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Experimental Investigation of Two-Pass Solar Dryer with V-Corrugated Absorber for Potato Slice Drying

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Abstract: Reducing the moisture level of food items can help prevent bacterial development and deterioration, extend shelf life, reduce packaging, and improve storage for convenient transportation. In this paper, a two-pass solar dryer with V-Corrugated absorber plate is developed. Its experimental performance evaluation in forced convection is carried out for potato chip drying. Various parameters like Hourly Variation of Solar Radiation Intensity, Temperature Distribution Curves inside Solar Dryer, Collector Efficiency Curve, Hourly Mass Loss of Potato Slices and Moisture Removal Comparison with Conventional Open Sun Drying Method are calculated and presented graphically. The peak temperature of the absorber plate reached 69.30C, and the air temperature at the collector outlet recorded the highest value at 57.5^{0}C. The average temperature difference of 28.58^{0}C is obtained for heat transfer by convection between the modified corrugated absorber plate and the air. An important finding in this experimental investigation was that there is an average 6.5^{0}C difference in temperature between the hot air exiting the collector and the air available at the bottom of the lower tray of the drying chamber, which should be reduced by applying means of avoiding heat loss. The highest collector efficiency is calculated as 88.9 % at 2 PM. The lowest efficiency is calculated at 9 AM as 66.8 %. The thermal inertia of the system adds to the collector efficiency in the last 2 hours of the experimentation and hence collector performs better than in the morning hours, though the insolation is nearly the same for the first and last two hours of sunshine. The percentage reduction in drying time was found to be 38.9 % for 50 % moisture removal from potato slices as compared to open sun drying.

Introduction

The method of moisture removal, including synchronous heat & mass transfer, is known as drying (Lamidi et al., 2019). Drying is a traditional food preservation technique that offers an extended shelf life, ease of transportation with reduced produce weight, and compact storage space (Ertekin and Yaldiz, 2004). The continuous rise of the global population creates a huge demand for food. To maintain the food demand and supply ecosystem, not only increased food production but also decreased perishable food products should be taken care of. Drying is the best option among all the techniques for preserving food over a long period. Drying can increase shelf life, preserve nutrition, flavour, and look of the food, minimize packaging, and shipping charges (Alp and Bulantekin, 2021; Kong et al., 2024; Omolola et al., 2017). Removing moisture from the agricultural produce involves consuming a huge amount of thermal energy (Plappally, 2012). Therefore, clean energy utilization in the drying sector efficiently solves energy depletion and associated environmental degradation. Renewable energy is available in several forms, such as biomass, solar, and wind energy. Solar energy is a non-exhaustive energy source used

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extensively for agricultural produce drying (Bal et al., 2010; Sudhakar, 2021). Solar drying techniques can be classified into four broad categories: (a) Sun or Natural Drying: The dried product is exposed to climatic conditions (Tiwari, 2016). (b) Direct Solar Dryers: The dried product is kept in the drying chamber with a transparent glass cover and side walls. The drying is achieved by directly absorbing solar radiation (Ekechukwu and Norton, 1999; Janjai and Bala, 2012). (c) Indirect Solar Dryers: The product being dried is to be kept inside the chamber and dried with pre-heated air that was heated in the solar air heater (García-Valladares et al., 2020). (d) Mixed Solar Dryers: This incorporates a mix of indirect & direct solar dryers (El-Sebaii and Shalaby, 2012).

In the past decade, many researchers (Majumder et al., 2022; Ndukwu et al., 2018; Pandey et al., 2024) have been reported focusing on aspects such as augmentation of the coefficient of heat transfer between air & absorber plate, flow passage modification, shortening the drying time, different configurations of drying chamber etc. Ertekin and Yaldiz (2004) studied the eggplant's thin layer behavior in a laboratory dryer, using heated ambient air and velocities from 0.5 to 2.0 m/s. They reported the drying characteristics and found shorter drying times with an increase in the drying air temperature and velocity (Ertekin and Yaldiz, 2004). The performance of an indirect sun dryer that is especially made for Meknes's (Morocco) climate and geography for the drying process of banana slices were studied by Ennissioui and El Rhafiki (2023). Their Solar Air Collector gave the maximum air outlet temperature of 58^0C. Vigneswaran et al. (2024) developed an indirect cabinet-type solar dryer with cost-effectiveness for removal of green peas moisture to a level of 14–15 % with very less use of external sources. Kherrafi et al. (2023) reported an increase of 33 % in the economic efficiency of their flat plate collector integrated with offset strip fins when compared to the conventional dryer. A comparative investigation of a flat plate collector & an evacuated tube collector (ETC) implying mathematical models and ANSYS Fluent simulations was presented by Kandukuri et al. (2024) and as per their findings, a significant enhancement in turbulence, air velocity, heat and mass transfer is observed due to perforated baffles. In another study for banana slice drying, El-Sebaey et al. (2023) investigated chimney-type and fan-type dryers and found that the banana piece moisture content as low as 10.59 % from the chimney-type which was 81 % improvement in the open sun solar dryer. Thanompongchart et al. (2023) designed and tested the automatic auxiliary heating unit for solar dryers and found a reduction of 12.5 hours from 32 hours in drying time with the automatic auxiliary heating unit-enabled dryer. The corrugated shot-blasted absorber's performance compared with flat plate was investigated by Ganesh Kumar et al. (2024) and found that the corrugated shot-blasted absorbers indicated a higher heat-absorbing capacity as compared to flat plate absorber (Ganesh Kumar et al., 2024). Table 1 represents the tabular summary of the literature reviewed.

