Experimental Analysis Performance Enhancement of Double Pass Solar Air Dryer Using Triangular Shape

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Abstract: ***This study focuses on the design and performance evaluation of a triangular shape double pass solar air dryer. The triangular shape configuration promotes uniform airflow distribution, which enhances convective heat transfer and increases the overall thermal efficiency of the system. Experimental investigations were carried out under real climatic conditions to examine the temperature rise, heat absorption characteristics, and energy utilization of the dryer. The results indicate that the triangular shape design significantly improves air–plate interaction, leading to higher outlet air temperatures and enhanced drying performance when compared to conventional flat or rectangular configurations. Furthermore, the double pass airflow arrangement increases air residence time within the drying chamber, resulting in improved heat extraction from the absorber surface and reduced thermal losses. Overall, the proposed triangular shape double pass solar air dryer demonstrates reliable, energy-efficient, and environmentally sustainable performance, making it a promising solution for solar-assisted agricultural and industrial drying application.***

Keywords: Double Pass Solar Air dryer, Solid Copper Rod & triangular shape, Solar Radiation, Drying Efficiency, Thermal Performance

1. Introduction

Solar energy has emerged as one of the most promising renewable energy sources due to its abundance, sustainability, and environmental friendliness. Among various solar energy applications, solar air heating systems have gained significant attention for their potential in industrial, residential, and technological applications. In particular, double pass solar air dryers (DPSAD) with triangular configurations have demonstrated enhanced thermal performance, compact design, and efficient heat transfer characteristics. The triangular shape is strategically employed in DPSAD designs to optimize the airflow path, increase the contact surface area between the absorber and the air, and facilitate uniform heat distribution. This configuration not only minimizes pressure drop but also enhances the convective heat transfer coefficient, contributing to higher overall thermal efficiency.

The double pass mechanism in solar air dryers involves directing the ambient air through the absorber plate twice before exiting the system. In a triangle-shaped DPSAD, the first pass allows air to gain initial thermal energy from the absorber surface, while the second pass ensures that the air achieves maximum temperature rise by passing through an additional layer of heat exchange. The triangular duct configuration offers a unique advantage by reducing dead zones in airflow, promoting turbulence, and increasing the residence time of air within the heated channel. These characteristics are critical for achieving uniform temperature profiles, improved energy utilization, and optimal heat extraction.

Thermal performance analysis of a triangle-shaped DPSAD involves parameters such as air temperature rise, thermal efficiency, pressure drop, and heat transfer coefficient. The geometric design of the triangular duct influences the Reynolds number, Nusselt number, and overall convective heat transfer. By employing a triangular cross-section, the system ensures higher turbulence intensity compared to conventional rectangular or flat-plate designs, which enhances the convective heat transfer rate. Computational fluid dynamics (CFD) studies and experimental investigations have shown that the triangular configuration reduces flow stagnation and promotes a uniform velocity profile, resulting in improved thermal performance of the DPSAD.

Material selection plays a vital role in the efficiency of triangle-shaped DPSADs. The absorber plate, typically made of high thermal conductivity metals such as aluminum or copper, is coated with selective surfaces to maximize solar absorption and minimize radiative losses. Transparent covers with high transmittance, such as tempered glass or polycarbonate sheets, are used to trap solar radiation within the duct while reducing convective heat loss to the environment. Insulation materials are applied to the outer walls of the triangular duct to limit conductive losses. The combination of these materials ensures that the DPSAD maintains high air outlet temperatures while minimizing energy wastage.

A double pass solar air dryer with a triangular cross-section also allows for integration with various heat enhancement techniques. Fins, turbulators, or vortex generators can be incorporated within the triangular duct to further enhance the heat transfer rate. The triangular geometry provides sufficient space for these modifications without causing excessive pressure drop, making it suitable for compact and high-performance applications. The design flexibility offered by the triangular shape is a key advantage over conventional flat-plate designs, allowing engineers to optimize thermal efficiency, airflow rate, and temperature uniformity based on specific requirements.

The performance of a triangle-shaped DPSAD can be further optimized by analyzing the impact of flow rate, absorber plate inclination, duct height, and air velocity. Variations in these parameters directly affect the convective heat transfer rate and the overall thermal efficiency. Triangular configurations have shown superior adaptability to different operating conditions due to their enhanced turbulence characteristics and optimized airflow path. This makes them particularly suitable for applications requiring high-temperature air delivery with minimal energy losses.

