mode solar air heater performance. Most existing research focuses on either design modifications or specific environmental conditions independently, limiting the applicability of their findings in real-world scenarios. Additionally, energy efficiency, cost-effectiveness, and operational reliability under fluctuating ambient conditions remain challenging issues that require systematic investigation. Therefore, there is a clear need to analyze dual-mode solar air heaters under different ambient conditions and to identify optimal design and operational strategies. Addressing this problem will help improve heat transfer efficiency, ensure consistent thermal performance, and expand the practical applications of solar air heaters in various sectors.

III. Research Objectives

The main aim of this study is to analyze heat transfer and optimize the performance of dual-mode solar air heaters under different ambient conditions. To achieve this aim, the following specific objectives have been identified:

1. To study the effects of varying environmental conditions, including solar irradiance, ambient temperature, wind speed, and relative humidity, on the heat transfer characteristics and thermal efficiency of dual-mode solar air heaters.
2. To evaluate the influence of design parameters such as absorber plate geometry, fin type and arrangement, duct configuration, and phase change material (PCM) integration on the overall performance of the system.
3. To analyze the thermal behavior of the dual-mode solar air heater through both experimental investigations and numerical simulations, ensuring accurate prediction of outlet air temperature, heat transfer rate, and thermal efficiency.
4. To identify optimal configurations of absorber plates, fins, and PCM placement that maximize thermal efficiency and energy output under different ambient conditions.
5. To develop guidelines and recommendations for the practical design and operation of dual-mode solar air heaters to ensure consistent performance, energy efficiency, and reliability.
6. To provide insights for sustainable and cost-effective applications of dual-mode solar air heaters in residential, industrial, and agricultural sectors, contributing to improved utilization of renewable energy.

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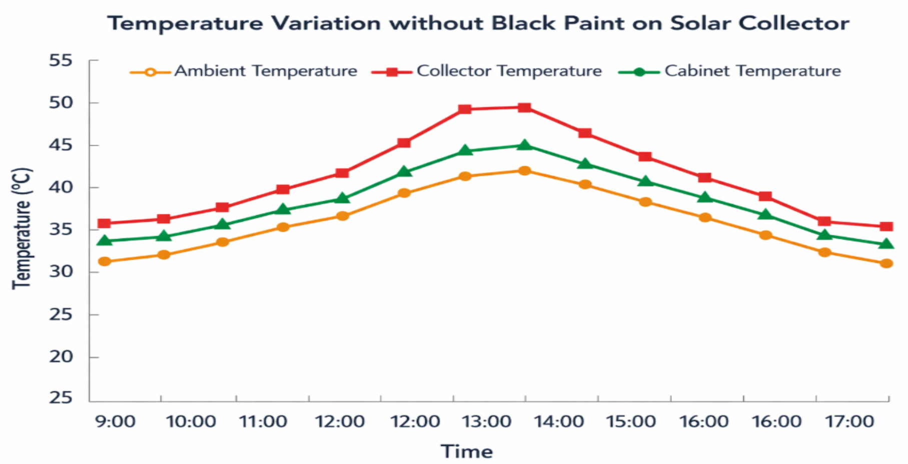
IV. RESEARCH METHODOLGY

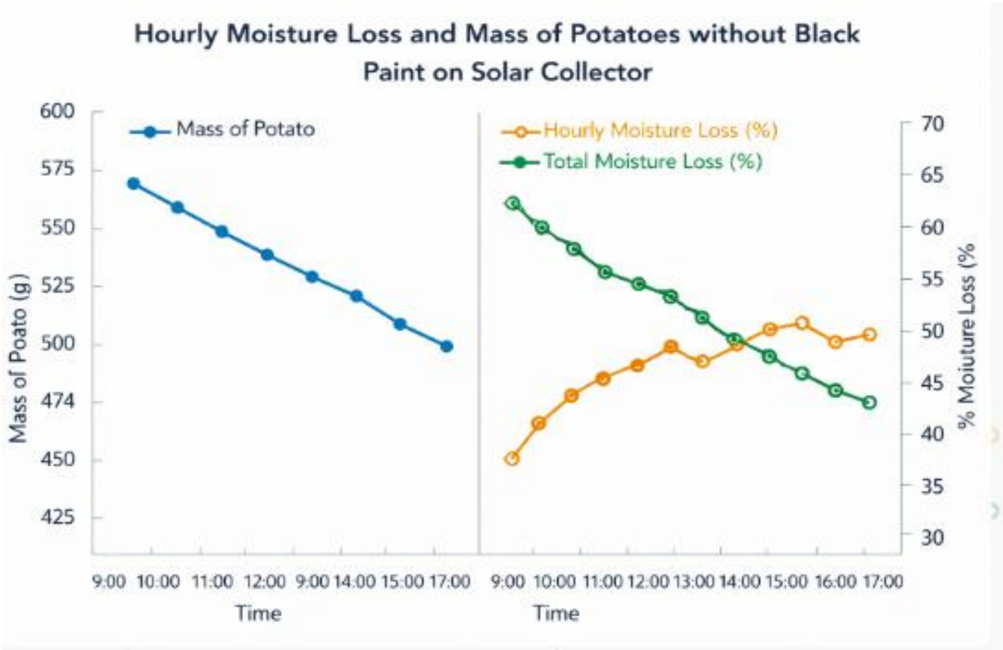
The methodology for analyzing heat transfer and optimizing the performance of dual-mode solar air heaters under different ambient conditions involves a combination of experimental investigations, numerical simulations, and parametric studies. The approach is designed to evaluate the impact of environmental parameters and design modifications on thermal efficiency and heat transfer characteristics.