In the past 5 years, many researchers worked on the flow passage modifications for augmentation of the heat transfer coefficient between absorber plate and air in solar dryers. The research gap evident from the previous literature is the breaking of the laminar sub-layer flow immediately adhering to the absorber plate. The present work develops an absorber plate with V-corrugation (APV) to break the laminar sublayer. The presented research focuses on the experimental assessment of a two-pass solar air heater with an Absorber Plate with V-corrugation (APV) for drying potato chips.

Idea and Execution

In the present work, the idea of enhancing turbulence in the incoming air which in turn will be helpful to break the laminar sub layer of the air flow field near the absorber. The idea of breaking the laminar sub-layer will facilitate the augmentation of the coefficient heat transfer between the air and the absorber plate, leading to efficient drying of the food products. To achieve the aforementioned, an absorber plate of V-Corrugated shape was fabricated, bending the galvanized iron sheet of 2 mm thickness with the help of a hydraulic press. The V-corrugation absorber plate is chosen for flow passage modification as it adds to the absorber plate's increased heat transfer surface area and introduces turbulence in the flow, which are the essential parameters to augment the heat transfer coefficient. The absorber plate is so placed that it creates a double pass for the inlet air before it enters the drying chamber. A 4 mm glass is used as a top transparent cover and the collector casing is made up of 20 mm thick engineered wood. The collector dimensions chosen are 1200 mm in length and 750 mm in width. The absorber plate's projected dimensions are 1000 mm in length and 750 mm in width.

The hot air after the collector enters the drying chamber from the bottom. The drying chamber consists of three tiers made up of 10 x 10 x 2 mm wire mesh. The drying chamber volume is 900 x 500 x 750 cu. mm. A chimney is installed at the top of the chamber for venting the air outside. Figure 1 shows the schematic of experimental setup along with the position of

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thermocouples. The photographs of the developed solar dryer test rig are shown in figure 2.

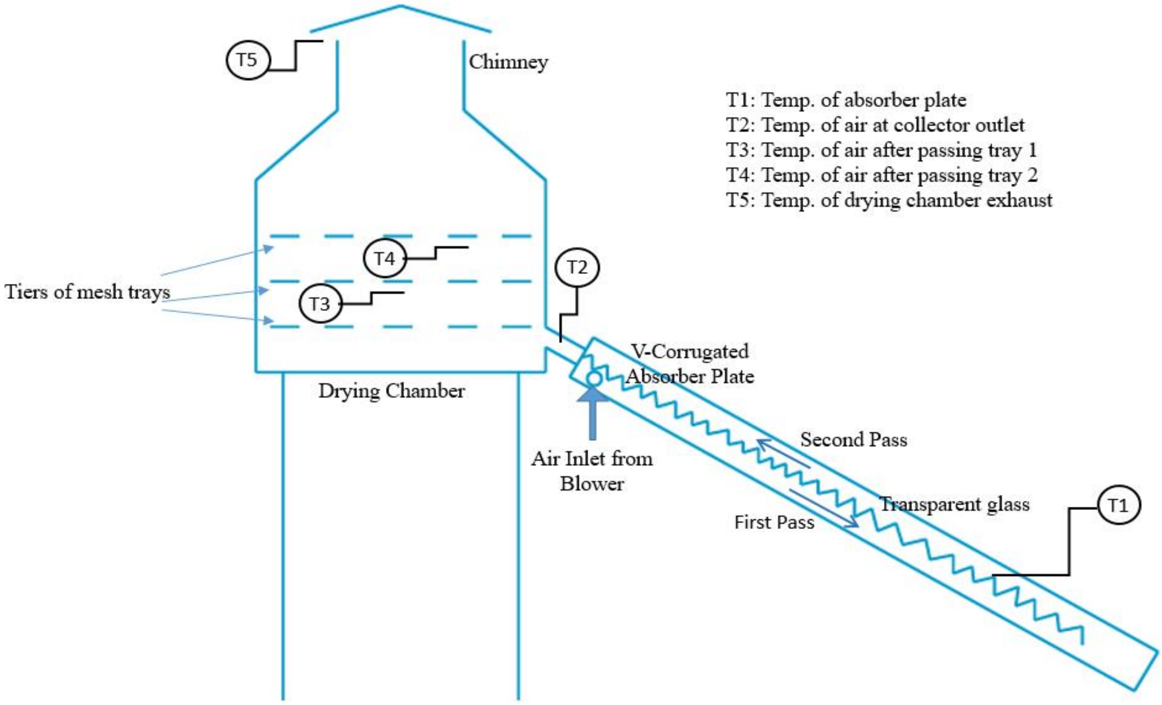

Figure 1. Schematic of Experimental Setup.