In addition to experimental validation, numerical modeling of triangle-shaped DPSADs has provided valuable insights into airflow dynamics, temperature distribution, and pressure drop. Computational simulations using software tools such as ANSYS Fluent or COMSOL Multiphysics help predict system performance under varying solar radiation and environmental conditions. These models allow engineers to refine the triangular duct design, optimize the placement of the double pass channels, and evaluate the impact of heat augmentation techniques. The combination of experimental and numerical approaches ensures accurate prediction of the DPSAD’s performance and facilitates the development of high-efficiency solar air dryer systems.

In conclusion, triangle-shaped double pass solar air dryers (DPSADs) represent a significant advancement in solar air heating technology. The triangular geometry, coupled with the double pass configuration, offers superior thermal performance, enhanced heat transfer, reduced pressure drop, and compact design. These systems provide a versatile platform for various technical applications requiring efficient and uniform heated air. Continuous research on material selection, geometric optimization, and flow enhancement techniques ensures that triangle-shaped DPSAD remain at the forefront of solar air dryer technology. Their ability to maximize solar energy utilization while maintaining high thermal efficiency makes them an essential component in modern renewable energy systems.

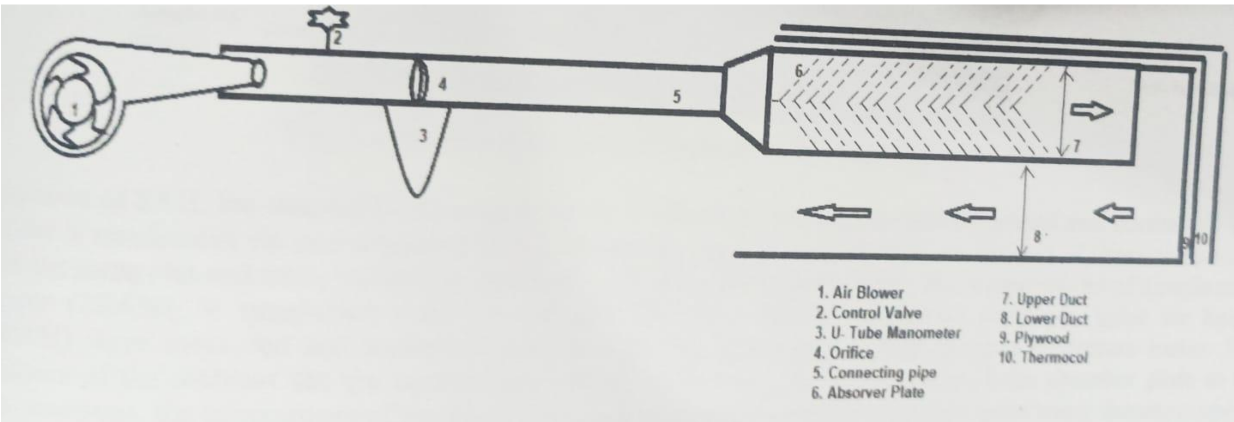

Figure 1.1: Solar Air Dryer

2. Literature Review

Manish Sharma et. al- The analysis of the thermal performance of a Solar Air Heater (SAH) with V rib with gaps, V rib without gaps and plain observer plate has been carried out in this research for varying mass flow rates on the SAH. The work on “V rib with gap,” “V continuous,” and “without rib. “Has been done to compare the performance of the three rib geometries for solar air heaters. [01]

Anand Patel et. al- The evolution of heat exchangers from the simplest to the most complex is examined, with a focus on how important they are for reaching better energy conversion rates. It focuses on design, material advancements, and the many heat exchanger types appropriate for different purposes while exploring developments from basic to advanced heat exchangers. [02]

Sachin Bhaskar, Santosh Kumar Rai et. al- Primary function is to capture solar thermal energy transfer hot air & Based on an extensive review of the existing literature, a substantial amount of research has been dedicated to the enhancement of Total Heat Power (THPP) and reduction of friction value in artificially roughened Solar Air Heaters (SAHs) with different shapes and design parameters, focusing on both single and double pass configurations. [03]

Poonam S. Pardeshi & Andries (Hennie) van Heerden et. al-Solar air heaters are devices that can convert solar energy into thermal energy for moderate and low-temperature applications such as space heating, preheating, crop drying, and the food industry. Different concentrations of nanoparticles mixed in black paint and hybrid nanofluid technology should be investigated. [04]