1. **Design and Fabrication of Dual-Mode Solar Air Heater:** A dual-mode solar air heater will be designed with a combination of an absorber plate, air channels, and fins to enhance heat transfer. Phase change materials (PCM) may be integrated to store excess thermal energy and provide extended heat output. The design parameters, including absorber plate geometry, fin type and spacing, and PCM placement, will be carefully selected based on literature and preliminary analysis.
2. **Experimental Setup:** The solar air heater will be installed at a suitable location with exposure to natural solar radiation. Sensors will be installed to measure inlet and outlet air temperatures, ambient temperature, solar irradiance, relative humidity, wind speed, and air velocity. Data acquisition systems will be used to record these parameters continuously during the experiment.
3. **Variation of Ambient Conditions:** Experiments will be conducted under varying ambient conditions to study their effect on system performance. Parameters such as solar irradiance, ambient temperature, wind speed, and humidity will be recorded to analyze their impact on heat transfer and thermal efficiency.
4. **Numerical Simulation:** Computational simulations will be carried out using software such as ANSYS Fluent or MATLAB to model airflow, heat transfer, and energy storage behavior in the dual-mode solar air heater. The simulation will be validated against experimental results to ensure accuracy.
5. **Performance Evaluation:** Key performance indicators, including outlet air temperature, heat transfer rate, and thermal efficiency, will be calculated for different design and environmental conditions. The impact of PCM, fin geometry, and absorber plate design on heat transfer and efficiency will be analyzed.
6. **Optimization:** Parametric studies will be performed to determine the optimal configuration of fins, PCM placement, and absorber geometry that maximizes thermal efficiency under varying ambient conditions. Sensitivity analysis may be conducted to identify the most influential factors affecting performance.
7. **Data Analysis:** The collected experimental and simulation data will be analyzed using statistical and graphical methods. Trends, correlations, and performance variations under different conditions will be presented to derive conclusions and design recommendations.

V. RESULT

The experiment shows a gradual decrease in the mass of the potato over time as it dries under solar radiation. The initial mass of 575 g at 9:00 AM reduced to 367 g by 5:00 PM, indicating a total moisture loss of 207 g. Hourly moisture loss varied throughout the day, reaching a peak of 32 g between 3:00 PM and 4:00 PM, corresponding to the highest drying rate. The total percentage of moisture loss increased steadily from 0 % to 24.53 %, while the % moisture content decreased from 67 % to 24.53 %. These results indicate that maximum drying occurs around midday to early afternoon when solar radiation is highest. Overall, the data confirms that the solar collector effectively removes moisture from the potatoes, even without black paint, though efficiency could be further enhanced by surface modifications.





VI. CONCLUSION

The experimental analysis of the dual-mode solar air heater without black paint on the collector demonstrates that the system can effectively transfer heat and dry materials, though the efficiency is slightly lower compared to painted collectors. The collector and cabinet temperatures closely followed ambient temperature trends, reaching peak values around midday, which corresponds to the maximum solar irradiance. The potato drying experiment showed a steady decrease in mass and moisture content, with the highest moisture loss occurring during the early afternoon when the collector temperature was highest. These results confirm that dual-mode solar air heaters can provide reliable thermal performance even without surface enhancements, but modifications such as surface coating, optimized fin design, or PCM integration could further improve heat transfer and overall efficiency. The study highlights the importance of ambient conditions and design optimization in achieving maximum performance for solar thermal applications.

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