Figure 2. Photographs of Solar Dryer Test Rig.

Table 1. Tabular Summary of the Literature.

Reference	Work Summary	Findings
(Kong et al., 2024)	• Reviewed various solar drying technologies including direct, indirect, mixed, and hybrid.	• Summarized construction, working principles, and performance of solar dryers
(El-Sebaii and Shalaby, 2012)	• Review focuses on solar dryers and air heaters for agricultural drying.	• Comprehensive description, foundational principles, and prior research conducted on solar air heaters and dryers are reviewed.

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(Ertekin and Yaldiz, 2004)	• Study on eggplant drying using air temperature, velocity, pre-treatment effects. • Drying models compared for eggplants, the model of Midilli et al. is found to be best.	• The model of Midilli et al. describes eggplant drying curves best. • Drying air temperature and velocity affect drying time significantly. • Thin slice thickness reduces drying time and increases the mean drying rate.
(Ennissioui and El Rhafiki, 2023)	• Designed ISD for local conditions in Meknes, Morocco, with improved moisture removal. • Investigated an indirect solar dryer system for efficient food drying.	• ISD achieved 74.83% moisture reduction, outperforming open solar drying. • Banana slices reduced in mass from 549.76g to 138.41g. • Mean efficiency of SAC and dryer: 23.37% and 18.8% respectively.
(Vigneswaran et al., 2024)	• Cost-effective solar dryer was designed to dehydrate green peas with minimal energy. • Modified solar cabinet dryer compared to conventional solar cabinet dryer in different operating modes for drying efficiency.	• Conventional solar cabinet dryer and modified solar cabinet dryer with 1.2 m/s, and 2 m/s of rate of airflow was found not suitable for green peas' dehydration.
(Kherrafi et al., 2023)	• Developed and investigated solar dryers with offset strip fins for enhanced performance. • Investigated impact on drying rate, economic efficiency, and environmental friendliness.	• Offset strip fins dryer showed higher drying rate than conventional collector. • Offset strip fins dryer had 33% increase in economic efficiency. • Reduced greenhouse gases emission, making dryers environmentally friendly
(Saini et al., 2023)	• Reviewed advancements in solar dryers globally from 2016 to 2021. • Focused on indirect and mixed-mode solar dryers with phase change material.	• Solar dryers with phase change material are more effective. • Indirect-mode forced convection dryers outperform other solar dryers.
(Kandukuri et al., 2024)	• Paper compares flat plate and evacuated tube solar dryers. • Focuses on enhancing drying efficiency and reducing heat loss. • Incorporates thermal energy storage, baffled trays, and phase change material. • Simulation study using ANSYS Fluent software for performance evaluation.	• Baffles with perforation enhance turbulence, heat and mass transfer rates. • Paraffin wax for thermal energy storage enabled autonomous operation for 3.5 hours. • Continuous solar dryer reduces drying time for apricots significantly.
(El-Sebaey et al., 2023)	• Investigated thermal performance of indirect solar dryers for drying bananas. • Designed and fabricated chimney-type and fan-type solar dryers.	• Chimney-type dryer showed 81% improvement in drying compared to open sun. • Indirect solar dryer dried bananas faster and shielded from pollution.

(Thanompongchart et al., 2023)	• Automatic control improves solar dryer performance. • Aims to design and test an auxiliary heating unit for solar dryers. • Auxiliary heating unit reduces drying time and enhances product quality.	• Reduced drying time to 12.5 hours from 32 hours. • Improved product quality with low pigmentation. • Economic analysis showed a payback schedule shorter than three months. • An auxiliary heating unit incorporated in Solar dryer enhance drying efficiency.
(Ganesh Kumar et al., 2024)	• Research compares performance of solar air heaters with different absorber plates. • Incorporates shot-blasted absorbers and pebble stones for improved efficiency.	• Corrugated shot-blasted absorber plate design shows higher heat-absorbing capacity than Flat plate absorber solar air heater. • Pebble stones enhance drying efficiency by approximately 30-36% in different cases. • Carbon credits for CO_2 mitigation are approximately 226.48 and 308.11 Rate $/year.
(Lingayat et al., 2020)	• Reviewed indirect-type solar dryers for agricultural crops. • Focuses on dryer setup, performance, energy storage, and key highlights.	• Forced convection indirect type solar dryers with reflectors improve drying quality. • Triple pass indirect type solar dryer has the highest thermal efficiency.
(Kalaiarasi et al., 2016)	• Experimental energy and exergy analysis of a novel flat plate solar air heater. • Designed with integrated sensible heat storage for enhanced performance.	• Solar air heaters with sensible heat storage outperformed conventional SAH without storage. • Experiments showed energy efficiency of 49.4 - 59.2% and exergy efficiency of 18.25 - 37.53%.