Antonio Delgado et. at- SAH he as knowledge is discussed and all the physics involved in terms of heat transfer is considered. The basic functionality of the solar air heater is also discussed and different designs are showcase. He simulations validated using references from experiments as well as theoretical calculations. [05]

Suneet Mehta et. al- The present water colling technique system is producing cooling effect by using refrigerants like Freon, Ammonia etc. Using these refrigerants, one can achieve maximum output but one of the major ack is its poisonous gas emission and global warming we can cope up this problem with use of thermoelectric module and thereby protecting the environment. [06]

Wajahat Baig, Hafiz Muhammad ali et. al- While using TSMs during the winter season in which outside air temperature ranges between 6 and 20°C and solar flux ranges between 350 and1050 W/m2, PCM' smelting strongly depends on outside air temperature. [07]

Ratan Sanjay, Rishabh Balun & Rohit Kumar et. al- Encompassing industrial environments, agricultural product dehydration, material conditioning, and residential heating. Inadequate convective transfer can hinder Variations of Pitch space between roughness can be improved and Heat transfer rate and focus on analysis the full life cycle of solar air heater. [08]

Ankush Headu et. al- Different heat transfer roughness elements were employed to Study on the thermal performance of double pass solar air heater with PCM-based thermal energy storage system Science enhance the heat transfer coefficient, while different PCM arrangements were used to increase efficiency and operational hours and Using semicircular PCM tubes and perforated blocks as roughness elements, a three-dimensional transient numerical investigation is conducted to analysis the thermal and pumping power characteristics of double pass solar air heater (DPSAH). [09]

Prashant Tirkey, Sunil Kumar et. al- This paper study includes an overview of solar air heater technology, and information on solar air heaters that use alternative absorber plate surface geometries to speed up heat transmission and PCM (phase change material) is used to deliver heat energy when it is cloudy. An overview of solar air heater technology and information on solar air heaters that use alternative absorber plate surface geometries to boost heat transfer comes under this study. [10]

Vijay Chaudhary et. al- The study's findings suggest a number of intriguing new directions for solar air heater research and development. The first step towards greater efficiency is the exploration of cutting-edge materials for absorbers and selective coatings. Nanomaterials, which have improved heat absorption capabilities, are an example of a novel material that deserves investigation. In addition, research into solar air heater integration with energy storage devices should be pursued. [11]

Anand Patel et. al- Solar energy is a clean, renewable energy that is used for drying, desalination and hot air heating. The aim of the current work is to design and develop an experimental setup and major conclusion of present work is that wire mesh better and cheapest option to improve thermal performance of solar air heater. [12]

A.F. Abd Hamid et. al- This paper investigates double-pass solar air thermal collectors with lava rock as the porous media. The addition of lava rock serves as short-term sensible thermal storage for a solar drying system. The use of lava rock in a DPSAH system was evaluated using energy balance in this study. Several findings have been achieved, including optimal efficiency, pressure drop, porosity, and differences between conventional and system that have been analysis against the time. [13]

Varun Pratap Singh et. al- Current efforts toward the necessary energy transition are predominantly focused on climate change mitigation in relation to decarbonization measures. The analysis has been performed to cope with the necessity to produce insights that traditional energy system optimization models are not able to deal with, attempting to answer to a crucial question in the actual energy field how much can we exploit carbon emissions as an indicator of sustainability. [14]

V.S. Hans et. al- Various designs of solar collectors viz, evacuated tube, flat plate, multiple passages, a cross-section of the flow passage, etc. are reported and discussed. Techniques which are used for performance enhancement of SAHs such as artificial roughness, fins, baffles, vortex generators, etc. The heat energy available in the solar radiation can be easily collected with the help of a solar collector and the collected heat is further utilized for heating and cooling applications. [15]

Yousif Muhammad et. al- The design and testing of a high-temperature thermal energy storage based on rocks is presented. Tec in a rock bed represents a low-cost energy storage solution with a high heat-to-heat storage efficiency. This paper presents the construction and performance of a downscaled HTTES for power to-heat or power-to-power applications with a thermal capacity. [16]

Murugesan Palaniappan et. al- The impingement jet Solar Air Heater (SAH) achieves roughening through the incorporation of conical ring shapes, strategically placed between the straight fins of the absorber plate. An innovative solar air heater design for hot air production to improve soler air dryer outlet temperature and used for industrial air heating Applications is reported in this research. The system integrates the jet impingement heat transfer technique with artificial roughness to improve performance. [17]

Eduardo Venegas-Reyes et. al- This work details the design, construction, and experimental evaluation of a novel double-pass V-trough solar air heater with semicircular receivers. According to the results, the double-pass V-channel solar air heater increased the air temperature by more than 30 ◦C for inlet temperatures close to ambient temperature. An air outlet temperature of up to 70 ◦C was achieved, which can dry most food products such as fish, beef, banana, grapes, mango, pineapple, chili, and others. [18]

Mahyar Abedi, Xu Tan, Share Cite Parnab Saha, James F. Klausner et. al- The performance of solar desalination systems based on a humidification–dehumidification (HDH) approach is significantly enhanced by preheating the air entering the evaporator. In this study, we examined the potential of an integrated SAH with a direct-contact packed-bed HDH desalination system that can be applied globally. [19]

Dogan Burak Saydam et. al- In today's world, many researchers are focusing on designs that occupy the same dimensions but can generate more useful energy. During the experimental study, the energy, exergy and enviro-economic analyses of both SAHs were made by using the measurements taken from different points on the system, and Experimental investigation and artificial neural networks (ANNs) based prediction of thermal performance of solar air heaters. [20]

3. Methodology

The primary objective of this study is to enhance the convective heat transfer rate and overall thermal performance of a solar air dryer (SAD) by introducing a continuous triangular shape roughness with gaps on the absorber plate. This modification generates turbulence in the airflow, increases air–plate interaction, and improves the system's thermal efficiency.

3.1 Materials

The experimental setup of the solar air heater includes the following components:

- **Duct Dimensions**: The inlet and outlet ducts are designed with a uniform dimension of 50 mm. Both ducts have identical cross-sectional size to ensure smooth airflow and reduce pressure losses. Maintaining the same duct dimension at the inlet and outlet helps achieve stable air velocity and consistent performance of the solar air dryer system.
- **Absorber Plate**: A mild steel (MS) plate of dimensions 1200 mm × 900 mm with a thickness of 2 mm was employed as the absorber plate. The plate was modified with continuous V-shaped ribs and interspersed gaps to create artificial roughness, thereby enhancing turbulence and improving convective heat transfer from the plate to the air.
- **Black Coating**: Black paint is applied to all internal surfaces of the wooden box as well as the MS absorber plate. This high-absorption coating improves the thermal efficiency of the solar air heater by maximizing solar energy capture.
- **Triangular Copper Wire**: Triangular-shaped copper wires are employed on the mild steel (MS) absorber plate. A total of 77 triangular copper wires are mounted on the surface of the plate to enhance heat transfer.
- **Airflow System**: A centrifugal blower supplied air to the duct, while a gate valve was used to regulate the airflow rate precisely.
- **Support Structure**: The solar air heater was supported by a wooden box reinforced with iron rods, with overall box dimensions of length 1500 mm × width 900 mm × height 200 mm, providing a rigid framework for the duct and absorber assembly.
- **Temperature Measurement**: J-type thermocouples were installed at the absorber plate, glass cover, inlet, and outlet air stream. The readings were displayed via a digital temperature indicator.
- **Solar Radiation Measurement**: A solar power meter was used to monitor incident solar energy throughout the experiments.
- **Pressure Measurement**: Anemometer was employed to record pressure variations across the duct.
- **Glass Cover (Kach)**: A transparent glass sheet is installed on the top of the wooden box. The dimensions of the glass cover are 1500 mm × 900 mm x 3mm. The glass used is of high-quality, clear type to allow maximum solar radiation to reach the absorber plate while minimizing heat loss.

3.2 Experimental Setup

Various parameters were measured and recorded from 11:00 A.M. to 03:00 P.M. For the experiment, cold weather and clear days from 06 December to 15 December 2025 were selected. During this period, the outside ambient temperature ranged from 09°C to 26.5°C. The inlet and outlet temperatures of the solar air heater, along with the incident radiation, were measured. Based on these measurements, the thermal performance and energy transfer efficiency of the system were analysis.