Analytical Correlations Available in the Literature

Drying Efficiency

It is associated with moisture removal energy provided by the wet product during drying. The drying efficiency in forced convection is given by equation 1 (Arun et al., 2020) :

$$\eta_{Drying} = \frac{m_{water} h_{fg}}{A_c I + P_b} \quad \text{Eq. 1}$$

where m_{water} is water mass evaporated per second from the produce to be dried, h_{fg} is the latent heat of evaporation for water in kJ/kg, A_c is the collector area in m^2, I is the solar irradiation in W/m^2 and P_b is the blower power in W.

Heat Required for Drying

It is given as

$$q = m_{air} C_{air} (T_{c,out} - T_{c,in}) \quad \text{Eq. 2}$$

Where m_{air} is the flow rate of mass of air through the collector, C_{air} is the specific heat of air at constant pressure and $T_{c,out}$ & $T_{c,in}$ are the air temperatures at collector exit and inlet, respectively (Young and Wilcock, 2002).

Efficiency of collector

The ratio of the available heat for drying within the solar air collector to the total amount radiation incident on the solar collector is known as collector efficiency and is given by the following correlation (Huang et al., 2024).

$$\eta_{collector} = \frac{m_{air} C_{air} (T_{c,out} - T_{c,in})}{A_c I} \quad \text{Eq. 3}$$

Moisture Content

The following equation gives the moisture content of the product to be dried (Pepler et al., 2006).

$$Moisture\ Content\ (\%) = \frac{Initial\ Mass - Dry\ Mass}{Dry\ Mass} \times 100 \quad \text{Eq. 4}$$

Materials and Method

Instrumentation & Data Acquisition

The experimental setup was built as shown in figure 1 and parameters like temperature at various points, velocity of air, solar radiation intensity etc. were recorded. The following instruments were employed for measurement.

- Digital Thermometers: For measurement of air temperatures at different points in the collector and drying chamber. The accuracy of the thermometer is ± 0.1^{0}C.
- Anemometer: Model HTC AVM-03 to measure velocity of air with ± 0.05 m/s accuracy.
- Lux Meter: G-Tech LX 103 2,00,000LUX Light Meter with inbuilt Sensor for measurement of solar radiation intensity with the range of 200000 LUX and an accuracy of 0.05 LUX

Digital Weighing Scale: For measurement of the mass of potato chips before and after experimentation with an accuracy of 0.005 grams.

Preparation of Potato Samples for Testing

For experiments, we have chosen potatoes from the Nagpur region of Maharashtra State in India with an average uniform size of 6.5 mm and slices/ chips of average diameter of 6.2 mm to 6.3 mm and 3 mm thick were prepared.

Moisture Content of Potato

The moisture content of the potato slices on a dry basis is found out by using equation (4) given by Lingayat et al. (2020). The convection oven method is used to find the dry mass of the 5 batches of potato slices and the estimated values are presented in Table 2.

Table 2. Moisture Content of five batches of Potato Slices.

	Potato Slices batch				
	1	2	3	4	5
Initial mass (grams)	2131.36	2790.72	2103.66	1961.56	1916.08
Dried mass (grams)	1211	1632	1209	1102	1114
Moisture Content on Dry basis (%)	76	71	74	78	72

Methodology

The experiments on a fabricated two-pass solar dryer with a modified absorber plate having V-shaped corrugation were carried out on 22nd May 2023 at the roof top of Suryodaya College of Engineering & Technology, Nagpur, Maharashtra, India (Latitude: 21°0846.72" N ;

Longitude: 79°05'5.68" E). The experimental procedure followed is described as under-

- The tilt angle for the modified AFPC with V-Corrugated absorber plate is kept at 28 degrees facing south.
- The prepared samples of 1 kg potato were weighed before keeping them in the drying chamber.
- The blower is put ON and the air is allowed to pass through the collector's 1st & 2nd pass and then to the drying chamber. Air at the mass flow rate of 2.3 m^3/min at constant velocity is pumped with the help of an external blower through the inlet of the AFPC.
- The solar radiation intensity is measured with the help of Lux meter and recorded on hourly basis.
- The temperatures at blower outlet, absorber plate, collector outlet, drying chamber etc. are recorded. The ambient temperature is also noted. The temperatures are recorded for each time interval of an hour from 9:00 AM to 6:00 PM.
- After each time interval of an hour the mass of the potato slices is recorded separately for each tray.

The utmost care has been taken while measuring and recording the data. The average ambient temperature recorded was 36.53^{0}C while the relative humidity was 33.71 % (averaged).

Results & Discussions

1. *Hourly Variation of Solar Radiation Intensity*

The variation of temperature with respect to various other parameters is presented in this section. Understanding temperature distribution is essential to puzzle out the Solar Dryer's overall operation and its solar energy utilizing capacity. The dynamic performance of solar dryers can be understood by closely observing the hourly solar radiation intensity variation. Figure 3 shows the hourly solar radiation intensity variation during the experimentation day in Nagpur. The solar radiation intensity was recorded hourly from 9 AM to 6 PM with the help of G-Tech LX 103 200000 LUX Light Meter. The lowest solar radiation intensity of 767.9 W/m^2 was recorded at 9 AM as the sun is at its lowest horizon, while the maximum solar radiation intensity was observed to be 885.7 W/m^2 at 2 PM again with the fact that at this time, the sun is at its highest horizon right on top of the head. The average insolation is observed to be 837.73 W/m^2.

2. *Temperature Distribution Curves inside Solar Drye*

Figure 4 offers intuitive information about how the dryer's temperature varies during the day. The temperature records within the dryer indicate that the temperature changes according to the position in the system. More specifically, it was discovered that when air passed through various tiers of the drying trays, the

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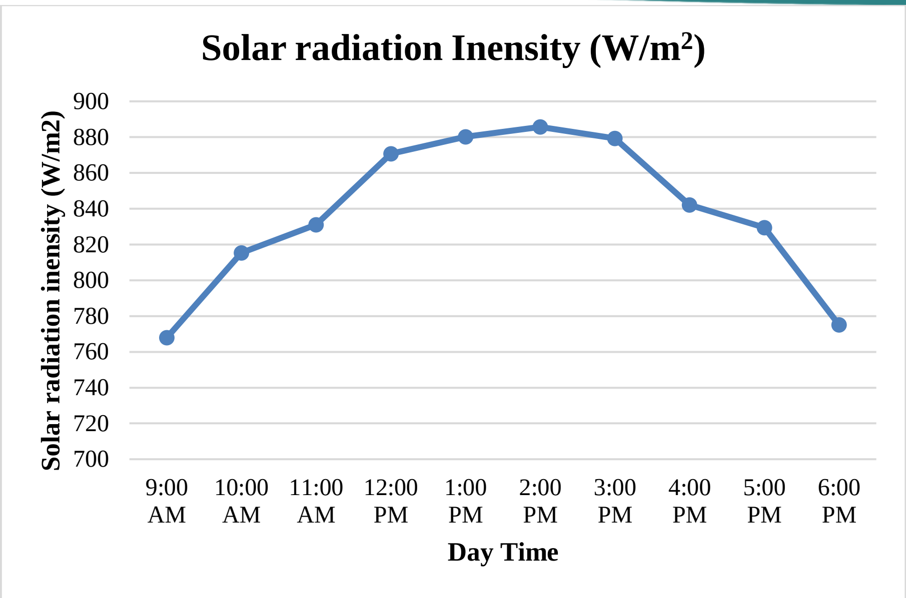

Figure 3. Hourly Variation of Solar Radiation Intensity.