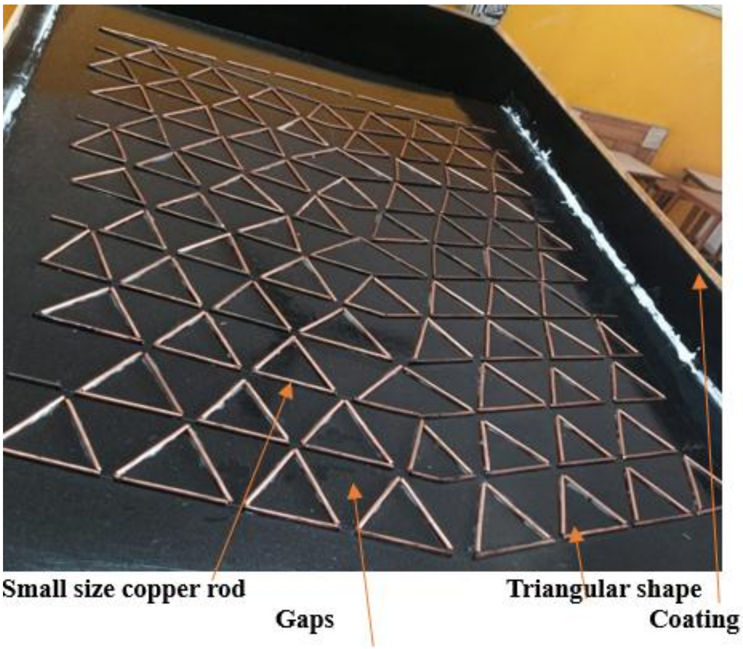

Figure 3.1: Triangular shape, in Absorber plate setup

The absorber plate is fabricated from mild steel and used as the primary heat-absorbing surface of the system. Mild steel is selected because it absorbs solar radiation efficiently and heats up rapidly when exposed to sunlight. The dimensions of the absorber plate are 1200 mm × 900 mm × 1.5 mm (length × width × thickness). To further enhance the absorption of solar energy, the entire surface of the absorber plate is coated with black paint, which minimizes reflection losses and improves thermal absorption.

After painting, copper wire is installed on the absorber plate to enhance heat transfer characteristics. A copper wire of 3 mm diameter is used, and the selection of relatively thick copper wire is intended to ensure that the absorber plate attains a higher and more uniform temperature. A total of 81 triangular-shaped roughness elements are formed on the absorber plate using the copper wire. The wire is cut into lengths of 80 mm, while in some rows 40 mm small pieces are used, and these pieces are bent into triangular shapes. The triangular copper wire ribs are fixed onto the absorber plate using Araldite adhesive, which provides proper bonding and satisfactory thermal contact between the wire and the absorber surface. This triangular roughness arrangement increases the effective heat transfer area and promotes turbulence in the airflow, thereby improving the overall thermal performance of the absorber plate.

Figure 3.2: Experiment Setup

3.3 Data Reduction

The heat transfer coefficient, Nusselt number, Average surface temperature, Average air temperature, Mass flow rates and friction factor have all been calculated using the data that was gathered. Below are relevant equations for the computation of the parameters as well as a few intermediate parameters;

a) Temperature of Air and Plate

The average of all the heated plate's temperatures is the plate's mean temperature. (T_p)

$$T_p = \frac{TP1+TP2+TP3+TP4+TP5+TP6}{6}$$

T_{p1} To T_{p6} are plate's temperatures at different points in °C

b) Average air temperature (T_f) is given by

$$T_f = \frac{Ti+To}{2}$$

Whear Ti and To are inflow and outflow temperatures in °C respectively

c) Mass flow rate measurement(m)

The following formula was used to calculate the mass flow rate of air from the pressure drop data via the orifice meter.

$$M = C_d \text{ x } A_0\sqrt{\frac{2\rho(\Delta Po)}{1-\beta^4}}$$

Whear.

C_d = coefficient of discharge.

$\Delta P_O = 9.81 \text{ x } (\Delta h) \text{ x } \rho_m \text{ x } \sin\theta$

ρ_m = Density of manometer fluid

d) Velocity of the air(V)

By the mass flowrate we can calculate velocity of air through of air through the duct

$$V = \frac{m}{\rho \text{x} W \text{x} H}$$

M = mass flow rate kg/s

W = Duct's width in m

H = Duct's height in m

4. Result and Discussion

Under the prevailing winter climatic conditions of Bhopal, Madhya Pradesh, India, characterized by clear skies, moderate solar radiation, daytime ambient temperatures ranging from approximately 22–27 °C, and relatively low humidity, the performance of the solar air Drayer (SAD) was experimentally investigated with and without ribbed roughness on the absorber plate. These weather conditions are for evaluating the thermal efficiency of SAD systems. The experimental results are discussed in terms of incident solar radiation, air temperature distribution along the flow direction, and overall thermal efficiency of the SAD. Power losses due to auxiliary components such as blowers, valves, and control devices were neglected in the present study.