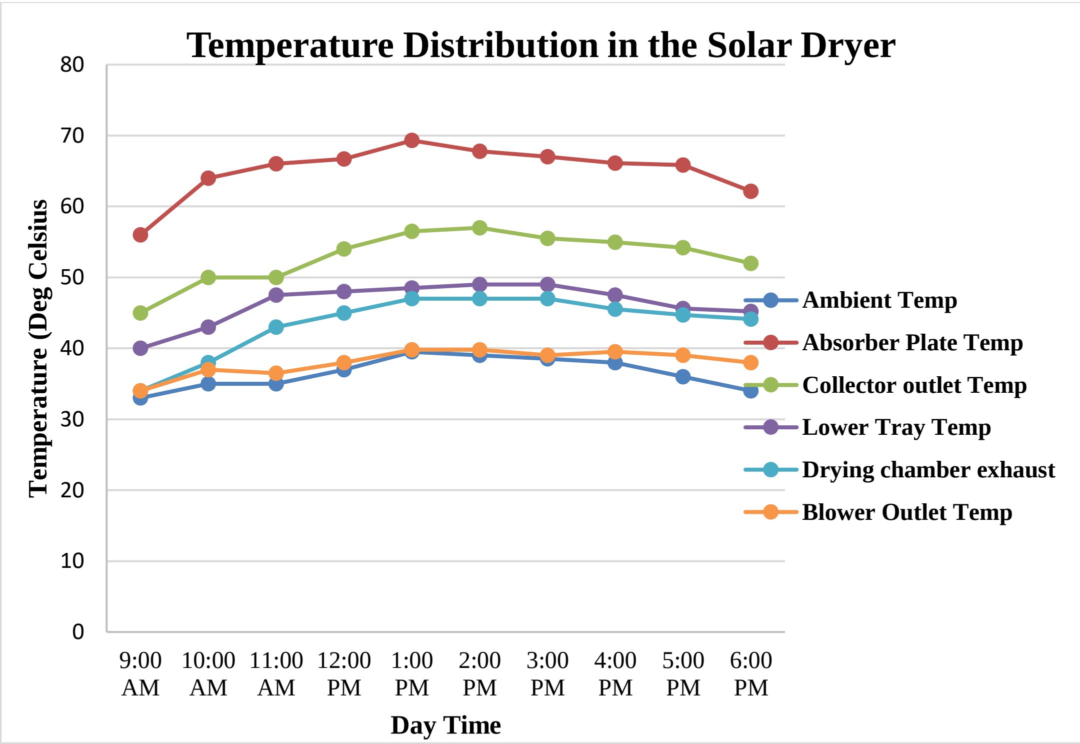

Figure 4. Various Temperature Distribution Curves.

temperature was on the higher side at the AFPC exit and progressively dropped at the chimney exit. The peak of every temperature curve occurred around 1 PM as the sun at that time was overhead and the beam radiation was maximum. The highest temperature up to which the absorber plate was heated was 69.3^{0}C, and the peak air temperature at the collector exit was recorded as 57.5^{0}C. The average temperature difference for heat transfer by convection between the corrugated plate and the air is 28.58^{0}C. A significant observation here was that the average difference between the exit air temperature from the collector and the air temperature available at the bottom of the lower tray inside the drying chamber is 6.5^{0}C which is significantly high and should be reduced to get higher drying efficiency. This drop in temperature between the outlet air from the collector and the air available at the bottom of the lower tray inside the drying chamber has occurred due to the fact that the gets expanded through the narrow connector pipe between the collector and the bottom of the drying chamber and expansion causes temperature drop. The average air temperature difference at the outlet of the developed V-corrugated collector is 14.85^{0}C and that of the Kherrafi's offset strip fins dryer is 11.3^{0}C (Kherrafi et al., 2023).

3. Collector Efficiency Curve

The hourly collector efficiency is shown in the fig 5. It is evident that the efficiency is very sensitive to the hour of the day and never indicates even a near constant value for any consecutive hour. Since insolation fluctuates by a value of 10 to 15 W/m^2, one cannot expect a constant performance efficiency from the Solar Collector and any solar thermal energy conversion device. Moreover, the highest efficiency is calculated as 88.9 % at 2 PM. The lowest efficiency is calculated at 9 AM as 66.8 %. The noteworthy point in the collector efficiency is that, though the insolation curve shows a rough symmetry at about 2 PM -the solar radiation intensity follows the roughly same trend (but in reverse), meaning the insolation at end of the sunshine hours i.e., at 6 PM is roughly equal to the insolation at start of the experiment i.e., 9 AM- but the efficiency curve does not follow the same trend. This is because though the insolation may be the same intensity in the morning and evening hours, the system's thermal inertia adds a higher efficiency trend, unlike in morning hours. The collector efficiency of the developed two-pass solar air heater with Absorber Plate having V-corrugation (APV) ranges from 66.84 % to 82.72 %, which is fairly better than 39.05 to 53.12 % of Ganeshkumar's absorber plate having corrugation with shot-blasting (Ganesh Kumar et al., 2024).

4. Mass Loss of Potato Slices

The loss in mass of the potato slices per hour of the day time for each tray has been recorded with the help of an electronic weighing scale. The loss in mass per hour of the potato slices from each tray was plotted in the figure 6. It can be observed that the mass loss started at the very first hour of the day time. The slope of the curve representing mass loss from tray 1 (lower tray) is steeper as compared to the slopes of the curves representing the middle and the top tray, as the lower tray comes in contact with the hottest air directly from the collector. It can also be observed that the maximum mass loss per hour from each tray occurs from 1 PM to 3 PM as the insolation, efficiency and temperature differences are at the peak during this period. The total loss in mass for tray 1, 2 & 3 is recorded as 208, 158 and 160 grams, respectively. The collector efficiency curve is shown in figure 5.

5. Mass Loss of Potato Slices

The loss in mass of the potato slices per hour of the daytime for each tray has been recorded with the help of an electronic weighing scale. The loss in mass per hour of the potato slices from each tray was plotted in figure 6. It can be observed that the mass loss started at the very first hour of the daytime. The slope of the curve representing mass loss from tray 1 (lower tray) is steeper as compared to the slopes of the curves representing the middle and the top tray, as the lower tray comes in contact with the hottest air directly from the collector. It can also be observed that the maximum mass loss per hour from each tray occurs from 1 PM to 3 PM as the insolation, efficiency and temperature differences are at the peak during this period. The total loss in mass for trays 1, 2 & 3 is recorded as 208, 158 and 160 grams, respectively.