4.1 Solar radiation

The performance of the solar air Dryer (SAD) was strongly influenced by the incident solar radiation. As solar radiation increased steadily from the morning hours and reached its peak between 12:00 P.M. and 1:00 P.M., after which it gradually declined toward evening. During the three experimental days, ambient conditions remained almost constant, with a maximum radiation difference of about 115 W/m². This small variation indicates similar climatic conditions, resulting in negligible differences in the output performance. Figure 4 also illustrates the hourly variation of solar radiation, where peak values around 1:00 P.M. for the second and third days were nearly the same.

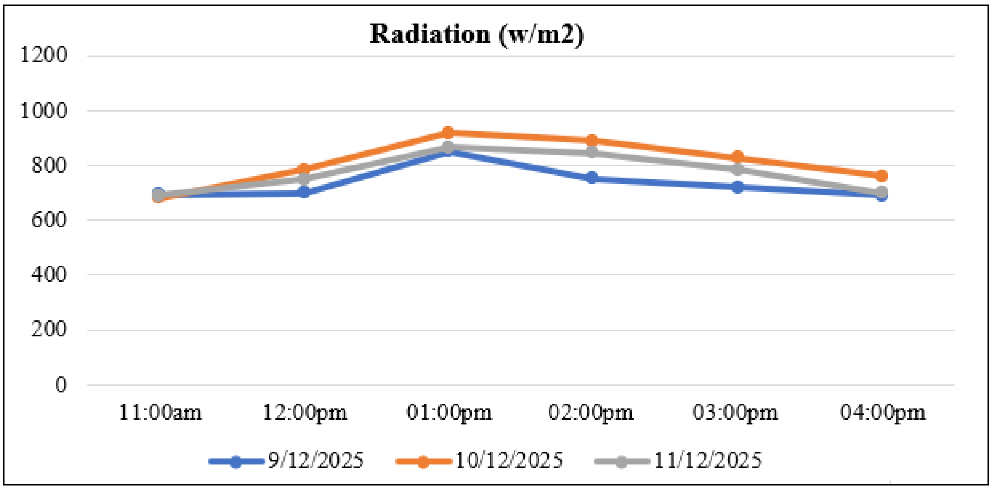

Figure 4.1: Solar radiation

4.2 Temperature of weather

During the experiment, ambient weather conditions were recorded under clear winter days. The ambient temperature varied between 18 °C and 26.5 °C. Such weather conditions affect the heat losses from the solar air heater; however, clear sky conditions ensured sufficient solar

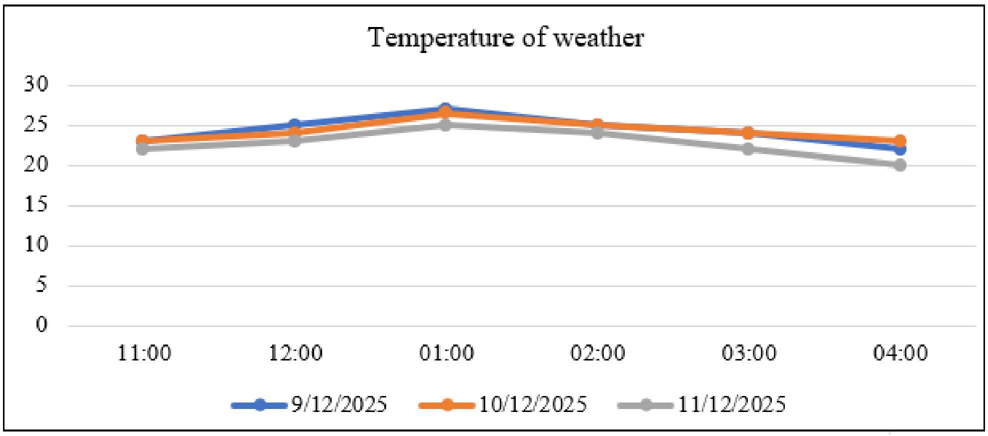

Figure 4.2: Weather Temperature

4.3 Temperature Inlet

Temperature inlet graph indicates that inlet air temperature increases from about 45–48 °C at 11:00 AM (lowest) and reaches a maximum of nearly 58–60 °C around 1:00 PM due to peak solar radiation. After 2:00 PM, the inlet temperature gradually decreases to around 50–52 °C by evening.

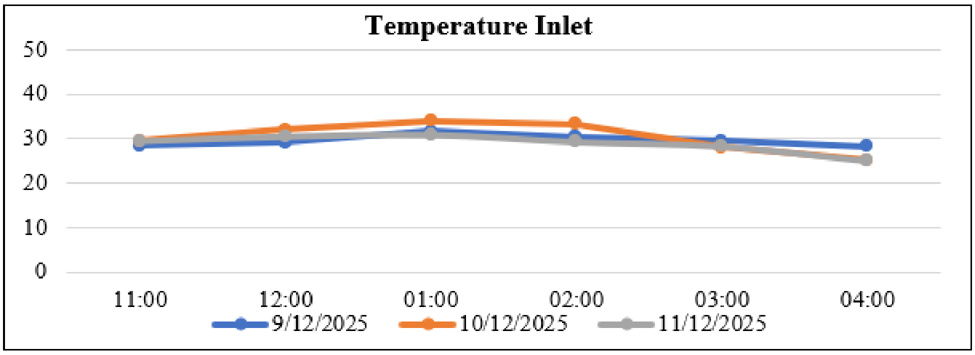

Figure 4.3: Temperature Inlet

4.4 Temperature Outlet

temperature starts around 46 °C at 11:00 AM. The maximum temperature of about 61 °C is observed at 12:00 PM on 10/12/2025, while the minimum temperature is nearly 45 °C at 4:00 PM on 9/12/2025. After noon, the outlet temperature gradually decreases.

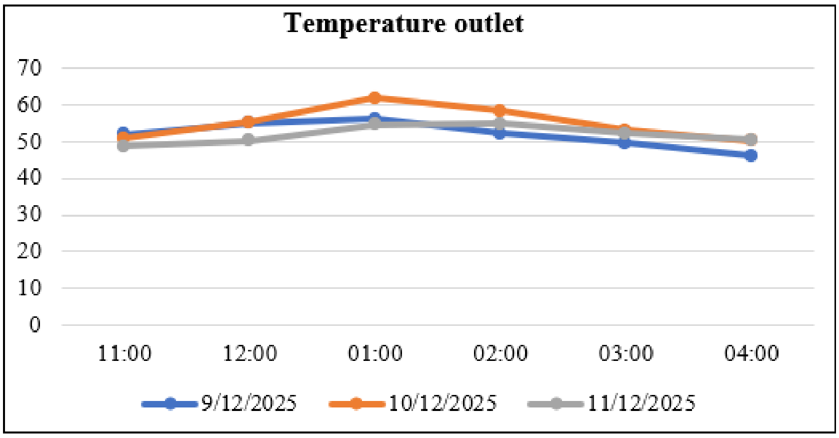

Figure 4.4: Temperature outlet

4.5 Thermal Efficiency

The experimental results clearly indicate that the triangular shaped solar air dryer consistently outer forms the flat plate (DPSAD) system under similar operating conditions. The maximum average thermal efficiency was achieved on 10-12-2025, while a marginal reduction in efficiency was observed on 11-12-2025 due to lower solar irradiance. The superior performance of the triangular configuration is mainly attributed to enhanced turbulence, improved airflow uniformity, and increased air residence time within the drying duct.

- The thermal efficiency of the solar air dryer was experimentally evaluated to assess its capability to convert incident solar radiation into useful thermal energy transferred to the flowing air. The thermal efficiency (η) was determined using the conventional energy balance equation.

$$\eta = \frac{mcp(To-Ti)}{IA}$$

- where m represents the mass flow rate of air (kg/s), c_p is the specific heat of air (J/kg·K), T_o and T_i denote the outlet and inlet air temperatures (°C), respectively, I is the global solar irradiance (W/m²), and A is the effective collector area (m²).
- For the flat plate solar air dryer, the inlet air temperature varied from 18.3°C to 19.6°C, while the outlet air temperature ranged between 46.0°C and 56.2°C. The corresponding solar irradiance during the experimental period fluctuated between 624 W/m² and 852 W/m². Owing to the smooth absorber surface and relatively lower turbulence intensity inside the air duct, the heat transfer rate remained moderate
- On 10th December 2025, the triangular shaped solar air dryer demonstrated the maximum thermal performance among all the tested configurations. The inlet air temperature ranged from 25.2°C to 33.4°C, while the outlet air temperature varied between 50.2°C and 61.7°C. The measured solar irradiance during this day ranged from 681 W/m² to 820 W/m², indicating solar conditions.
- Experiments conducted on 11th December 2025 revealed a slight reduction in thermal performance compared to the previous day. The inlet air temperature varied between 25.1°C and 30.9°C, while the outlet air temperature ranged from 48.7°C to 53.6°C. The solar irradiance was comparatively lower, varying from 528 W/m² to 651 W/m².