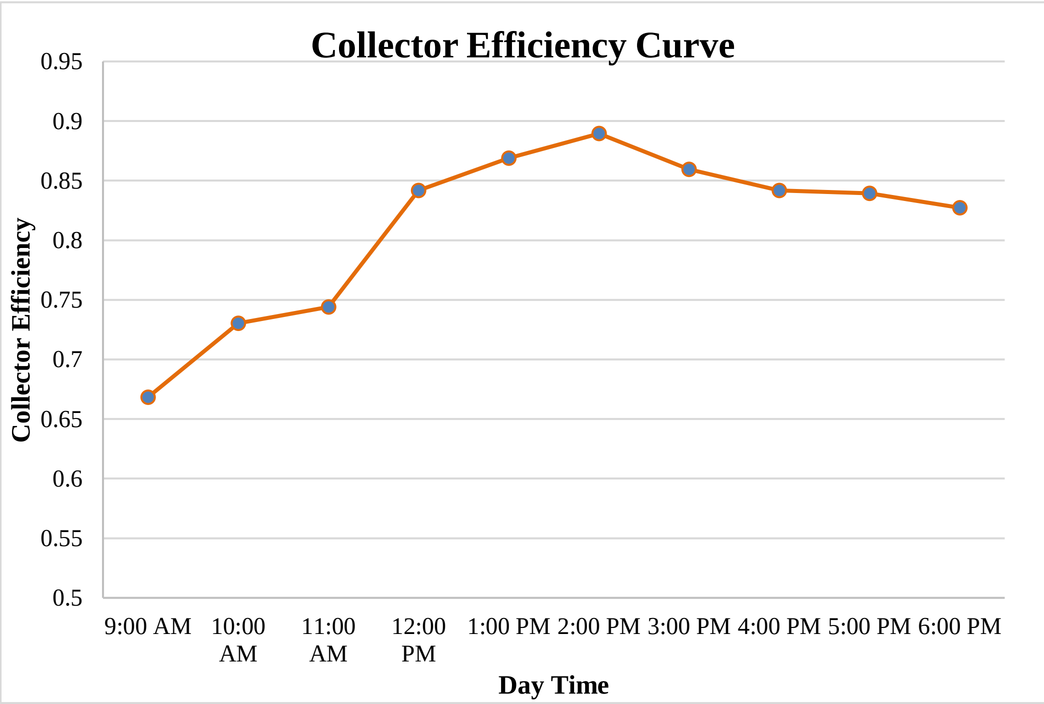

Figure 5. Collector Efficiency Curve.

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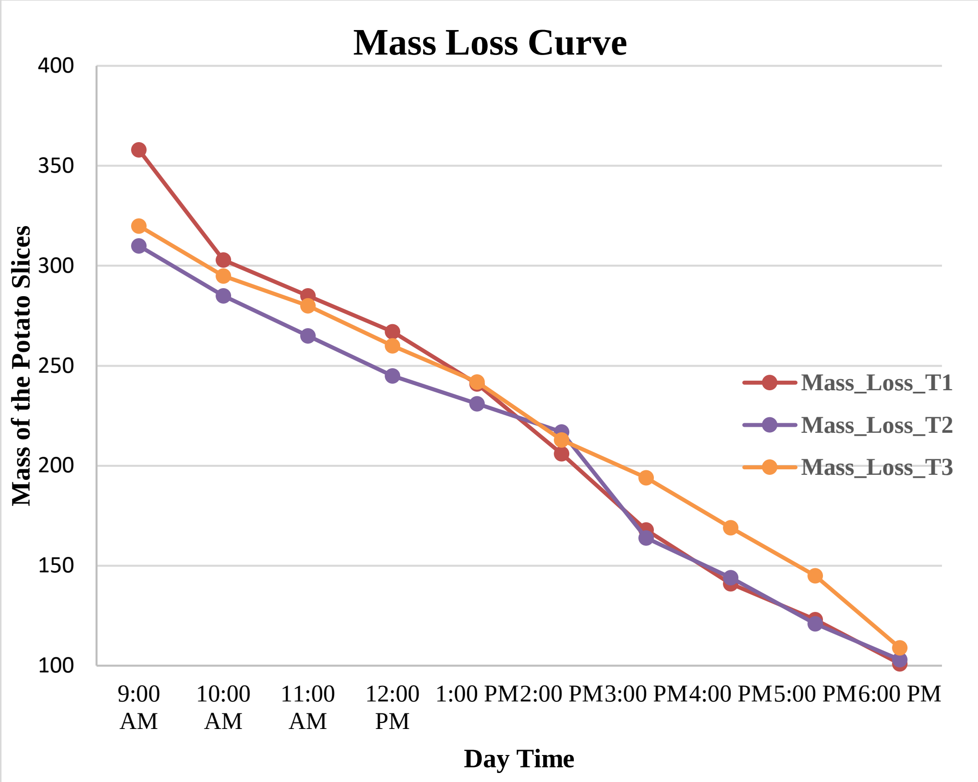

Figure 6. Mass Loss versus Day Time.