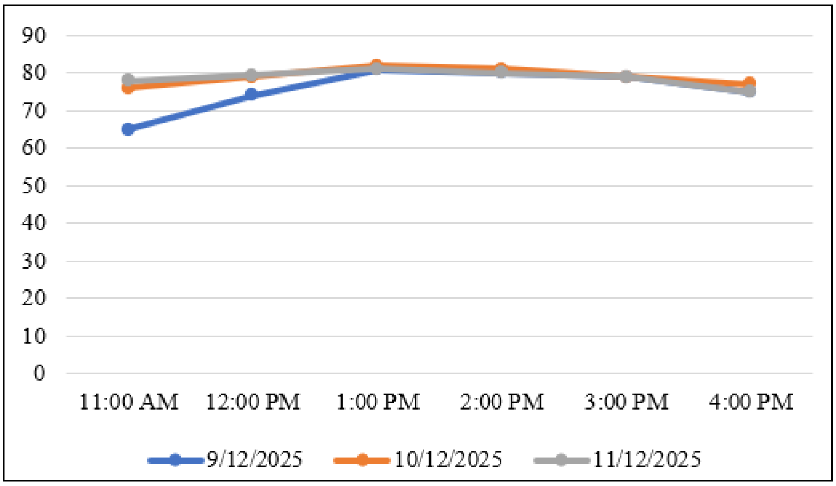

Figure 4.5: Thermal Efficiency

4.6 Future scope

1) The performance of the system can be further improved by exploring advanced artificial roughness geometries and configurations.
2) The present experimental results may be validated through CFD simulations for detailed flow and heat transfer analysis.
3) Integration of thermal energy storage materials can be considered to ensure continuous operation under low solar radiation conditions.
4) Optimization of operating and design parameters such as mass flow rate and duct geometry can be carried out to maximize thermal efficiency.
5) The developed system can be extended to large-scale and practical agricultural drying applications.

5. Conclusion

The experimental investigation confirms that the triangular shape double pass solar air dryer offers superior thermal efficiency, improved convective heat transfer, and higher outlet air temperatures compared to the conventional flat plate configuration. Therefore, the proposed DPSAD can be considered a reliable, efficient, and sustainable solar drying system.

1) Design Effectiveness: The triangular shape double pass solar air dryer (DPSAD) was successfully designed and experimentally evaluated under winter climatic conditions, demonstrating reliable and stable operation throughout the testing period.
2) Effect of Double Pass Airflow: The double pass airflow arrangement significantly increased the residence time of air inside the dryer duct, allowing enhanced heat absorption during both the first and second passes, which directly contributed to improved thermal performance.
3) Role of Triangular Duct Geometry: The triangular duct configuration promoted better airflow distribution and minimized flow stagnation zones, resulting in a more uniform temperature profile along the air flow direction.
4) Impact of Triangular Copper Wire Roughness: The triangular-shaped copper wire roughness elements mounted on the mild steel absorber plate effectively induced airflow turbulence, thereby enhancing convective heat transfer between the absorber surface and the flowing air.
5) Thermal Performance Improvement: Due to the combined effect of triangular geometry, double pass arrangement, and artificial roughness, higher outlet air temperatures were achieved compared to the conventional flat plate solar air dryer.
6) Day-wise Thermal Efficiency Analysis: The maximum thermal performance was observed on 10 December 2025, with an average thermal efficiency of approximately 86%.
7) On 11 December 2025, a slightly lower average thermal efficiency of about 83% was recorded, mainly due to comparatively lower solar irradiance.
8) Comparison with Flat Plate Solar Air Dryer: The flat plate solar air dryer exhibited a lower average thermal efficiency of approximately 81%, which can be attributed to reduced turbulence intensity and limited air–plate heat transfer.
9) Energy Utilization and Stability: The triangular shape DPSAD demonstrated better energy utilization, consistent thermal performance, and stable outlet temperature under similar operating conditions.
10) Practical Applicability: The enhanced thermal efficiency and uniform heating characteristics make the triangular shape DPSAD suitable for low- to medium-temperature agricultural and industrial drying applications.

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