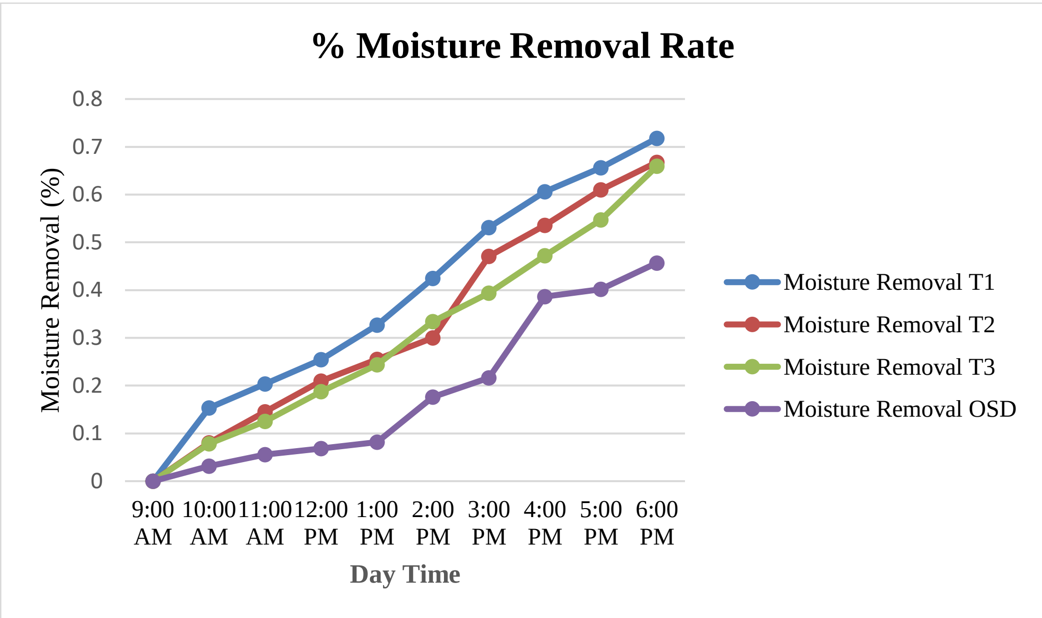

Figure 7. Moisture Removal Comparison with Open Sun Drying.

6. Moisture Removal Comparison with Conventional Drying Method in Open Sun

Figure 7 compares moisture removal from the potato slices kept in different tiers in the developed solar dryer with a modified absorber plate having V-shaped corrugation and the potato slices dried in the open sun. It is evident from the plot that even the topmost tier in the drying chamber shows far better moisture removal than that of the conventional open-sun drying method. The distribution of heat and, hence, the drying chamber temperature is not uniform, which is obvious as the tray in the lowest tier comes across the hot air first and the air, after removing moisture and losing heat, goes to the next tiers inside the drying chamber. The percentage reduction in drying time was found to be 38.9 % for 0.5 dry potato slices as compared to open sun drying.

Conclusion

A solar dryer incorporated with a modified absorber plate having V-shaped corrugation is designed and developed and experimental investigation of various performance parameters is carried out under forced convection.

The highest and lowest insolation occurred at 2 PM and 9 AM, respectively. By deploying the designed solar dryer, the ambient air temperature was raised to 28.58^{0}C in forced convection. The loss of drop in temperature from the collector outlet to the lower tray in the drying chamber was 6.5^{0}C, which is significantly high and should be reduced to get higher drying efficiency. The collector efficiency is at its peak at 2 PM since the insolation is highest at this hour. The peak collector efficiency of the developed solar air heater is 82.72 %, which is fairly better than 53.12 % of Ganesh Kumar's absorber plate having corrugation with shot-blasting (Ganesh Kumar et al., 2024). The thermal inertia of the system ensures better collector efficiency at the tail hours of the sunshine duration than the morning hours, though the insolation for both spells is roughly same. The moisture removal in the designed solar dryer is far better than that of the drying method under open sun. The drying time is reduced to 38.9 % 50 % moisture removal from potato slices as compared to open sun drying. The average air temperature difference at the outlet of the developed V-corrugated collector is 14.85^{0}C and that of the Kherrafi's offset strip fins dryer is 11.3^{0}C (Kherrafi et al., 2023). The present study will surely provide a concrete reference in the field of solar dryers and the experimental results and inferences will help researchers, agriculturists, policymakers and other stakeholders in their ongoing efforts to create ecologically friendly drying solutions.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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